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THE IMPACT OF PARAMETRIC DESIGN METHODOLOGIES ON CREATIVITY IN HOSPITAL DESIGN PROCESS

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Abstract

This research investigates the potential impact on design creativity of using parametric CAD methodologies (BIM design and algorithmic design) in the early design stage/process of hospital buildings. The research design consists of comparative studies between parametric and nonparametric CAD methods, and the study of creativity, which focuses on two domains: process creativity and product creativity. Besides, the study extends the creativity research to the area of reviewing design behaviour and design cognition to investigate the advantage and disadvantage of using CAD to improve, or hinder, the performance of the problem solver throughout the design process. The selection of research methodologies was designed to support evidence-based objective research findings. Dual methodologies were employed: 1. a retrospective questionnaire evaluation of design performance and 2. a computer-based protocol analysis of the on-going design process.

The first part of the research findings went through a questionnaire survey and the data was mined, processed and statistically analysed using the SPSS package. Two seminal works were used and adopted as a bench mark criteria for assessing and determining creativity during the design process: that of Torrance's test for creative thinking (TTCT) for measuring creativity as a 'process' and that of Amabile for appraising creativity as a 'product'. The result indicates that parametric CAD, especially the algorithmic CAD method, significantly supports the creativity process during the initial hospital ideation process and is significantly different from the other two CAD methods in the production of idea numbers, variety, and uniqueness. While judging the product creativity of the hospital building design, the parametric CAD architects (the algorithmic CAD and the BIM design) both reported that the CAD working environment helped a lot in this regard. On the one hand, the BIM group replace reported with either that CAD supported them in their idea development, spatial functional coordination, and design message delivery. On the other hand, the algorithmic

CAD group recounted that the CAD method enhanced the elaboration of their ideas and novel thinking.

In the design cognition review, the computer-based protocol analysis was applied to investigate the ongoing design process with different CAD groups. It was found that when using the algorithmic CAD process, the participants could construct to a large extent reconstruct their long-term memory (LTM) in the design cognition process, which has ultimately assisted the architects' design learning and helped them focus more on the creation of the design strategy rather than repeatedly using the same examples. Thus, the algorithmic CAD process through suggesting different mathematical interpretation was found to reinforce cognitive design reasoning and offering varied idea segmentation (considered as a measure for divergent thinking, an essential indicator for creativity). It is believed that the CAD method can create a flexible with systematic and associative ideation activity. With this advantage of the algorithmic CAD program, this PhD study also discovered a parameter-based real-time design representation (3D models) and visible design content/script (node diagrams) so architects can instantly revise their design and update their cognitive processes to perform a better design synthesis and evaluate their proposed ideas.

This PhD research will contribute to current architectural design knowledge and future hospital design research and will help to develop a better environment in healthcare design practice as well as in the areas of architectural CAD teaching and Its promotion within the curriculum.

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Chapter 1 – Introduction

1.1 Thesis introduction

This research investigates the potential impact on design creativity through the use of parametric Computer-Aided Design (CAD) methodologies, BIM design and algorithmic design, in the design of hospital buildings.

A hospital is a very specific building typology which plays an important role in social development, from the past to the present. It has accompanied each movement of medicine, science, technology and policy, helping to create civilization. According to future expectations in national research published by the National Health Service (NHS) in the UK, healthcare architecture will need to keep developing innovative design ideas for hospitals, combining these with latest technologies as well as reliable building design processes to create better places for the future healthcare environment (The Nuffield trust, 2001). Therefore, the study of hospital building design in this Ph.D. thesis focuses on the design idea, creativity, an evidence-based process and a workable design approach at the early architectural planning stages rather than talking about design practices such as construction design or building regulations.

Computer Aided Design (CAD) has provided sophisticated progress in engineering research and has also helped efficient development of technology. This research will demonstrate the impact of different CAD methodologies (parametric and non-parametric CAD) on the hospital design ideation process and will discuss the feasibility and potential of the CAD tools for improvement in design creativity as well as the optimization of design cognition in hospital design. Comparative studies between parametric and nonparametric CAD methods are employed in the research plan. The evaluation of creativity includes measurements of creativity, testing the performance of design ideas as well as examining judgments of the building design. Also, the study extends into the area of design behaviour including design cognition, design problem-solving and design planning.

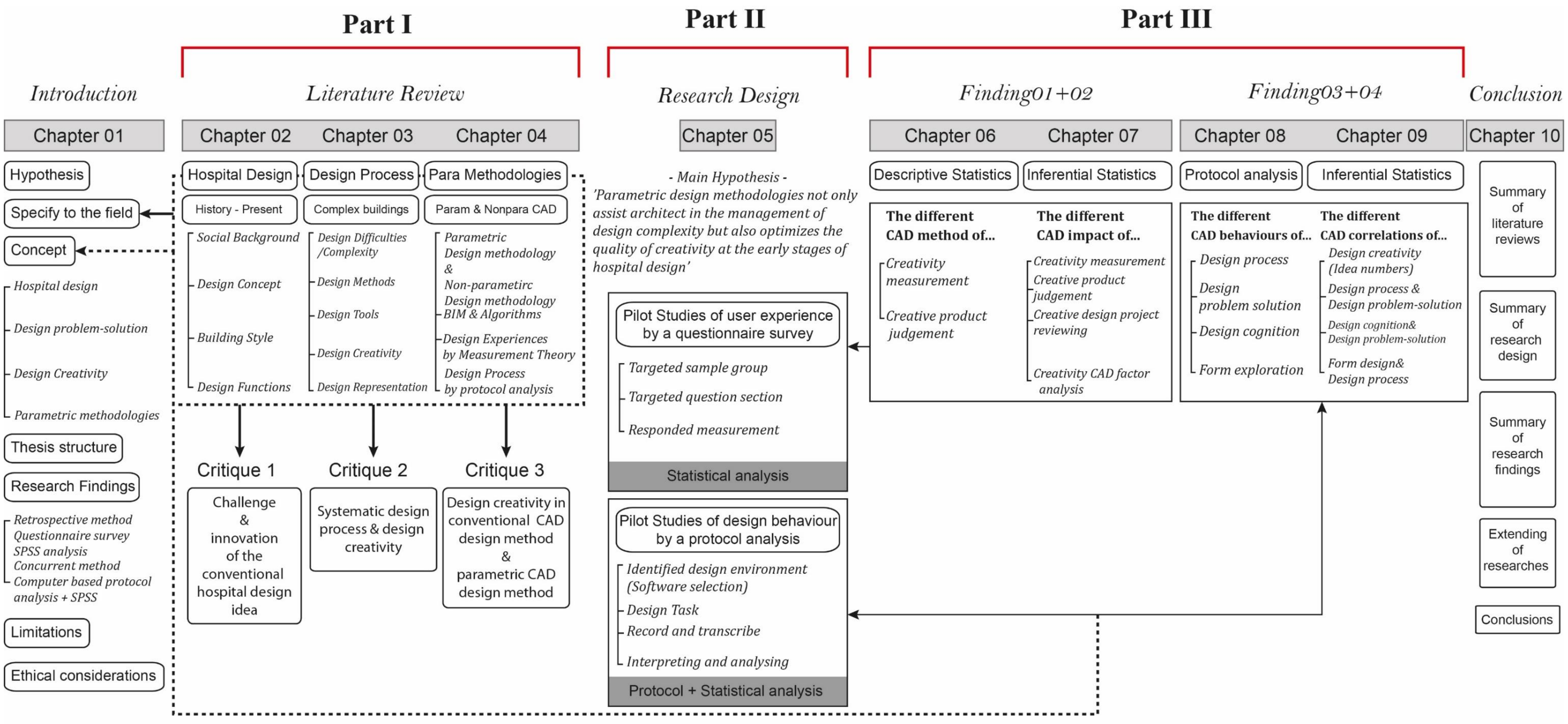
The thesis structure is divided into three parts: *Part I* is a literature review, *Part II* focuses on research design & methodology and *Part III* provides case studies and research findings (Fig.1.1).

The first part, the literature review, contains three relevant research areas for the PhD thesis: hospital design, the hospital design process, and CAD methodologies. Hospital design in Chapter 02 is reviewed from a historical aspect, re-evaluating hospital design ideas and linking the background period with idea innovation in the design solutions. Chapter 03, the chapter on the hospital design process, investigates fundamental aspects of the architectural design process and theory in order to provide a systematic review of hospital design development. Also, a case study of systematic hospital design employed by the UK Department of Health and Social Services (DHSS) in the 1970-80s is introduced as a template for viewing the systematic design methodology in practice.

Design creativity and relevant theory identification and research are also reviewed as important background to discover the necessary research structure. The last chapter on the literature review, Chapter 04, examines computer aided design and its influences on the architectural design profession, and further explores the differences in design thinking and process between parametric and nonparametric CAD.

In Part II, Chapter 5 employs a dual research methodology in the planned study. Two research methods, a survey questionnaire and a protocol analysis, explore different reactions to the comparative study of CAD methods in the hospital design process. The questionnaire evaluation focuses on a longer-term feedback on parametric and nonparametric CAD methods in hospital design. The protocol analysis further takes the investigation into cognitive aspects of the parametric and nonparametric design observation including the architects' design reactions and behaviour while they were engaging in a pre-specified hospital design task. This empirical research method helped to establish objective judgements and arguments for the in-depth investigations.

Fig.1.1 The thesis structure



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Part III contains two case studies. The first is a survey questionnaire based on creativity design measurements for evaluating architects' experience of parametric and nonparametric CAD methods in a hospital design project in practice. The collected data is analysed and interpolated using different statistical methods presented in Chapters 06 and 07. The second is a computer based protocol analysis for a comparative hospital design process study using the different CAD methods. The study data is recorded and transferred using diagrammatic interpolation with the design outputs presented as images in the findings in Chapter 08. Chapter 09 extends this protocol data into a statistical process and further explores the correlation between design behaviour and design creativity.

1.2 Hypothesis

This research aims to explore the potential impact on creativity from the use of parametric Computer-Aided Design (CAD) methodologies in the early design stages of hospital buildings. From a review of literature on hospital design and CAD background, and a short interview with hospital design architects, the research hypothesis is established as follows: *'Parametric design methodologies not only assist the architect in the management of design complexity but also increase the potential of creativity at the early stages of hospital design process'* To verify this hypothesis, the research is designed in three parts.

1. Investigation of the effects of the length of experience of CAD methods among hospital architects, with particular focus on the impact on design creativity at the early stages of the design ideation process.
2. Evaluation of CAD performance when used by experienced CAD consultants in the different aspects of hospital building design, especially the testing of the impact of design variables on factors such as materials, shapes, design plan, etc.
3. Pre-selected CAD architects are asked to participate in a practical design exercise in which their behaviour is studied. This observation aims to find out how the CAD methods applied influence hospital design activities, such as divergent design thinking or the design problem-solving process.

More details of the research design such as sample background, research methodology and related research questions can be found in Chapter 05.

1.3 Significance of the field

As this research title '*The impact of parametric design methodologies on creativity in hospital building'* indicates, the scope of the study is defined by these three areas: the hospital building design process, parametric CAD and design creativity. The following identifies a problem with current research in this field and suggests a new direction for this research development.

Hospital buildings present multiple roles in modern society. From birth to death, critical times in human life are associated with this particular type of architecture. Also, hospitals have a unique function in social care. For example, traditionally in the UK, the local hospital dominates a large part of community identity such as charitable activities, voluntary work, fund-raising and support for the socially vulnerable. On the other hand, progress in medical technology forces hospital design to change more rapidly than any other building type. As Verderber & Fine (2000) cite, more than 40% of hospital budgets are spent on the construction of complex clinical layouts. James & Tatton-Brown (1986) argue that the necessity of increasing hospital facilities has caused the growth of the building size by over 100% when compared with hospitals in past decades. In addition, associated with the new idea of a social healthcare system proposed by the Nuffield Trust (2001), future hospital building design will focus on the specialized treatments rather than providing large amounts of inpatient beds. This means the design of a hospital building, from the earliest proposal stage, should have an organized, reliable, evidence-based and innovative method and should be able to generate better design idea outcomes to achieve this expectation of the future healthcare proposal.

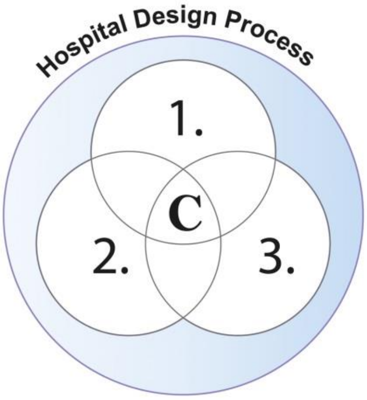
However, there is very limited research material on hospital architecture design focused on the discussion of the design method and ideation process. The majority of research is portfolio based i.e. focussed on reviews of building designs, where there is very little concern with exhibiting the design method or ideation process. Some other sources are mainly written as regulations or guidance, as document-based reports, where it is also difficult to identify and follow the utilization of design ideas. For example, the Health Building Note is a design guide published by the UK Department of Health. Only a few papers focussed on the hospital design approach, ideas and planning, in the earlier period around the 1970s-80s. But these are out of date and are limited to the UK DHSS. (See the case study of the ‘systematic design hospitals’ reviewed in Section 3.4.2-a-b-c, Chapter 03). As a result, those design references are hard to apply to the practices for hospital design ideation and barely help to develop design creativity.

Despite that, computer-based design applications are widely integrated into the current architectural design realm. In particular, the growing use of parametric CAD methods has significantly influenced the development of new architectural design ideation. Novel design projects created by advanced architectural firms such as Zaha Haddie (UK), UNstudio (Netherland), and Foster+Partners (UK) have perfectly demonstrated the potential of parametric CAD and its association with design creativity. Unfortunately, none of the recent research focuses on the topic of design creativity associated with parametric CAD methods or design optimization in the hospital design process. Therefore, this Ph.D. thesis focuses on the above topics and hopes to contribute its findings to the necessary knowledge for future hospital design improvements.

1.4 Key concepts

This thesis investigates the potential effects on design creativity from the use of the parametric CAD methods in the hospital design process. The research will review three aspects of design and seeks to understand how creativity can be identified during the hospital design process. The following figure (Fig.1.2) shows the relationship between three research variables and design creativity: 1. Systematic design process, 2. Design cognition, 3. Parametric CAD process, **C**. Design creativity.

Fig.1.2 The research key concept



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1.4.1 Systematic design process

From the 1960s to the 1980s, the most innovative hospital design plan announced by the DHSS was aimed at developing a new hospital design idea based on a ‘Universal Hospital Space’ and a ‘Low-rise approach’ (Stone, 1980). There were four design exercises or projects: the Greenwich District Hospital, the Best Buy Hospital, the Harness Hospital and the Nucleus Hospital. These were planned using a systematic design standard and helped architects to work efficiently with medical teams and governors to achieve the design concept. Therefore, through understanding and review of these systematic design activities, we can also discover how a systematic design process can support the achievement of the design proposal as well as aid our understanding of the potential impacts on the design creativity.

The British government was the first national authority to bring document-based systematic design methods into hospital building. From the early investigation stages to the final design proposal, this systematic design methodology extensively influenced the coordination and cooperation of different professions in the design team. Regarding the design process itself, the systematic design process clearly shows that hospital design contains much design synthesis before the design moves to the next stage of design evaluation, and that the process involves multiple disciplines, such as finance, zoning and engineering. This cross integration between design areas and functions helps architects to recognize complex design problems and correlations. For example, the method is able to dominate the early stage of hospital design planning following scientific approaches of design data collection, analysis, synthesis and discussion to discover proper solutions at the primary investigation stage (See the case study on 'systematic design hospitals' reviewed in Section 3.4.2-a-b-c, Chapter 03).

1.4.2 Design cognition

Cognitive psychology is the complete opposite of behaviourism, and produces explanations through the study of mental processes (Ashcraft, 2002). According to Neisser & Shepard (1967) 'Cognitive psychology refers to all processes whereby sensory input is transformed, reduced, elaborated, stored, recovered, and used'. The mental process has been likened to an approach of exploring cognitive activity through environmental information. A review of related disciplines such as psychology or neural science could help us to understand the reactions of designers and their mental processes during the design problem-solving process. In addition, a review of creativity in design could consider the related topic of creative behaviour from the different aspect of social forces (Hennessey and Amabile, 2009). Although the current research on creativity is wide, deep and varied, there is no universal conclusion about what creativity is and how to become creative. Hennessey and Amabile (2009) concluded that it is important to use a systematic view in understanding creativity and to identify the interrelated forces working at multiple, wide and different levels.

1.4.3 Parametric CAD process

Parametric architectural design is one of the CAD approaches relevant to the study of contemporary architectural design. There are many creative design projects built by advanced parametric CAD firms, for example, Thomas Heatherwick (UK), Zaha Haddie (UK), and Gehry partners (USA). Their innovative projects are believed to have been influenced by parametric design thought as well as the establishment of new statements in the architectural design process. This process contains variable attributes using mathematical or geometrical algorithms. The parametric model is created by values for parameters or variables, and equations to establish the correlation between objects or geometries (Barrios, 2006). Stavric & Marina (2011) stated that since the parametric idea was created in 1990, two kinds of parametric design have been defined: the first is architectural design using parametric conceptions, the second is architectural design using constructive parameters. In other words, the conceptual parametric design means creating new computing objects, or geometries, and operating them by using parametric values, such as in Grasshopper (a plug-in to Rhinoceros). Furthermore, constructive parametric design can assemble the design elements by using a pre-set parametric system and integrates the relationships for building construction, such as in Revit (Building Information Management/Modelling).

Regarding the design process, parametric CAD is constructed using design parameters with algorithmic structures. It is a mathematically based design process which improves the logical thought of designers and defines problems with relevant design parameters. These parameters present design information and this is able to be coordinated in different design representations such as a link to automatically generate 2D drawings from a 3D drawing (Woodbury, 2010). In addition, parametric design increases the number of ideas in the problem-solution process which means more divergent thinking or creative thought is generated during the design process.

1.5 Design review of hospital departments

Before moving on to the main research sections, this brief introduction to design ideas for hospital departments and facilities provides an overview examining the correlation between design considerations and functional requirements. Especially when compared with general architectural types such as residences or office buildings, the design idea for hospitals has a strict relationship with its functional arrangements (James and Tatton-Brown, 1986). The design concerns are not only for each individual department, but there is also a need to structurally plan for the connection with associated departments. Therefore, this section reviews the departmental design ideas and functions for modern hospital buildings as well as exhibiting the reasoning behind relating medical processes to the spatial layouts.

1.5.1 The inpatient department

The inpatient department comprises mainly ward units and nursing stations. It is the place where patients recover from their sickness while they continuously undergo medical treatment. The place should be comfortable, so the reasonable comfort of patients and help with their recovery in the hospital is the main concept in its design (Health Building Note, 1986).

a) Privacy

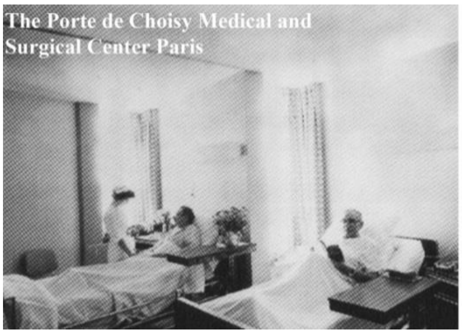
Fig.1.3 The Nightingale's design ward

Cited: Leicestershospitals.nhs.uk, 2017

During the age of modern nursing which was first established by Miss Florence Nightingale, the Nightingale Ward design became the mainstream for modern inpatient departments. Good-ventilation, lighting, and easy supervision were all recognized as the advantages of this design solution. In Europe and the United Kingdom, the Nightingale open ward design (Fig.1.3) was the most common ward style. Although the open ward style of ward unit was evidenced by stable performance, there are many examples of research pointing to the fact that the Nightingale ward design allowed no privacy.

As a result, the small or single room design finally appeared in European hospitals, but it was only evident late in the twentieth century. For example, The Porte de Choisy Medical and Surgical Center (Fig.1.3-1) in Paris, 1962-64 by Stainov and Orieme was a rare European hospital which was designed with a mix of open and single wards. Also, in the University Hospital in Zurich (Fig.1.3-2), 1986-94 by Haessing and Partners arranged sixty-bed departmental floors with eight one-bed wards, twenty two-bed wards, and three four-bed wards. Elsewhere, the privacy issue arose in US hospitals from the early 1940s, many patients reported privacy problems in open ward design, they also raised the issues of noise and interruption during their stays. Consequently, the small or single ward had replaced open wards from the US Hill-Burton period, the period of public health care for hospitals, and until the 1970s almost all American hospitals had only single bed design (Fig.1.3-3) in inpatient centres. Despite this, there was always controversy regarding the single or open/multi-bed design. For example, Dr. Beddard, Senior Administrative Medical Officer for Aberdeen, supported the open ward because it took less time to clean than a single bed ward. Also the open ward showed better safety and standards of supervision when compared with the single bed ward. Others reports from nursing research indicated patients, particularly the elderly, in open or multi-bed wards felt the environment was more sociable, but single bed residents felt isolated or depressed due to insufficient social interaction. In contrast, a single bed design supporter, John Burrough, referring to an expert, Sir Rupert Vaughan Hudson, said ‘The truth is that the open ward is an anachronism. It is socially undesirable and medically unsound.’ The U.S General Accounting Office, in the 1970s was against the open or multi-bed ward because the single ward provided better cost efficiency in terms of daily operation and maintenance. To sum up, although currently new hospitals are no longer designed as open ward, the single or semi-privacy/mixed room still shows different and variable effects regarding patient care (James and Tatton-Brown,1986).

Fig.1.3-1 Small room design ward



Cited: James and Tatton-Brown, 1986

Fig.1.3-2 Six beds ward design

Cited: James and Tatton-Brown, 1986

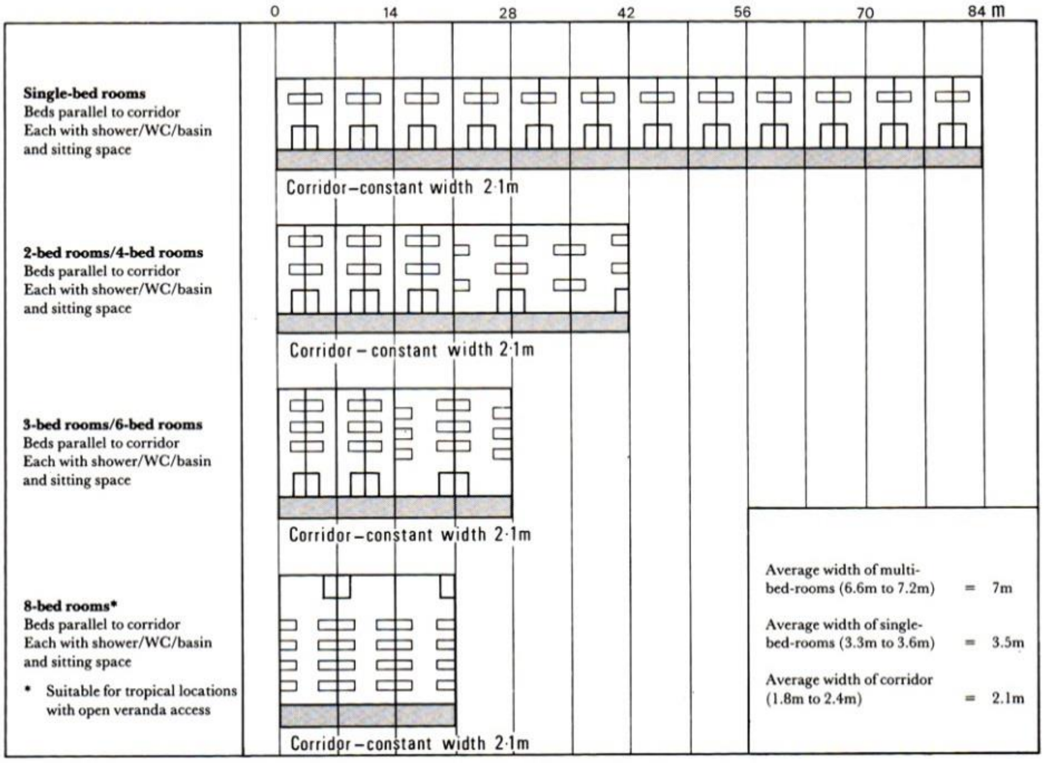
Fig.1.3-3 Single bed design

Cited: www.bbc.co.uk,NHS,UK

b) Size

The ward size is often varied. The verifying unit of scale used is 'Gross Area per square metres' for the bedding area. This means there should be a set distance between each bed according to the floor plan area and medical service capacity. The idea was inspired by the Nightingale principles of her open ward design to provide maximum ventilation, lighting and visibility. When it comes to this century the bed room size and gross bedding area usually follows the function and design targets. For example, the size of the bedding area and corridor of a single bed room is larger than the one in a multi-bed room. A maternity bed room or intensive care room is also bigger than normal bed rooms because it needs more space for related equipment and storage (Health Building Note, 1986). The diagram (Fig.1.4) shows the different distances between ward beds in different hospital projects.

Fig.1.4 Distance between ward beds



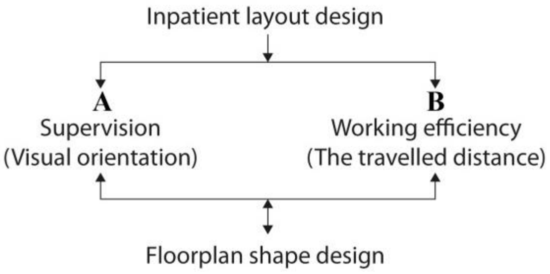
Cited: James and Tatton-Brown, 1986

c) Psychology

Psychology is a complex issue in inpatient design. In the expression of nursing principles, patients and nurses exist in an interactive relationship. For instance, the visibility of ward design is not only about supervision but also gives the confidence of seeing nurses while patients are undergoing their recovery. According to the research results of the St. Thomas's hospital commissioned by Medical Architecture Research Unit (MARU) in 1977, the patient is more concerned about the people who are coming to service them rather than the room's decor. In other words, this means not only that nurses need to see patients for supervision issues, but also the patient cares about the nurse's location in case they have some emergency requests (The Nuffield Trust, 2001). In this part of the design consideration, the psychological issue could be considered as the physical distance between the nursing station and wards.

d) Layouts

Fig.1.5 Inpatient design key issues



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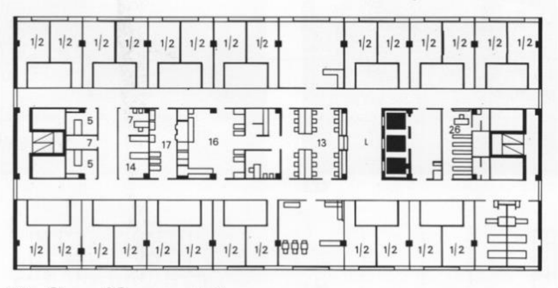
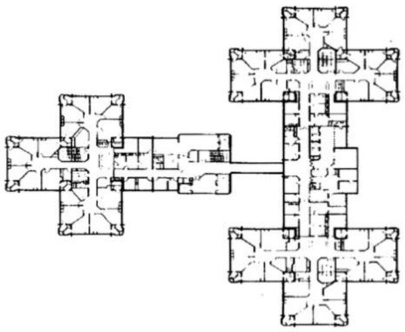
There are two key issues for inpatient layouts. The first is supervision (Fig.1.5-A), the second is working efficiency based on distance travelled (Fig.1.5-B) by nursing staff. In America, because the single ward is the common design for inpatient departments, the layout is more of a compact shape, such as the Racetrack/Double corridor (Fig.1.5-1-A), cruciform (Fig.1.5-1-B), radial (Fig.1.5-1-C), sawtooth (Fig.1.5-1-D), and cluster styles (Fig.1.5-1-E). The Racetrack and double corridor system was created by the Hill-Burton scheme in the 1940s. The concept aimed to follow concentrated medical services for the hospital. The floor plan (Fig.1.5-1-A) shows the racetrack plan in Archbishop Bergan Mercy Hospital, Omaha, Nebraska, 1965, with single and two-bed rooms with en-suite toilet facilities. The radial system was believed to perform best for supervision and working efficiency. However, the room had complete lack of privacy and was difficult to use because of its core design. The Prentiss Hospital for Women and Psychiatric Institute (Fig.1.5-1-C), 1975, Chicago, by Chicago architect Bertrand Goldberg was designed with four circular units of 2-bed room wards with centralized support core and nursing stations. Sawtooth inpatient layouts were popular around the 1960s. In the Mary's Help Hospital (Fig.1.5-1-D), 1966, California, by Stone, Marraccini and Patterson, the plan kept the advantage of a racetrack centralized system, and further upgraded the bed room with rotated angles to gain more dynamic views from outside.

Fig.1.5-1 Inpatient design layout types

A. Racetrack/Double corridor style

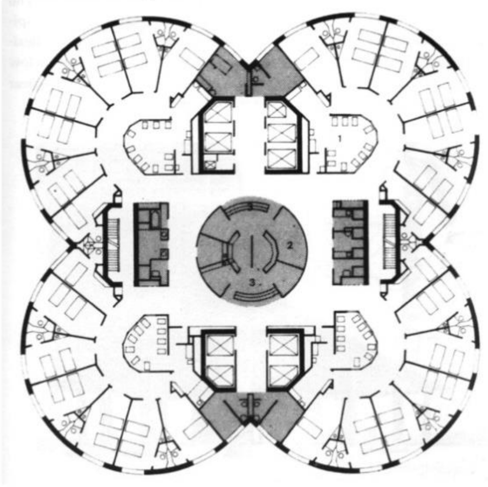


B. Cruciform style

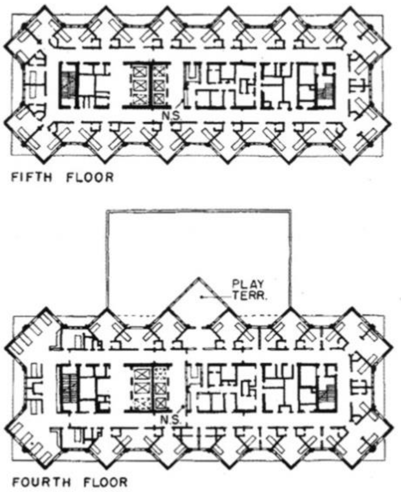


E. Cluster style

C. Radial style



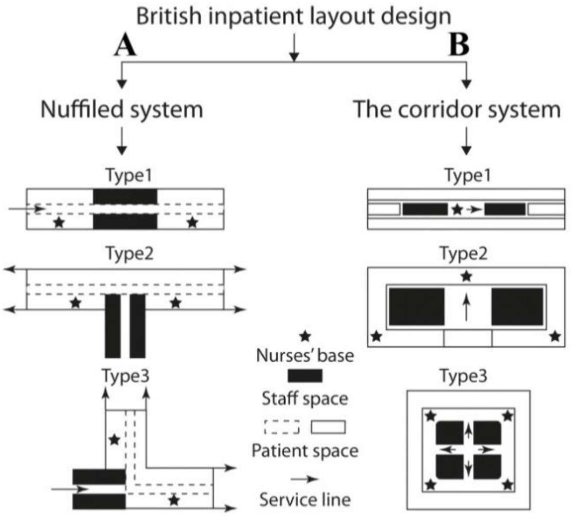
D. Sawtooth style



Cited: James and Tatton-Brown, 1986

However, this shape of space raised the issue of difficulty of use, also the sawtooth windows in fact narrowed down views outside. The last type is the cluster inpatient layout which demonstrates innovative design outcomes. According to the research on cluster layouts, it can reduce floor plans by 14 percent when compared with more traditional design. The cluster shape creates a shorter distance between wards and nursing stations and nurses can offer more services to inpatients with 3.1-3.4 extra hours of service per day. Moreover, in the 1990s the design of St. Michael’s Hospital (Fig.1.5-1-E) developed a new idea of Pod (cluster) design in the ward layouts. Each pod contained a bed room and these were aligned together into an inpatient department. This remarkable design idea was very different from the earlier one where the architect designed the tower shape and then divided floor plans into ward units. As a consequence, cluster layouts for the inpatient department established a new layout strategy and broke up the traditional geometric type of floor plan design (Moss, 1974).

Fig.1.5-2 Inpatient ward design system



Cited: James and Tatton-Brown, 1986

By contrast, European hospitals developed single and semi-private wards later than American hospitals. The common European hospitals were horizontally designed, therefore the inpatient design was based on pavilion like shapes. In England, there were two kinds of ward layouts which were the corridor (Fig.1.5-2-A) and Nuffield systems (Fig.1.5-2-B). St. Thomas' Hospital (Fig.1.5-3-A), built in the 1960s in London, UK, shows a plan with a rectangular form and four beds as a unit. The nursing station was located in the central part of the floor plan. When compared to the corridor system, the Nuffield layout in Swindon Hospital (Fig.1.5-3-B), UK, arranged two nursing stations on both sides of the rectangular plan (James and Tatton-Brown, 1986). This design offered better supervision and shortened the travel distance for nurses. The courtyard inpatient floor plans improved the problem of insufficient lighting and the nature of the traditional pavilion wards. The entire floor plan was comprised of one or two courtyards for access to the natural landscape. York Hospital (Fig.1.5-3-C), UK, demonstrates this courtyard inpatient departmental design. Two nursing stations were located at the ends or edges instead of in a central location. This was believed to enable more efficient viewing and oversight of patients (Moss, 1974). However, there might be some factors in inpatient department design which have not been mentioned in this section. The design of the inpatient area needs to follow or reflect the type of hospital and its services. For example, general hospitals and specialist hospitals, like childrens' hospitals, should be designed with different layout systems and interiors. Therefore, architects should think comprehensively about design and have discussions with nursing staff to create the proper inpatient layouts combining relevant structures with comfortable design environments.

Fig.1.5-3-A The St.Tomas' hospital, UK

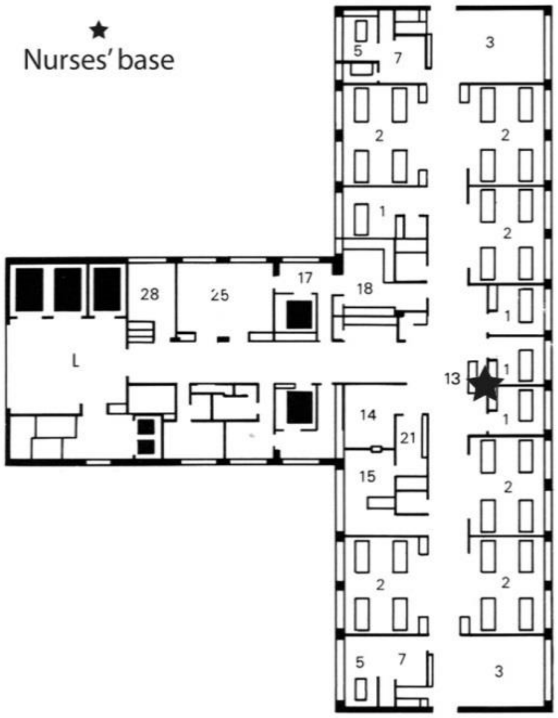
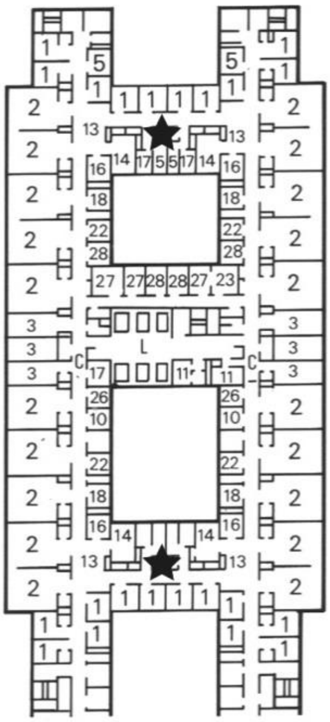


Fig.1.5-3-B The York hospital, UK



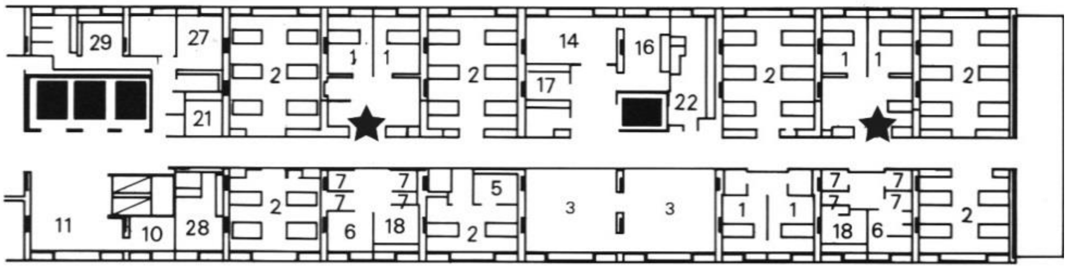


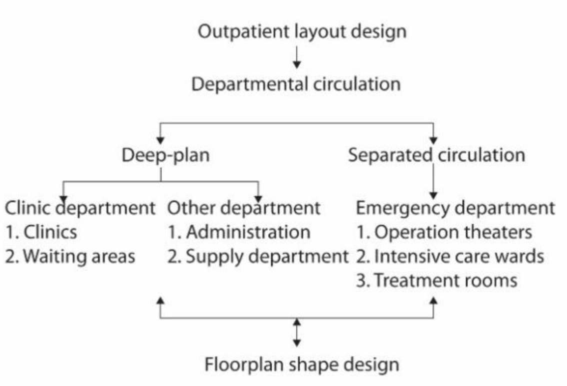
Fig.1.5-3-C The Swindon hospital, UK

Cited: James and Tatton-Brown, 1986

1.5.2 The outpatient department

Hospital outpatient buildings consist of several sub-departments which include clinics, emergency centres, operating theatres, administration offices and others. It is the busiest area of the hospital and each department contains many specialised functions as well as interrelating with other areas. As a result, the outpatient area is often designed as a podium shape or hall-style to provide better communication between departments. The diagram (Fig.1.6) identifies the main programs of the outpatient department and shows the key design points as well as the necessary interrelationships for consideration in the system design.

Fig.1.6
The diagram of outpatient design key issues

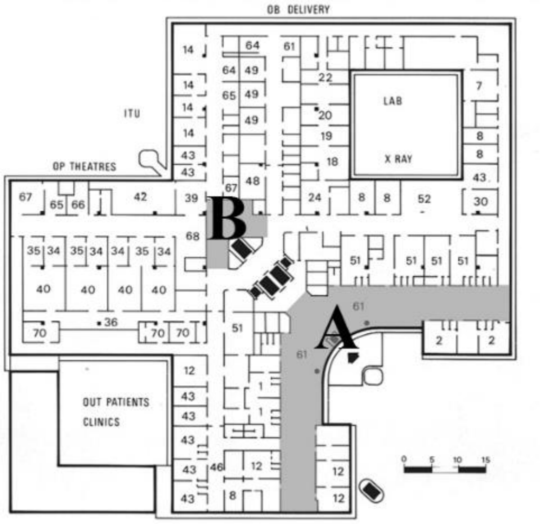


Source: Author reproduced

a) Clinical department

There are two key points which are of important concern while architects are addressing clinic design. First is the waiting space; there are usually one or two open waiting areas facing the departmental entrance as a clinic reception. This helps new patients to meet their needs without blocking the entrance. Then these are further sub-divided smaller waiting spaces in surrounding clinics. Nordenham Hospital (Fig.1.7), West Germany, has an open waiting area (Fig.1.7-A) located next to the main gate with the other side providing another small waiting area (Fig.1.7-B).

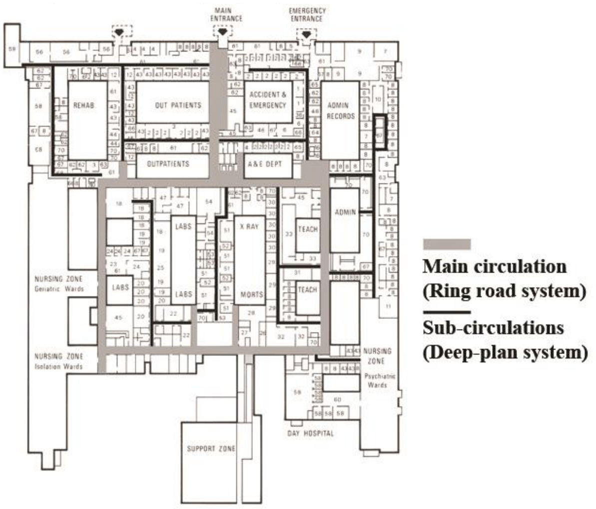
Fig.1.7 The separated waiting zone design



Cited: James and Tatton-Brown, 1986

The second key design concern is the inter-departmental relations. This means that clinics are usually grouped with similar types allocated to the same zone. The Deep Plan (Fig.1.7-1) is a special corridor system for connecting related sub-departments. Every hospital has their own deep plan system to reflect their service cooperation between departments. From the functional aspect, the deep plan is designed to optimize the working correlation and maximize the utilization of space. (Smith, 1984).

Fig.1.7-1 The deep-plan building circulation

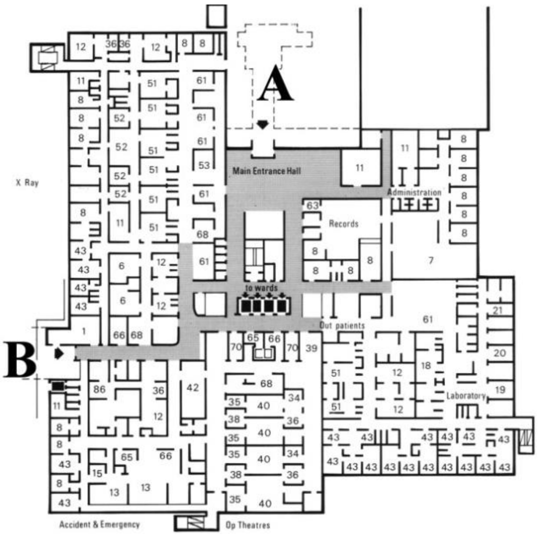


Cited: James and Tatton-Brown, 1986/ Author reproduced

b) Emergency centre and operating theatre

The emergency centre must be designed with an independent entrance to provide emergency services. The separate entrance is sometimes just next to the main gate (Fig.1.8-A), but normally is located on a different side of the hospital to avoid general visitors and patients (Fig.1.8-B). The design of the emergency centre follows the standard processing system for an accident and emergency guidelines where patients are received at the entrance, arranged in the examination area then processed by different services dependent on their conditions. X-ray and operating units are included as parts of the service networks. Therefore, they are usually grouped in the emergency centre.

Fig.1.8 Separated entrance design



Cited: James and Tatton-Brown, 1986

On the other hand, operating theatre layouts are often decided by hospital types and service capacities. It could be single (Fig.1.8-1-A), double (Fig.1.8-1-B) and multi-bank (Fig.1.8-1-C) theatre design. A standard operating suite includes reception (Fig.1.8-2-A), preparation spaces (Fig.1.8-2-B), recovery lobby (Fig.1.8-2-C), patient corridor (Fig.1.8-2-D) and supplies and disposal corridor (Fig.1.8-2-E), stores and processing and the operating theatre (Fig.1.8-2-F) itself. The design layout strictly imposes two separated corridors, a clean corridor and a dirty corridor, to reduce cross infections. Also, independent air ventilation is required with special high ceiling structure for generating an Ultra Clean Air system (UCA). The UCA system (Fig.1.8-3) not only provides clean air to cover the patient and surgical team, but is also cost effective by reducing infection during patient recovery (Moss, 1974).

Fig.1.8-1
Operation theatre design types

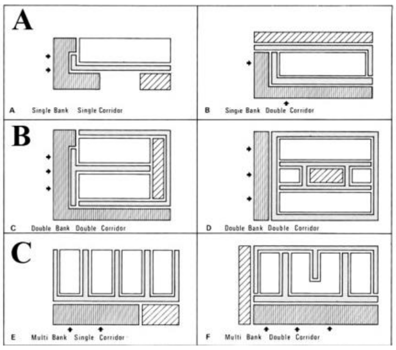


Fig.1.8-2
A standard operating suite

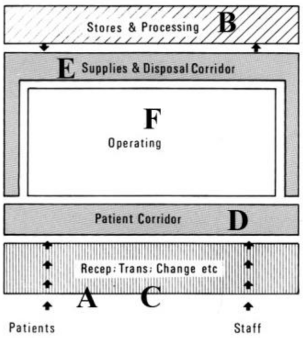
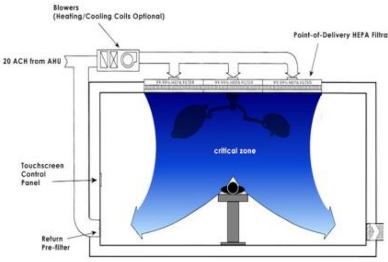


Fig.1.8-3
Ultra Clean Air system (UCA)

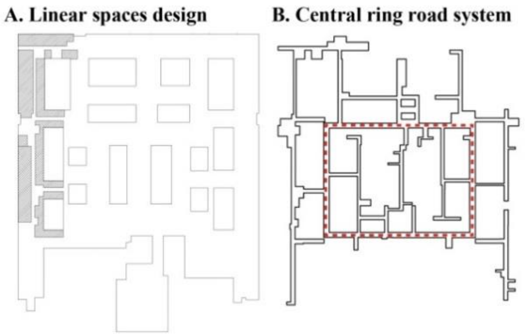


Cited: James and Tatton-Brown, 1986/ Precisionairproducts.com, 2017

c) Other departments

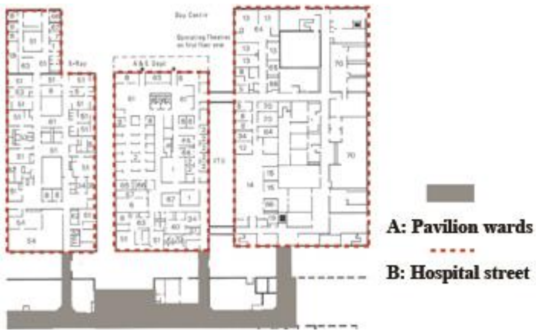
Besides clinics and the emergency centre, there are many departments in the outpatient centre. For example, administration, laboratories, teaching spaces, etc. The placement and organisation of such departments needs to follow the type of hospital and service provision. For layouts, the proposed design is related to the hospital type. For example, Bury St. Edmunds (Fig.1.9), UK, aimed to provide economic and efficient medical services. Therefore, all departments were designed as linear spaces (Fig.1.9-A) to increase communication with each other. The central ring road system (Fig.1.9-B) for layouts further emphasised the concentrated work flow. By contrast, York Hospital (Fig.1.9-1), designed its outpatient centre with a finger shape or pavilion style (Fig.1.9-1-A). The clinical area, emergency centre and examination department were located in a different building but were connected by a hospital street (Fig.1.9-1-B). This layout offered each department a more complete area and sufficient space (Health Building Note, 1986).

Fig.1.9 Best-Buy hospital design



Source: Author reproduced

Fig.1.9-1 The York hospital, UK



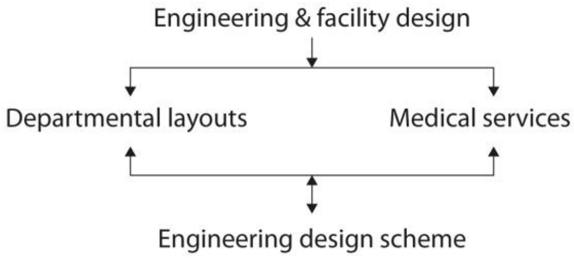
Source: Author reproduced/
James and Tatton-Brown, 1986

1.5.3 Engineering and facility design

a) Engineering layers

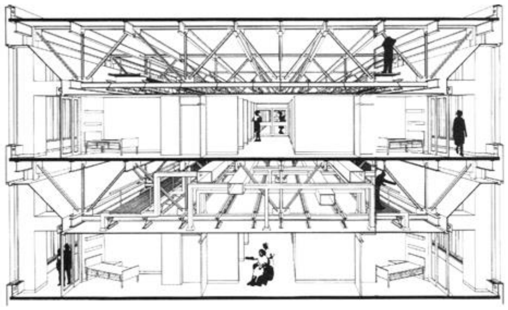
The design of engineering for a hospital is very complex each department carries out its own functions and thus demands different engineering facilities. However, an integrated engineering design scheme is necessary for the hospital design process. The diagram (Fig.1.10) shows a design plan for engineering and supply facilities in the hospital design process. Engineering solutions are normally integrated with floor slabs or inner walls in order to simplify the construction process. For example, 1970s mechanistic hospitals all relied upon mechanical support, so integrated engineering layers, as in the sandwich style (Fig.1.10-1), were designed for that purpose (Moss, 1974).

Fig.1.10 Hospital engineering design process



Source: Author reproduced

Fig.1.10-1 The sandwich engineer layers



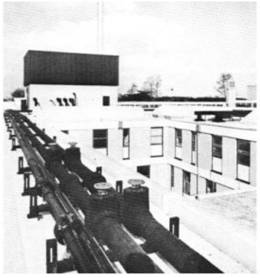
Cited: DHSS/ Moss, 1974

b) Energy source or boiler/heating system

It is important to decide the location of energy sources or boiler/heating systems before the hospital is erected. Those energy structures are normally located in the basement as in the Santé de Hospital (Fig.1.11), because it is easy to supply services from the centralized system to each sub-department. The system is most suitable for vertically developed hospitals. On the other hand, a separate or roof based energy source or boiler/heating system has safety and maintenance benefits. For instance, Frimley Park Hospital (Fig.1.11-1), UK, located the energy structure on the roof top with four penthouses plants. The energy supplies went through the attached pipes on the roof as the plugging facility; this design was aimed at easy maintenance if the pipes were damaged. Since technology is changeable, more functional and smaller-sized machinery often needs to replace the older and bulkier systems. The latest mechanical solutions needed cooperation between professional engineering teams and medical staff to continuously update and improve systems for each new hospital project (Health Building Note, 1986).

Fig.11.1
The boiler/heating systems

Fig.1.11-1
The roof top engineer system

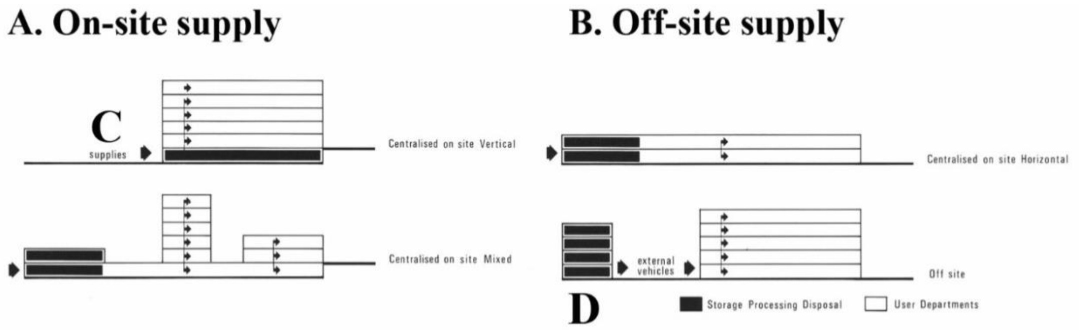


Cited: Stone, 1980/ James and Tatton-Brown, 1986

c) Storage

Support and disposal is always an important part of hospital design. In the 1970s megahospitals dominated the market, and architects and design teams invented some systematic supply systems for this market. There were two kinds of systems (Fig.1.12), one was on-site supply (Fig.1.12-A), and the other was off-site supply (Fig.1.12-B). The on-site centralized and vertical system (Fig.1.12-C) located the storage area in the basement then transferred resources with vertical lifting equipment (Samuel, 1964). By contrast, the off-site supply hospital needed to be located in a wider regional medical services zone (Fig.1.12-D). It meant hospitals did not need huge storage space but out-sourced from a regional supply infrastructure.

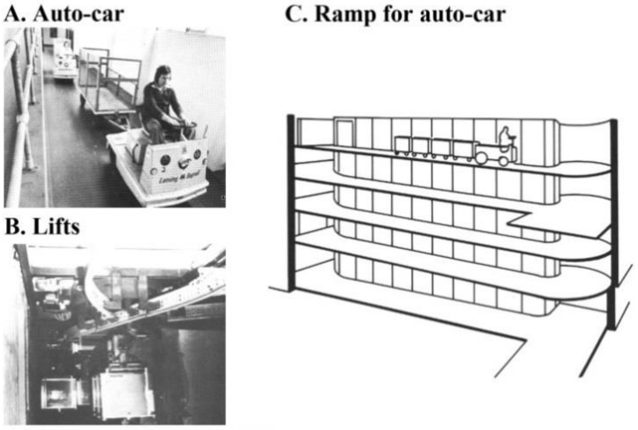
Fig.1.12 Support and disposal system of the hospital design



Cited: James and Tatton-Brown, 1986

For internal departmental supplies, there were alternative methods of supply such as using auto-cars (Fig.1.12-1-A) or lifts (Fig.1.12-1-B). In the case of Greater Baltimore Medical Centre, USA, the design of auto-cars was further rationalized with different types to provide efficient delivery services such as meal trays, clean linen, refuse, etc. In West Suffolk Hospital in the UK, the design for auto-cars with a train negotiating ramp (Fig.1.12-1-C) was used to separate transfers of supplies. Although new hospitals might have more efficient methods of delivering resources, support and disposal is still a primary issue that needs to be considered while the hospital is in the early design stage. This influences service efficiency, costs and budgetary control. In addition, on-site or off-site will always be critical to the hospital's supply of services (James and Tatton-Brown, 1986).

Fig.1.12-1 Internal departmental supplies



Cited: James and Tatton-Brown, 1986

1.5.4 Visual design of hospital environments

a) Interiors

Interior design is a growing issue for new hospitals; it is believed the 'Patient Centred' concept is mainstream for certain medical operations. Especially as some departments are providing services to special groups such as paediatrics and obstetrics. So, clinic design demands sensitivity to psychological considerations for the patients' visual environment.

The Evelina Children's Hospital (Fig.1.13-A), 2005, London, UK, was designed as an atrium hospital with decorated interiors and vividly painted coloured halls to create an open and warm atmosphere for young patients. Moreover, the Mercy Memorial Medical Centre (Fig.1.13-B), 1986, St. Joseph, Michigan, USA, designed their maternity ward with a home-like appearance. It is believed it gives a warm and homely atmosphere and that while patients stay in the hospital this is very important in improving patient recovery (Verderber and Fine, 2000) (Verderber, 2014).

Fig.1.13-A
The Evelina children's hospital, London

Fig.1.13-B
The Mercy Memorial medical centre

Cited: Verderber, 2014

b) Landscapes

Landscape design in hospitals aims to help patient relief while they are undergoing medical treatments. For the outpatient department, site landscapes are usually designed with local or regional plants or providing some public facilities such as a small park and cycling area for local activities. If patients can easily see the views from waiting areas, they might not feel as isolated while they are in the hospital. For the inpatient department, inner courtyards or a roof garden play an important role especially for long term patients. For example, The REHAB Basel Centre (Fig.1.14) for Spinal Cord and Brain Injuries, 2002, Basel, Switzerland, by Herzog & De Meuron is a private treatment centre for patients with spinal cord and brain injuries. So, the courtyards of the hospital were designed to rebuild patient's cognition of their surroundings. Each yard uses local greenery to give points of reference for those patients (Health Building Note, 1986) (Guenther and Vittori, 2013).

Fig.1.14 The REHAB Basel centre for Spinal Cord and Brain Injuries

Cited: Guenther and Vittori, 2013

1.6 Future healthcare architectural design and expectations

Hospital design is ever-changing because its building functions follow the latest medical trends. There is no single solid design concept to define future hospitals especially in terms of design developments. But the NHS UK and the UK research unit, the Nuffield Trust, in its publication ‘Building a 2020 Vision, Future health care environment’, suggest some conceptual guidelines for future hospital building design and planning. There are three key concepts in this vision:

1.6.1 A Social model for health

Future hospital design ideas should be connected as part of a social care system, which means different hospital buildings will be connected and supported according to the same design standard but for different functions, such as specialist hospital or medical centre. In addition, sharing design parameters in a systematic design process is needed to control the quality of building facilities and to make sure the integrated medical services operate as part of wider social care policy.

1.6.2 Patient centred approaches

Health care will be increasingly focussed on the idea of patient psychology and well-being, rather than relying only on clinical studies. That means the patient’s care experience is very important to this research area. The clinical network should be well-managed, to provide excellent communication of information. The building design process should be concerned with innovative ideas, evidence based design data, real-time evaluation, etc. Those design parameters need to be considered from the early design stage and need to support decision making in the following design plans.

1.6.3 Quality of design

It is vital to ensure that professional workers have high morale during the healing process in a clinical department. The quality of health care needs to be managed from physical therapy to mental aspects. Therefore, in the design ideas for therapeutic environments, privacy, public space and visual impacts all need to be included. In addition, creative thinking in design improvement is highly encouraged. In order to create a better healthcare environment, the design team should provide a clear design standard and allow a variety of design ideas with effective evaluation from the earliest stages of the building design proposal.

To sum up, besides the above points or ideas, hospital building design should not just be based on existing design projects. The type and idea might be varied, but functions need to be more compact and integrated. In other words, the design process for hospital building needs a flexible and adaptable method to effectively reflect complexity and to ensure different professions are involved in matters of design.

1.7 Ethical considerations

This research employed two survey methods, a questionnaire and protocol analysis. Both investigation processes targeted hospital design architects and divided them into different user groups. The participants in the survey questionnaire and protocol analysis were anonymous and were strictly used only for this research. All of them signed a permission form for the purpose of this published research. The study survey was also approved by the GSA Research Ethics Policy (Appendix 1), details of which can be accessed online at ***http://www.gsa.ac.uk/media/497492/gsa_research_ethics_policy.pdf***

Part I/ Chapter 2 – Literature reviews 1

Changing ideas regarding healthcare facilities and hospital design

2.1 Introduction

Healthcare and its facilities have a long history that has always been linked with social activities and developments. There is a wide range of aspects when we are reviewing the history of design ideas in healthcare architecture, so this literature review focuses on the building style or type and the associated background influencing hospital building design concepts as well as exploring the advantages and disadvantages of designs from different eras of hospital building. The chapter is separated into three parts:

The first part (Sections 2.2-2.4) considers healthcare facilities development with reference to the period and the building style from the ancient to the contemporary period. This part focuses on the idea that social background inspires design and how social issues have influenced architectural design, as well as what were the characteristics and functions of hospital buildings in their local communities.

The second part (Section 2.5) reviews new age (21st century) hospital design with reference to particular ideas and functions. This section further discusses the use of Computer Aided Design (CAD) tools in the hospital design process and their impact on the presentation of ideas. Through selected case studies, a view of medical treatment combined with the latest design proposals is provided, explaining the potential of CAD for the design of next generation healthcare architecture.

The last section (Section 2.6), discusses, reviews and concludes the changes in hospital building design and ideas from a chronological perspective. There are two aspects mentioned in this timeline, building type and function and the design tools and methods.

2.2 The historical development of healthcare facilities

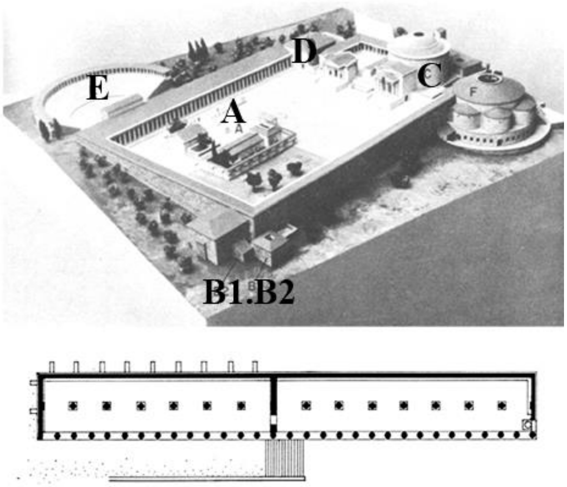
Early civilizations did not develop sufficient professional knowledge of medical practice and associated building construction. Most of the historical healthcare facilities used other buildings' space and changed the original layouts to healthcare use. These adapted layouts were called Derived Plans (Thompson and Goldin, 1975) and this design method was widely used until the nineteenth century, such as in monastic and infirmary hospitals.

2.2.1 The ancient Greeks and the Roman empire

a) Ancient Greece – the dreamer hall

Healthcare facilities in the time of Ancient Greece were just a dedicated room without any programmed functions. The precise name for this space was “Hall for dreamers” (Asklepieion of Pergamon, Turkey, second century A.D.). As the title of the hall suggests, it was simply just an open chamber, sometimes separated into two parts for the different genders. The general intention was to provide a place for sleeping and recovery while people were experiencing illness or discomfort. The patients hired servants for limited support services during their sickness, such as food and cleaning. It is believed that the room's name originated in a story of a sick man who was suffering from a groin tumor during a long horseback ride, suddenly a deity appeared in a dream and presented him with a prescription which resulted in his condition improving and later in a full recovery. Nevertheless, sufficient sleep is unquestionably an important factor for the sick and in the process of restoring energy and health.

Fig.2.1 The Asklepieion of Pergamon entury B.C.



The floorplan of the dreamer hall

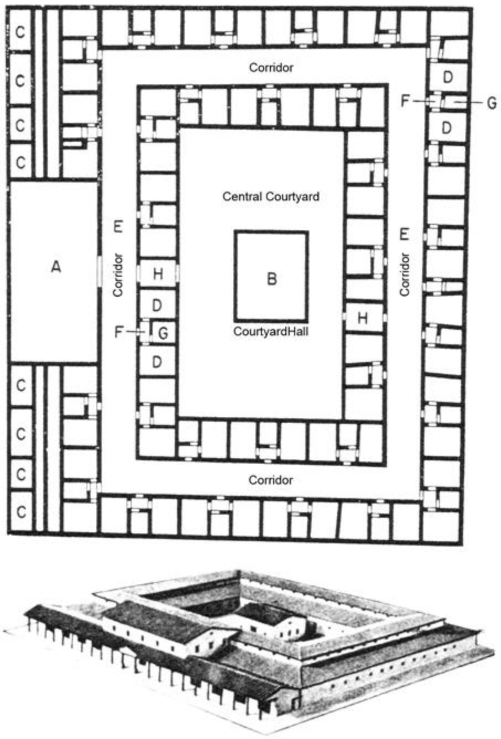
Cited: Thompson & Goldin, 1975

The image shows the hall for dreamers at the Asklepieion of Pergamon, built in the second century B.C. (Fig.2.1). The Dreamer Hall (Fig.2.1-A) is separated from the main buildings. Other structures like the Emperor’s Room (Fig.2.1-D), Temple (Fig.2.1-C) and Stadium (Fig.2.1-E) are situated around the Dreamer Hall. The closest structure to the hall is the latrine (Fig.2.1-B1-B2), for sanitary purposes. It was also divided into two detached rooms for the two sexes. The other associated facilities for patients were treatment only rooms which were combined in a hall (F) next to the temple. Six bath places provided tubs and mud baths with heated water from a sacred spring. This ancient healthcare building displayed a fundamental caring process in which patients accepted treatments from the thermal baths and rested in the dreamer lobby with independent toilets. This allocation shows the oldest idea of separating sick people into a series of independent structures and providing for basic needs while they were fighting disease (Panagiotidou, 2016).

b) The Roman empire – the military hospital

With the fall of Greece and the rise of the Roman Empire, the military hospital became an important part of military structures used for curing wounded and diseased soldiers. Accordingly, uniform layouts in building design with efficient service provision were required for the hospitals. They were located to provide easy access from other army barracks so that the wounded could be sent direct to the hospital. The military hospital of Vindonissa, Switzerland, first century A.D. (Fig.2.2) was a two stories high building and designed in a square shape with a central courtyard (Fig.2.2-B). The site was surrounded by water and sewage facilities provided by a canal infrastructure. The wide-open entrance hall (Fig.2.2-A) was combined with the administration (Fig.2.2-C) on the ground floor. Other structures such as treatment rooms, public latrines, kitchen and a hypocaust heating area, were located next to the entrance hall. For the efficient operation of ward units a back room (Fig.2.2-G) was provided for storage. An interesting part of the military hospital was privacy space, shown for the first time in an ancient healthcare building. Before entering the bedding area, visitors needed to pass through the vestibule (Fig.2.2-F) This layout filtered the noise and dust from outer areas and increased the privacy for inpatients or wounded. Sleep in a quiet environment was the most important part of patient care. It also shortened the recovery time and encouraged soldiers back to the field sooner. Moreover, there was a passage (Fig.2.2-H) across the floor plan which was designed to connect end and side departments. The entire design for Roman military hospitals indicated organized functions and provision for privacy as well as offering all patients or wounded the same standard of healthcare (Byrne, 1910).

Fig.2.2
The military hospital of Vindonissa



Cited: Healtharchitecture.wikifoundry.com, 2011

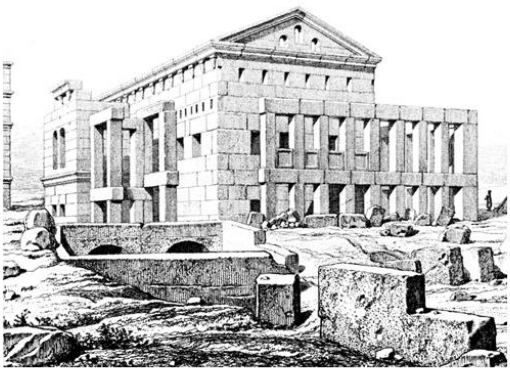
2.2.2 The medieval period and Christian monasticism

The Medieval Period is an important milestone in the history of healthcare facilities and shows developments towards the prototype of early hospitals. There were three stages of this evolution, primary, secondary and tertiary. In each phase the type of hospital building was significantly associated with the social background and environment.

a) The early medieval period – the convent building

Early Christian monasticism, without doubt, provided the beginning of public healthcare. The Bible provides an early reference,” *For I was hungered, and ye gave me meat; I was thirsty, and ye gave me drink; I was a stranger, and ye took me in; naked and ye clothed me. I was sick, and ye visited me; I was in prison, and ye came unto me*”- (Matt,25,35-36). This is the basis of the concept of “act of mercy” monks who had to give support to travellers or pilgrims on long journeys from their places of origin. They often suffered from a range of injuries and lack of nutrition. Many of them experienced sickness or discomfort and needed a place to rest. Therefore, the open hall space called “the convent building” next to the church provided services for the sick pilgrims. Treatments such as dispensing hospitality and food were delivered overnight by monks if requested by travellers. The monastery of Turnain, Syria, about 475 A.D. (Fig.2.3) shows an example of a convent building. It was a large, open structure, two floors high with a 90 by 47 feet rectangular plan (Thompson & Goldin, 1975).

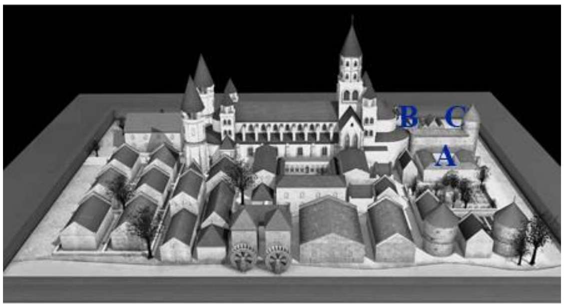
Fig.2.3 The monastery of Turnain



Cited: Thompson & Goldin, 1975

b) The mid medieval period– the monastery & infirmary

Fig.2.4 The St. Gall infirmary, Switzerland



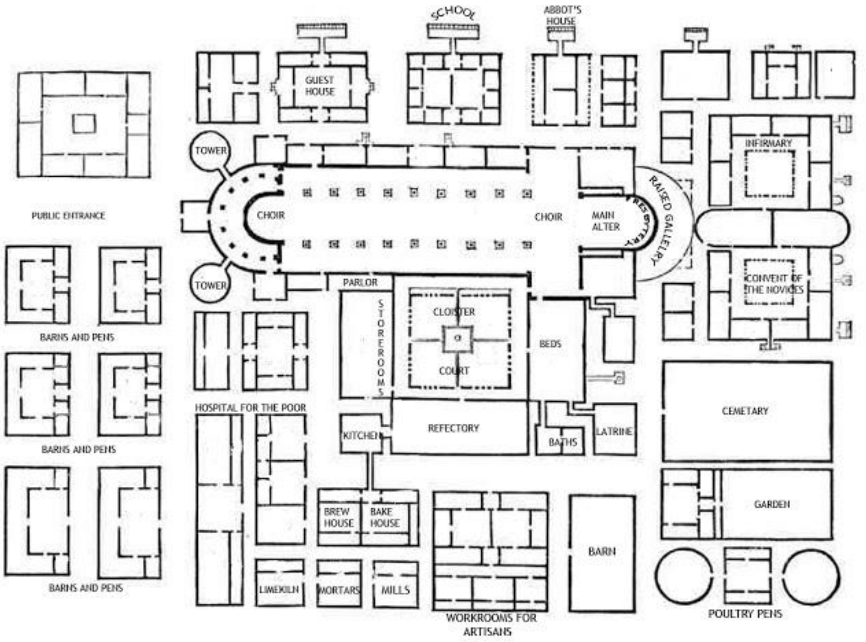
Cited: Medieval Histories, 2017

When it came to the middle of the Medieval period, the increasing size of healthcare facilities created added complexity in the building functions and structures. The Christian monastery mainly included two building categories, the church and the monastic hospital or infirmary (Francis, 1999). In St. Gall, Switzerland about 820 A.D. (Fig.2.4), buildings were organised in a cluster. The church was placed in the centre and surrounded by the monks' houses. Different dedicated structures such as the bakery and kitchen brought the small community an autonomous system. This sub-organization was very similar to the idea of a departmental organization.

Sick pilgrims, were firstly sent to the infirmary to receive acute illness treatment then rested in the open-hall-like ward unit (Fig.2.4-A). People who were very ill and required intensive care were directed to the House of Physicians (Fig.2.4-B) and bloodletting (Fig.2.4-C) located behind the infirmary. These treatment services were discovered in the earliest hospital structures.

Also, building locations on the site followed the characteristics of visitors to the site. For example, the plan of St. Gall, Switzerland about 820 A.D. (Fig.2.5), shows that rich and poor pilgrims were accepted through different gates. The poor walked and passed yards into the church (Fig.2.5-A) where monk porters were prepared to welcome them. On the other hand, noblemen or royalty riding on horses were guided to the House of Distinguished Guests (Fig.2.5-B). This was equipped with its own bakery and brew house - (Fig.2.5-C). The size of the guest house for rich pilgrims was a single unit (Fig.2.5-D), but ordinary pilgrims needed to share with others in an open hall (Fig.2.5-E) (Thompson & Goldin, 1975). Although the various buildings showed the hierarchy in monasticism, it did not indicate that travellers received unequal medical treatments. So, those complexities in the workflow revealed the progression of early healthcare, and how the monastery balanced local relationships between healthcare, religion and society.

Fig.2.5 The plan of St. Gall infirmary, Switzerland

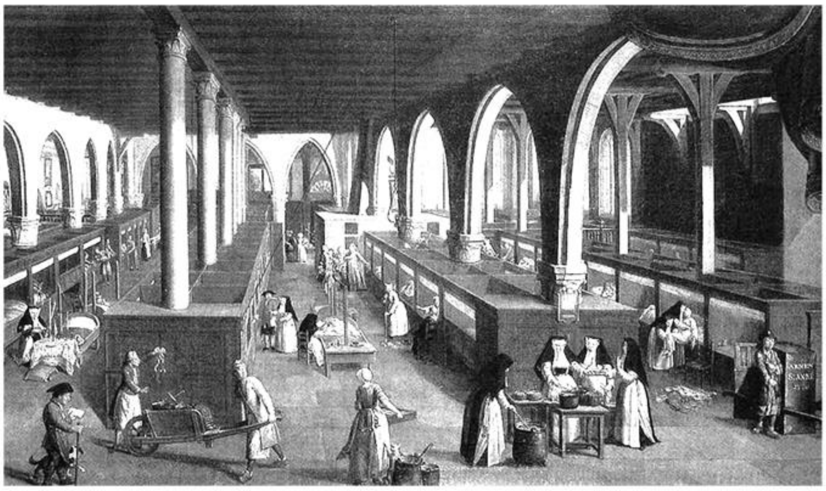


Cited: Gardenvisit.com, 2017

a) The late medieval period – the church hospital and the open ward

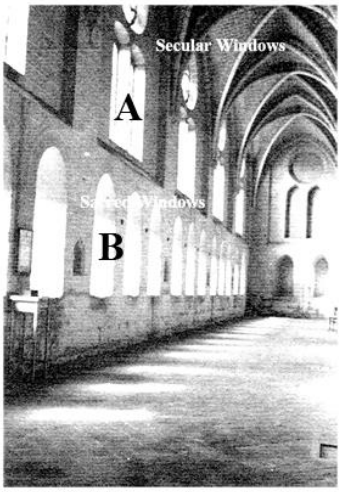
In the late Medieval period, the ward building of monastic hospitals rapidly developed in scale into a new vision for inpatient facilities called the Open Ward. From the twelfth century, less Sacramental communion was held in church, so this empty hall was converted to ward facilities (Verderber and Fine,2000). This open hall, or derived plan, in Christendom normally corresponded to a great hall and was located next to the chapel or church. It offered patients the opportunity to see and hear the sounds from the altar while they stayed in bed. To compare the original ward buildings with the open hall, the late Medieval open hall for health care held all functions in a single complete zone such as beds, kitchen, altar and simple medical provision. The image (Fig.2.6) provided shows the sick ward of St. John's Hospital (Bruges), 1778. This design for inpatients was more similar to an ideal inpatient department rather than dedicated functional houses. The advantage of this open space was good ventilation and lighting provided by "sacred" (Fig.2.7-A) and "secular" (Fig.2.7-B) windows. Although in the winter the issue of low temperatures might have arisen, the stone material kept the interior warmer than in timber or brick houses.

Fig.2.6 The sick ward of St. John's Hospital, Switzerland



Cited: Wikiwand, 2017

Fig.2.7 Window types



Cited: Wikiwand, 2017

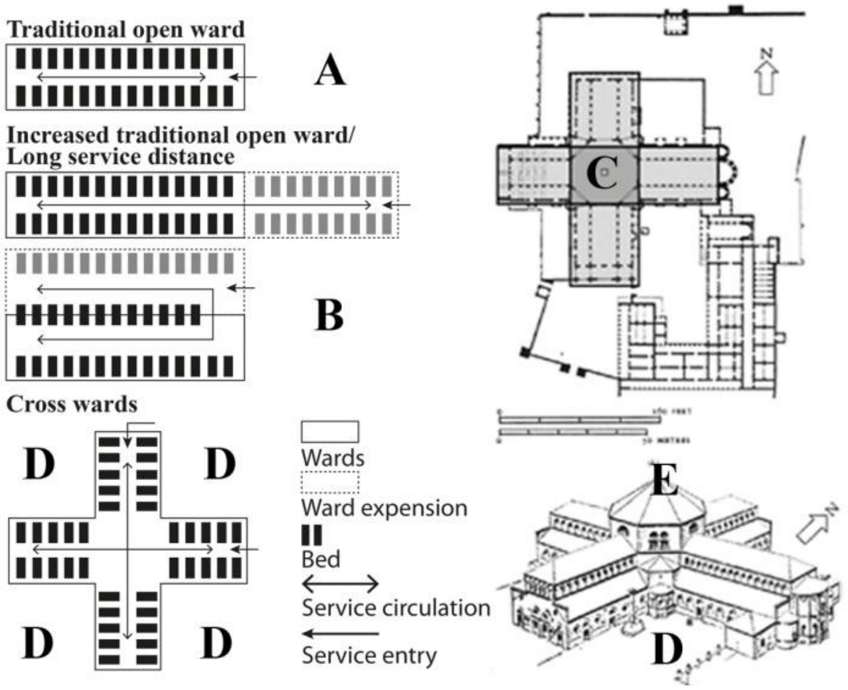
2.3 Renaissance to the early modern hospital design

Renaissance architects thought the universe followed a perfect pattern of creation in mathematical definitions (Shuttleworth, 2017). For that reason, architecture and its design layouts were usually associated with mathematical principles such as symmetry and proportion. As a result, hospital design in the Renaissance could be specified with cross wards, symmetrical building planning, and panoptical institutions. Interiors were divided into small or private rooms and medium sized wards.

2.3.1 The cross wards

Because of increasing populations, overcrowding problems and lack of beds soon became the urgent issue for Infirmary hospitals. It was not possible to keep enlarging the size of the open hall because the construction was limited by the necessary size of the arches. Besides that, if a wider space was created, it raised other problems such as more distant patients not being able to see or hear Mass, and service distances were too long to give adequate support (Fig.2.8-A). Therefore, the idea of Cross Wards (Fig.2.8-B) firstly appeared in de Santa Cruz Barcelona, Spain in the fifteenth century. The design took two open halls, with rectangular shape, intersecting them, and then raising the center part as a chapel (Fig.2.8-C). The layout provided four sides for patients to hear and see the same Mass and distance for services did not become longer. Also, each hall had on two sides courtyards (Fig.2.8-D) for natural lighting and ventilation. The cross hall design not only

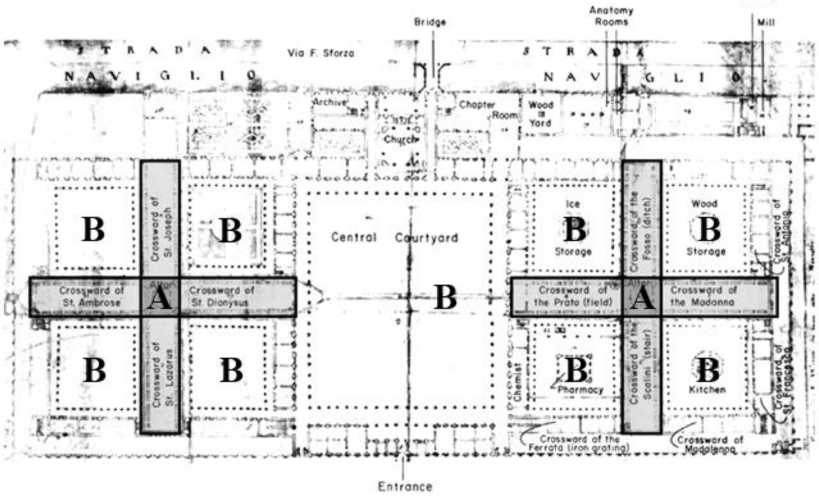
Fig.2.8 The cross wards design, de Santa Cruz Barcelona, Spain



Source: Author reproduced/ Photo: Thompson & Goldin, 1975 solved overcrowding problems but also used basic mathematical principles in architectural function and layout. Moreover, natural airflow was created by the central dome (Fig.2.8-E) of the cross wards acting as a ventilated chimney.

The interior also placed a few big fireplaces, at the end or sides of wards and heated the room at all times. According to the air circulation principle, the architect controlled the opening and closing of the chimneys and successfully kept the interior's temperature at twenty-seven and half degrees during the winter. In another original design, for the Ospedale Maggiore, Milan, 1456 (Fig.2.9), the architect designed a series of buildings with a symmetrical master plan using a double cross layout for wards (Fig.2.9-A). These offered different gender ward buildings, courtyards (Fig.2.9-B) and provision of spaces perfectly combining into a campus.

Fig.2.9 The Ospedale Maggiore, Milan

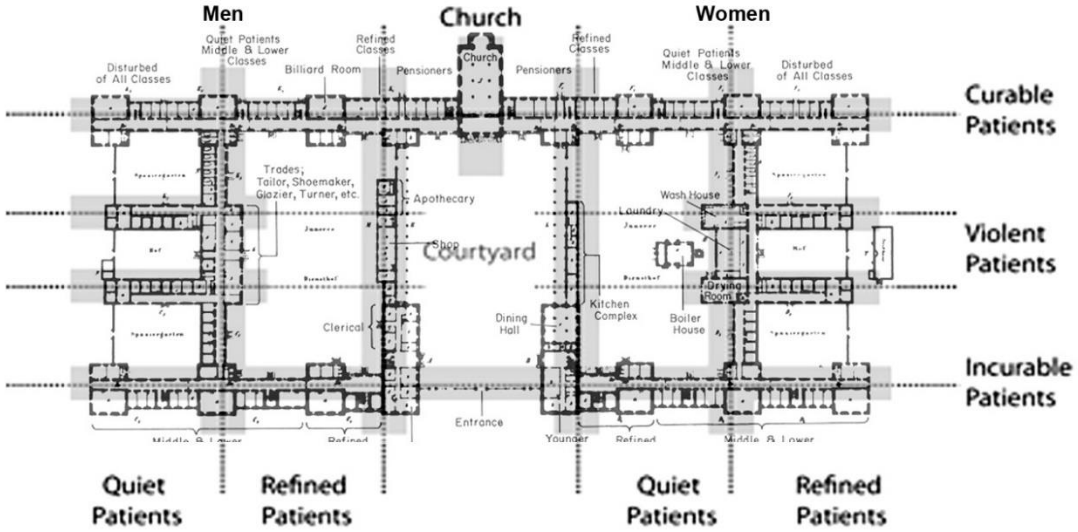


Source: Author reproduced/ Photo: Thompson & Goldin, 1975

2.3.2 Symmetrical or panoptical institutions

Insane Asylum hospitals were very different from other healthcare institutions, because of the design consideration of supervision and management. Therefore, a mathematical design with symmetrical or circular floor plans answered these functional concerns (Verderber and Fine,2000). The interior wards were built with small or individual cells. Patients were simply classified through their mental conditions as aggressive or harmless. Most of the harmless patients were kept in a group room, and the dangerous ones were kept in single rooms. A few decades later, psychiatrists further classified the insane with more categories according to their symptoms such as epileptics, paralytics, melancholy, and monomaniacs, etc. (Fig.2.10).

Fig.2.10 Symmetrical campus design



Source: Author reproduced/ Photo: Thompson & Goldin, 1975

This classification was intended to improve the management and quality of life for patients. The layout also refined the primary idea by using symmetrical allocations of space to improve convalescence and offer better lighting, air and tranquility for those who were undergoing recovery. In time, more moral treatments and improvements in the restraint system influenced the design of English asylums. The hospital was designed with an open garden and beautiful appearance. Patients were encouraged to move freely within the campus but were restricted from moving outside by the fences or walls. This idea was broadly exported to Europe and the United States (Gutsandgore.co.uk., 2017). For instance, The Bethlehem Insane Asylum, England, 1676 (Fig.2.11) shows a symmetrical campus design for insane asylums which appropriately adapted advantages for supervision and presented varying shapes of geometrical layouts with particular functions for court yards, common spaces, and private spaces.

Fig.2.11 The Bethlehem insane asylum, England

Cited: Country Asylums, 2003-2017

2.3.3 Small and private wards

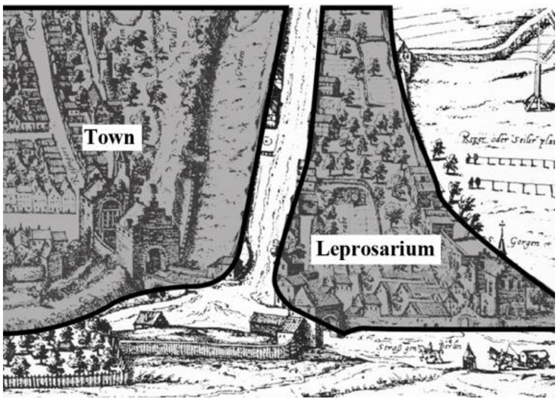
There were three types of ward design which provided small and private spaces in the Renaissance period. They were the Pensioners, Leprosaria, and Insane Asylum wards. Each type of ward was adapted to different functions for medical needs and had an associated floor plan (Thompson & Goldin, 1975). For example, in the Holy Ghost hospital for pensioners in Denmark in the late 13th century (Fig.2.12), the interior was subdivided into several bunk beds, each for a person who was retired and rich. However, they preferred to stay in a single room with less shared facilities. Consequently, the pensioner’s healthcare facility was designed in an open hall but subdivided into a series of ward cubicles. The interior looked more like an apartment and the room profiles were easily defined by regular windows and features.

Fig.2.12 Bunk beds design

Cited: Thompson & Goldin, 1975

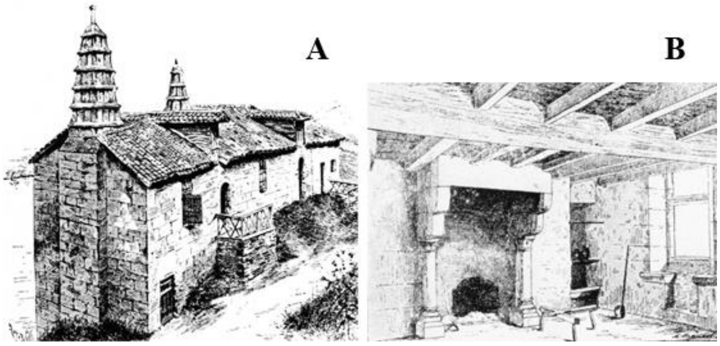
Aside from the consideration of privacy for the pensioner’s hospital, the possibility of infection from disease also necessitated an isolated ward type. In the leprosaria and plague hospital segregated design was crucial. The buildings were even thoughtfully located out of the city but near to waterfronts for sanitary purposes. For example, in the case of the St. George’s leprosarium, Stettin, Poland, sixteenth century (Fig.2.13), the image shows on its right side that the leprosaria hospital was totally separated from the town wall. When compared with the ward size of pensioner hospitals, the room in a leprosarium was larger and more like a single house (Fig.2.14-A). This might have been because as those serious pestilence or plague patients might be segregated in a signal ward for a long lifetime, complete housing facilities gave them better-living conditions. The picture (Fig.2.14-B) shows the exterior and interior views of ward units from the leprosarium of Perigueux, France, twelfth century; every room was equipped with a fireplace and small windows (Thompson & Goldin, 1975).

Fig.2.13
The St. George’s leprosarium, Poland



Cited: Thompson & Goldin, 1975

Fig.2.14 The leprosarium of Perigueux, France



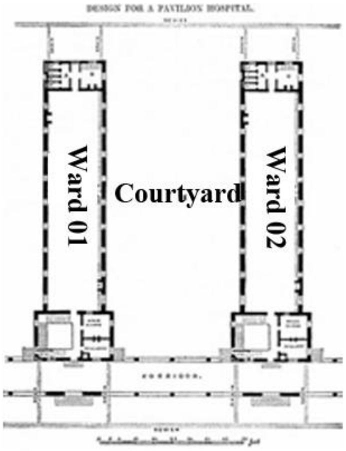
Cited: Thompson & Goldin, 1975

2.4 Modern hospital design

Ancient hospitals showed the link between early design ideas and the history of religious contributions. On the other hand, from the nineteenth century to the present, modern science has dominated societal development. The idea of the derived plan for hospitals has been replaced by scientific medicine and nursing. Especially after the Second World War, the world adopted infrastructure based on industrial principles for rebuilding their society (Verderber and Fine,2000). As a result, the International Style demonstrated design based on productivity and lead to rapid development in these countries. The style soon became the icon for modern hospitals and the image for contemporary hospitals. Consequently, the design of new hospitals followed engineering production principles and created a unique design language, with terms such as solid shape, industrial material and steel and concrete structure. This section is divided into two parts, from pre-war to the 1960s; it shows the change from pavilion hospitals towards the international style of contemporary hospitals.

2.4.1 The Nightingale wards

Fig.2.15-A Open courtyards design

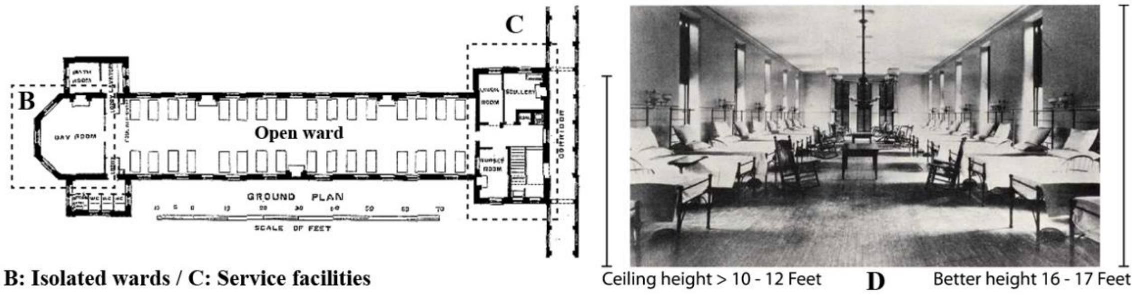


Cited: Health Architecture Home/ Wikifoundry

Miss Florence Nightingale, was a British nurse who founded modern nursing in the nineteenth century. She used her work experience with the British army and contributed her nursing knowledge to inpatient layouts. Miss Nightingale pointed out that the problem in certain healthcare buildings was insufficient ventilation, especially in the inpatient department. She believed that the human body constantly circulates and exchanges air through lungs and skin to release putrefaction from the body. This essential process keeps organs in good health but brings polluted and watery vapours into the environment. Therefore, she designed new standards for inpatient departments. For the floor plan layout, the idea was based on the pavilion style but provided added dimensions for ventilation – 33 feet wide and 128 feet long. If the floor plan width was over 33 feet, it could prevent effective ventilation (McDonald, 2013). For the site plan of the Nightingale wards, the buildings needed to have additional open courtyards between ward buildings (Fig.2.15-A). This helped to create space between the ward buildings and increased natural ventilation. Any buildings next to the inpatient pavilion had to be the same height to allow sunlight and fresh air to reach the bedding area.

For interiors, patients needed to be separated according to their sickness, if one got infected, he or she had to be isolated in another ward (Fig.2.15-B) to prevent transmission of infection. Unnecessary decoration of the interior including curtains, closet, scullery and sink had to be kept away from the open ward due to the ventilation issues (Fig.2.15-C). The building needed to provide sufficient windows, and provide both sides and ceiling height (Fig.2.15-D) not lower than 10 or 12 feet, better if it was 16 to 17 feet high. If it was lower than this specification, air might not able to circulate inside the department. Generally, 30 to 32 were the maximize numbers for bedding capacity in a unit (McDonald, 2013). The most well-known hospital based on Nightingale's ideas was St. Thomas's Hospital, London, UK, 1871 (Fig.2.16). Moreover, the diagram shows the Nightingale standards used for the ventilation design of John Hopkins Hospital, USA, (Fig.2.16-1). This long architectural section shows how airflow relates to the building design.

Fig.2.15-B-C-D Nightingale's ward design zoning



Cited: Workhouses.org.uk, 2017/ Health Architecture Home/ Wikifoundry

Fig.2.16 St. Thomas's hospital, UK

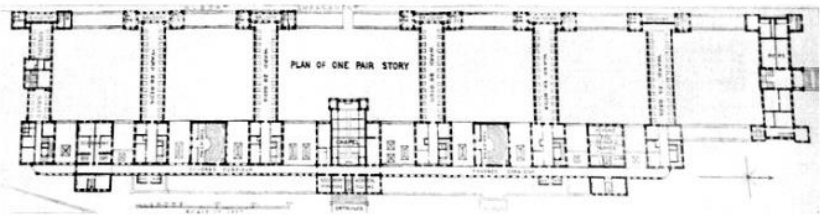


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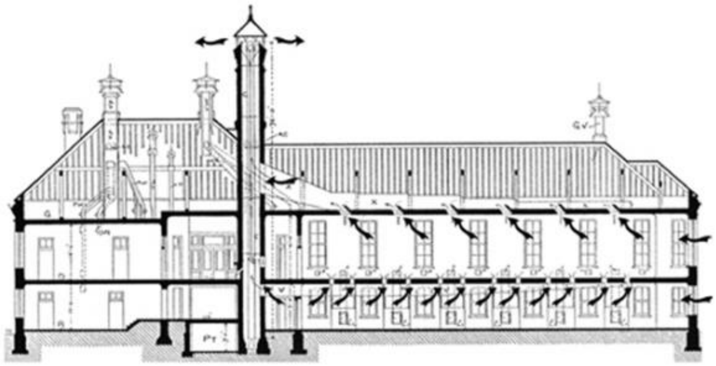
Fig.2.16-1 The ventilation design of Nightingale design ward



Cited: Health Architecture Home/ Wikifoundry

2.4.2 International style hospitals

At the end of World War II, European countries urgently needed to rebuild their society and infrastructure. The international style of architectural design naturally replaced the neoclassicism present in design at that time. The International style of architecture identified in this section does not reflect the 1920's Bauhaus or other theories, it more reflects the post-war period. This style, associated with the early 1960s, was influenced by certain leading architects and their ideas, for example, “Form follows function”- Luis Sullivan, “Less is more”- Mies Van Der Rohe and “Machine for living in”- Le Corbusier. Therefore, the International style and those statements ruled the architectural world as well as dominating urban planning and the building industry over decades. However, the international style present in the United States and Europe each created a different horizon for the design of hospitals. The following shows the distinctions between the results of each design.

a) International style hospitals in the United States

In the United States traditional courtyard or pavilion hospitals faced the major problem of the rising price of land in the early twentieth century. As a result, the challenge of gaining maximum utility from the limited land available turned hospital design toward an international style that was inspired by office buildings with vertical development (Verderber and Fine,2000). The style was established with flat roofs, monolithic building blocks, less façade decoration connected by large glazing and a single colour or a white only coating, constructed with precast concrete and a steel structure. The building organization was divided simply into a ground floor with a podium shape, for outpatient use such as clinics or an emergency centre, and upper levels, or towers, for inpatient facilities (Hitchcok and Johnson, 1996).

a-1) The Hill-Burton or the racetrack plan

From 1941 to 1946 the Hill-Burton Act and U.S Public Health Service controlled most American hospitals including mapping existing healthcare facilities and establishing building standards for healthcare buildings. The Hill-Burton Standard optimized the management of hospital design for medical services. It consisted of construction methods, room layouts, bedding numbers, and the reduction of unnecessary procedures for diagnosis and clinics, etc. The series of regulations was to further ensure a quality service for medical operations. The design idea utilised the experience of architects and medical staff through their professional feedback to provide some design guidelines (Stevens, 1999).

For example, the Hill-Burton guidelines virtually created a specific type of ward layout, called the Double-Loaded corridor system. It also became known as the Racetrack plan. The Racetrack plan of Archbishop Bergan Mercy Hospital, Omaha, Nebraska, 1965, (Fig.2.17), allowed a circular delivery service (Fig.2.17-1-A) operating between nursing stations and ward units, which improved the service efficiency and provided better supervision. The design layout, the central core (Fig.2.17-1-B) contained all service areas such as lift space, two nurses' stations, storage for clean linen, mechanical shafts, staff rest rooms, meeting spaces, and treatment units. The central core was surrounded by wards (Fig.2.17-1-C) with each room allowing four beds to share a sanitary space. However, there were some disadvantages of this design plan. For effective service quality and supervision, wards had to be at a short distance from nursing stations, so one problem of this ideal layout is that dimensions couldn't be extended (Fig.2.17-2).

Fig.2.17 The racetrack plan design at the Archbishop Bergan Mercy hospital

Fig.2.17-1 The racetrack plan design

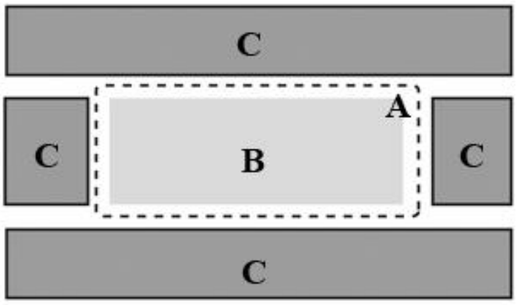
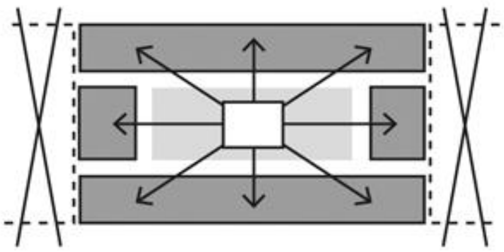


Fig.2.17-2
Disadvantage of racetrack plan design



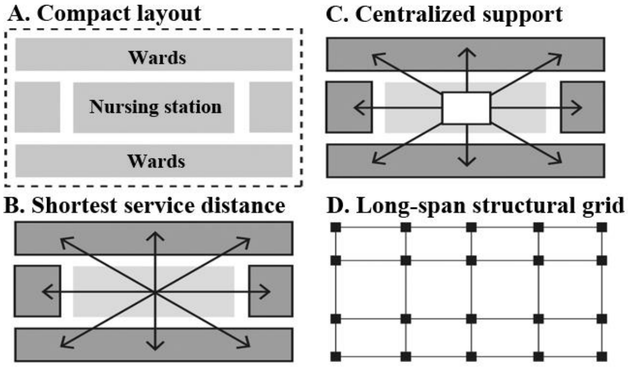
Cited: Verderber and Fine, 2000/ Author reproduced

The mid-1960s monolithic and cubic style hospital (Fig.2.18) reflected high density populations and its sophisticated design made the high-rise international style hospital become a symbol of healthcare buildings in the United States. Over twenty floors, skyscraper hospitals dominated the skyline with other high-rise office buildings in the city. Many advantages of the high-rise hospital were evident. For example, for medical services, the design provided compact layout (Fig.2.18-1-A), shortest service distances (Fig.2.18-1-B), efficient lift core and centralized support (Fig.2.18-1-C). For floor plans, the long-span structural grid (Fig.2.18-1-D) gave the maximum freedom of layout for departments, with inpatient rooms facing natural views, and for the engineering facilities, lighting systems and advanced heating, ventilation and air circulation systems (HVAC). Moreover, artificial illumination was extensively used in its interior space. It was believed such artificial lighting made staff perform better. Economic considerations were important, typical American hospitals in the 60s provided the highest capacity with regard to people, services, and modern technology (James and Tatton-Brown, 1986).

Fig.2.18
The Nebraska Methodist hospital

Cited: Verderber and Fine, 2000

Fig.2.18-1 High-rise hospital design advantages



Source: Author reproduced

However, this extreme design based on efficiency reflected busy workflows. Hospitals were criticized as cold and unfeeling organisations creating inhumane environments. This was partly because the general departments lacked natural views and lighting. Staff and visitors easily get lost inside the building. After long days exposed to artificial lighting, staff became easily depressed. Furthermore, if the economy after the 60s faced financial crisis then the government would not be able to afford continued public medical support. Finally, the Hill-Burton system and the U.S. public health service was deconstructed, and the investment in hospitals returned to the free market after decades in the public sector (Verderber and Fine, 2000).

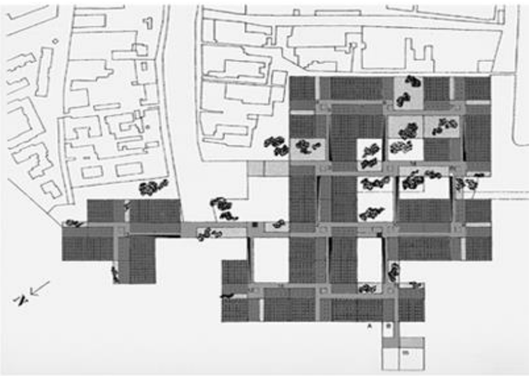
b) International hospitals on the European continent

When we compare the international style hospital design in the United States with that of Europe, hospitals in Europe developed in line with the attributes of urban renewal. Therefore, horizontal hospital development presented very different results compared to the vertical hospitals in America. To understand this trend for horizontal-style architecture in Europe it is important to consider the background to this design inspiration then illustrate the results with a particular project.

b-1) Le Corbusier, urban design aided hospital

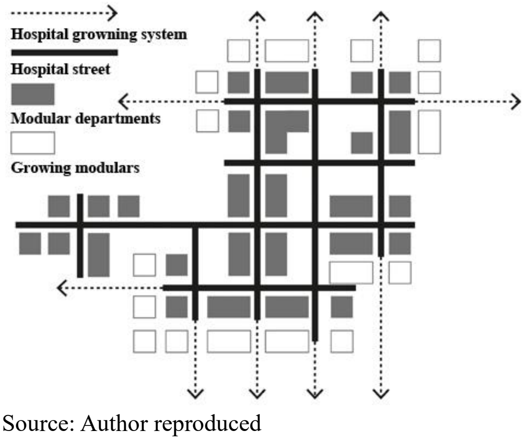
The most influential architect in the twentieth century, Le Corbusier, designed a hospital for the city of Venice in Italy, 1965 (Fig.2.19). He established the trend of the low rise, environmentally concerned and extendable master plans. Although the Venice hospital was never built, the idea demonstrated well how healthcare facilities interconnected with the city context. The hospital had four stories and sprawled with building blocks and multi-court yards interweaved on the site. The ground floor was to be avoided because of the frequent flooding in Venice; the first floor was the outpatient centre for the clinical departments and reception; the second floor was for staff including rest rooms and preparation space; the top floor was for the inpatient department and nursing support. Le Corbusier maximized the modular concept in order to systematically and flexibly add extensions for hospital growth (Fig.2.19-1-A).

Fig.2.19 Le Corbusier's Venice hospital, Italy



Cited: Allard, Hyde, Sarkis and LeCorbusier, 2001

Fig.2.19-1 A Modular design & extension

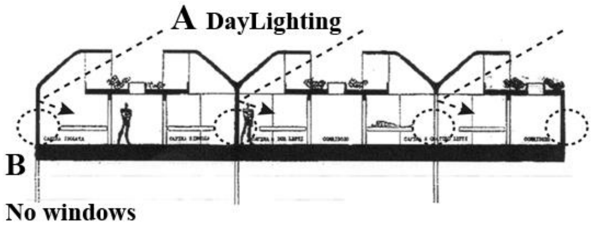


Source: Author reproduced

In addition, an advantage of low-rise and horizontal development provided elements such as better natural lighting and landscape views from the interior (Fig.2.20-A). On the other hand, this hospital design contained many drawbacks for practical use. For example, there were no regular windows for the wards (Fig.2.20-B), and the walking distances from the nursing station to the wards were too long (Allard,Hyde,Sarkis and

LeCorbusier, 2001). In conclusion, Corbusier displayed many successful points from urban-planning ideology in his hospital design, and his ideas certainly inspired the development of horizontal hospital types. If vertical hospitals presented a solid mechanism for health care buildings, the horizontal hospital demonstrated the potential of flexible and systematic hospital design (SHAH, 2016).

Fig.2.20 Advantages and disadvantages of the Venice hospital

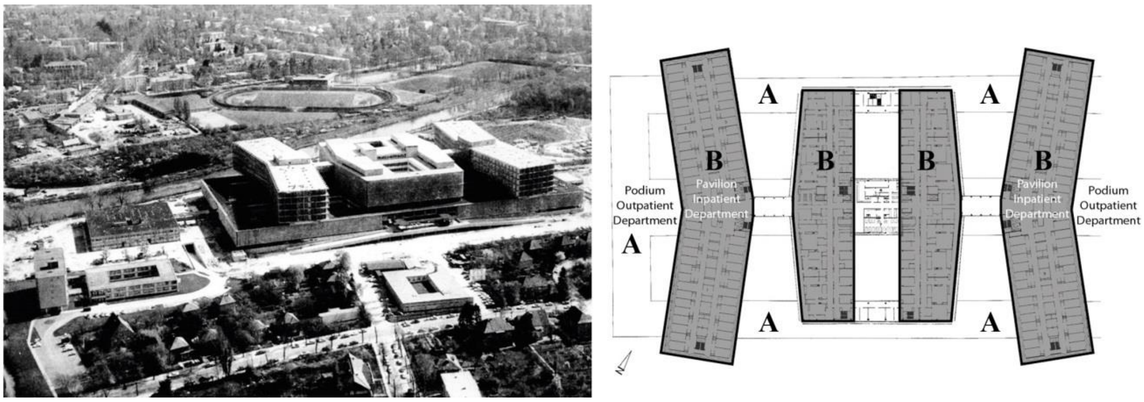


Cited: Allard, Hyde, Sarkis and LeCorbusier, 2001/ Author reproduced

b-2) Horizontal hospital design in Europe

The typical European modern hospitals during the 1960s were designed to match the urban environment. For example, in the Free University Hospital Centre, Berlin, 1969 (Fig.2.21), the hospital had a huge scale ground floor (Fig.2.21-A), containing entire outpatient departments, and upper towers. The pavilion-like ward towers (Fig.2.21-B) were symmetrically located on opposite sides of a central block building.

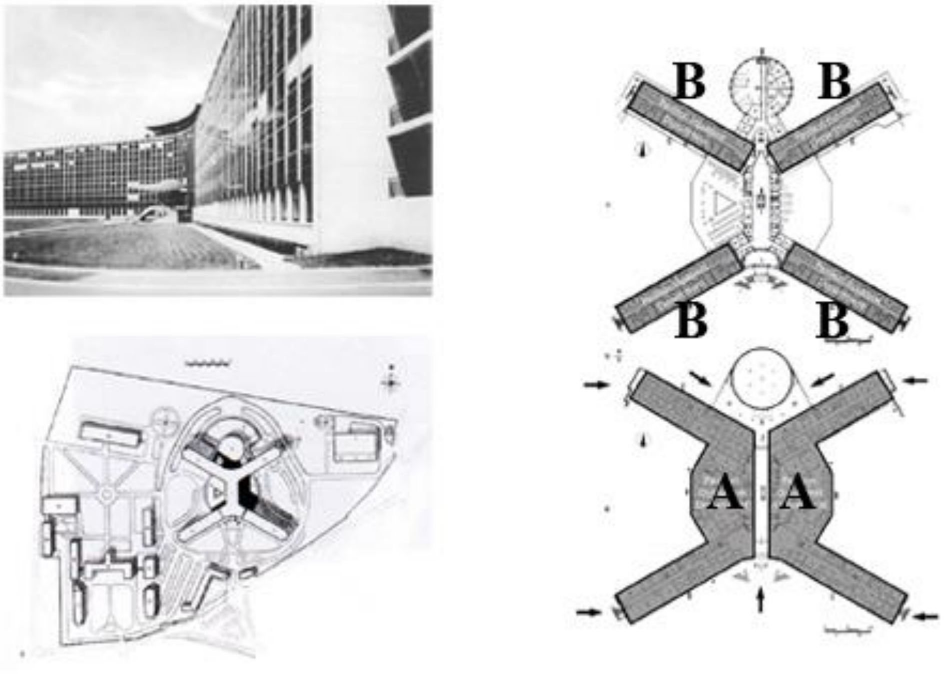
Fig.2.21 The Free University Hospital Centre, Berlin



Cited: Verderber and Fine, 2000

Moreover, the Gonesse hospital centre, France, 1967-70 (Fig.2.22) was designed like the human body. The ground floor was a podium design (Fig.2.22-A) including an entry hall and four outpatient pavilions (Fig.2.22-B) (Verderber and fine, 2000). The podium design and wide entry hall presented an image of welcoming visitors and the pavilion design connected with the surrounding environment through natural lighting and views.

Fig.2.22 The Gonesse hospital centre, France

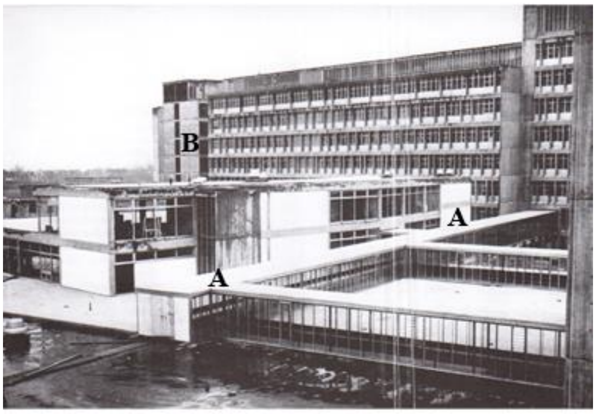


Cited: Verderber and Fine, 2000

b-3) Brutalism hospitals of England

At the same time, other horizontal international style hospitals were being developed in the United Kingdom. This new style was also known as the Brutalism hospital. The style was followed in the hospital design scheme of the National Health Service (NHS). UK hospitals were analogous with village and town development, providing healthcare services for the local community (Stone,1980). For example, the Norwich Park District General Hospital, 1965-70, England (Fig.2.23), was built with an extendable master plan. Buildings on the campus were connected by one major service pedestrian hospital street (Fig.2.23-A). The height of the ward building (Fig.2.23-B) was not to be over four floors, and ward interiors were designed with racetrack layouts and self-sufficient structures. This horizontal planning provided a flexible and extendable system and the idea offered variable design strategies and patterns for hospital design in the UK.

Fig.2.23 The Norwich park district general hospital



Cited: Stone, 1980

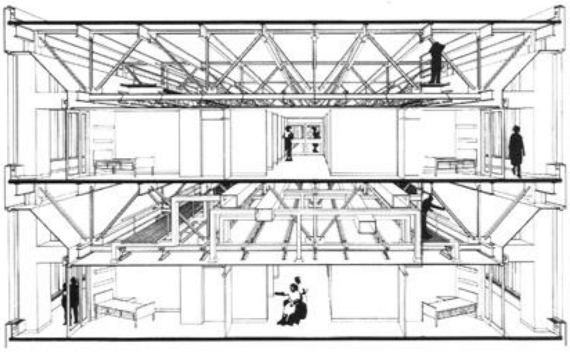
2.4.3 Late twentieth century modern hospital design

In the late twentieth century there was a mass production of modern hospital developments with similar functional designs and aesthetics. In the architectural design of 70s hospitals, the style followed the templates from the 60s, the international style of architectural design. The architectural expression kept traditional geometric shapes in the building's profile but further intensified the concept of concentrated layouts for the efficacy of medical services. By contrast, the 80s and 90s hospitals reduced the building scale. The hospital design changed towards specialised facilities rather than locating all medical departments in the same building. This meant fewer functional programs were involved in each architectural plan and it gave more coherent management of spatial planning. In addition, flexible design was also inspired by post-modernism creating a variety of forms of architectural design such as curved walls and separated building plans.

a) Centralized medical services and mothership hospitals

High-tech Industrial manufacture and production in the 1970s changed the vision of hospital design. Hospitals were designed as a medical mothership, combining many high-tech facilities run with efficient functions. So, hospital design in the planning stage was divided into multiple disciplines including equipment specification, interior layouts, schematic plans, engineering and service/supply structures. The design direction was highly focused on centralizing medical services. Examination departments were located in the central part of the building, such as Magnetic Resonance Image (MRI) and Computed Axial Tomography (CAT scanner) rooms. Other facilities were located according to clinical need or diagnostic process. The distance between departments needed to be kept short in order to save time and to optimize cooperation. Consequently, centralized floorplan design became the universal standard for 70s hospitals. In addition, the mechanical and electrical networks were contained within a special layer (Fig.2.24); an additional space between ceilings and floors, for mechanical and plumbing engineering, such as HVAC electrical systems. This specially designed layer also allowed technicians easy access to and maintenance of those systems. Moreover, each ward was equipped with coordinated panels for nursing care; most facilities could easily

Fig.2.24 The mechanical and electrical layer

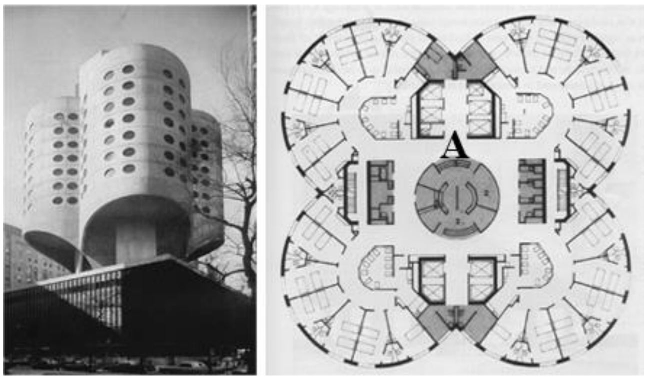


Cited: Verderber and Fine, 2000

be plugged-in or clipped-on right next to the bedding area (Francis,1999). The medical services followed an American hospital planner - Gordon Friesen, who designed the so-called Friesen System. It was highly recommended that this efficient system be applied in all hospital departments by the early 1970s. The service system covered patient wards, ICU, clinics as well as material supplies.

The examples of 70s hospitals show compact design allied with advanced building technologies. In the United States, vertical development hospitals dominated the healthcare industry. It was easy to recognise the appearance of those mothership and high-tech hospitals by their compact but bulky tower profiles. For example, in the Prentiss Hospital for Women and Psychiatric institute, (Fig.2.25) Chicago, 1975, by Chicago architect, Bertrand Goldberg, the building presented a circular form with a concentrated floor plan design. The façade was concrete made with only a few fixed windows. All departments were equipped with artificial illumination and ventilation, so there was no necessity to provide massive windows for the hospital. All services relied upon the centralized and vertical transport system (Fig.2.25-A) which delivered goods or staff from the different floors to the target department. Nursing stations on the inpatient floors were located in the centre to insure nursing services could operate with the shortest distance as well as giving better supervision.

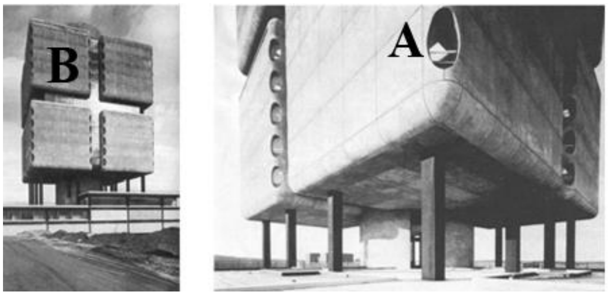
Fig.2.25 The Prentiss hospital, USA



Cited: Verderber and Fine, 2000

Another similar example was Stony Brook New York, the University Hospital, 1974-76 by Goldberg (Fig.2.26). Designed in a huge cubic shape, it was divided using radial layouts with compact floor plans and nursing stations. This project removed almost all windows from the facades. Windows only appeared on four corners (Fig.2.26-A) and public corridors (Fig.2.26-B). Although the powerful mechanical approach supported all functions of these mothership hospitals, the generally negative

Fig.2.26 The Stony Brook hospital, USA

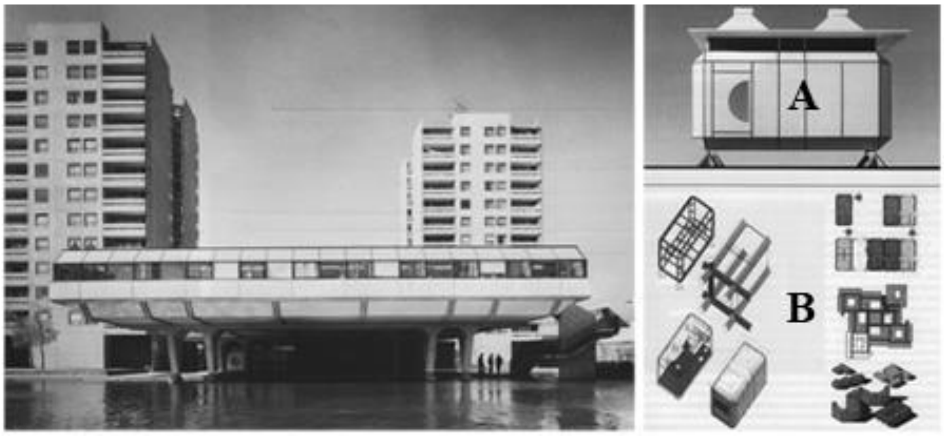


Cited: Verderber and Fine, 2000

reviews from patients and staff were about the lack of natural environment, the inhumane environment and the difficulty of finding one's way in the hospital (Francis, 1999).

In England, the high-tech 70s hospital was developed focusing on the idea of a systematic strategy including flexible plans and feasible constructions. The Lakeside Health Centre (Fig.2.27), 1972, Thamesmead, England, by Derek Stow & Partners was designed to be an outstanding high-tech hospital and the entire hospital consisted of advanced modules. The hospital followed a three-dimensional master grid as a building system. Each department was divided into single pre-planned blocks (Fig.2.27-A) combined with environmental engineering facilities. Half of the hospital was built upon an artificial lake and showed the design flexibility provided by this modular system. It meant that this hospital type could adapt to many site conditions. This building system (Fig.2.27-B) was formally called The British Modular Building Consortia (BMBC) and was also used for delivering primary health care centres and emergency hospitals for Middle-East countries (Prasad, 2008).

Fig.2.27 The Lakeside health centre, England



Cited: Prasad, 2008

Another brilliant project of British contemporary hospital design ‘The Greenwich District Hospital’ (Fig.2.28) was built by the DHSS and its associated teams. The project looked very like a typical solid mothership hospital of the 1970s, but the design went for a horizontal development.

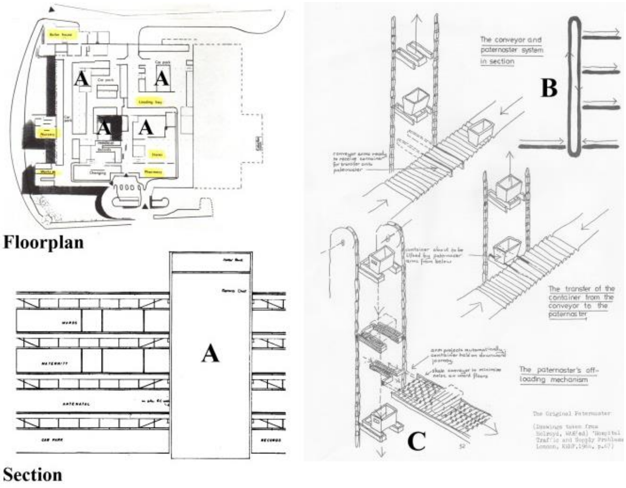
Fig.2.28 The Greenwich district hospital, England

Cited: DHSS/ Photographer-Toomey, 1922

The design was similar to typical centralized layouts but combined four vertical shafts (Fig.2.28-1-A) to transport resources from the storage floor. Also, the supply system was equipped with the latest automatic conveyer (Fig.2.28-1-B), and goods were specified in different sizes with pre-set baskets and then delivered to departments (Fig.2.28-1-C).

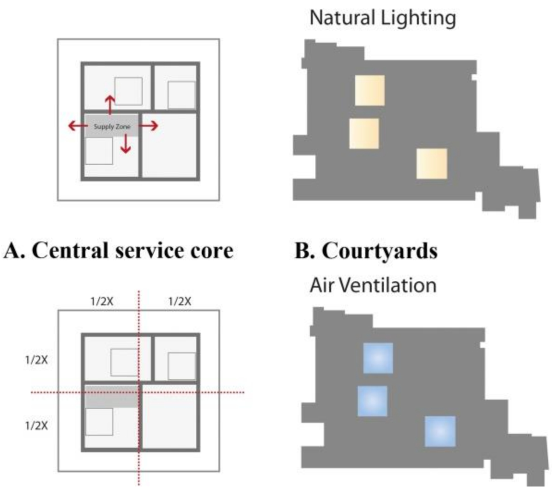
This high-tech facility successfully demonstrated advanced auto-technology integrated with hospital design. Furthermore, the central service core (Fig.2.28-2-A) was surrounded by four courtyards to solve problems of insufficient natural lighting and ventilation (Fig.2.28-2-B). The design of inner courtyards also solved the problem of loss of direction while people moved around this huge hospital. The Greenwich District Hospital presented the high level of sophisticated design achieved by British healthcare authorities. It achieved not only the incorporation of high-tech facilities use in hospitals but also took into account the opinions of users' experiences in contemporary hospital design (Samuel, 1964).

Fig.2.28-1 The vertical shift/mechanical system



Cited: DHSS & Grayson & Hope/ 1983Prasad, 2008

Fig.2.28-2 Core service/ courtyards



Cited: DHSS/ Stone, 1980/ Author reproduced

b) 1980s and 1990s, pluralism design and functional deconstruction of hospitals

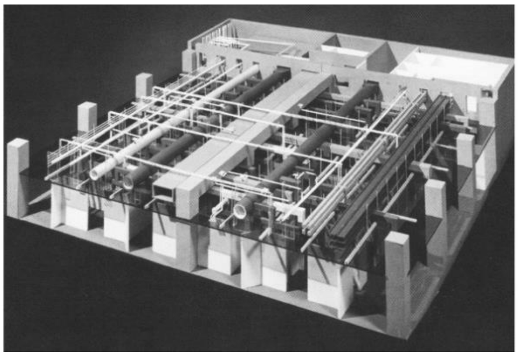
The 80s and 90s produced the most diverse changes in the history of hospital design. The imperfect mechanistic hospitals of the 1970s did not provide design sustainability. Heavy facilities and standard design guidelines did not provide cost savings to the public health department, quite soon the funding from those public authorities was discontinued and the hospitals were released to private management. Hospitals needed to find new solutions for their development. As a result, the name 'hospital' gradually changed to 'medical centre'. In practice this meant the hospital no longer covered every service for patients. It also meant that medium-sized and specialist services not requiring huge architectural structures were becoming the trend. Different departments might be outsourced to separate medical centres in different locations. This trend made hospital design more diverse and unique because of the simplified structure. Subsequently hospital design was impacted by post-modernism such as pluralism and deconstructivism, the style of the 80s and 90s hospitals represented their expression (Francis, 1999).

The hospitals of the 1980s and 90s diverged from the enormous building scale of the international style. The building appearance clearly showed a change in design related to a variety of social backgrounds and technological developments. This section identifies some specific types of design: the mega-hospital, the high-tech romanticism hospital, the atrium hospital and the new resistentialism and regionalism hospital. These appeared in the 80s and 90s and they explain the evolution of hospital design in the late twentieth century (Verderber and Fine, 2000).

b-1) Megahospital

The Megahospital was an idea developed from the Utopian hospital of the 60s and 70s. This type of hospital heavily emphasised engineering and mechanical integration into building structures (Fig.2.29). The compact and solid shape covered all departments and was normally supervised by national governments. For example, the Canadian government built some megahospitals around the 1980s: The McMaster University Health Sciences Centre (Fig.2.30) in Hamilton, late 70s-80s, Ontario and The Walter C. Mackenize Health Sciences Centre (Fig.2.31) in Edmonton, 1980-86, Alberta. The image

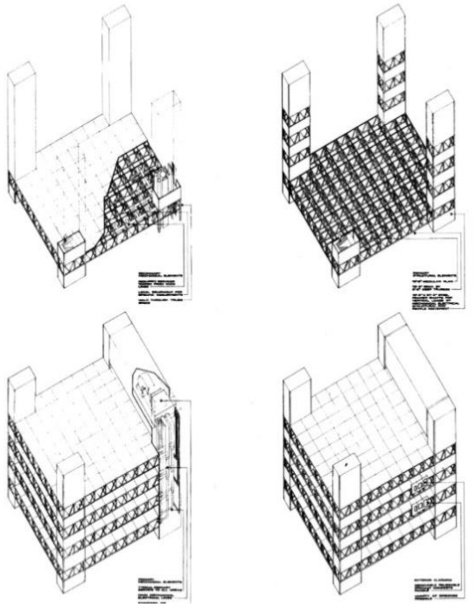
Fig.2.29 Mechanical integration design layers



Cited: Verderber and Fine, 2000

shows the atrium of the Walter C. Mackenzie Health Science with lots of mechanical plumbing. It demonstrates the typical mechanistic hospital design with centralized engineering support.

Fig.2.30
The McMaster University hospital, Canada



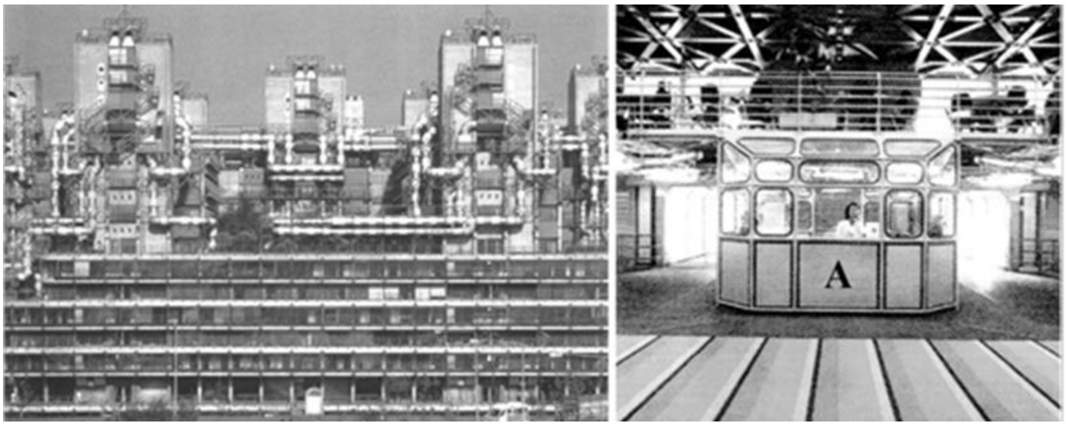
Cited: Verderber and Fine, 2000

Fig.2.31
The Walter C. Mackenize hospital, Canada

Cited: Verderber and Fine, 2000

Also in Germany, The Medical Center, Technical University of Aachen (Fig.2.32), 1984 by Weber, Brand and partners was built as an automated factory-like hospital, and the interior was designed with mechanical systems and plug-in nursing stations (Fig.2.32-A) (Francis, 1999).

Fig.2.32 The Medical center, technical university of Aachen, Germany



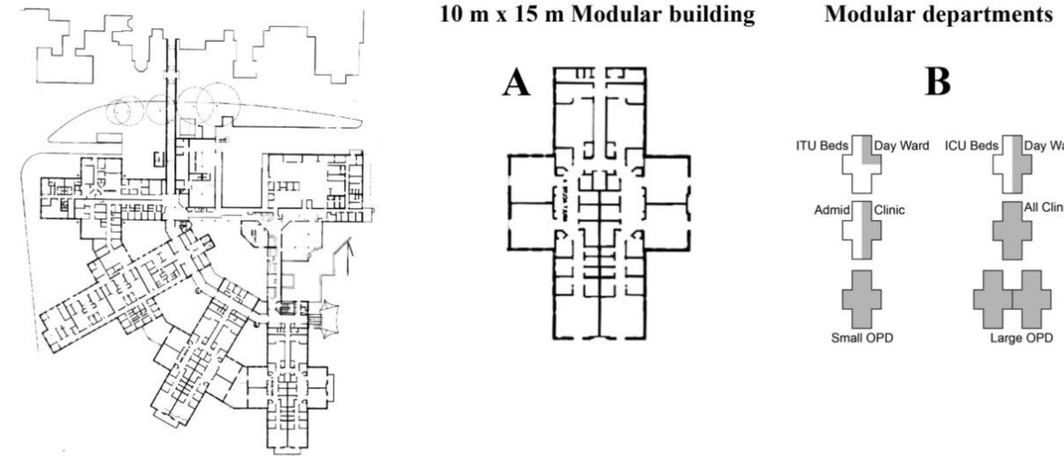
Cited: Verderber and Fine, 2000

b-2) High-tech Romanticism hospital

In England, the high-tech romanticism hospital presented aspects different from the traditional mechanical hospital. The design balanced artificial and natural functions for hospital environments. For instance, St. Mary's Hospital (Fig.2.33), 1981-91, by DHSS, was a medium size project following a novel design idea by the UK Department of Health (DHSS) i.e. the nucleus hospital design system. The design system was based on a 10 metre x 15 metre modular building or unit (Fig.2.33-1-A) with an adaptable system. Each module was inspired by Nightingale's hospital principles but integrated high-tech facilities in the construction. The master plan of the St. Mary's hospital consisted of four modules; each module represented a department such as clinic or ward (Fig.2.33-1-B).

The building section shows that the engineering facilities were hidden in the ceiling structure (Fig.2.33-1-C) and each ward gains sufficient natural lighting and views from the two side windows (top and front) (Fig.2.33-1-D). This modular structure and its high-tech features improved the flexibility of the design. Also, the low-rise development improved visual impact for patients and visitors. In addition, the overall design harmonising with natural considerations balanced well with the comfortable health care environment for hospital inpatients (Stone, 1980).

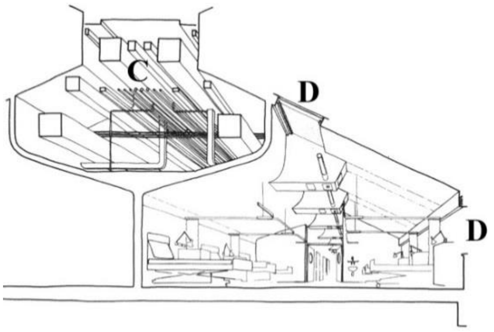
Fig.2.33-1-A-B Modular building design



Cited: DHSS/ Stone, 1980

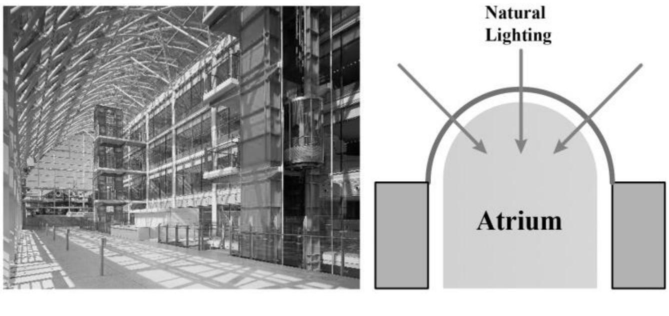
Cited: DHSS/ Stone, 1980/ Author reproduced

Fig.2.33-1-C-D The engineering ceiling layer



Cited: DHSS/ Stone, 1980

Fig.2.34 Atrium design hospital & section view



Cited: Verderber and Fine, 2000

b-3) Atrium hospital

Atrium hospitals were influenced by hotel lobby and shopping mall design with a big and transparent atrium (Fig.2.34). The function of the atrium was to diminish the intensive and busy feeling of hospital life. Thus, this theatrical atrium became one of the hallmarks from the 1980s to the present. In comparison with the atrium of traditional big hospitals such as the megahospital, there were no exposed mechanical facilities. Instead of artificial plumbing the entire atrium space was decorated with comfortable colours and a glass ceiling with natural sunlight was provided, as well as indoor plants. For example, the Berlin-Neukolln Hospital (Fig.2.35) in Berlin shows a classic and elegant atrium design while The Dartmouth-Hitchcock Medical Center (Fig.2.36), Lebanon, New Hampshire, 1992, by the Boston firm Shepley, Bulfinch, Richardson, and Abbott, demonstrated a street-like atrium in their hospital design. Another example was the Lakeland Medical Centre (Fig.2.37), Athens, Texas, 1986, by Ellerbe Associates of Minneapolis which showed a design connecting a water landscape and atrium views (Verderber and Fine, 2000).

Fig.2.35
Neukolln hospital

Fig.2.36
Hitchcock medical center

Fig.2.37
The Lakeland medical center

Cited: Verderber and Fine, 2000

b-4) New Residentialism and Regionalism hospital

Meanwhile, in the UK and Europe the postmodernist stream of the “new residentialism” became an important design direction for medium or small local hospitals. The hospital, in the style of residentialism, was designed like a residence with brick facades, canopy entrance, gable roofs and home style interiors with patterned carpets. In contrast to traditional modernism hospitals, the residentialism hospital reflected local viewpoints, especially those of daily residential life, and presented its site plan as a free-standing system with the building design fully responding to the regional landscape.

Therefore, the style also became known as the “Regionalism Hospital.” The Vrinnevis Hospital, Norrkoping, Sweden (Fig.2.38), 1980-83, by Bo Castenfors, showed a small hospital institution with an apartment-like appearance. The dayroom image was found in The Renfrew Centre, Philadelphia (Fig.2.39), England, 1985 by Tony Atkins and Associates of Philadelphia. The Shenandoah Regional Campus (Fig.2.40), Virginia, 1989-91 by Richard Rauh and Associates of Atlanta had a site plan with five free-standing buildings in an open landscape area (Verderber and Fine, 2000).

Fig.2.38
The Vrinnevis hospital

Fig.2.39
The Renfrew centre

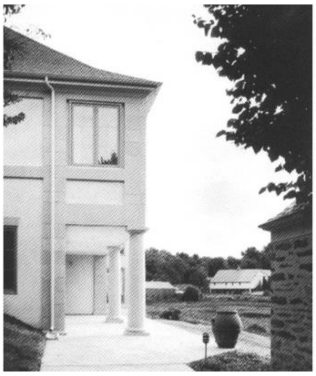
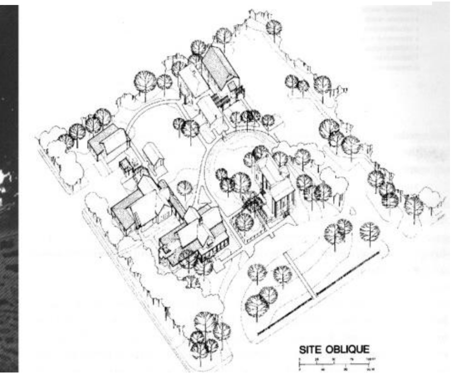


Fig.2.40
The Shenandoah regional campus



Cited: Verderber and Fine, 2000

2.5 New age (21st century) hospital design and CAD

New age hospital design introduces a digital world of architectural design in practice. In contrast to the more traditional architectural design with styles such as modernism or post-modernism, Computer Aided Design (CAD) in healthcare architecture was applied precisely to optimize the architectural design process as well as improve working efficiency. For example, complex geometry in the building shape studies, mixed materials utilization for facades and environmental simulation systems, all rely on the CAD process. Consequently, the style of current hospitals no longer follows any specific presentation method. By contrast, new age hospital design is developing towards synthesized disciplines, multifunctional structures and integrated design schemes. The final part of this section shows a few cases of new age hospital design and considers the concept of building development.

2.5.1 Sustainable design Hospital

Architectural sustainability aims to reduce and minimize the adverse environmental effects which might result from architectural operations, such as through sustainability measurement factors including saving energy, recycling materials and cultural redevelopment. The Providence Newberg Medical Center (PNMC) (Fig.2.41), 2006,

Fig.2.41 The Providence Newberg medical center, USA

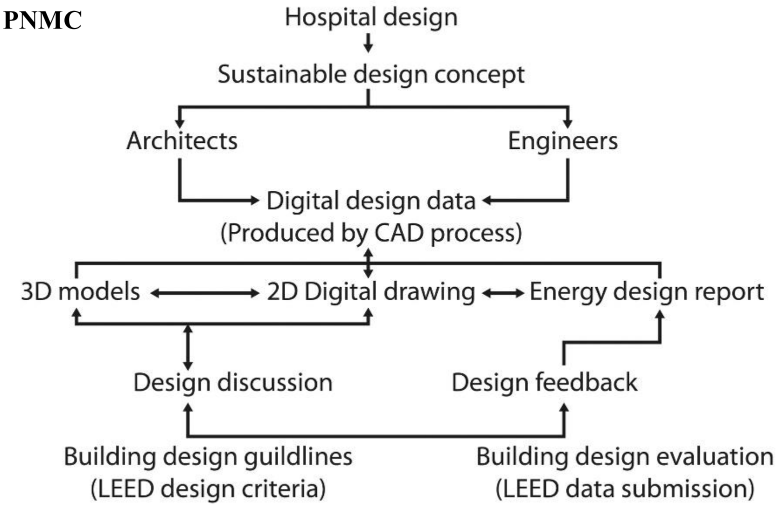
Cited: Mayerreed.com, 2017

Fig.2.41-1 Open landscape design views

Cited: Mayerreed.com, 2017

Newberg, Oregon, USA by Mahlum Architects was the first to receive a *Sustainable Architectural Certificate (Gold Level)* by the American LEED system. The building site is an open landscape design with drought-tolerant plants (Fig.2.41-1) which adapt to local changes in weather. The site has direct links to the public transport infrastructure, besides that free car and bike parking encourage visitors and staff to come to the hospital and enable free access to a large local community zone. For the building, high-reflective and low-emissive materials are used in the roof design. Wood and non-toxic, low impact products are used mainly for interior decoration. 70% of building components were fabricated using local materials and 80% of construction waste was recycled or provided reusable materials. The interior is fully naturally lit with a two-level glazing system. Inpatient wards are designed with a home-like atmosphere with large glass window for better views and maximized sunlight (Verderber, 2014). The design process diagram (Fig.2.41-2) shows how those complex design ideas were managed through the CAD system. The digital drawing process allowed architects to easily transfer their design drafts and enabled communication with the different professions such as energy engineers and medical staff. Also, in the digital design process, materials were evaluated through sustainable criteria (LEED) and gave more reliable building quality through third party approval.

Fig.2.41-2 The CAD process for PNMC



Source: Author produced

2.5.2 Return of the megahospital

The 2000s megahospitals are different from those of the 1970s or 1980s. The new megahospital idea did not just focus on mechanical performance but proposes that the design should respond to the needs of the local community (Prasad,2008). For example, the Katta Public General Hospital (Fig.2.42), 2002, Shiroish City, Miyagi, Japan was built as the disaster response centre for the region.

Fig.2.42 The Katta public general hospital, Japan

Cited: Futurarc.com, 2017

The design of the hospital aimed to connect the local area as well as providing a public community zone for residents. The hospital site is located on a hill (Fig.2.42-1-A) in the region which means that residents can easily identify the hospital, especially in the case of earthquakes. The building design comprises three floors of mega-rectangular blocks with a grid system layout (Fig.2.42-1-B). The avoided ground floor (Fig.2.42-1-C) is supported by a seismic foundation isolation system with a shock-absorbent structure to protect the building and allow patient evacuation during earthquakes. Each floor contains several courtyards with different themes expressing traditional Japanese garden arts. For example, the meditation space is for prayer or for visitors while the roof garden with themed gardens has easy access from the wards. The entire interior is decorated with Japanese traditional wood sculptures and graphic patterns (Fig.2.42-1-D).

Fig.2.42-1-A The hospital site is located on a hill

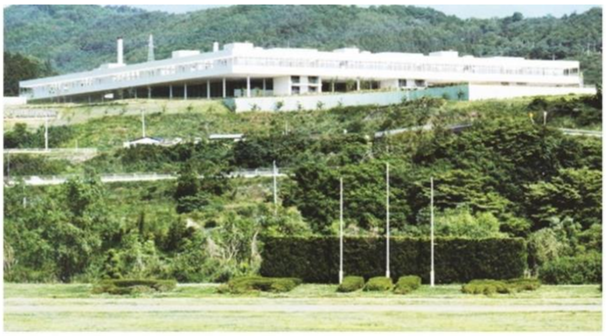


Fig.2.42-1-BThe grid system layout

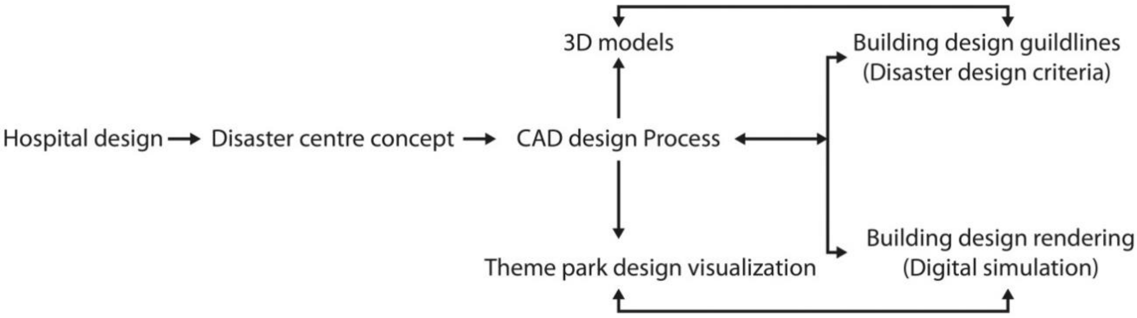
Fig.2.42-1-C The avoided ground floor

Fig.2.42-1-D The theme courtyards

Cited: Futurarc.com, 2017/ Verderber, 2014

According to feedback from staff and visitors this interior successfully creates a relaxing and stress-free experience in contrast to their previous hospital experiences (Verderber, 2014). In the design process (Fig.2.42-2), CAD had an important role in design simulations. This type of megabuilding requires the highest standard of structural evaluation, especially as Japan is an earthquake country. This hospital is designed to be a disaster centre which demands a trustworthy process for disaster testing. So digital modelling processes and evaluation were intensively utilised in this stage. Besides that, digital visualization (computer rendering) helped to identify the focal point and building visibility for emergency evacuations as well as the design of landscapes.

Fig.2.42-2 The CAD process for the Katta Public General Hospital



Source: Author produced

2.5.3 Therapeutic hospital

Fig.2.43 The REHAB Basel centre, Switzerland

Cited: Guenther and Vittori, 2013

Extensive medical research has indicated that medicine and traditional medical services might not be the only solution for healing patients. Some research has found that therapeutic architecture might help some patients suffering from special diseases or conditions to relieve their symptoms during the recovery stage (Guenther & Vittori, 2013). The REHAB centre (Fig.2.43) for Spinal Cord and Brain Injuries, 2002, Basel, Switzerland by Herzog & De Meuron is a private treatment organization for patients with spinal cord and brain injuries. This rehabilitation centre only accepts people with long term recovery periods up to 18 months, during their recovery from illness. Therefore, the hospital’s spaces are created for them to rebuild or reconstruct their everyday abilities, for example, spatial cognitions and environmental responses. The elaborate inner landscape (Fig.2.43-1-A) selects plants from the local area to help patients regain their memory of the local scenery. Moreover, the timber design appearance including louvers and rails (Fig.2.43-1-B) provides indirect natural lighting for the

Fig.2.43-1-A The selected plans and gardens at the REHAB

Fig.2.43-1-B Wood louvers

Fig.2.43-1-C Disable accessible

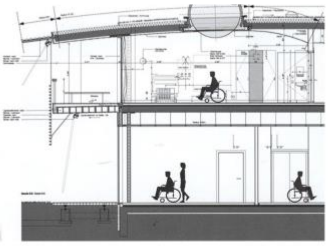
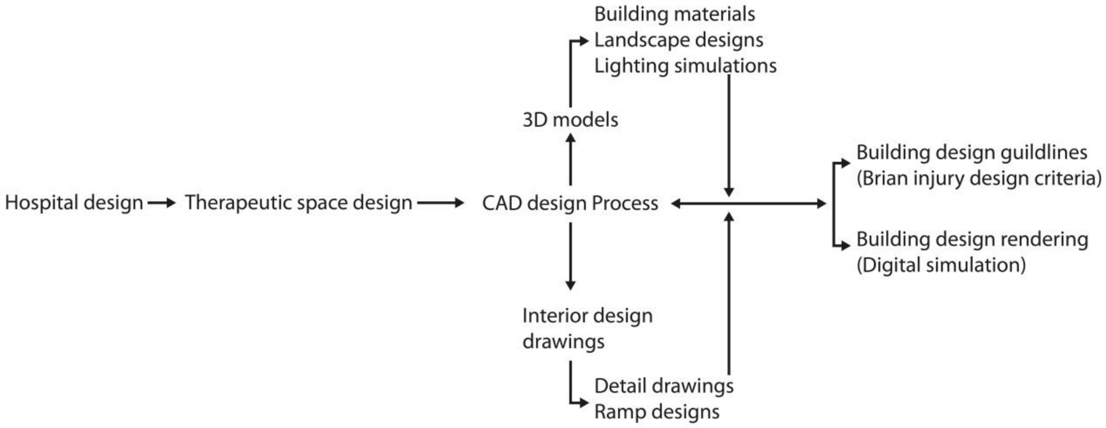


Fig.2.43-1-D Roof terrace

Fig.2.43-1-E Natural lighting

Cited: Rehab.ch, 2017/ Guenther and Vittori, 2013/ Ksamedia.osu.edu, 2017 residents and softens the feeling of staying in a treatment centre. The floor plans allow disabled access (Fig.2.43-1-C), and wheel chairs can be easily used in every space in bedrooms and roof terraces (Fig.2.43-1-D). Moreover, each ward is equipped with a large transparent plastic sphere-dome in the ceiling structure to provide ready access of natural lighting into the bedding area (Fig.2.43-1-E) (Guenther and Vittori, 2013). Using CAD (Fig.2.43-2), a significant amount of design information was managed through digital integration such as drawing management and file export. For example, special scales for the ward design and details need to be integrated with factors of concern for brain injury patients. Also the natural lighting building system and landscape design previews were all presented by CAD visualization.

Fig.2.43-2 The CAD process for the therapeutic hospital design



Source: Author produced

2.6 Discussion

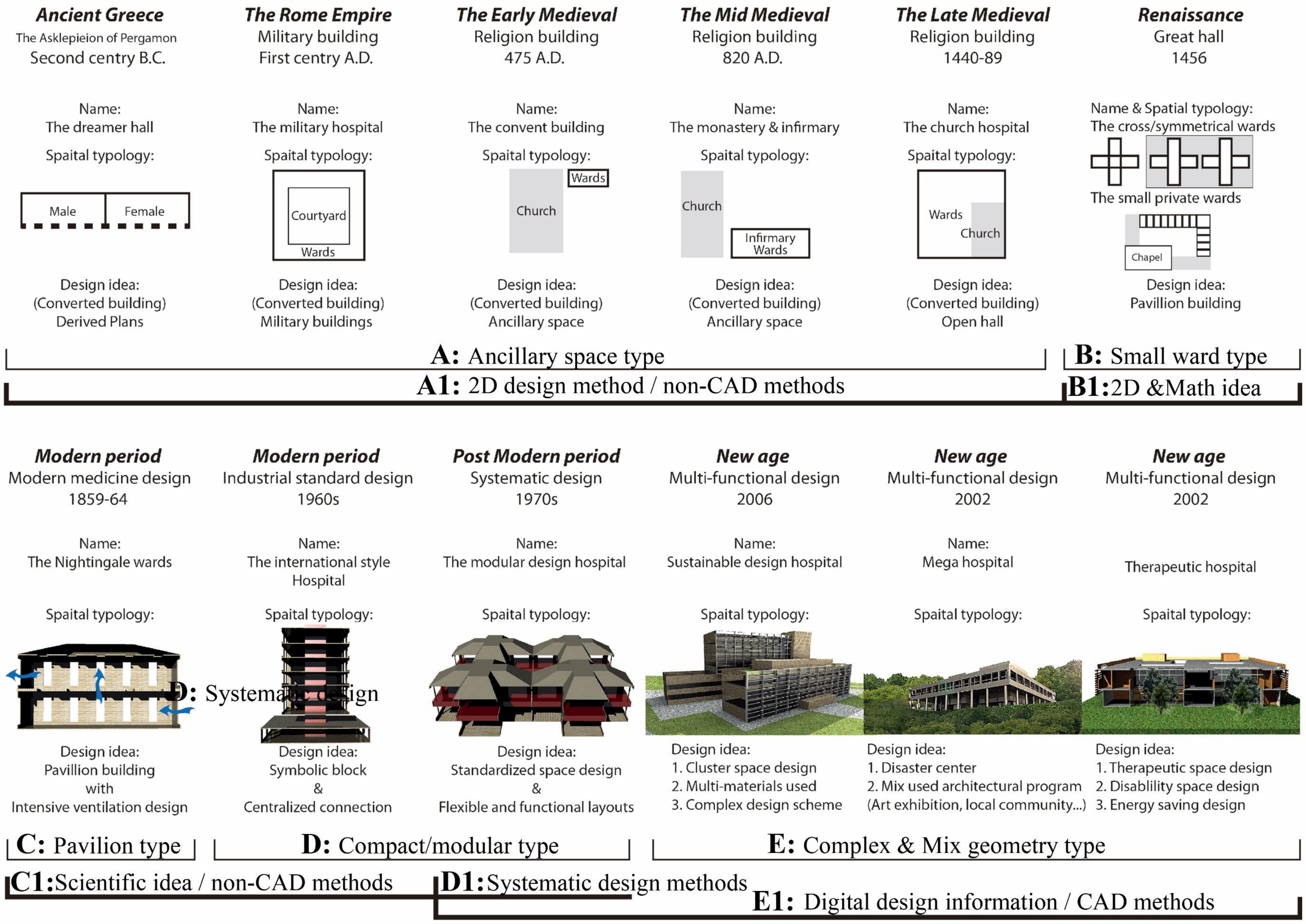
The discussion section aims to review the changes in hospital building design and ideas from a chronological perspective (Fig.2.44). There are two aspects considered in this timeline: 1. Building type and function and 2. Design tools and methods.

Firstly, from the earliest recorded time to the late medieval 1400s, hospitals were just an ancillary space or building such as the dreamer hall (Ancient Greece), the convent building (early medieval) and the great hall (late medieval) (Fig.2.44-A). These buildings only provided very simple care and healing with religion blessing. In the Renaissance period around the 1500s, design of inpatient departments established some functional requirements which showed more and better concern for inpatient environment design, such as privacy through small ward units and improved supervision through symmetrical or panoptical design (Fig.2.44-B). In the 19th century, the Nightingale ward established scientific evidence on effective ventilation, changing inpatient design standards and successfully reducing the problem of cross-infection (Fig.2.44-C). So, ward design became a standard-based design space as well as establishing and separating its building type from other forms of architecture. When it came to the 20th and 21st centuries, the huge progression of modern technology and contemporary medicine updated hospital building programs to a very complex level which now includes inpatient, outpatient and emergency departments etc. Hospital building is no longer an ancillary space, it is a highly professional architectural typology and it focuses on design supporting medical services (Fig.2.44-D). However, the ever-evolving trend in medical improvements means new hospital design can never stop and more recently New Age hospitals have become specialist service buildings with elaborate design layouts produced by CAD (Fig.2.44-E).

Secondly, regarding the design tools and methods used, historically hospitals were designed using non-CAD tools and the building proposal was only shown in 2 dimensions (2D). Especially from Ancient Greece to the late Medieval period, hospitals were adapted from other buildings like churches or infirmaries, the floor plans showed very few design ideas and they could not to be easily extended (Fig.2.44-A1). Although growing the building size was offered as the only design solution to meet changing demand, this extension created other design problems such as lack of supervision or construction limitations. When it came to Renaissance hospitals, mathematics was used to solve design problems arising from over-loaded wards by playing with some simple mathematical proportions. Even so those mathematical ideas were only manipulated in 2D drawings.

Mathematics offered a few options such as symmetrical and cross ward designs (Fig.2.44-B1). Centuries later, the Nightingale wards established a 3D design parameter for creating better interior ventilation by modifying building width, length and height but the building developments and drawings were still limited to 2D horizontal pavilion design (Fig.2.44-C1). However, by the late 1970s, the systematic design process founded by the DHSS and the National Health Service (NHS) in the UK, with its document based design parameters helped the emergence of 3D hospital design thinking (Fig.2.44-D1). By the late 80s, AutoCAD1986 sold over 1000 copies, and CAD products started to be found in contemporary design markets. The increasing use of CAD in hospital design has improved the quality of their design, particularly regarding their complex shape development, material utilization and construction efficiency (Fig.2.44-E1). To sum up, CAD not only helped new hospital design through better management of complex building functions but also provided a standardized process for architectural design.

Fig.2.44 A chronological reviews of hospital design idea



Source: Author produced

Part I/ Chapter 3 – Literature reviews 2

Healthcare architectural design process and creativity

3.1 Introduction

Hospital design is a complicated process because such a design has to accommodate different medical operations and functions that are critically connected to life and death. Therefore, general design methods and processes are not always able to cover these complexities. The publication, 'Building a 2020 Vision, Future healthcare environments' (The Nuffield Trust, 2001), suggests that future hospital design should provide organized consideration of political issues and policies, the prevailing social background, psychological issues, sustainable design, etc. However, healthcare building literature is mainly based on project reviews rather than focusing the discussion on the design process. Also, there is very limited literature identifying hospital building design ideation from a systematic aspect, especially exploring design cognition and its links to creativity in this specialist area. It is these aspects which this chapter focuses on. The chapter is divided into two distinct parts:

The first part considers the systematic aspect of the architectural design process and then moves on to definition of design complexity and design problems. The review connects different literature on architectural design in order to understand the architectural design process with particular reference to hospital design. In addition, four systematic design hospitals in the UK (NHS, 1970-80s) are introduced as case studies of how the design methodology has operated in practice. In the case study section, the design project analysis explains how the plan and ideas associated with relevant functional problems and challenges brought about a better vision for and understanding of the systematic design process.

The second part provides a deeper investigation into the study of architectural design psychology including design behaviour and design cognition. It extends the research on the hospital design process into the psychological domain in order to understand the designer's mental process and the link between the physical environment and mental cognition. Also, the study of design creativity references certain literature supporting the recognition of creativity criteria and creativity measurements. This section also reviews the design process with two kinds of evaluation approach to design protocols, concurrent and retrospective, and provides relevant case studies showing how the design process was evaluated and studied.

3.2 Architectural design process

Post-World War II design methods were established in industrial countries around the 1950s and 1960s. Those methods aimed to produce an industrial process for building projects for clients. These general design methods were all endeavouring to isolate the design process and break it down into a series of steps as the standard approach to production (Jones, 1970). However, despite this standard approach to the design process, there are some other sources indicating that the design process is not just about procedures. For example the following propositions state that it is: ‘A goal-directed problem-solving activity’ (Archer, 1965), ‘Simulating what we want to make (or do) before we make (or do) it as many times as may be necessary to feel confident in the final result’ (Booker,1964), ‘A creative activity – it involves bringing into being something new and useful that has not existed previously’ (Reswick, 1965). So the design process is a hybrid activity consisting of different functions and proposals. Jones (1970) suggests that in its different stages, design is related to three approaches: artistic; scientific; and mathematical. For example, the designer needs scientific tests and established controls to predict questions or problems through experiments or solutions. Artistic approaches such as sketching or formatting object formation problems, give the designer a vast number of alternative ideas during the decision-making stage. Mathematics is good for defining the design problem with abstract symbols and manipulating these using mathematical relationships when finding solutions (Jones, 1970). In conclusion, the design process is not just about breaking down the design into work stages but is also about improving and optimizing design quality using problem-solving and creativity. The following sections go into more depth in reviewing the background to design methods, giving a definition of relative aspects to explore the understanding of design activities.

3.2.1 Mapping of the design process

Lawson (1990) describes the idea of design methods as a mapping sequence which consists of different but recognized activities; these logical mapping processes are able to predict and define problems in the early stage and then arrive at solutions in the final stage. According to the architectural design profession in the RIBA Architectural Practice and Management Handbook (1965) the design process can be divided into four phases:

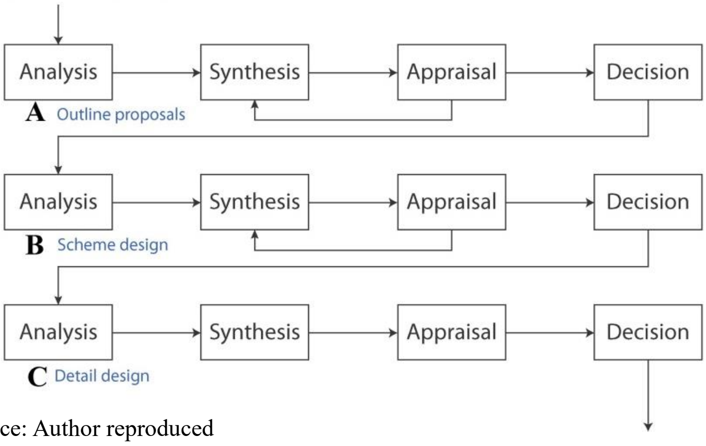
Phase 1: Assimilation
– The collection and ordering of general information necessary to specify properly the design problems.
Phase 2: General study
– This research maintains that phase 2 is more akin to 'design syntheses' than the notion of the general study of architectural phenomena, i.e. the design problem.
Phase 3: Development
– Further development or clarification of the solutions which were defined in Phase 2
Phase 4: Communication
– Communication with other people or professionals who might be associated with the design.

The purpose of these statements by RIBA is to help allocate the design stage work to design teams and provide guidance for organizing the progress of the design. In addition, each stage defines the architect's professional procedures for clients and gives briefs for design developments.

3.2.2 Models for the design process

If design activities can be defined as a mapping process, the following design methods provide different approaches for exploring relevant knowledge of the design process. Markus (1969) and Maver (1970) suggest an elaborate design mapping system (Fig.3.1) for the architectural design process with three stages proposed: outline proposal (Fig.3.1-A), scheme design (Fig.3.1-B), and detailed design (Fig.3.1-C). Each stage includes four essential activities of analysis, synthesis, appraisal and decision.

Fig.3.1 Design mapping system by Markus (1969) and Maver (1970)

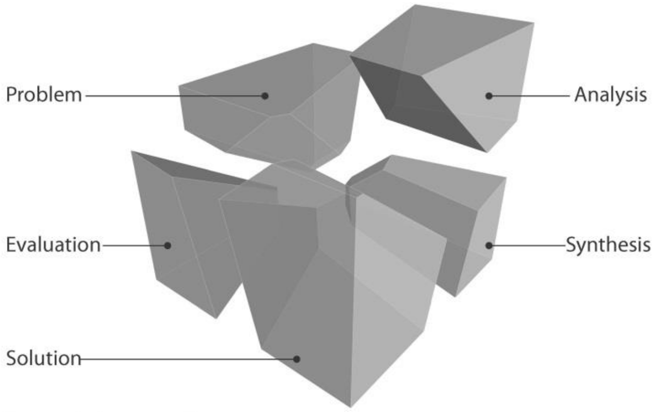


Source: Author reproduced

Analysis explores the relationships between design information and the designed objects; it aims to structure the design problem defined in this network of design stages. The next activity, synthesis, is gathering those design problems and finding proper solutions for them. An appraisal is a re-evaluation of the draft solutions which have been generated from the synthesis stage. The final decision follows the above three activities and decides the necessary following actions, for example, to return to further appraisal if the solution did not answer the design problem, or on the other hand, if the process is confirmed at each main phase, to keep progressing the design. This process or model contains flexibility with open loops from any design stage back to the preceding stages. The looping process offers architects better understanding of the design problems and produces more accurate and suitable solutions. Consequently, these three design activities: analysis, synthesis, and appraisal (or evaluation) became highly important for most frameworks of design processes and/or related methodologies.

In addition, Lawson (1990) summarises his research on design practice as a multi-faceted design process model (Fig.3.2) based on the activities of analysis, synthesis, and evaluation. This model does not show the starting and finishing points or the ordering of steps; he thinks the design process should ideally be a negotiated process between design problems and

Fig.3.2 Multi-faceted design mapping system, Lawson (1990)



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solutions. Problem-solving as a concept is shown as a flow from one step to another (analysis, synthesis, and evaluation) during the design development.

Jones (1963) introduces a design method based on logical and creative thought. His design process concentrates on design procedure and recording design data through a series of evaluations then converting this through creative thinking or brainstorming during the synthesis activities. He believes that by fully exploring activities through brainstorming and re-evaluation, designers can better choose the final solution and generate a good response to the design process.

Archer (1965) thinks design activity is an open-ended process which contains a series of creative steps. His design model involves mapping with four steps: identifying the design goals, identifying essential constraints, preparing a list of sub-problems, and rank-ordering the sub-problems. He suggests computer science and its logic can be applied to examine sub-problems in the design process through the rank-ordering. The computing process speeds up the sub-problem review process but leaves various responses to the designer's judgement. He further emphasizes that there is no way that any design process can be completed without careful, comprehensive and valid studies.

3.3 Complex building design and design problems

Hospital design is generally described as one type of complex building design; because of the scale of the design problem and the need for multifunctional planning with professionals from different backgrounds involved, making problem-solving more difficult. Considering the design solution at the conceptual stage, we need to investigate the reasons as to why hospital design is a complex task and identify interrelationships between different aspects of design problems. This section consists of two parts: design complexity and design problems, and examines the correlation between them.

3.3.1 Architectural design complexity

Why is design difficult and complicated in its development? It is because the general design process lacks sufficient information on the design challenges during the problem-solution process. In traditional design methods, the craftsman applies scale-drawing of components and final products as their problem-solving process to minimize the construction problems following from the design stage. However, this process certainly lacked a connection to external considerations such as weather effects on materials, because the drawing certainly does not identify any relationship with the physical environments. Problem-solving in traditional design depends solely on the craftsman's experience, and it was not easy for others to replicate this. On the other hand, modern design, in its industrial aspects, often covers multiple considerations; design complexity often has a significant connection to the variety of problems encountered. For example, urban-design or town planning needs to solve the problems of urban morphology associated with traffic congestion, parking problems, road accidents, etc. The wider design problems need to be solved in a systematic pattern through pre-organized relationships and an improved problem-solving process. (Jones, 1970)

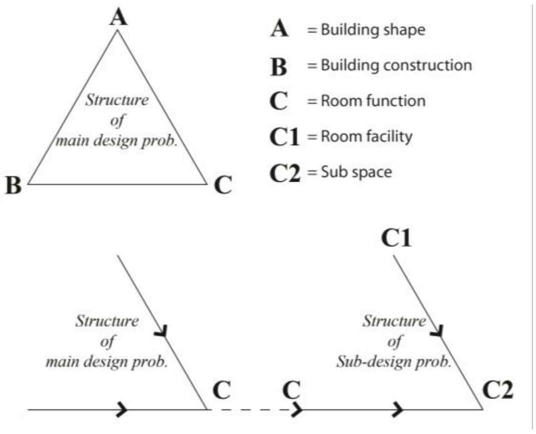
In addition, Lawson (1990) suggests that design complexity has a significant relationship to its scale. For example, town planning must accommodate more complicated contexts such as housing, environmental policies, traffic, etc., in contrast to product design which might only consider materials, functions or shapes. So, the definition of design problems is obviously associated with the level of detail which is initially required by different scales of design.

3.3.2 Architectural design problems

'If the nature and structure of design problems are understood, then methods for tackling them may be developed with more certainty of success' (Cross, 1984). This section aims to introduce different models for the understanding of design problems as well as to highlight the relevant constraints and causes for those within the process.

Levin (1966) maintains that design is an activity found in man-made rather than natural environments, so design problems are naturally generated within a structural relationship. He used the idea of a systematic process to produce a conceptual tree-like structure for discovering design problems and sub-problems in his proposed model. This systematic process is similar to mathematical thinking with parameters or variables and constraints, or controlled or uncontrolled causes used in the exploration of the design problem. Design variables or subjects, in Levin's model, are primarily classified into different categories following a diagrammatic pattern to identify the relationships between each other; this is a so called 'tree-like' structure. When a designer starts to consider the correlation between design variables, the structure diagrams help to define the relationship between design subjects. For instance, in the design process (Fig.3.3), building shape (Fig.3.3-A), building construction (Fig.3.3-B) and room functions (Fig.3.3-C) are associated as the main problematic parts of the building design process. Any changes in one of them could affect the others, so within this triangular structure, the architect can recognise the relationship between those three design factors and potential conflicts. Also, this ‘tree-like’ structure is flexible; any new variable can be added to extend the design relationship as an additional structure of the sub-problem types. For example, a room function (Fig.3.3-C) could link with another two sub-factors: a room facility (Fig.3.3-C1) and sub-rooms (Fig.3.3-C2). Designers can use this structure with a looping operation to re-evaluate the design problems as well as to systematically explore the understanding of those problems’ correlation to the design logic. Levin suggests that this systematic discovery and understanding of design problems helps architects to understand man versus natural environment interaction. So, architects might be better able to find suitable solutions for their design problems.

Fig.3.3 Tree-like structure for design problems, Levin, 1966



Source: Author produced

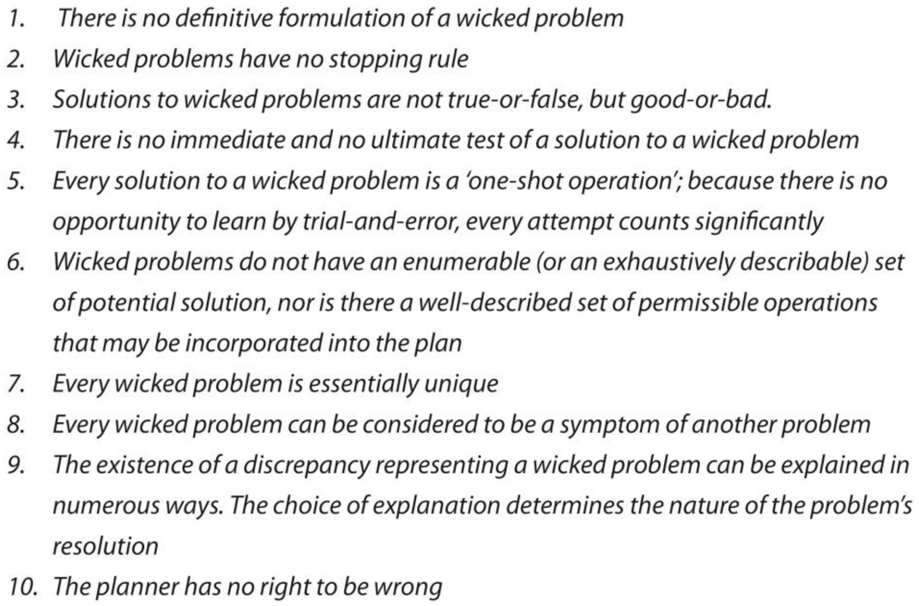
Alexander & Poyner (1967) examine design problems through an abstract model which suggests design, especially architectural design, should not only be decided by a geometrical structure. In other words, they think that architectural design deals with the problem in environmental contexts but not through geometrical arbitrariness. Geometric building blocks can never simply replace our environments; we architects should deeply consider the relationships between ‘nature’ and ‘function’ by utilising such building blocks to respond to the design problems. In terms of architectural explanation, ‘nature’ means that an existing design problem such as an overcrowded space should not stop visitors entering. On the other hand, ‘function’ means a solution for that design problem like simply increasing the size of the space.

In addition, a natural design problem often comes with more than one possible solution. Architects have to think comprehensively and discover the relationship between these problems and solutions. For example, architects building a park should ensure that is not only designed using geometric site plans but that it should meet the needs of local communities and users of the park. Those user requirements naturally form ‘tendencies’; once those ‘tendencies’ have increased the results are likely to create some conflicts or design problems. Local residents might have many requirements or tendencies as to the park design; some people might want just open greenery, but others might prefer an exhibition space. However, an exhibition can't be placed in the park without blocking the open view, therefore the architect might design a pavilion to resolve this conflict. According to Alexander & Poyner, a good design environment should not create conflict but should satisfy all tendencies. On the other hand, only a problematic design reveals that conflicts or problems still exist and means the design did not resolve these. This concept establishes an externalized and objective model for design problem discovery with the structural relations linking user tendencies and conflicts to the geometric design solutions. It avoids intuitive or illogical responses when resolving the problems. The correlation between tendencies causes the designer to think carefully about the design process and clarify the design problems.

3.3.3 Unpredictable design problems and design process

As previously stated, hospital building is normally identified as a complex design project in terms of its large scale and complicated functions. In order to process a design problem-solution for this complex building type, it is important to understand the types of architectural design problems and structures. Rittel & Webber (1973) suggest that the reason why architectural design problems are hard to predict is because they are ‘wicked problems', in contrast to engineering design problems, which they call ‘tame problems'. Architectural design contains too many uncertainties. According to the identification of a wicked problem in the architectural design process, the problem contains many unpredictable factors and structures. It is not possible to easily identify individual issues without fully understanding the context of the problems. However, there are ten factors identified in a list suggested by Rittel & Webber to provide an accurate specification of the wicked problem (Fig.3.4). According to those factors, architects can better compare the different wicked problem types with appropriate problems identified by different professions such as engineering and then find appropriate solutions

Fig.3.4 Definition of the ‘wicked problems’, Rittel & Webber, 1973



1. *There is no definitive formulation of a wicked problem*
2. *Wicked problems have no stopping rule*
3. *Solutions to wicked problems are not true-or-false, but good-or-bad.*
4. *There is no immediate and no ultimate test of a solution to a wicked problem*
5. *Every solution to a wicked problem is a ‘one-shot operation’; because there is no opportunity to learn by trial-and-error, every attempt counts significantly*
6. *Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solution, nor is there a well-described set of permissible operations that may be incorporated into the plan*
7. *Every wicked problem is essentially unique*
8. *Every wicked problem can be considered to be a symptom of another problem*
9. *The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem’s resolution*
10. *The planner has no right to be wrong*

Cited: Rittel & Webber, 1973

Simon (1973) refers to architectural design problems as ‘ill-structured problems’ (ISP) which means their structure lacks sufficient definition in some respects and is not explained. However, He also compared them to a ‘well-structured problem’ (WSP). The comparison discusses the correlation between the WSP and ISP and suggests that they can probably be connected in some situations. ISPs and WSPs are very similar to the wicked problems and tame ones which were identified in Rittel & Webber’s research. Both of them describe the distinct character of architectural design problems of the wicked type and with ill structures, further exploring the knowledge of their background then giving information to architects to better understand their design problems. Furthermore, hospital design is considered as a complex building design because of the need for multifunctional planning with professionals from different backgrounds involved, making problem-solving more difficult. Simon’s finding challenges us to define those ISPs by a logical process and to establish a relation to WSPs to help architects more easily reframe problems, rather than just attempting to deal with them by intuition. In addition, Simon (1973) suggests if the structure of architectural design problems could be managed structurally, like chess-playing activity, it might help architects to define problem types and reduce unpredicted design situations. The next section, reviewing systematic design methods for hospital buildings, exhibits practical design projects followed by well-structured plans solving design problems during the complex hospital design process.

3.4 Systematic design methodology for hospitals

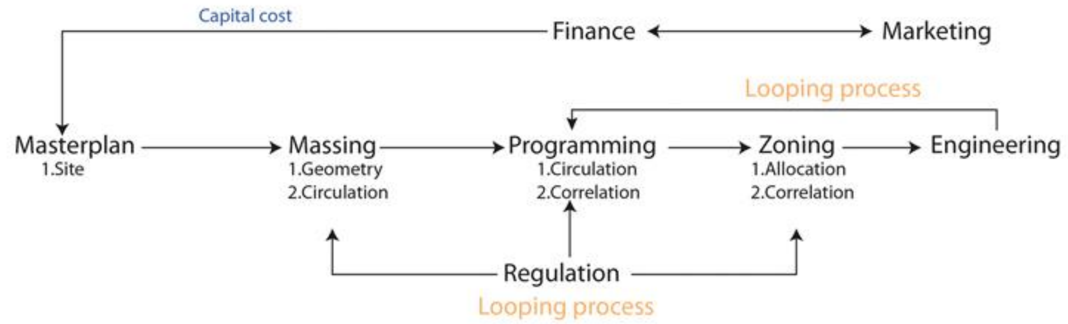
This section illustrates four impressive systematic hospital designs carried out by the UK NHS in the 1970s-80s. Through these case studies, we can see how for complex buildings such as hospitals, design can be organized and architects can be helped by a systematic process for problem-solving in the design stages of a proposal.

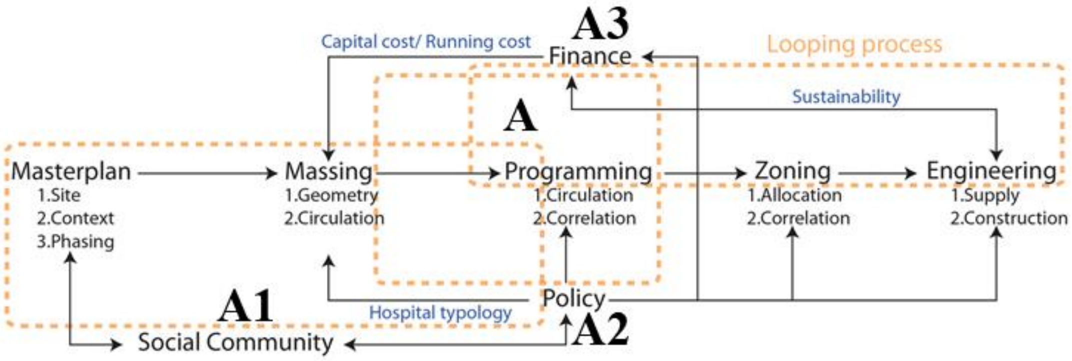
3.4.1 Systematic design methodology

The British government was the first national authority to bring documentary-based systematic design methods to hospital building. From the early investigation stages to the final design proposal, the systematic design methodology extensively influenced the coordination of different professions in the design team. This brief review is divided into three sections:

The first part (Fig.3.5) shows the comparison between general building design and systematic hospital design. The diagram clearly shows that hospital design contains more repeated looping processes (Fig.3.5-A) illustrated by multi-directional feedback arrows as the design moves to the proposal stage, and that the process involves multiple disciplines, such as finance, zoning and engineering in design considerations. This systematic template (Fig.3.5) exhibits different parts of the hospital building design process and the lines show the interrelationship of those design stages. In particular the yellow dot-lines (Fig.3.5-A) indicate three cyclical procedures of design evaluations for a particular design subject. For instance, the social community (Fig.3.5-A1), policy (Fig.3.5-A2) and financing (Fig.3.5-A3) are interrelated through an intensive design evaluation that means the main design problem should be focused on these three aspects and associated building design criteria such as energy saving plan or medical service circulation. Such a systematic design method for hospital buildings follows the idea of WSP (Simon,1973) which contains identification of different design criteria, repeated testing, and classification of the stages for providing a better structure of problem-solving in architectural design.

Fig.3.5 Comparison between general architectural design & NHS systematic hospital design

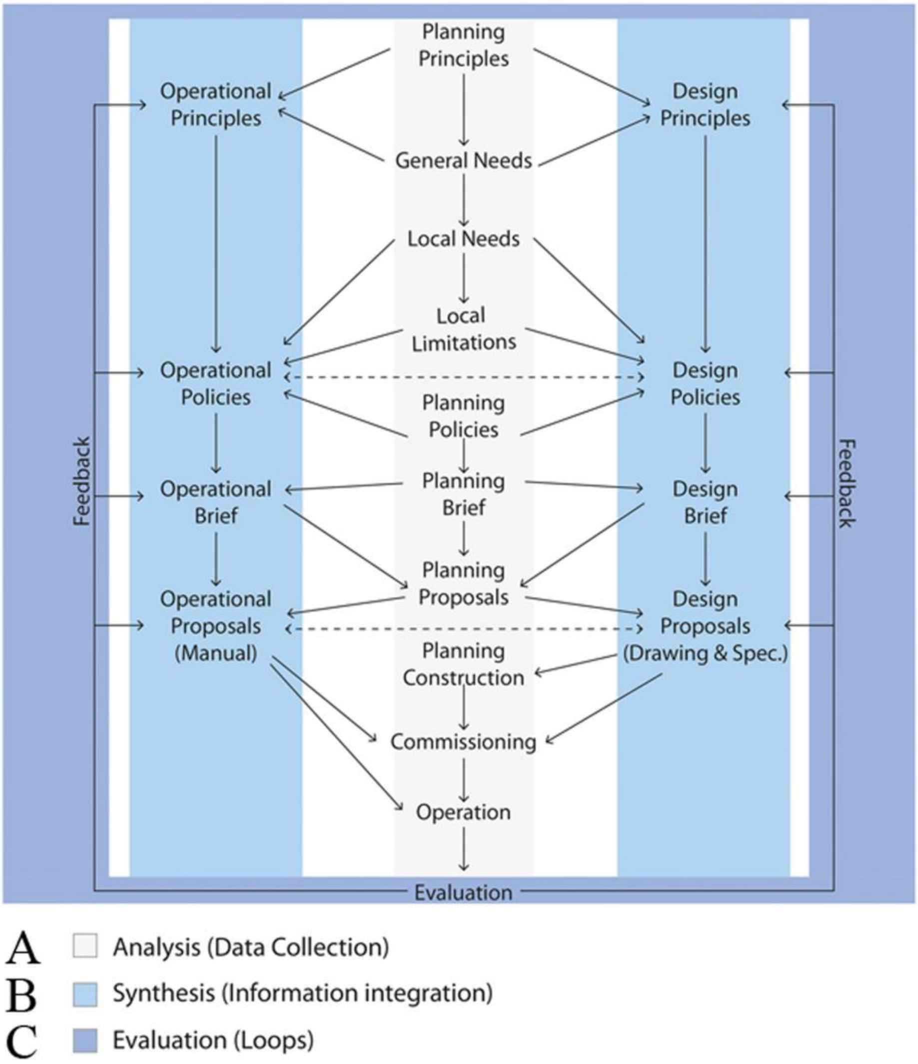

General Building Design and Development


Systematic Hospital Design and Development

Source: Author produced

The second part shown in Figure 3.6 demonstrates the early stage of hospital design planning using a systematic template; the further steps follow the scientific approaches of design, analysis (Fig.3.6-A), synthesis (Fig.3.6-B) and evaluations (Fig.3.6-C) to discover the problems at the primary investigation stage (Baynes, Green, Moss, and Jackson, 1971).

Fig.3.6 The early stage of systematic hospital design template



Cited: Baynes, Green, Moss, and Jackson, 1971/ Author reproduced

The third part, the diagram (Fig.3.7) of the NHS systematic hospital design process, exhibits the design analysis part (Fig.3.7-A) which plays an important role in investigating and formulating the actual design issues or problems, as well as providing the relevant evaluation programme (Fig.3.7-B) for testing design ideas such as mock-up rooms or user feedback. Besides that, to extend the design discussion, the use of visually based diagrams (Fig.3.7-1) is encouraged to help architects to coordinate the design ideation outputs with other professional teams. (Baynes, Green, Moss, and Jackson, 1971)

Continuing the discussion of systematic design principles for hospital buildings, the next section provides a review of four systematic design hospitals constructed in the UK during the 70s-80s by the UK DHSS, and their associated design concepts: the Greenwich District Hospital, the Best Buy Hospital, the Harness and Nucleus Hospitals.

Fig.3.7 NHS systematic design process & outputs

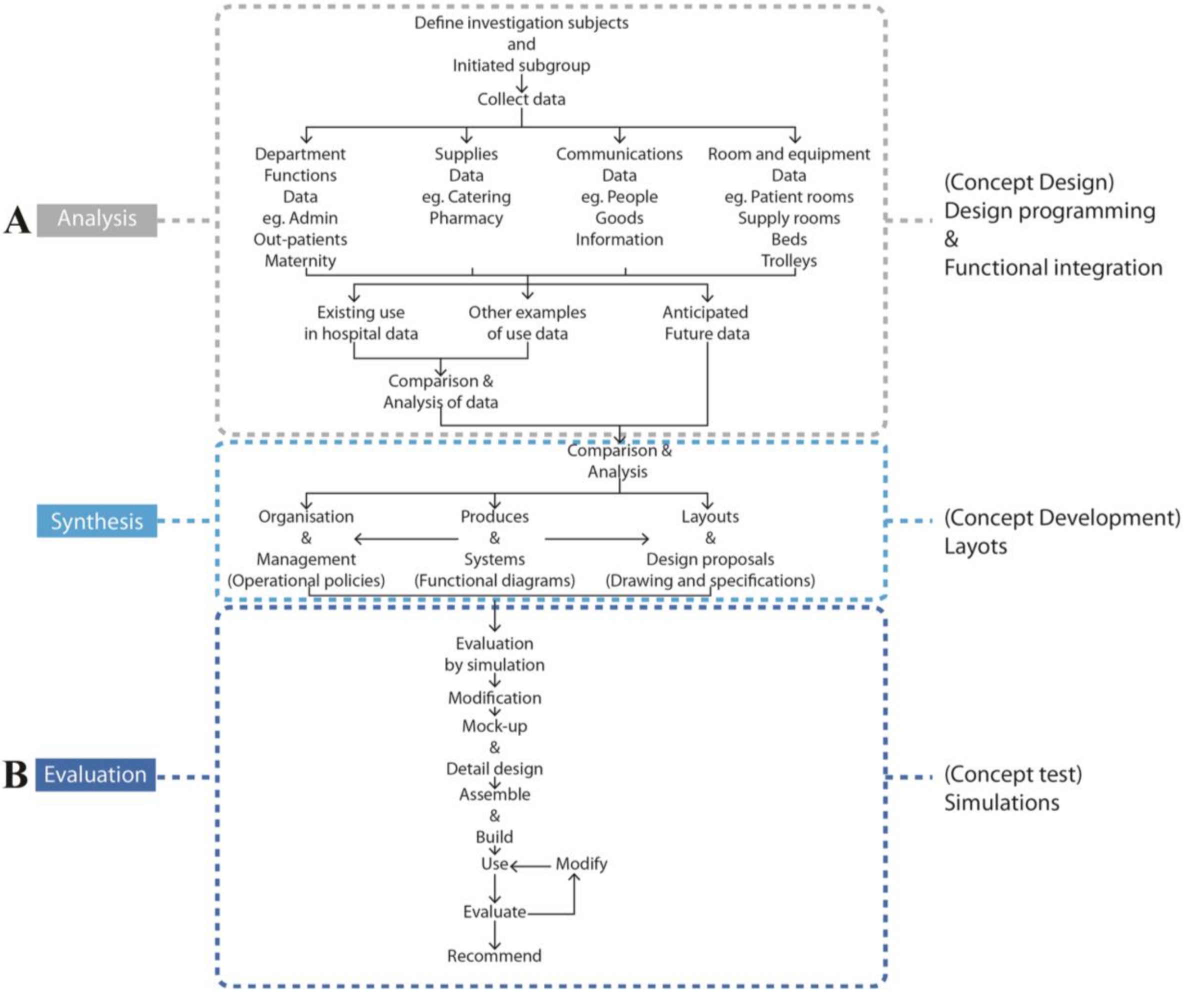
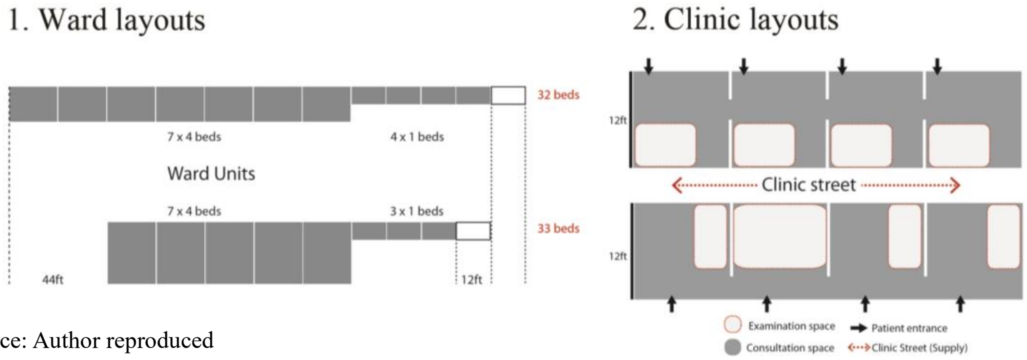


Fig.3.7-1 Diagrammatic design process

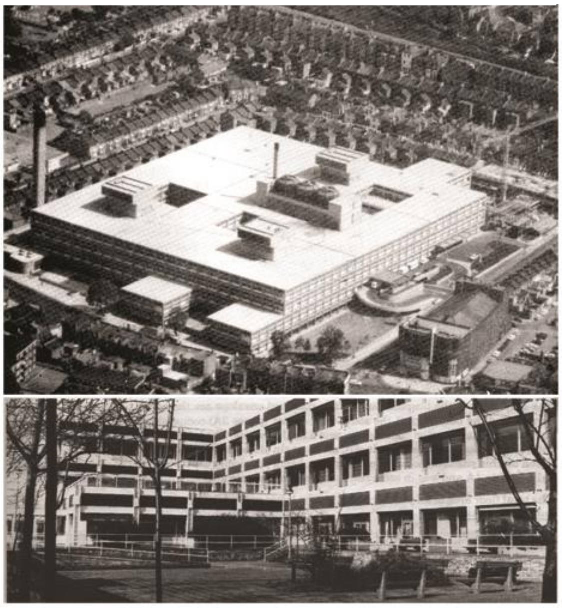


Source: Author reproduced

3.4.2 Case studies of systematic design hospitals, UK

a) The Greenwich District Hospital – *The mothership & compact design hospital*

Fig.3.8 The Greenwich district hospital



Cited: DHSS, 1960-70s

The Greenwich District Hospital (Fig.3.8) (GDH), 1960-70s, Greenwich, UK, was a DHSS research project to replace an existing old district hospital, St. Alfege’s Hospital. The completed project was started in 1960, went through 16 years in 3 phases and was finally finished in 1976. The initial proposal was to create a district healthcare depot for local services as well as covering a wider range of medical services than the old hospital (St. Alfege’s) Therefore, the design aims included providing the medical capacity for district healthcare services and phased construction without stopping existing hospital services; these were the most complex challenges. The design briefing diagram (Fig.3.8-1) shows the systematic planning process from the first stage of collecting the existing hospital’s functional data (Fig.3.8-1-A) to meet district healthcare requirements (Fig.3.8-1-B). Then the data is integrated with design considerations, such as medical service capacity and site context, and then the information provided is carried forward into construction design developments.

In addition, the architectural design diagram (Fig.3.8-1) shows the work of professional teams (Fig.3.8-1-A), data collection (Fig.3.8-2), and analysis with individual outputs (Fig.3.8-1-C) such as architectural drawings, technical reports, and medical operations, etc. Through this structural process, the design teams often needed to check back to the previous stages to identify problematic situations then provide relevant solutions (Fig.3.8-1-D). Besides that, the departmental visual diagrams (Fig.3.8-2) for design layouts demonstrate the architects' design ideas on the layouts and phasing proposals. For example, Figure 3.8-2-A displays how the central supply system for centralised medical services responded to the building phasing design; Figure 3.8-2-B indicates the circulation and vertical shaft design and the distribution of the departmental services; Figure 3.08-2-C shows the natural lighting and ventilation relating to the four-courtyard design (DHSS, Greenwich District Hospital, 1983).

Fig.3.8-1 The GDH design briefing diagrams

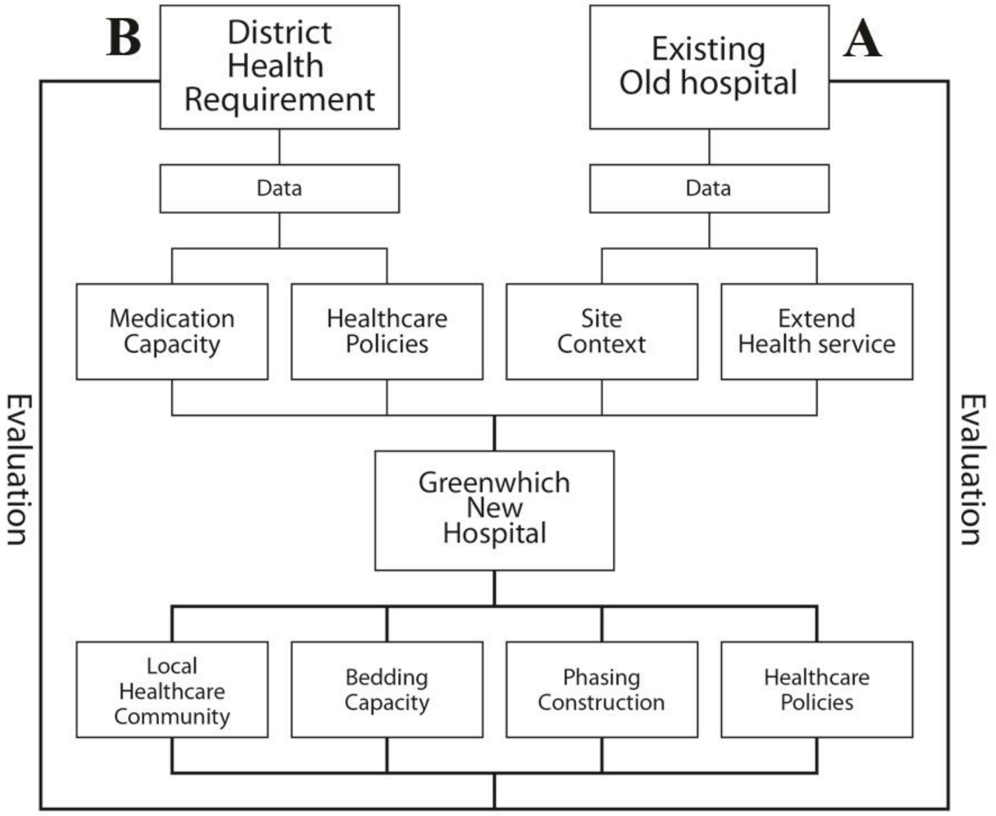
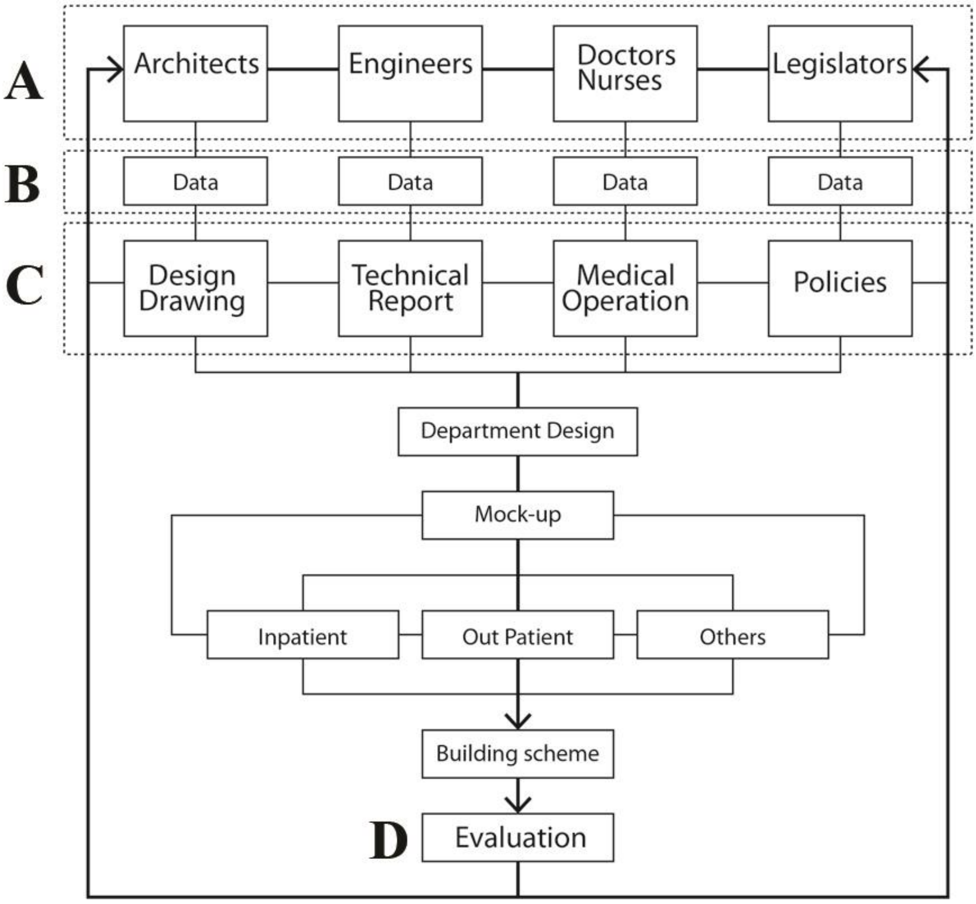
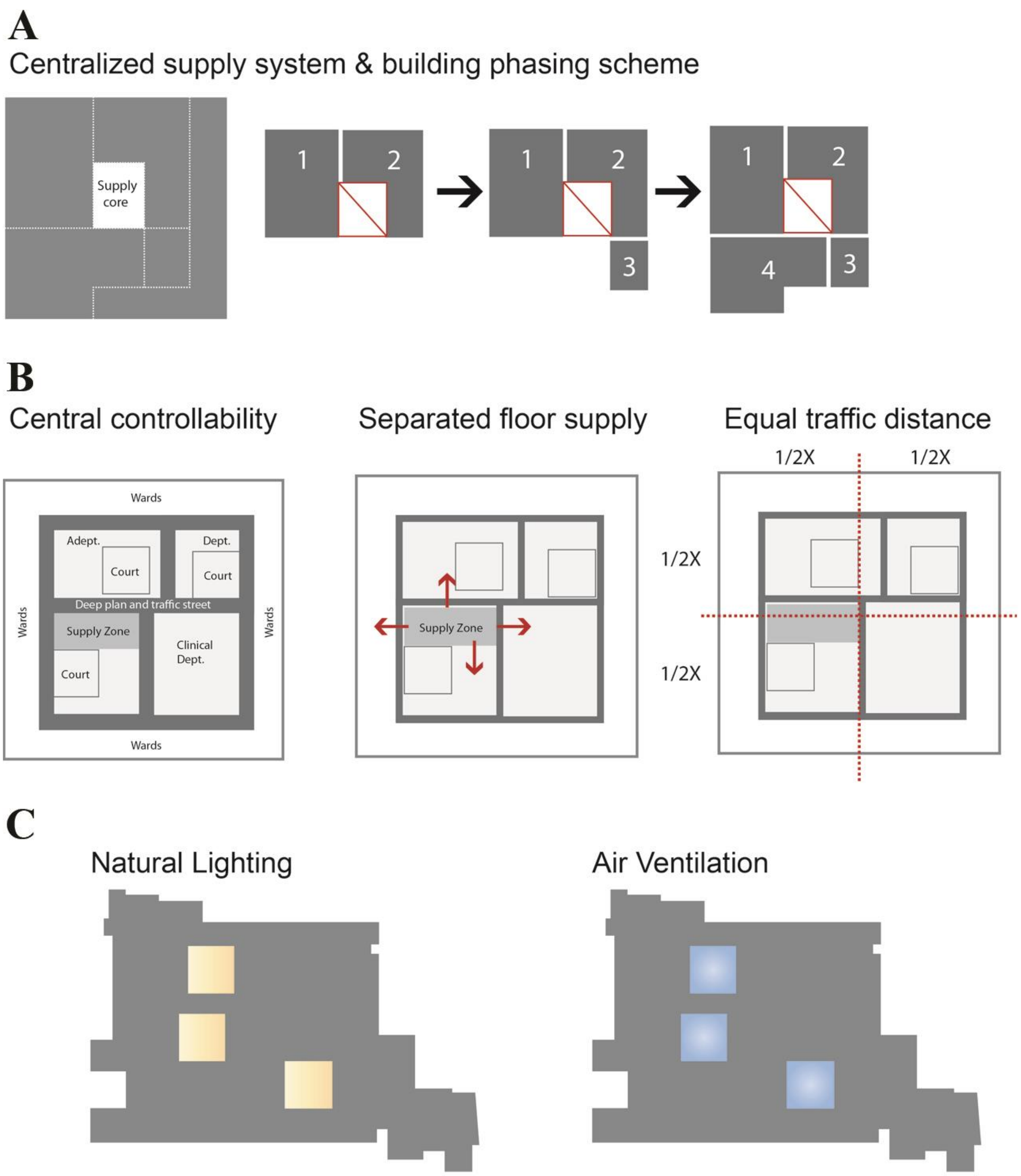


Fig.3.8-2 The GDH architectural design diagrams



Source: Author reproduced/ DHSS, 1960-70s

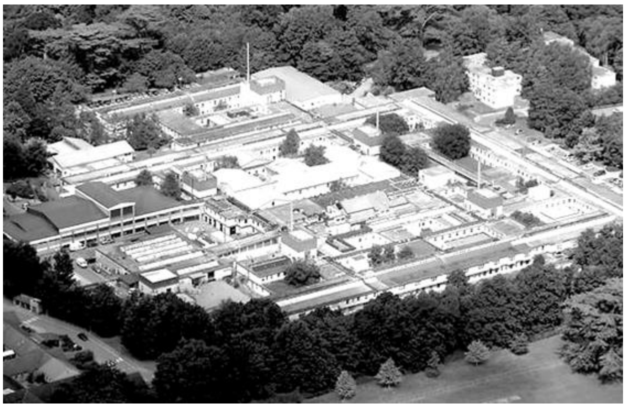
Fig.3.8-3 The GDH departmental visual diagrams



Source: Author reproduced/ DHSS, 1960-70s

b) The Best buy hospital – *The economic & compact design hospital*

Fig.3.9 The Best buy hospital



Cited: DHSS, 1960-70s

The Best Buy Hospital (BBH) (Fig.3.9), 1967, St Edmunds, UK, was another research project of the DHSS. It aimed to provide an economic hospital design to replace certain expensive district hospitals such as the GDH. Although the design focused on economical improvements, it still needed to be concerned with the standard of district healthcare services. So existing district regulations (Fig.3.9-1.A) and cost cutting requirements (Fig.3.9-2.B) for the new hospital buildings became the vital issues shown in the design briefing diagram. In the briefing process (Fig.3.9-1), primary data collected (Fig.3.9-1.C) and the resulting analysis showed how to cut medical spending by introducing the idea of a 'healthcare zone'. For example, distributed or shared medical services among local healthcare networks (Fig.3.9.D), intensive medication services (Fig.3.09.E) and maximized shared treatment spaces (Fig.3.9.F). Thus, the building programs and new construction could reduce and save unnecessary costs. Also, the building design scheme (Fig.3.9-1) incorporated the ideas of different professions (Fig.3.9-1-A) and provided an economic and centralized departmental design (Fig.3.9-1-B) tested during the mock-up process (Fig.3.9-1-C). The finance manager for the architectural design development further collated the data from studies of specific over-spending district hospitals with mechanical ventilation and lighting being among the highest ranked over-expenditure factors, and gave suggestions on how to improve the proposed design prototypes (Fig.3.9-1-D).

As a result, architects worked out a solution with multi-courtyard layouts to optimize the use of natural resources (Fig.3.9-2-A). Moreover, evidence supported by medical staff (doctors and nurses) showed that intensive medication using a linear space design (Fig.3.9-2-B) and centralized services (Fig.3.9-2-C1) using ring-road circulation (Fig.3.9-2-C2) had a considerable correlation to efficient treatment (the distance based studies) as well as improving patient's recovery rates without lengthening hospital stays (Stone, 1980).

Fig.3.9-1 The BBH design briefing diagram

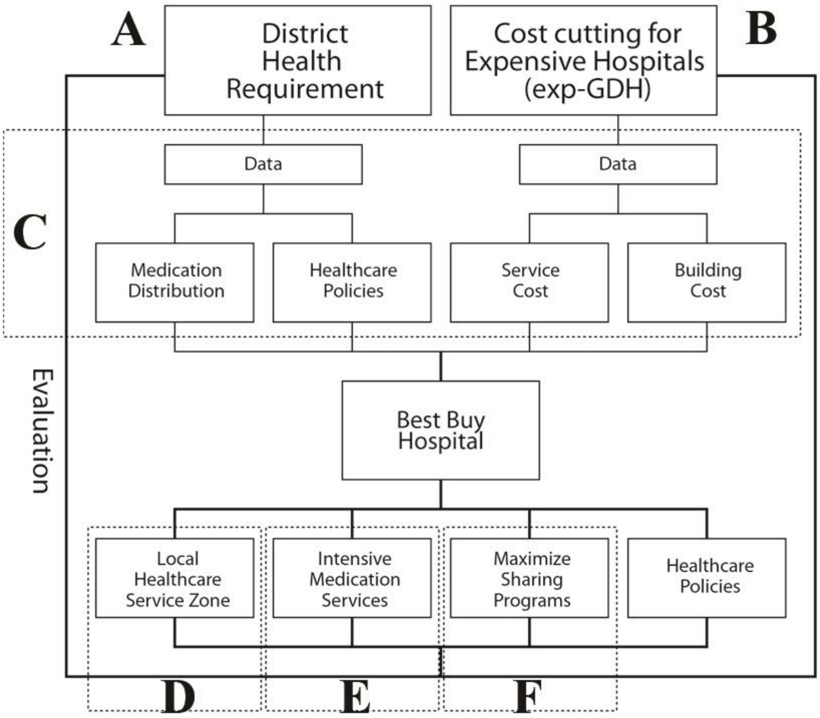
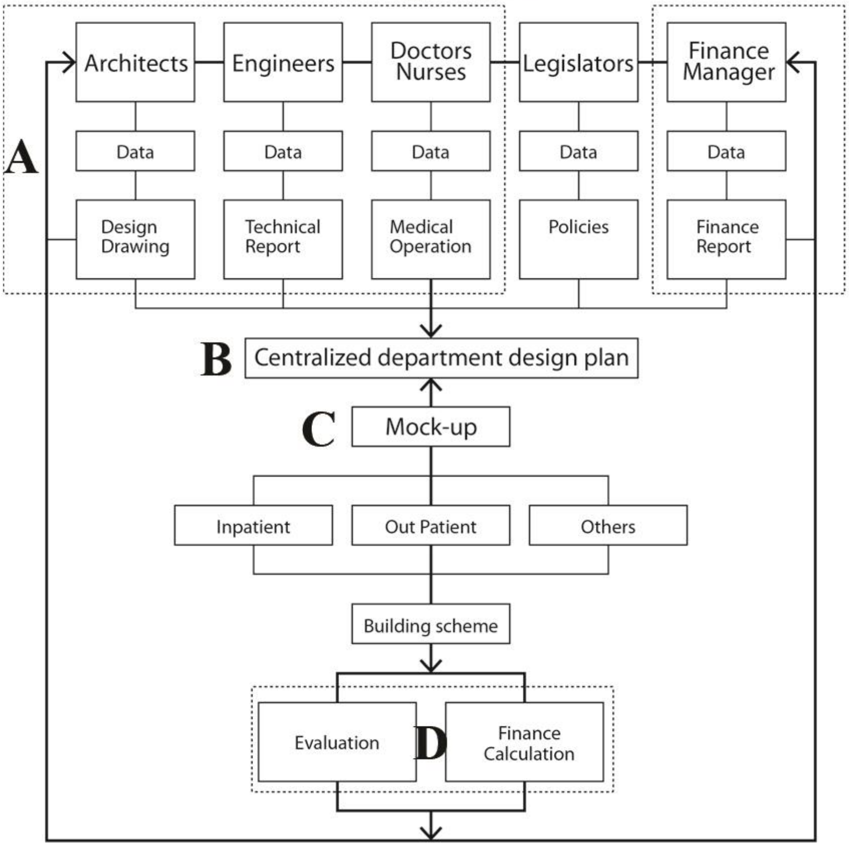
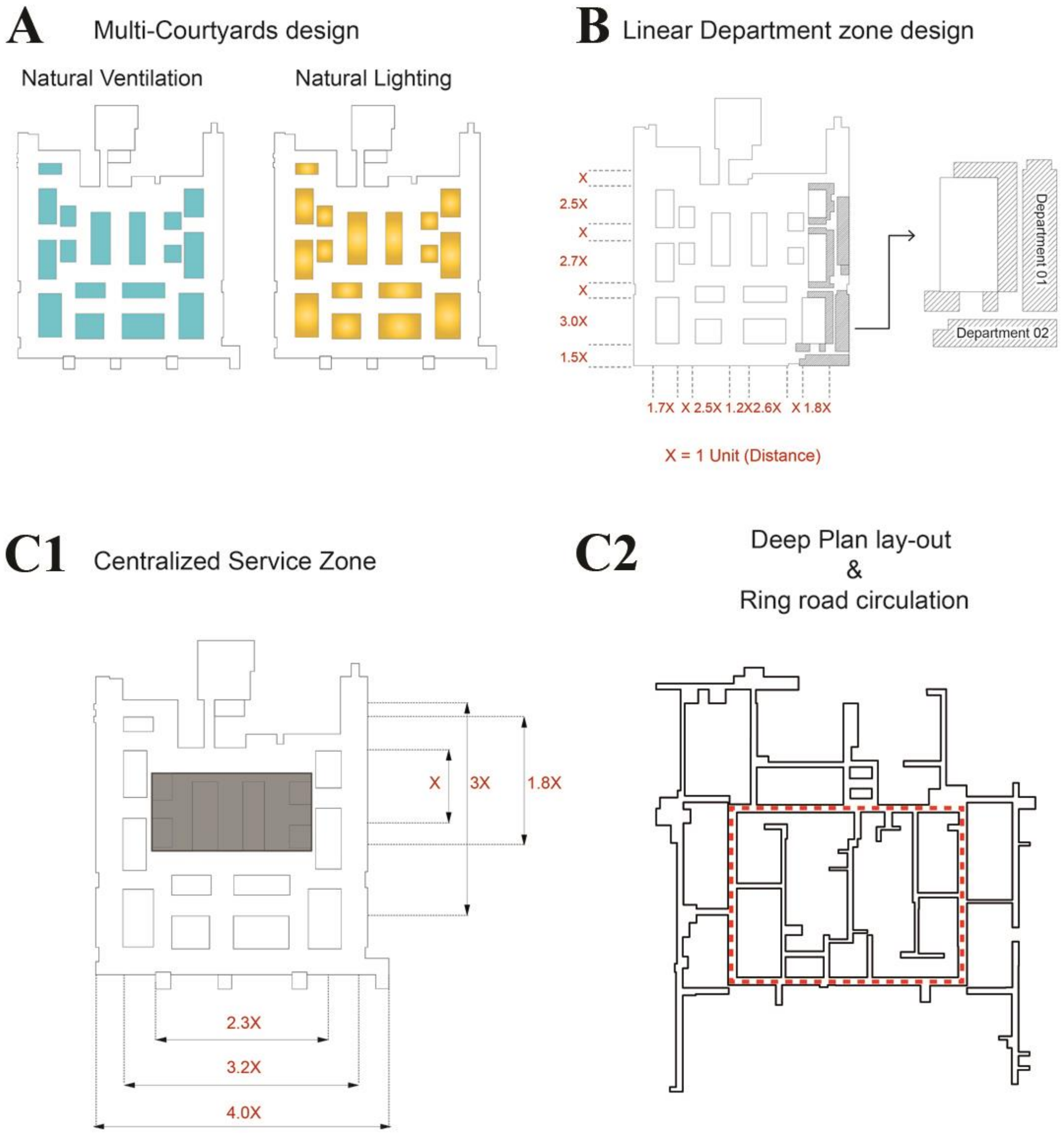


Fig.3.9-2 The BBH architectural design diagram



Source: Author reproduced/ DHSS, 1960-70s

Fig.3.9-3 The BBH departmental visual diagrams

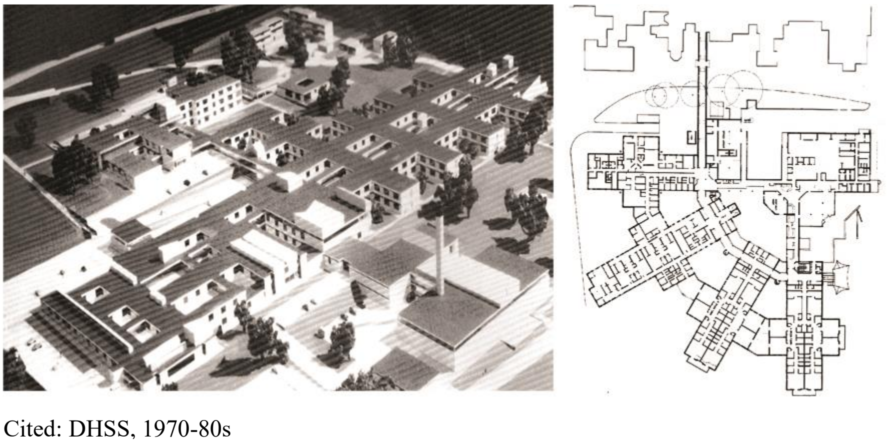


Source: Author reproduced/ DHSS, 1960-70s

c) The Harness and Nucleus hospitals – *Modular and economic design hospitals*

The Harness and the Nucleus Hospitals (HH & NH) (Fig.3.10) were modular design types for new DHSS research projects in the 1970s-80s, in the UK. In the design briefing (Fig.3.10-1) Harness and Nucleus, by matching standard healthcare requirements (Fig.3.10-1-A) and specific hospital designs (Fig.3.10-1-B), found that the most efficient building layouts are based on T, H and cruciform shape design. So, the modular design was based firstly on 15 metre x 15 metre planning grid, for the Harness design and then further revised for efficient construction in 15 metre x 7.5 metre cruciform shapes for Nucleus hospitals. This design idea was upgraded from the GDH and BBH models into a more modular construction process with standardized building design (Fig.3.10-1-C). Also, the purpose of creating a modular design strategy was to unify the quality of the healthcare building design as well as offer flexible design operations (Fig.3.10-1-D). For the architectural design development (Fig.3.10-2), standard data was collected from policies (Fig.3.10-2-A) and standard medical services (Fig.3.10-2-B). Then the project went through a series of evaluations (Fig.3.10-2-C) such as architectural design, engineering design and medical treatment design, so that building programmes could finally fit into a universal modular design. The advantage of this design strategy was that it not only permitted increased flexibility (Fig.3.10-3-A) and building growth but it also improved natural lighting and ventilation in the departmental interiors (Fig.3.10-3-B). Moreover, the modular spatial design template could easily be adapted for most of the medical departments (Fig.3.10-3-C) and functions as well as allowing connection to the hospital street design (Fig.3.10-3-D) to optimize the circulation of services (The HARNESS hospital development programme, 1976), (Stone, 1980).

Fig.3.10 The Harness and Nucleus hospitals



Cited: DHSS, 1970-80s

Fig.3.10-1 The HH&NH design briefing diagram

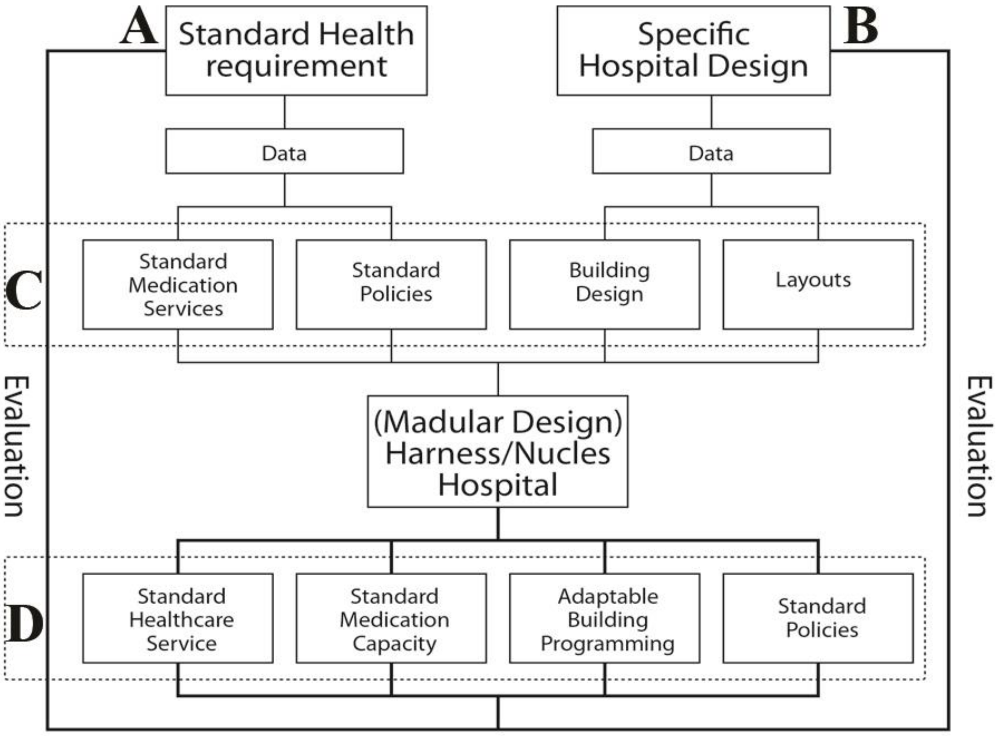
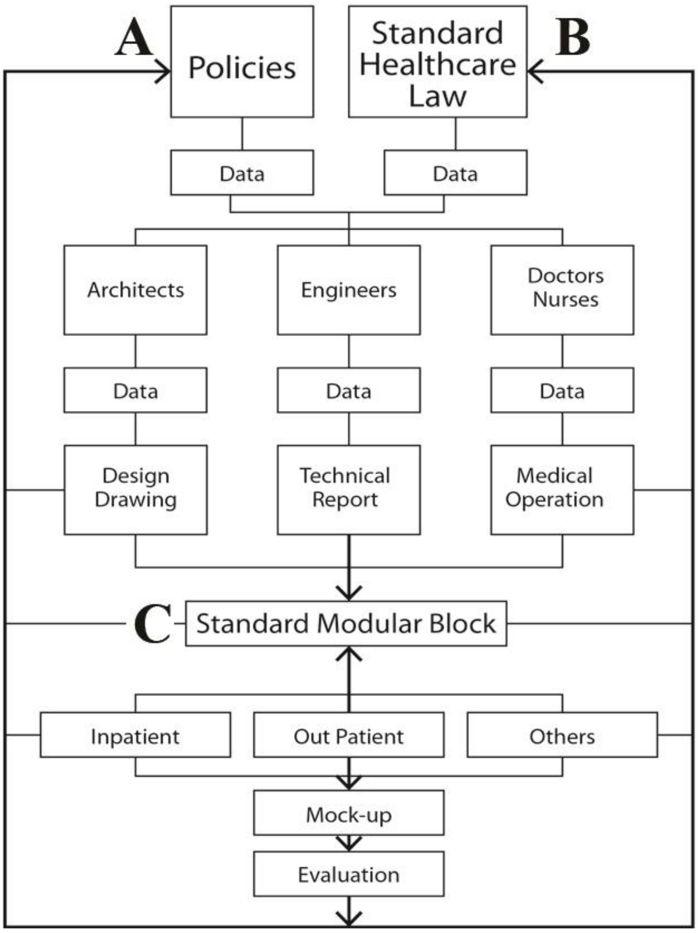
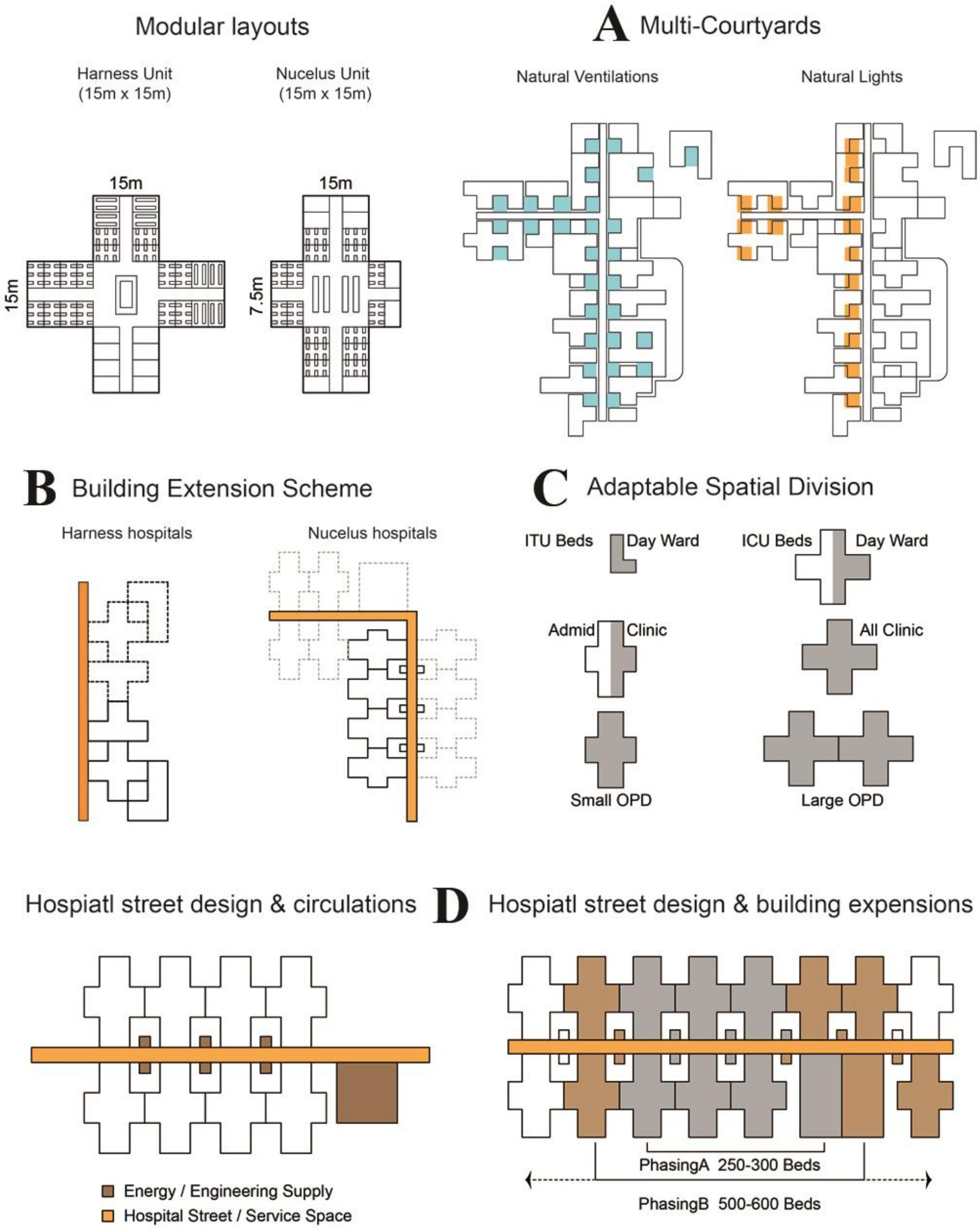


Fig.3.10-2 The HH&NH architectural design diagram



Source: Author reproduced/ DHSS, 1970-80s

Fig.3.10-3 The HH&NH departmental visual diagrams



Source: Author reproduced/ DHSS, 1970-80s

3.5 Design psychology

The previous sections have reviewed systematic design methods and problems as well as providing relevant design case studies; this section will discuss designers' behaviour and psychological factors while they are undertaking their design projects. Lawson (1990) thinks design theories using a mapping process might provide a better structure for design thinking, but not all architects apply those methods exactly in their design process. This might be because many designers use drawings to express their thoughts but drawing by thought cannot explicitly express their design process; therefore, it is necessary to conduct empirical work on designers and observe their cognitive behaviour and mental processes during the design process to suggest improvements in certain design methods.

3.5.1 Systematic thinking of design behaviour

Darke (1979) suggests that scientific or systematic design methods and processes go against human nature because of predefined constraints, because designing is a complex activity associated with many environmental backgrounds. If the designer follows rational methods such as analysis, synthesis and evaluation from the beginning of the design, the design activities might be limited and cannot produce design efficacy. She interviewed selected architects and evaluated their design experiences. She found sophisticated architects used ‘conjecture-analysis’ (Hillier, 1999) to identify the design problems in the early stage of the design process. In addition, she concludes that many designers apply an ideation process with a ‘primary generator’ to produce early design concepts with limited objectives. This subjective and drafting concept, in fact, is not as well-defined as systematic or scientific design methods but it provides a fast mapping so that the designer can target the design problems and think of the relevant solution. Design behaviour based on a primary generator helps the designer to cross the ‘rationality gap’ between problem information and solution; it means designers can always regenerate the targeted concept if the first concept has appeared faulty. Although the behaviour might create a contradiction to the logical process of the conventional design method, this primary generator is indeed characteristic of all architects. In other words, this subjective design behaviour using a primary generator was strongly preferred in many design expressions or styles such as Le Corbusier’s modular design and the Modernism style of international architectural design.

However, not all design behaviour goes against the design methods described in the scientific or systematic process. Thomas & Carroll (1979) describe their research into designers' behaviour as ‘design dialogues’ which means creating a ‘dialectic’ interaction between the client’s expectation, or partial goal, and the designer’s proposal, or partial solution. They found the design-aided methodology, or scientific way, provides the designer with more creative solutions. Also, the problem-solving process can be applied in various design contexts. The variety of design activities by design-aided methods makes the designer look deeply into the problem structure and it allows more interesting findings for designers. For example, sub-problems of a design activity are typically dynamically generated during the design process, not at the beginning, and design problems have a significant correlation with those sub-problems. In addition, unstructured design data found from analysis or synthesis, in fact, helps designers to produce ideas. Goals stated, like a primary generator, in the early stage do not help in identifying the design interpretation, even for experienced designers in the field.

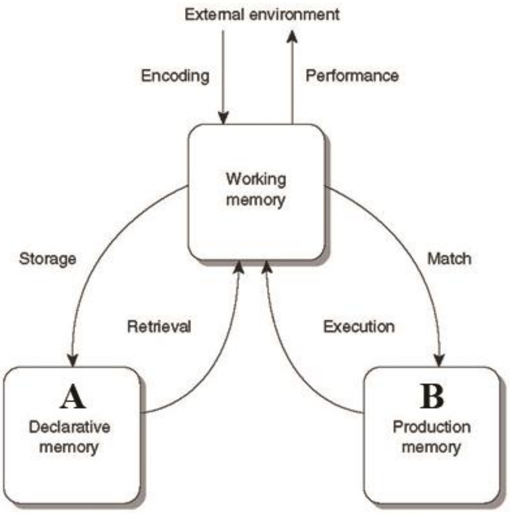
Although design behaviour might not be predicted by or follow a particular theory, it is essential to constantly explore our knowledge of the design process. Because the more we understand, the more we are able to construct a background to the study of design. In terms of managing some complex design activities such as hospital design, the understanding of its development, including design behaviour, might be very important in improving the quality of design outputs. The next section shows different design behaviour research focusing on design cognition and cognitive science.

3.5.2 Systematic thinking of design psychology

a) Cognitive psychology

The study of cognitive psychology provides a disciplined approach to answering how the human brain processes information and reacts during the design process in the real world. The purpose of this section is to discover the structure of the thinking process through an in-depth investigation of design and to find supporting research information on the design process. Cognitive psychology is the complete opposite of behaviourism, and produces explanations through the study of mental processes (Ashcraft, 2002). According to Shepard and Neisser (1967), ‘Cognitive psychology refers to all processes whereby sensory input is transformed, reduced, elaborated, stored, recovered, and used’. The mental process has been likened to an approach of exploring cognitive activity through environmental information. There have been some different explanations of the mental process. For example, Fodor’s theory of the modular mind (1983) and Norman (1972) suggested their model of visual pattern recognition through a pandemonium architecture or model, Marr (1982) published research based on the metaphor of computer activities as a cognitive process to make transitions from two to three-dimensional shapes and Treisman & Gelade (1980) focused their attention on visual studies with colour, motion, orientation and curvature. The research results stated, 'the colour and line segments are effectively linked together by attention in one location in the visual field'.

Fig.3.11 A long-term memory with ACT*



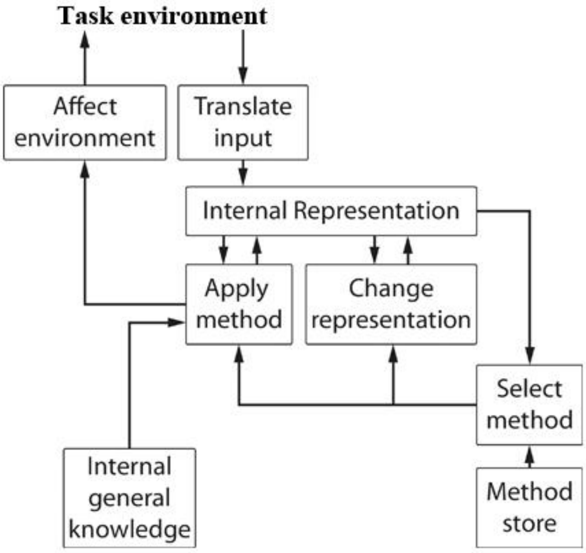
Cited: Friedenberg & Silverman, 2006/ Anderson, 1983

However, there are three important features of the cognitive process: memory, Imagery and problem-solving. Firstly, memory provides the important feature of storing information from different situations; it means the ability to learn from the environment. There are two different memory types: short-term memory and long-term memory. These have different impacts on our mental operations and cognitive processes. Anderson (1983) explains long-term memory with his research model – Adaptive Control of Thought (ACT*) (Fig.3.11). He thinks there are two kinds of long-term memory associated with the working process, one is called declarative memory (Fig.3.11-A), and the other is production memory (Fig.3.11-B). When we accept stated information, our minds start to search our declarative or explicit memory and we react with appropriate actions. For example, when students are answering multiple-choice questions, their minds are certainly using declarative memory in finding the suitable replies. On the other hand, production memory provides an implicit process to match random situations to our external environment then execute the necessary actions for them. For example, car driving and our reactions on the road are generally performed according to rules and conditions to give related responses. Anderson (1983) also found that declarative memory, in fact, could be organised and taught by a diagrammatic system with nodes for concepts and lines for relationships; the visual image presents metric spatial information through a process of isomorphic reference. In contrast, production memory is hard to predict.

Secondly, visual cognition contains two parts, one is image structure, and the other is image process. Kosslyn & Schwartz (1977) suggested 'Deep representation' which means images in the mind are not independent objects but are an associated mapping system. By 'Literal encoding' and 'Propositional encoding', our brains store imagery as coded information then take action on it in different situations with related mental activities. For example, DIY furniture comes with a package of components and assembly instructions. When we open the package, our cognition identifies those components, or object images, as a propositional encoding, then we follow a literal encoding, through diagram-based instruction, to construct the furniture. This cognitive image process is the activity of our mind when building or identifying real-world objects as well as understanding their meaning in our mind. The more we can see of the object or image through scale and rotation, the more we can store that information in our brains. Kosslyn (1975) suggests 'Zoom in' as a skill for the inspection process. According to Paivio's theory (1971) of 'Dual-code hypothesis', if ideas as are presented with both clear visual image and verbal representation, their identification can be more accurate.

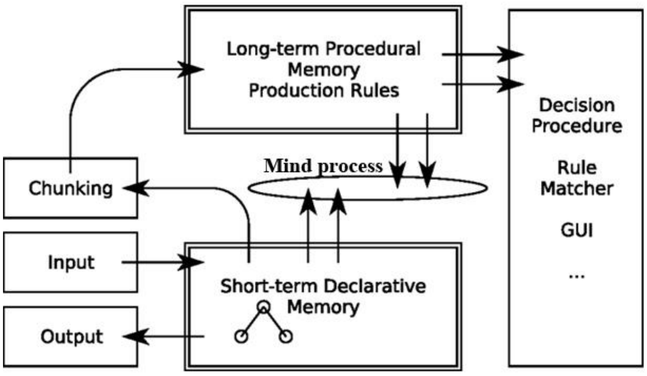
Lastly, problem-solving is a process to get an expected response from the given situation or goal (Hayes, 1989). This process could be seen as similar to the initial motivation for the design problem-solving process in many design theories. There are two kinds of problem-solving model. The first is the General Problem Solver (GPS) (Fig.3.12), the other is the State, Operator and Result (SOAR) model (Fig.3.12-1). GPS is based on a means-end process to construct 'plans with plans' for the problem-solving activity. The

Fig.3.12 GPS general problem solver model



Cited: Poltrock & smart, 2010 / Newell and Simon, 1972 process has also been described as a hill-climbing strategy; each action brings us closer to the goal, step by step. However, Greeno (1974) indicates the GPS has limitations due to the means-end heuristic usually not being well planned, sometimes causing failure in the solution. The second, SOAR, is an open-ended and dynamic model with a cyclical system. To be precise, the model is based on cognitive construction. A different cognitive system could be defined and built into the problem-finding model for interaction. Problems input are broken down into several sub-problems in order to clarify the relationships. This interactive process is very similar to the systematic or scientific design method of construction

Fig.3.12-1 SOAR model



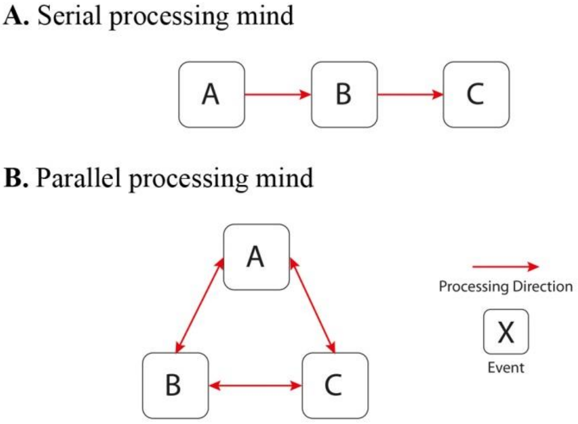
Cited: Newell and Simon, 1972

b) Cognitive science – the neuroscience of the network approach

This section focuses on explanations of different cognitive methods from the definition of neural sciences. Similar to physiological research on the cognitive process, neurological study explores the variety of mental models which could be referenced to their potential impacts on the study of creativity.

The Artificial Neural Network (ANN) model (Fig.3.13) is a practical method based on the Theory of Connectionism when studying the brain's mental processes, including mind operation, organization and representation. In this network model there are two types of mental process, the first is the 'serial processing mind' and the second is the 'parallel processing mind'. The serial processing mind (Fig.3.13-A) is based on mental activity which creates behaviour by series of neuron groups transferring inside the brain and generating final activity outputs. In the other type, the parallel processing mind (Fig.3.13-B), information

Fig.3.13 ANN (mind) information process



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or data from the environment is treated as a pattern, not an individual symbol. In this network approach, the mental operation is concerned with the interrelation of behaviours including information patterns and parallel activities in problem-solving. It is also called a behaviour-based approach. When compared with traditional cognitive psychology, environmental data is present as meaningful or individual symbols; during the mental process, the mind's activities are able to generate pre-set or anticipated results. This is called a knowledge-based approach to problem-solving.

However, the network approach in ANN provides an adaptable process of cognition which is easy to renew by new information inputs as well as being better for learning and developing the structure. Furthermore, the ANN structure is based on a value-based node and line system with values, using ‘the weight’ or an activation value (Fig.3.14). This weight could be positive, negative or zero to present the strength of a function which is determined by the network’s designer. For example, a person is riding a bike. While his brain is working at making a decision to cross a road, there should be a mental process operating at that moment. The cognitive process is evaluating according to the observed information, such as time needed to cross the road (Fig.3.14-A), car numbers (Fig.3.14-B), bike’s functions (Fig.3.14-C), etc. Those values are finally decided by the cognitive weight and this stimulates the neuronal system to complete the action. The process is like inserting data as values to operate computing units in an artificial network and then allowing algorithms (Fig.3.14-1) to calculate the results.

Fig.3.14 The weight of ANN (mind) information process

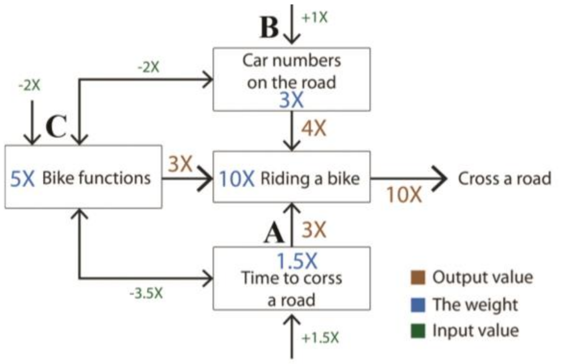
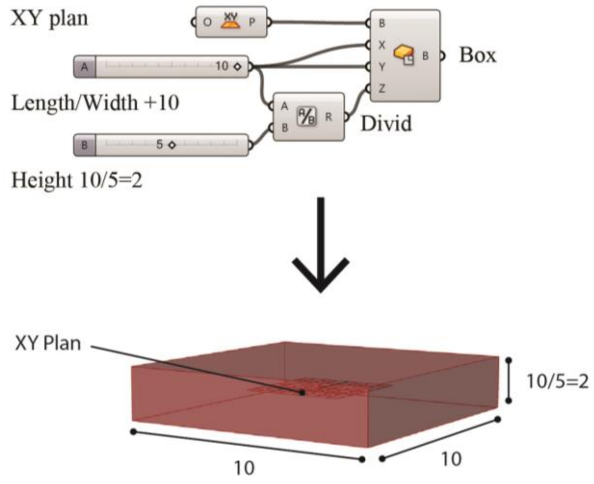


Fig.3.14-1 The algorithmic design process



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When it comes to the ANN typology, it is usually defined as a layer based system using different functions or aims. These are generally called input layer, output layer and hidden layer (Fig.3.15). Hopfield & Tank (1985) proposed a single layer neural network

(Fig.3.16), in this type, nodes are connected directly to each other. It is found to be a good model for optimizing problems as well as giving limited numbers to maximize the possible combinations, because the cross-interaction, or hidden information process, presents multiple neural activities providing a flexible cognition process. Although it is a better neural activity type when compared with the more general neural network, the single layer still shows limitations in its applicability, such as a lack of input information. Kohonen (1998) published his model with a two-layer neural network (Fig.3.17), also called ‘the Self-Organized Map (SOM)’. This two-layer type maximizes various feature maps during its operation; designers can use any mapping process to self-organize information and get rich solutions. This idea is similar to mathematical algorithms (Fig.3.17-1), and it is a process that well represents real brain activity. Many research papers show the SOM approach gives a designer better self-learning behaviour during the problem-solving process. This different method or pattern of neural operations shows a similarity to computing algorithms. In the computing process, the algorithmic process means a mathematically aided computation process. Jones (1970) stated, ‘When a design problem can be stated mathematically it can also be solved automatically inside a computer without human intervention’.

Fig.3.15 A general neural network (ANN typology)

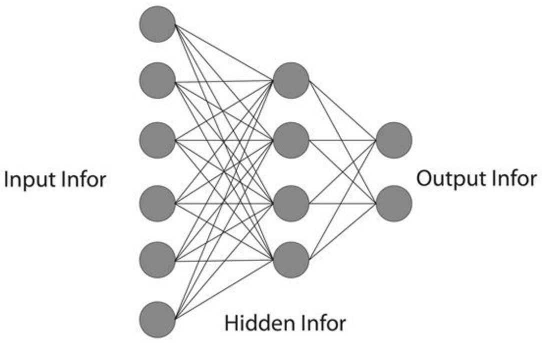

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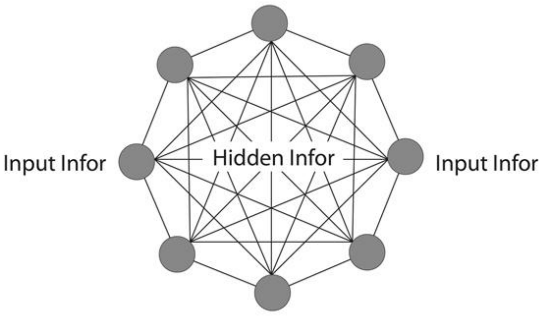
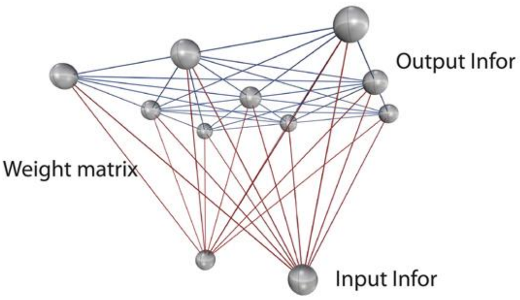
Fig.3.16 A single neural network (Hopfield & Tank, 1985)



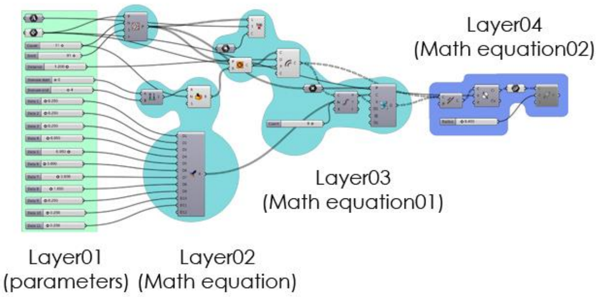
Source: Author reproduced/ Hopfield&Tank, 1985

Fig.3.17 A two-layers neural network (Kohonen, 1998)



Source: Author reproduced/ Kohonen, 1998

Fig.3.17-1 Mathematical algorithms



Source: Author reproduced

3.6 Design creativity

'Creativity is one of the key factors that drives civilization forward' (Hennessey & Amabile, 2009). When we talk about design and its value, most people believe that design outputs are the most creative of human pursuits. Creative thought is not only applied to the arts such as musical composition or painting but is also closely related to social sciences, medicine, science, design, management, etc. The essence of creativity is presenting novel and original experiences to other people (Lawson, 1990). When we examine the modern design process, no literature loses the connection between the fundamentals of creativity and creative thought. (Lawson, 1990). This section aims to review the definitions of creativity as well as unearthing studies that deal with its measurement.

3.6.1 Creative thinking

a) The creative process

Poincaré (2000) considered creative achievements in his mathematical thought. He described this experience as three stages in the creative process. The first is identifying the various problems forming the task. The next is taking some time to reflect on organizing the problems within the mental process. Finally, the solution comes overnight and then there is further verification and development of the ideas; he calls this process 'Fuchsian'. In this observation of mathematical creation, the fuchsia is not like the general mathematical process of following the rules and arriving at a solution; the creative process sets very flexible and adaptable conditions and allows our mind to self-organize the combinations required for the solutions. However, Poincaré was not able to explain how this subliminal self operates in the mind as a creative process, but he believed there was a correlation between this process and deep discovery work at the primary stage of problem definition or understanding.

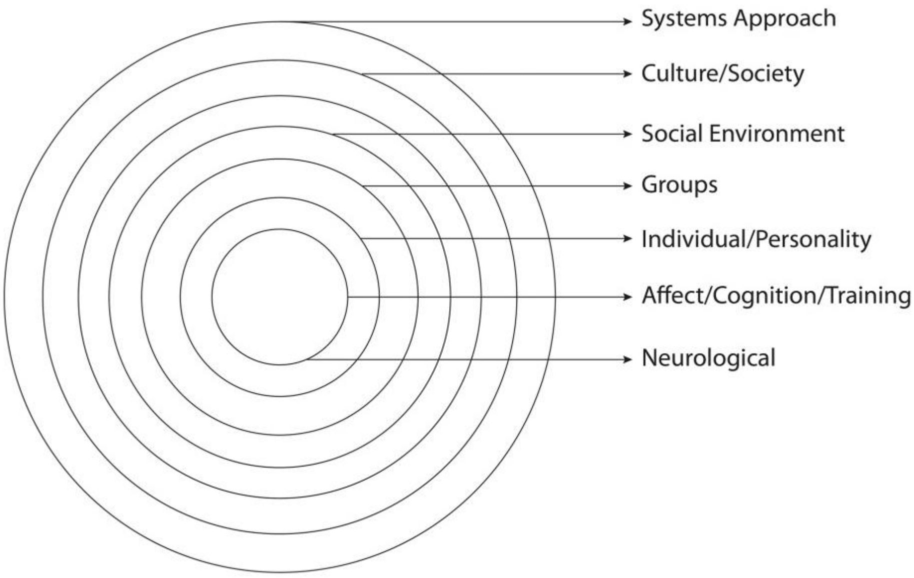
b) Creativity classification

There are still many different ways of describing creativity. Beghetto & Kaufman (2007) propose two types of creativity: 'Big C or eminent creativity: relatively rarely displayed creativity that has a major impact on others' and 'Little c or everyday creativity: daily problem solving and the ability to adapt to change.' This distinction provides a different aspect of the research into creativity which can help researchers clarify the direction of their creativity studies.

c) The creative forces operating

However, Hennessey & Amabile (2009) further present creativity as an organized representation; an increasingly large concentric circle representing the major levels of the creative forces operating (Fig.3.18). The circle identifies the creativity level and relevant effects of culture or society and personality on the neurological aspect. They concluded that although there is much creativity research published in this area, the most important factor is how systematic and organized the interrelationship is between the creative impacts of the different forces or contexts. Also, the different backgrounds of the creators should not be checked as part of such a creativity test. However, more research on the different backgrounds of the research subjects helps an understanding of their creative potential.

Fig.3.18 Level of creativity forces



Cited: Hennessey & Teresa, 2009

3.6.2 Creativity measurement

The specific domains of creativity that have been widely discussed in the literature mainly focus on four aspects: process, product, person, and context (environment). However, there are very few studies on architectural design creativity. Hanna (2015), in his research of examining the correlation between creativity domains and computing tools, applied statistical analysis to examine two types of CAD architects: parametric and nonparametric with the intention of measuring performance of process creativity and product creativity. The result indicated that both parametric and nonparametric CAD tools had a similar design potential (no significant variance, $p=.78>.05$) on the process and product creativity. On the other hand, the architects' design using parametric tools got a slightly higher score on the idea fluency section, which implied better process creativity. In addition, the study presented a regression equation ($Y=0.83*X+1.83$) to predict product ratings from creativity of process ratings.

This section explores related literature from the domain of design activity and highlights the areas of process and product creativity without considering personality or environment. As design is about the process of problem-solving (Lawson, 1990), to build arguments based on the process and product, creativity could offer operational measures for the performance in problem solving and a more objective framework to compare outcomes from deploying different processes in design problem solving. The following sections provide a discussion of the case studies with their associated creativity criteria and the progressed system of measurements for ideation that could be referenced to build up the study's argument for the doctoral thesis.

a) Measuring creativity as an ideation process

Torrance (1971) made an evaluation of creativity based on experimental findings from testing college students, the Torrance Test of Creative Thinking (TTCT). The results indicated that, in the ideation process, idea fluency (idea numbers), idea flexibility (idea types) and idea originality (uniqueness) have a significant relationship to the creative functioning of the subjects. Also scores on design enjoyment and stimulation further support the expression of original ideas.

Guilford (1950) suggests there is a considerable relation between design behaviour, or design planning, and the performance of creativity. He particularly emphasises that an organized process including design synthesis and an evaluation process could help to improve the thought process in idea generation. In addition, motivation and experience of designers are vital factors which could inspire novel ideas.

Runco & Chand (1995) concluded that creative behaviour connects the original product, idea, and adaptive problem-solving activities. This is an insight into cognitive outputs. Their research suggests a two-tier model of creative thinking and presents the process as three main activities: problem-finding, ideation and evaluation. There are two additional sub-factors involved in the model: knowledge and motivation. Importantly the entire process depends on interaction; the process shows the deep interrelation between those activities, and the looping action optimizes the cognitive process in creative cognition. Runco & Chand (1995) identify that thinking activity is an important information process. Firstly, the defined information, or categories, and experienced knowledge are established with data inputs from the environment. Secondly, before the information or data is taken forward into the ideation activity, there is a problem identification which is divided into three parts: problem construction, problem formulation and problem expression. These aim to clarify the problem structure before proceeding to the next stage. Thirdly, ideation directly influences the creative thought and gives detail to the creativity. Runco & Chand (1995) also identify three criteria in ideation activities: with ideation fluency identifying productivity or numbers, ideation originality indicating uniqueness or novelty, and ideation flexibility showing variety. Finally, there is the evaluation process, and accurate evaluation is closely correlated with creativity (Runco & Vega, 1990). There are two types of evaluation: intra-personal and inter-personal. These two categories are based on the design process and product to further the evaluative accuracy of creative thought. The research concludes that cognitive research on creativity is unique but should not be restricted by any organized process or traditional structure of cognitive psychology. The result not only provides an understanding of creative thought by using several criteria in different activities such as ideation and evaluation, but also by defining the correlation between cognitive research and creativity.

b) The measurement of product creativity

Amabile (1982) published her model of creativity in her social psychology studies. She established some criteria for creativity by reviewing the products rather than the conceptual definitions process, the Consensual Assessment Technique (CAT). She thinks that creativity research based solely on cognitive psychology does not provide a clear definition. Therefore, she suggests a ‘Product-centred’ definition as an empirical research methodology for defining creativity. By referencing the product features through objective assessments, this might help to clarify the correlation between conceptual identifications of creativity and subjective judgements. In the studies, there are two different determinations: artistic and verbal creativity. Each has three clusters, for example, artistic creativity consists of three parts: a creativity cluster, a technical cluster and aesthetic judgement. Verbal creativity contains a creativity cluster, style cluster and technical cluster. In terms of the analysis dimensions, novel ideas and materials are used in artistic creativity analysis. On the other hand, the use of novel words and expressions and originality of ideas are measures of verbal creativity. Amabile suggests that by using these measures of creativity we could improve the outcome through a social psychology research model. When compared with the general research methodology used for defining creativity, based on cognitive psychology, this new method has two benefits. Firstly, the product-centred analysis creates a correlation which could be applied independently with skills such as writing or drawing. Secondly, the product- aided assessment could be more reliable and objective rather than using a given person's psychological rating for the evaluation of creativity. Most importantly, this uniquely subjective but explicitly structured analysis of creativity could be demonstrated and extended for further analysis.

Piffer (2012) suggested a creativity measurement from the product perspective in three dimensions: novelty, appropriateness, and impact. 'I assume that a product's creativity is a continuous rather than a categorical variable (a product is not simply either creative or not but it can be more or less creative than another product.)' In addition, one product's creativity could depend on the measurement of its usefulness, suitability, influence, and novelty. On the other hand, Piffer criticised how some creativity measurements overlap with the definition of people, product, and creative potential. He stated that a person's creativity is a biographical phenomenon that should not be assessed with psychometric instruments. Therefore, before the measuring process, researchers should clearly establish the criteria with an empirical study and employ various methods so they could reduce confusion and produce a more comprehensive assessment of the creativity study.

Simonton (2012) argued the importance of reaching a consensus for the study of creativity. He cited three criteria, novelty, utility, and surprise, to define the terms of creativity and provide an understanding of the phenomenon. He further identified that these three criteria had four implications regarding '(a) the limitation to domain-specific expertise, (b) the varieties of comparable creativities, (c) the contrast between subjective and objective evaluations and (d) the place of blind variation and selective retention in the creative process.' These implications and the three criteria could bring the creativity measurement into a different aspect that is 'quantitative and multiplicative rather than qualitative or additive.'

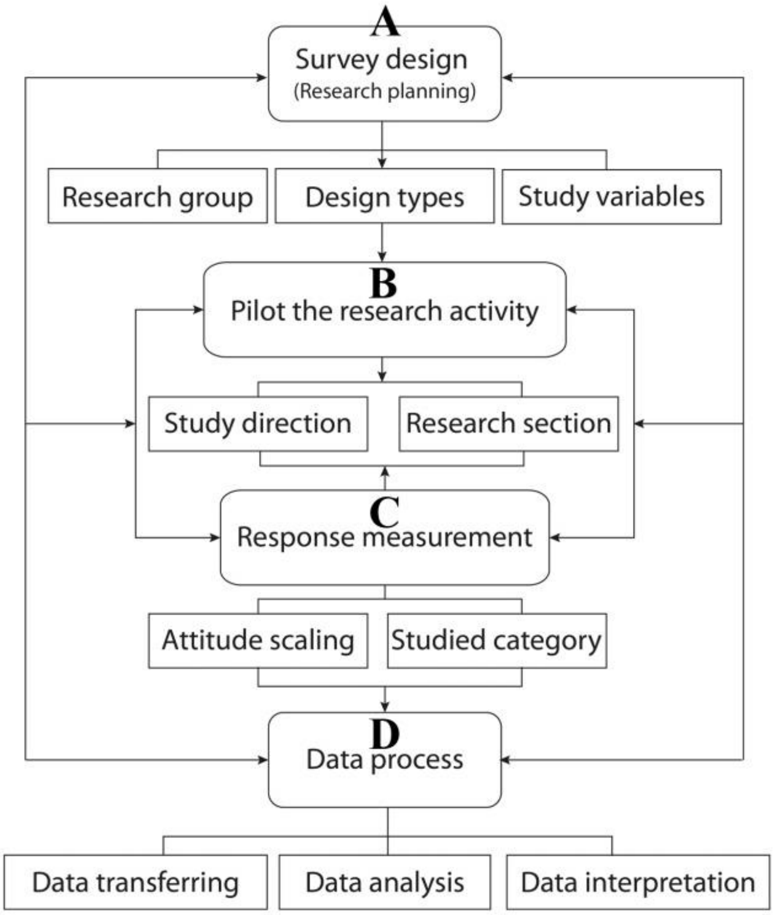
3.7 Evaluation of the design performance

The design process is generally thought of as one of the significant forms of intellectual behaviour in human creativity. The process is often associated with varied activities such as innovation, synthesis, and problem-solving as well as the highest cognitive behaviour of the human brain. In terms of evaluation of the design process, either observing the design activity as a real-time process or evaluating the design experience by giving feedback could both be considered a valid assessment of the design process. It is surprising that current literature has very little material presenting evaluation of design during the hospital design process. This might be that because of the complexity of the functional design and the non-visible mental processes, the hospital architect's design process cannot easily be identified. In other words, the design behaviour could be unpredictable. Although it might be true that the design process is uncertain, analysis of this specific design process is still possible. There are two kinds of impartial methods which have been applied in relevant design research: the first is a concurrent method using protocol analysis, the second is retrospective analysis using a survey questionnaire. The following sections review background knowledge on the methods and provide relevant case studies from the available research literature.

3.7.1 Retrospective method – *feedback survey on the design process*

Oppenheim (1992) proposed that research techniques should be constructed with measurements, quantification and construction instruments in order to generate findings containing specific attributes or research variables allowing further study of the relationship between them. He defined a research process based on data collection, or feedback, in four main steps. The first is to analyse the type of survey design which means focusing on the research plan (Fig.3.19-A). This includes classifying the research group and type and choosing the list of study variables. The second is piloting the research activity (Fig.3.19-B). A questionnaire is selected as the survey method so the pilot activity needs to be planned and sections of the questionnaire are constructed to investigate attitudes appropriately. The third step focuses on response measurement which means necessary attitude scaling (Fig.3.19-C). The range of scales or the category types present different feedback so they should be very carefully selected according to the research plan and pilot activity. The last section is about the data processing (Fig.3.19-D). There might be many different ways of evaluating data but it is important to select a proper mathematical model to establish an impartial investigation for further discussion. However, there are some disadvantage of the feedback survey method. For example, the interviewer might have inaccurate memories of answers to questions or attempts to direct the questions giving the opposite response to the one intended. So, in the design of a questionnaire with respect to attitudes, and in the pilot activity, there should be very careful selection of sentences and words.

Fig.3.19 Questionnaire Design Interviewing & Attitude Measurement, Oppenheim, 1992



Source: Author produced

a) Case study of a feedback survey

Hanna (2012) applied a feedback survey to investigate the impact of parametric and nonparametric tools used in the architectural design process. He collected research feedback from around 32 architectural design offices including 18 nonparametric design offices and 14 parametric design offices. A comparative study was employed with the null hypothesis *'there is no significant difference between traditional or nonparametric CAD practices and parametric practice regarding their use of CAD in the design process.'* The statistical analysis using computer software (SPSS) to analyse the relationship of variables and gave a statistical value based on the significance definition $P<0.05$ required to reject the null hypothesis. In other words, if a significant value has been confirmed in the comparison between groups, the research hypotheses (H+) '*there is significant difference between traditional or nonparametric CAD practices and parametric practice regarding their use of CAD in the design process'* will be confirmed.

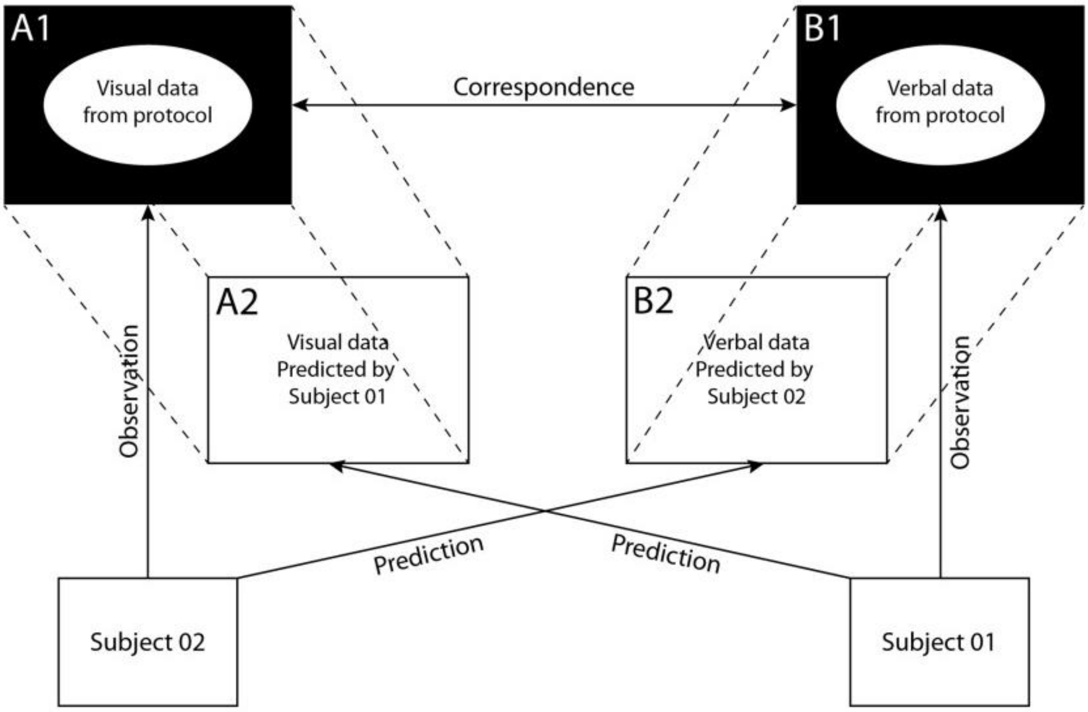
The analysis results found there had been no significant difference between the two groups on the development of a complex geometric design. But the parametric design architects presented a significant difference as to the performance of creative decision making being enhanced by the parametric tool with $P < 0.05$. Also in design aspects such as environmental simulation, detail fabrication and articulation of façade design, the parametric group demonstrated impressive scores in this survey.

3.7.2 Concurrent method – *protocol analysis in the design process*

The earliest protocol analysis was used in the development of psychology in the early twentieth century. Apparently, the initial purpose of this method was to investigate problem solving and through a 'Talk-aloud' process to represent participants' thinking activities (Austin & Delaney, 1998). From the 1970s, protocol analysis in architectural design research began to be used by researchers such as Akin (1986), Schön (1988) and Goldschmidt (1991).

In 1991, the Deft Workshop on 'Research in Design Thinking' applied protocol analysis in their research studies. Cross, Christians and Dorst (1996) suggest a number of advantages of protocol analysis. First, the analysis is the technique most likely to show what designers' cognition is like during their design thinking through verbal accounts (talking aloud). Second, it is believed that a verbal account is the most straightforward expression to demonstrate what people have in their minds, concurrent verbal accounts offer reliable evidence from participants, or subjects, who are externalizing their cognitive activities. In addition, Ericsson & Simon (1993) compared standard protocol analysis (Fig.3.20) in thinking silently (Fig.3.20-A1/A2) and talking aloud (Fig.3.20-B1/B2). They found that talking aloud produces dramatic results from verbal accounts only during the behaviour observations, in contrast, thinking silently results provide very limited information.

Fig.3.20 Dual-mode protocol analysis



Cited: Akin&Lin, 1995

However, protocol analysis has some disadvantages. For example, the verbalization may sometimes have side-effects which may change the subject's behaviour as well as the cognitive process. Subjects sometimes present irrelevant accounts which cause misunderstandings of the design task (Cross, Christians, and Dorst, 1996). Therefore, 'non-verbal thinking' accounts such as sketching, writing or body language should also be considered as part of cognitive reactions; such data can be seen as part of the externalization of thought processes during protocol analysis.

a) Case study of computer-based protocol analysis

Niblock (2012) applied a computer-based protocol analysis in the investigation of the use of a free-form CAD method, offered by Rhinoceros, to enhance the novice designer's design creativity especially with respect to cognitive characteristics such as perception and conception. Similar results have also been discovered among expert design engineers with respect to the inspiration of creative design. The computer process used a digital camera and Camtasia software as the recording media, and then employed an analysis process run by other software (NVivo08), a qualitative data mining and analysis tool. In the protocol studies, she divided the process into three main steps. The first was to pilot the research direction when she applied a feedback survey to a first-year university students' computing lecture and then she combined the research questions to give direction to the protocol analysis. In the second part she classified the design process into four parts as the coding scheme: Conceptual, Perceptual, Operational and Design Information. In the last part the recorded data was transferred and with the aid of software (Nvivo08) the analysis was presented in a diagrammatic format. The comparison of the data recorded in the design process indicated the percentages of design behaviour and offered these as evidence to support the research findings. For example, the protocol analysis found that novice architects produced twice as much design information or interpretation, with around 75% utterances, whereas expert architects produced around 31% utterances. Also, there was 76.5% score on perception of the visual features of design shapes or textures found in the novice architects' design process. These findings indicate the CAD was not only helping architects in the design drawing, but also assisted them, especially the new architects, to rationalise their design ideas. Although the author concluded that CAD, using Rhinoceros, did not turn the novice architects' behaviour into something more like that of an experienced designer, CAD and its free form design process had inspired them in their design creativity by using varied design cognitions such as perceiving forms, scales and material utilization.

3.8 Discussion

Section 3.2 considered theoretical aspects of the design process and introduced some ideas for mapping the design process or modelling the design activity. It is important that we investigate complex design projects such as hospital buildings from the fundamental aspects of the architectural design process. Besides that, these design models or methods, in fact, present a logical and organised view of evaluating different design developments.

Section 3.3 directed the study to the core aspect of architectural design; the problem-solving process (Lawson, 1990). This addresses functional issues as well as novel ideas in design representation. Especially in complex design projects like hospital buildings, it is very important that architects understand or predict design problems and solve them before the project design has been finished. Otherwise those design problems will not only cause failure in the building design but might also affect the lives of hospital patients (Baynes, Green, Moss, and Jackson, 1971). However, the nature of design problems cannot easily be completely identified, especially in complex design projects. This is because the design problems are associated with very wide ranges of contexts, while the scale of the project is also connected to the complexity of design problems. Therefore, a detailed, logical and organized process of design might help architects to understand the challenges of the design problem as well as to more easily identify the problem-solving activity.

The review of systematic design of hospitals (Section 3.4) provided practical evidence on the use of systematic design methods in a complex building project as the traditional design process might not suit this specialised type of building design. By carrying out these systematic design activities architects can not only discover the design problems but also achieve greater understanding of various aspects of design knowledge. Systematic design methods involving a constant problem-solving process could improve design quality and reduce structural problems.

When it comes to the section 3.5, the psychology of design, cognitive activity is well-researched and is essentially based on the brain's operation (Akin, 1986). A review of those related disciplines such as psychology or neural science might help us to understand the reactions of designers and their mental processes during the design problem-solving process. The studies exhibit that visual impacts such as those of 3D objects, materials, and varied shapes could improve the efficiency of the cognition process. On the other hand, the neuronal operation models of the mental process exhibit how human cognition follows different logical rules and patterns, with information inputs optimizing the cognitive process. The study of neuroscience also shows a similarity between human mental processes and computing algorithms in terms of the flexibility of the problem-solving process.

The review of creativity in design (Section 3.6) considered the related topic of creative behaviour from the different aspects of social forces (Hennessey and Amabile, 2009). Although the current research on creativity is wide, deep and varied, there is no universal conclusion about what creativity is and how to become creative. Hennessey and Amabile (2009) concluded that it is important to use a systematic view in understanding creativity and to identify the interrelated forces working at multiple, wide and different levels.

Section 3.7, The last part of the chapter, reviewed certain design evaluation methods with a case study using computer based protocol analysis (Niblock, 2012) and a feedback survey investigating the link between CAD and creativity (Hanna,2012). However, there are many further examples in the literature on analysis of design activities. They might use different or unique approaches in terms of the initial research targets, but the examples provide well-structured data to understand the designer's reactions and interpolations. As we earlier mentioned in this chapter, it is important that we can systematically and objectively explore the secrets of design methodology and processes through examining designers' activity, cognition and reaction. The more we know about design activities, the more we can develop a creative design process which may improve the quality of complex building designs and this may well be the case in the design process for hospital buildings.

Part I/ Chapter 4 – Literature reviews 3

Parametric design methodologies for architecture

4.1 Introduction

Computers and technology have significantly changed our lives, especially in industrial areas, and processes in architectural practice have also been influenced by this digital wave from the early design stages to final construction. Computer Aided Design (CAD) is not just a tool for architects but has extended architectural design activities into advanced visualizations such as free-form shaping and digital fabrication. In especially complex designs such as hospital buildings, CAD plays a role both in establishing the new design process and solving design problems during the process. However, it is important to understand how the computational design methodology affects the architect's design thinking and how specific CAD behaviour is related to design creativity as well as how we can measure these creative design activities.

The chapter consists of four parts: the first part reviews the background and impact of tools and designers on design activities, the second shows the comparison between nonparametric and parametric design methods in architectural design, the third and final parts provide information on hospital and complex building case studies using the BIM parametric design methodology and algorithmic design, comparing their impact on design creativity.

4.2 Design tools and architectural design

Design tools, such as paper-and pencil and CAD software, in modern architectural design are varied and commonly used in the design process. It is important to understand the interaction between design tools and designers in order to improve the quality of design cognition. So, this review intends to look at the historical evolution of design tools as well as how designers use design tools to influence their cognition at the early stages of the design process. This section comprises two parts: the first gives a brief history of design tools in architectural design development, the second indicates the impact of using CAD design tools in the design process and their cognitive influences on the designers.

4.2.1 History of architectural design tools

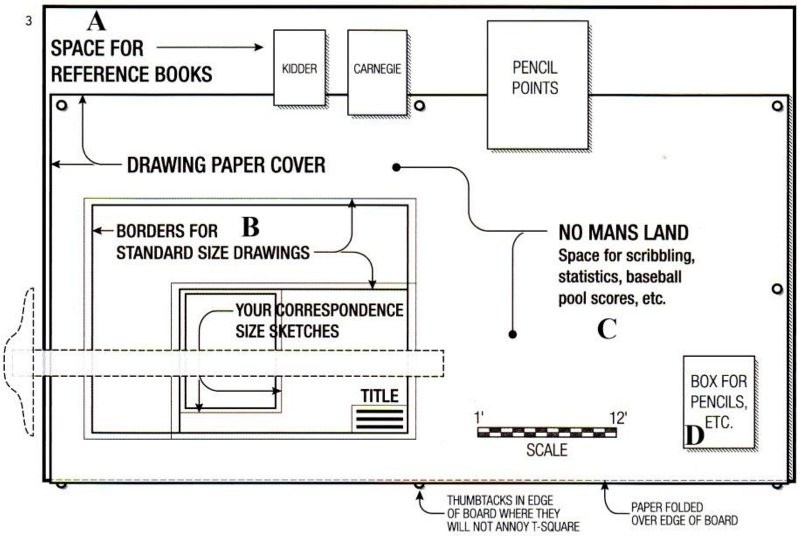
a) Before the age of metric tools – *Early practice*

Free-hand sketching with a pencil was probably the earliest design activity and tool used by ancient architects. In early architecture, there were no formal architectural or engineering drawings detailing the construction plans. Although visual projections were commonly used by some Italian architects, this does not mean there was any construction accuracy. Early architects sketched their designs without scales; then builders worked out the relevant methods and tools for their construction work. This weak connection between the architects' design process and construction work was perhaps because they did not have the idea of scales or dimensions in their drawing systems nor the necessary tools. As a result, the design representations, such as free-hand sketches, only showed the architect's painting skills and aesthetics. However, those beautiful drawings did not help the design process or building aspects (Cadhistory.net, 2016; Garber, 2014).

b) The era of metric tools

In the fifteenth century, Leon Battista Alberti (1435-36) suggested architectural drawing should apply the ideas of Euclidian geometry and mathematics to develop multiple views for the representation. This would allow architects to add more design information to their drawings and reduce the potential errors caused by drawing from a single viewpoint. Because of this mathematical drawing process, architects started to apply scales and dimensions to their designs and started to use related tools. From the 18th century, the industrial revolution changed the entire civil engineering world including architectural design and manufacturing processes; architects were obliged to adopt accurate design tools to inform the construction process. Therefore, design tools included T-squares, triangles, scales, irregular (French) curves and a compass, became extensively used in design. The Universal Drafting Machine was the typical drawing set for architectural firms in the 1900s. Consequently, design drawings and tools increasingly incorporated fine calculations and accurate dimensions (Garber, 2014).

Fig.4.1 Plan of a traditional drafting board



Cited: GRO Architects, New York, 2013/ Garber, 2014

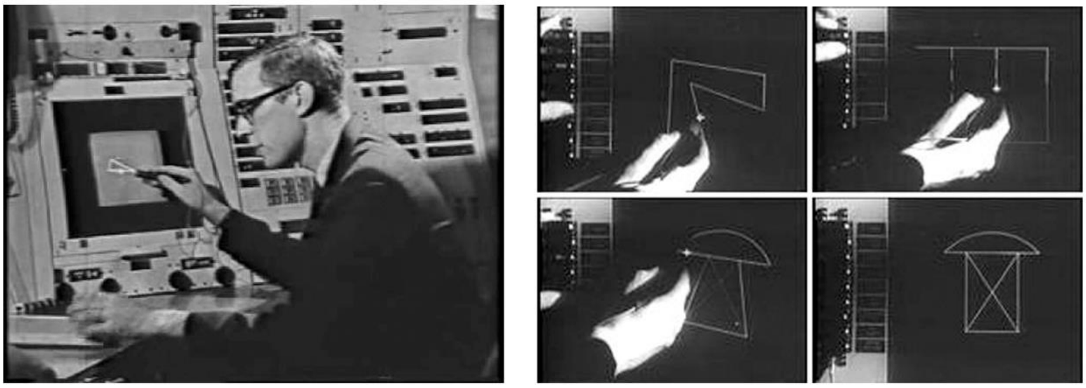
Figure 4.1 shows a drafting board used in an architect's office in 1929. The board included most design tools and design reference materials. The top ribbon or space (Fig.4.1.A) contains the design resources (books). The main drawing area (Fig.4.1.B) is located on the left bottom side with a slide rule and other relevant instruments. The right side is the free sketching space (Fig.4.1.C) which allows architects to develop their concept sketching. The lower space (Fig.4.1.D) contains pencils and other instruments. When compared with the tools of ancient architects, pencils and painting instruments, modern architects apply calibrated tools in their design process and show the potential of standardized design quality in architectural developments. In addition, those tools not only establish design standards but also improve working efficiency and accuracy from the design to the construction stages. Jones (1970) suggests scale drawing with such tools in the design process not only increases output and rate of production but also enables better distribution of work in design teams.

c) Design tools using computer-based technologies

In the post-Second World War period, European countries required mass production in construction to rebuild the environment. This trend raised another issue for architects, that of a standardized design process for such mass production. This process required more architectural drawings and accurate measurements. For example, a high-rise office building or large apartment requires complex technical calculations and dimensional notes to create the floor plan drawings. Traditional drawing by slide rule or hand-held instruments was no longer sufficient or efficient in this working environment. Consequently, the concept of computer-aided drawing was introduced into the modern design industry (Cadhistory.net, 2016).

The development of Computer Aided Design (CAD) was not easy; the drafting programs cost a lot of money and required extensive space for hardware. In 1963, the first sketchpad interface (Fig.4.2) was created by an American computer scientist, Ivan Sutherland (Castle, 2013). It responded to the given commands (computer scripts) and the machine drew points, lines, and arcs on the screen. However, this sketchpad was just experimental and did not become commercial. AutoCAD (1982) became the earliest CAD software used by the commercial design industry, although there have been many other CAD programs developed and sold widely since then. AutoCAD provides effectively the functions necessary to assist architects' work such as the repetitive task of drawing and creating multiple drawings using layer management and blocks for entities. Various scale outputs also save time when converting one drawing into different scales for the representation. Moreover, architects and engineers, by using the same drawing tools or interface, find it easier to work together. This means that CAD not only optimizes drawing efficiency but also enables the sharing of design data among different professions. (Cadhistory.net, 2016)

Fig.4.2 The lvan's sketchpad, 1963



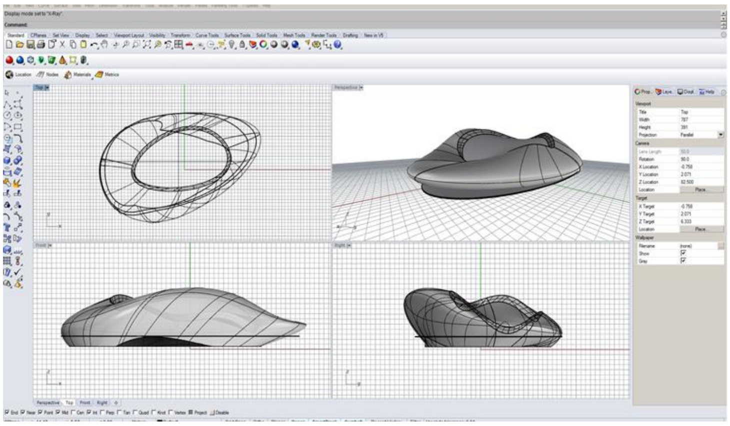
Cited: Wikipedia_sketchpad

d) Three-dimensional design tools using computer-aided technologies

The earliest CAD system only produced two-dimensional graphics or data, and subsequent early three-dimensional computer drawings were developed using wireframe geometries only. However, this line constructed surface or geometry could not effectively display shadows as real objects. A surface modelling system was consequently developed for three-dimensional CAD. From the mid-1960s, MIT researchers constantly explored new systems to apply to the three-dimensional modelling area. Finally, geometric modelling systems such as Bezier curves (1960), B-splines (1973), NURBS (Non-Uniform Rational B-Splines, 1979), and B-Rep (Boundary Representation technology, 1973) were developed for solid modelling applications. Finally, in the late 1980s solid modelling systems became the main CAD tools for the commercial market (Cadhistory.net, 2016).

Despite the name of such CAD tools, it is necessary to realize the computational backgrounds for the modelling systems. Because each program uses a mathematically-based drawing technique, these functions have significantly influenced the architect's design process. For example, Rhinoceros3D (Fig.4.3) is a NURBS-based modelling program, launched in 1980. It allows the architect to create many mathematically-based freeform surfaces and complex geometries which are impossible to generate by traditional tools such as ruler or pencil (Rhino3d, 2017). 3ds Max is a polygon mesh based modelling system, launched in 1990. The mesh system allows the designer to create solid modelling and easily modifies meshes on the surface to create different forms. Its rendering visualization is based on polygon meshes and gives realistic lighting effects and accurate physical environment calculations (3ds Max 2017 user guide, 2017). With such CAD tools architects can design complex forms and predict their final design outputs as well as improve their design ideas during the early stages of the design process.

Fig.4.3 The NURBS models (Rhinoceros)



Source: Author produced

4.2.2 The interactions between CAD tools and the design process

Lindsay (1989) argues that externalized technologies, such as CAD tools, can change the human mind in much more depth than is commonly understood. She thinks there are some very profound impacts on human cognition while people are processing tasks with these tools. This Ph.D. research explores the link between cognitive processes and CAD tools as well as the influences on the design of hospitals. The following reviews focus on two areas of current literature: the first is the way in which CAD tools are thought to be extending the cognitive process, the second is the extent to which CAD tools influence users during the design process in areas such as problem-solving and learning development.

Janney (1999) thinks that when people use externalized tools for their tasks, it is similar to the effects of using prosthetic tools to replace parts of our bodily functions. His research particularly focuses on the user of computers; the results indicate several potential influences of computers on extending or enhancing our mental processes. For example, when the user is using the computer to produce documents, his cognitive processes can be enhanced or extended by computer functions such as template selection or editing style. As a result, computer produced documents are quite different from the output generated by non-computerized procedures.

Moore (2011) considers how CAD technology and tools can extend cognitive activities such as generating ideas in a problem-solving process and producing divergent thinking in a creative design process. It is like a mental prosthesis which extends our thinking process and the reaction of our body. Each instrument contains information, like user instructions, and these can be read and understood. Therefore, instruments can determine the direction of the mental process; even influence the decision making of the user when completing a task with some specific results. Moreover, Moore suggests the use of tools and technology literacy have a close relationship. The process of using CAD tools increases our expertise on the technology; this impact can be defined as cognition extension. In addition, instruments are designed to complete a specific task, especially CAD tools, but the specialist can structurally refine, or reprogram, the CAD tools to adapt to changing situations. This indicates CAD tools can interact with the user's learning experience or cognition and the tools can also be refined to improve their function and provide more experience to the user.

Friesen (2010) suggests that technologies such as computer tools are not only instruments of data analysis but also help the development of variable learning processes; he describes this developmental process as the ‘tools to theory heuristic’. His paper pointed out that ‘the technologies have the tendency to inspire theories about the nature of the mind, memory, thinking or learning’. Moreover, by using CAD tools, the user might able to explore the cognitive process and establish its partnership with computers. Because the initial purpose of computer-aided design aimed to help the computational process such as information processing or symbol manipulations, these functions, as in the human mind process, were inserted into the programming to optimize the computations. This functional similarity creates an interaction between user and CAD tools. While the user is undertaking the computer programming, their behaviours are acting as in the computing process; therefore, the computer is cast as a kind of 'cognitive technology' or a 'mindtool'. Friesen further states 'computational procedures, representational structure and information processing are all keys to the cognitivist paradigm'.

Salomon, Perkins and Globerson (1991) argue that effects of technology can redefine and enhance performance as students work in partnership with intelligent technologies. Moreover, effects of technology can occur when partnership with a technology leaves a cognitive residue, equipping people with thinking skills and strategies that reorganized and enhanced their performance even away from the technology in question. However, these effects are not without structure; in fact, the effects of CAD tools or technology could be studied, logged and analysed through the cultural surrounds or working environment.

Jonassen and Cho (2008) tested students' reflections on their use of computer-based mind tools to demonstrate what they learned and now know from this experimental process. The paper indicates that externalizing mental models improves the utility, coherence, and cogency of mental models. Also, students present critical thinking, problem-solving, decision analysis and knowledge construction about ideas while they are studying. Through a series of computer aided programming tests, 'the use of computer modelling tools as mind-tools can help users to refine their cognitive models'.

Spector and Kinshuk (2011) address the issue of how technologies and their tools can support the development of problem-solving processes. Technology tools offer users support in two important ways: firstly, technology tools are able to accumulate user 'expertise' for progressing the problem-solving process and evaluating decisions in problem identification, secondly, the technology simulations help users learn about the problem-solving process. 'Technology can be used to generate many realistic problem-solving scenarios and interactive simulations to help learners gain competence and confidence.' Moreover, some technologies and tools are created to measure the interaction of the function and task; such measures can in principle 'be used to dynamically generate new learning activities' and 'help instructional designers identify learning activities that are not particularly helpful for learners'.

Hanna (2013) uses statistical analysis to test the impact of using digital tools during the architectural design process, with regard to design cognition and creativity. His studies found that the time length of user involvement with the CAD tools had statistical significance when related to three measurements of creativity: ‘rho=0.487, P<0.05, for elaboration of design ideas; rho=0.605, P<0.05, for volume of ideas; rho=0.687, P<0.05, for ideation variety. Moreover, where there was more interaction between designer and computer this helped in the discovery of various forms of design, about rh0=0.591, P<0.05, ‘the study also found little evidence to support the notion that computers prevent other ‘forms of knowing’.

4.3 Nonparametric and parametric design methodologies

Traditional design methods such as pencil-and-paper have created many masterpieces and to some extent it has established the classical architectural design language. On the other hand, in recent decades, Computer Aided Design (CAD), especially parametric applications, has dominated the working environment in architectural practices creating advanced design solutions with creative ideas. This section compares our knowledge of parametric and nonparametric design methodologies as well as relating software to design activities in the development process.

4.3.1 Nonparametric architectural design methods

Nonparametric architectural design methods normally indicate architectural design using conventional tools and approaches. The tools include pencil, T-square, scales, drawing board (Universal Drafting Machine, 1920s), and conventional CAD products such as the electric sketchpad (Ivan, 1963) or AutoCAD (Autodesk, 1982), and representations like hand sketching, physical modelling and traditional CAD digital drawing (Cadhistory.net, 2016).

For the nonparametric methods, Wodbury (2010) defines conventional design activities as those which can easily build a model and erase it. Each object or step which is created by designers is independent and logically bears no relation to others. Although the product can be made more complex by changing scales or dimensions and making it look complicated, any modification is required after the model has been generated. It means the designer can only manipulate their decisions on design through completed design results without any predictability. Also, tools like these restrict discovery through happy accidents, unexpected outcomes and inspiration in design creativity. However, this section divides design methods through nonparametric design into four categories and examines the relationship to the traditional architectural design process and its design representations.

4.3.2 Nonparametric architectural design ideation and expression

a) Craft evaluation – *Ideation*

In the traditional, nonparametric process, design working methods such as making physical models were looked at as an essential process for architects to explore their ideas. Jones (1970) identified that the man-made process discovered design problem-solutions through a series of crafting rather than pre-drawing them. The design idea can only be defined through the final products. For example, many natural and organic designs for early vehicles, such as farm wagons and rowing boats, have no records of design drawings; their inventors or craftsmen did not have prior education through design drawings or other industrial sources. Briggs (1929) maintained that in late medieval period, architects and builders used to design the structure using tools or plans while the building was under construction (Fig.4.4). From small objects to large buildings, the crafting process established the earliest nonparametric design methods as an unidentifiable process. Lawson (2005) described the process as 'blacksmith design', the method linked the design thinking directly back to the process of construction. Craftsman or builders kept trying to improve design proposals by trial and error then achieved the final design through individual experience.

Fig.4.4 Builder & architect of medieval era

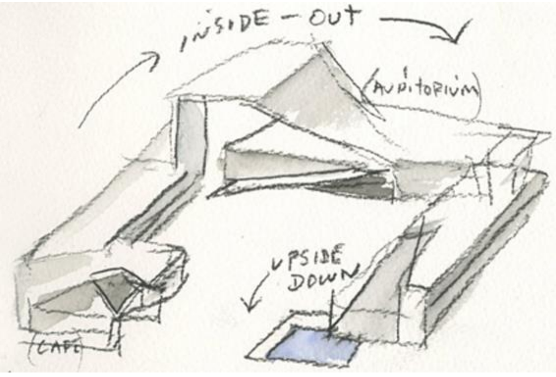
Cited: Murry, 2014

Such designs might achieve some aspects of design creativity, but the ideas were only retained in the builder's mind. Furthermore, the craft based method only provided few or even no instructions for the development of designs. Most ideas were only acquired through apprenticeship and could not be examined and redeveloped without personal experience (Jones, 1970).

b) Design by drawing – *Design expression*

When designers were no longer working as individual craftsmen, they had to transmit their design by communicating instructions to builders. 'Design by drawing is not a product but the design expression of designers' (Lawson, 2005). Donald Schön (1983) described the drawing process as the designer ‘having a conversation with the drawing’. Jones (1970) defined the process of design drawing and redrawing as a continual process to help the designer clarify the design stage of problem-solving. He also suggested drawing to scale was a necessary procedure for earlier designers to divide the complete work into separate components for craftsmen and builders. Moreover, the advantage of pre-drawing in design encouraged the designer to solve the critical dimension issues of complex constructions. Therefore, design by drawing not only helped designers to express their designs but also to establish the collaborative platform for the design communication. However, Jones (1970) indicates that using traditional drawing methods in design is an addictive process which means the designer can, through an overlapping process, increase the complexity of the representation, but, in fact, there is no full interconnection between the 2D sketches and the completed 3D objects. In addition, design by drawing (Fig.4.5) limits creative cognition by fixing interrelations rather than developing new information. Drawing activities ignored physical conditions such as gravity which provide important design elements for real buildings. Lawson (1990) concluded that in design by drawing, ’The designer can see from a drawing how the final design will look but, unfortunately, not necessarily how it will work.’

Fig.4.5 Design by hand drawing



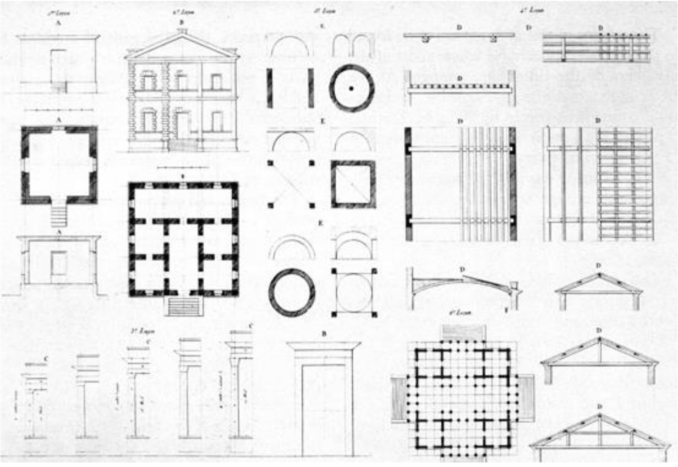
Cited: Steve holl architect, 2011

c) Typology design – *Classification*

Typology design is a traditional design methodology using systematic thinking which was inspired by comparative physical building environments. The method extends traditional design activities, such as hand sketching and physical modelling, into logical design thinking but the design process is still based on nonparametric tools and backgrounds.

In the theory of typology, man-made objects are transferred from natural elements then made distinct with different types or forms according to the design inspiration. In the architectural world, this imitation activity indicated a synthesizing construction with form, function, ecology and nature combining with surrounding environments to determine the particular building types such as house, temple and cities (Quatremere de Quincy, 1755-184709). Durand (1760-1834) identified the approach of comparative taxonomy and descriptive geometry listing a series of building elements such as column, wall and foundation to explain the typological world of architectural design (Fig.4.6). After the Second World War period, as cities needed urgent redevelopment, the concept of typology became the form-making process to optimize the mass-production of standardized building types. Le Corbusier’s Domino System (1914) was cited as the building prototype for this design process. He followed a modular typology, designing by mathematical and metric systems which successfully contributed to modern buildings and functional layouts. Typology design upgraded design thinking not only in the presentation but also improved functional design in areas such as construction and structural constraints (Tedeschi 2016). In the late 19th century, the architectural world was entirely dominated by typology design in form-finding. The form-finding process represented alternative visions of conventional drawings, but drawing by sketches did not optimize the form-finding process because traditional tools, like pencil and paper, could not predict the problem-solution to extend design thinking and creativity. One of the main criticisms of typology design is that it brought about stereotypical thinking and constrained flexible ideations (Ungers, 1985). In addition, De Carlo (1985) criticized typology design as just repeating pre-established ideas for the design generation without allowing for variation and individual qualities.

Fig.4.6 Typological Architectural design



Cited: Graphic portion of the lectures on architecture, 2000

4.3.3 Parametric architectural design methods

Parametric architectural design is one of the CAD approaches in the study of contemporary architectural design. Although CAD in architectural design has been developed over decades, most design media were just used as representational tools such as digital drawing or digital modelling. The parametric design process offered variable attributes with mathematical or geometrical algorithms. The parametric model is created by values for parameters, or variables, and equations to establish the correlations between the objects or geometries (Barrios, 2004). Stavric & Marina (2011) summarized that since the parametric idea was created in 1990, two kinds of parametric design have been defined: the first is architectural design using parametric conceptions, the second is architectural design using constructive parameters. In other words, conceptual parametric design means creating new computing objects (geometries) and operating them by using parametric values, a norm used in programs such as in Grasshopper (a plug-in to Rhinoceros). On the other hand, constructive parametric design assembles the design elements by using a pre-set parametric system and integrates the relationships for building construction, such as a procedure found in software packages such as Revit (Building Information Management/Modelling) and ArchiCAD.

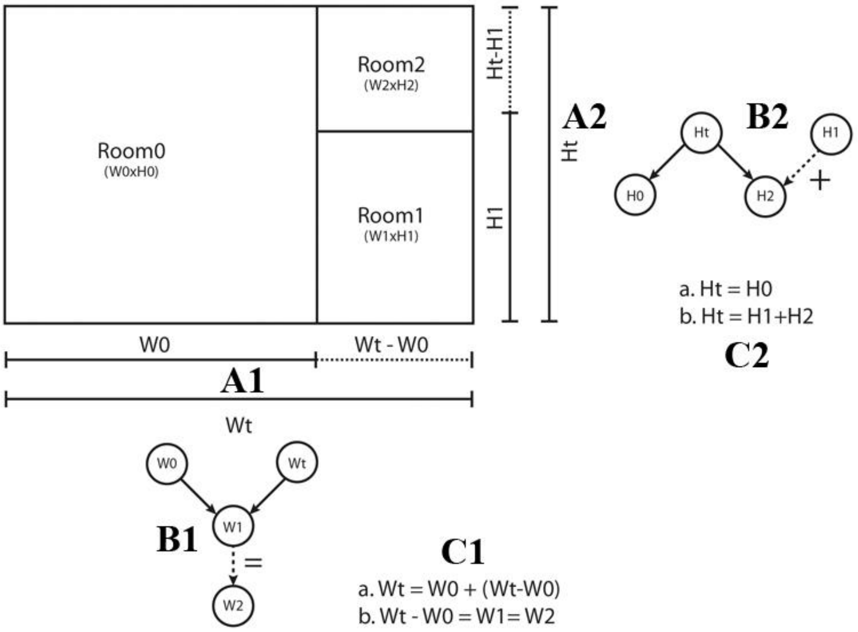
Bentley & Corne (2002) introduced an idea for an evolutionary system of creativity including an algorithmic structure and parametric design definition; the system is used for iterative design evaluation which can finally generate the best solution to the design problem. They believe that creativity happens in a constant and structured evaluation and refinement process rather than picking up on an idea without giving the context. Therefore, this section focuses on the concept of the parametric design process and design examples to explore parametric design thinking and operations through providing backgrounds as well as investigating the creative potential of the design methods.

4.3.4 Parametric architectural design ideation and expression

a) Parametric concept

Woodbury (2010) suggests that is important to define parametric thinking before we start the consideration of parametric design. Although the definition might be complex, some points can provide useful reference when reviewing the study of parametrics. He firstly asserted that parametric design is a conceptual process. The designer needs to rebuild the design idea or task as a conceptual data flow rather than a solid image in their mind. That data works with a system which is defined by relationships, divisions, and naming within the theoretical exercise. The designer draws or plans the data's correlation with a series of Node based graphics. For example, Woodbury (2010) used a conceptual room design with node diagrams to explore the design thinking by parametric manipulation. The room is divided into few sub-rooms by length (Fig.4.7-A1) and width (Fig.4.7-A2); through different mathematical definition using ratio or division (Fig.4.7-B1&B2), the scale of each room shows a dependent relationship with another room. The layouts change according to the parametric system (Fig.4.7-C1&C2) rather than by manually hand drawing them. However, the design task does not show the architectural layouts but explains the design thinking through the flexibility of the parametric coordination. The result of those node graphics is reflected in the visible design structure and can be re-defined by designers.

Fig.4.7 Parametric concept of the design process



Cited: Woodbury, 2010

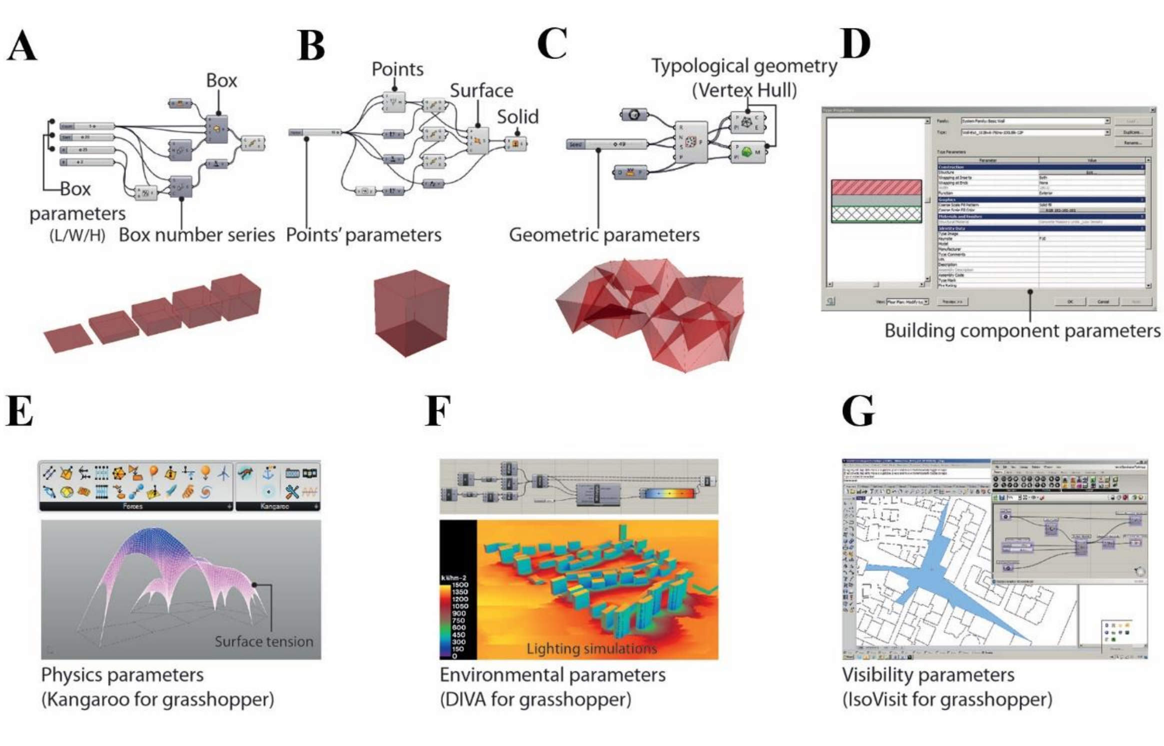
Woodbury (2010) described those nodes and their sequential dependency as a chain system, which can be grown, redefined and modified. He also stated that 'Dependencies may correspond to geometric relationships (for example, between a surface and its defining curves), but are not restricted to this and may in fact represent higher order (or more abstract) design decisions. Parametric approaches to design aim to provide designers with tools to capture design decisions in an explicit, auditable, editable and re-executable form.' (Woodbury, 2010). The author of this thesis considers parametric design a step between conventional CAD, using software such as AutoCAD or Sketch-up and algorithmic CAD using Grasshopper or Generative Component, the latter system uses mathematical functions to generate form which is unattainable or impossible with parametric tools.

b) Taxonomy of parameters

Jabi (2013) considers that parametric design is a process based on algorithmic thinking and parameter input, then a process of problem-solving activity between design intent and response. He also points out that it is important to classify the types of design parameter in order to correctly respond to the everyday design activities of designers. There are seven types of design parameters defined by Jabi (2013) (Fig.4.8):

The first, 'mathematical parameters' mean the basic numerical information considered while designers are engaging in the 3D modelling process, such as calculated numbers, logical values and series of objects (Fig.4.8-A). The second, 'geometric parameters' are present in the geometric design process including points, lines, vertex, surfaces and solids. Certain 3D modelling software packages, such as 3ds Max and Rhinoceros, are all based on this type of parameter for the manipulation of geometric shapes (Fig.4.8-B). The third, 'topological parameters' are based on a higher mathematical concept presenting associated numbers to define some complex 3D modelling processes. For example, a diagrid pattern contains topological parameters which are applied to define the complex shape and design intent (Fig.4. 08-C). The fourth, 'representational parameters' mean the described information for designed objects. For example, in BIM design, the wall, window or door has individual design parameters such as weight, structural strength and construction method which present the different types of design entities (Fig.4.8-D). The fifth, 'material parameters' are associated with the physical attributes of the designed object, for example, tension, friction, elasticity, etc. Those parameters not only represent the physical types of the designed object, but are also used for design simulations in the development of form (Fig.4.8-E). The sixth, 'environmental parameters’ include the environmental forces that surround us such as time, wind, thermal factors, lighting, etc. It is important to have an in-depth understanding of those environmental factors with their associated parameters in order to optimize and rationalize the design solutions (Fig.4.8-F). The last, ‘human parameters’ indicate the design information interacting with human activities. For example, ergonomic design could be applied for planning human movements in the object design (Fig.4.8-G). However, although there are more parameter types which could be raised in this discussion, Jabi’s (2013) classification of the taxonomy of parameters provides a good analysis and helps architects involved in a parameter based design problem-solving process.

Fig.4.8 Taxonomy of parameters (Jabi,2013)



Cited: Jabi,2013/ Author reproduced/ blogs.uoregon.edu./ Diva4rhino.com/ representationak3.blogspot.co.uk

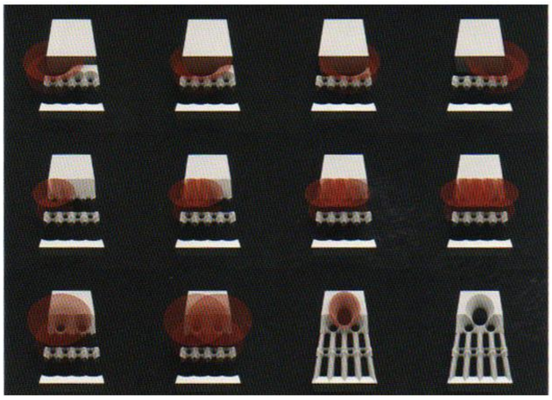
d) Mathematical activities – *Concept ideation*

If craft evolution is the method of the blacksmith in nonparametric design, mathematical ideation in parametric design presents a visual and logical process for this design process. ‘The mathematical phenomenon always develops out of simple arithmetic, so useful in everyday life, out of numbers, those weapons of the Gods: the Gods are there, behind the wall, at play with numbers.’ Le Corbusier (1968).

In traditional design procedures, design function and aesthetics could be related to mathematical systems. For example, DaVinci’s Vitruvian Man, Palladio’s proportional systems of buildings, Antoni Gaudi's form-finding design methods and Le Corbusier's modular and golden ratio ($ø=(1+\sqrt{5})/2$), but normally the ideation process only takes place in the designer's mind and he expresses them with some simple formulae. With parametric design methods, the mathematically associated design concept is no longer invisible and it offers a complex calculation process for designers.

Burry & Burry (2010) highlighted that mathematics has been used in the architectural design realm which includes mathematical surfaces, emergent architecture design, structural optimization, CAD typology architecture, and datascapes architecture. For example, in the Sagrada Familia project, Barcelona, by Antoni Gaudi, Burry (2001) used parametric tools to study Gaudi's 'rule surface' based on mathematical Boolean knowledge. He also described the Sagrada Familia redeveloped project as a process of negotiation between parametric variables and geometries (Fig.4.9). D'Arcy Thompson (1961) used an abstract mathematical system to explore physical strength then created a new design structure and pattern. Burry thinks that mathematical understanding of the design process between geometric laws and external forces encouraged his work in form-making and manufacturing processes. Woodbury (2010) suggests that a parametric modelling process using mathematics will enrich design ideas; these can be further integrated within different professions as the new tools for architectural development. In addition, computational geometry using mathematical systems of inspiration, such as convex hulls, Voronoi diagrams and Delauney triangulations, has the potential to help designers to explore complex design thinking and to take it towards a new architectural horizon.

Fig.4.9-B Gaudi's parametric rule surface



Cited: Burry, 2011

e) The characteristics of a parametric design system

Jabi (2013) states that all parametric design systems have similar constructs and they could help improve the design process as well as explore possible design alternatives. He defines four characteristics (Fig.4.10):

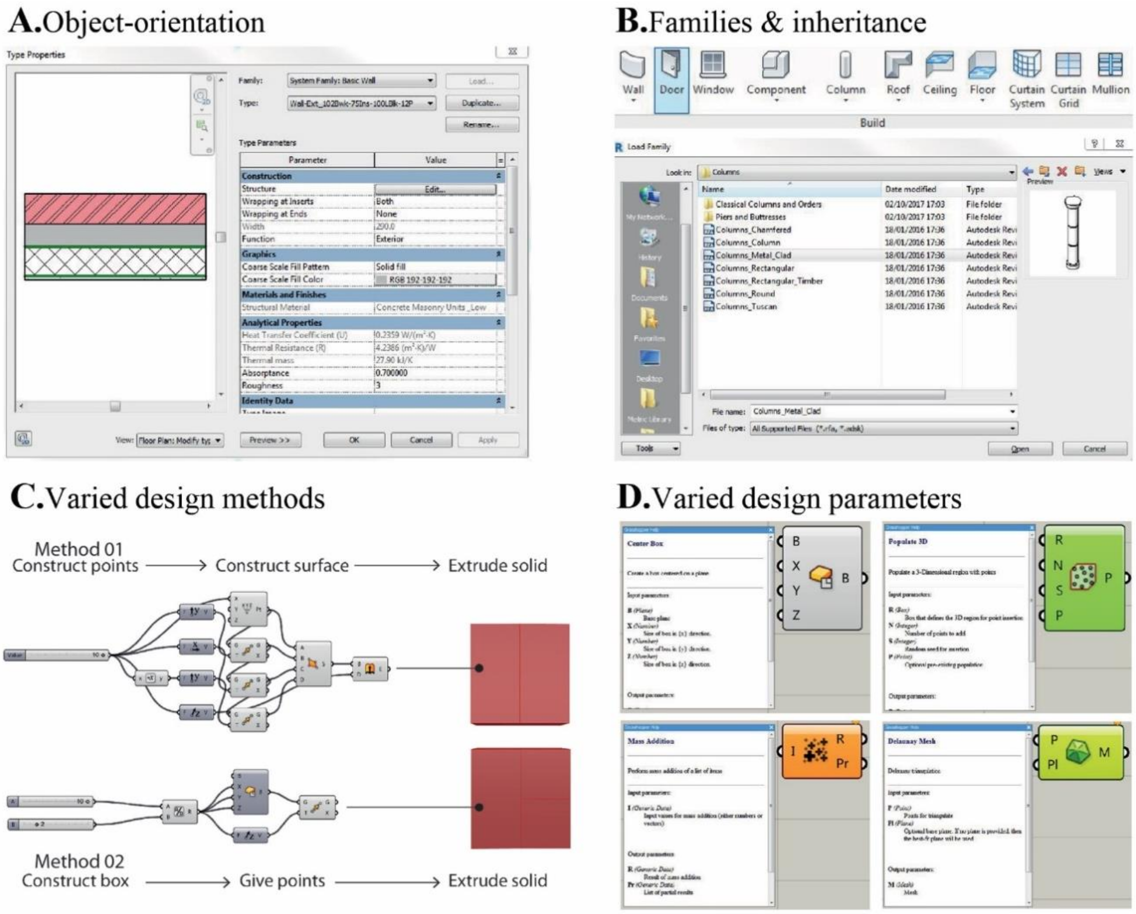
The first is 'object-orientation' (Fig.4.10-A) which is referenced from the programming function in computer science. It means that all digital objects such as circles, spheres, doors and walls are well-defined by an internal algorithmic structure in the parametric design method. Each object has values like height, width or depth and from them can be determined its attributes. Under the same algorithmic structure, all design objects are individually formed but are associated with other structural values and attributes. This means that changes in one value could derive values in other objects. For example, a radius is linked in value with diameter and circumference. This is the power of one parametric characteristic, it ensures the design process can derive unknown entities from known ones.

In the second characteristic, parametric objects can be organized and classified in a family system called ‘families and inheritance’ (Fig.4.10-B). For example, in the parametric design process, a door family includes different types of door such as hinged doors, sliding door, folding door, etc. Each family member shares certain attributes according to the shape proportions or construction method, and any changes in the family system can directly affect sub-objects, which provides efficient management rather than individually customizing single design objects.

The third characteristic is the parametric design ‘method’ (Fig.4.10-C). The design method also means that algorithms which make one design object can be interpolated using a different process. For example, there are several ways to draw a circle using a parametric design algorithm. The circle could be drawn from a centre point, or drawn according to 2 or 3 points to find a circle. This characteristic also introduces the idea of a generative algorithmic process.

The final characteristic, the ‘parameter’ (Fig.4.10-D), is the core of the modern parametric system. The term ‘parameter’ in CAD has a different meaning from the mathematical concept. In mathematics, a parameter normally means a ‘variable’ and can determines a specific form or function such as $(x) = \mathrm{ax}$, where ‘a’ determines the slope of the line defined by $f(x)$. On the other hand, CAD uses a parameter as a variable term in an algorithmic process to decide another value. As Jabi (2013) states ‘A parameter, as opposed to a constant, is characterized by having a range of possible values.’

Fig.4.10 Four characteristics of parametric design system



A.Object-orientation

Type Properties

Family: System Family: Basic Wall

Type: Wall-Ext_102Bwk-75Ins-100LBlk-12P

Type Parameters

Parameter	Value
Construction	
Structure	Edit...
Wrapping at Inserts	Both
Wrapping at Ends	None
Width	290.0
Function	Exterior
Graphics	
Coarse Scale Fill Pattern	Solid fill
Coarse Scale Fill Color	RGB 192-192-192
Materials and Finishes	
Structural Material	Concrete Masonry Units _Low
Analytical Properties	
Heat Transfer Coefficient (U)	0.2359 W/(m²·K)
Thermal Resistance (R)	4.2386 (m²·K)/W
Thermal mass	27.90 kJ/K
Absorptance	0.700000
Roughness	3
Identity Data	

View: Floor Plan: Modify typ

B.Families & inheritance

Load Family

Look in: Columns

Name	Date modified	Type
Classical Columns and Orders	02/10/2017 17:03	File folder
Piers and Buttresses	02/10/2017 17:03	File folder
Columns_Chamfered	18/01/2016 17:36	Autodesk Revi
Columns_Column	18/01/2016 17:36	Autodesk Revi
Columns_Metal_Clad	18/01/2016 17:36	Autodesk Revi
Columns_Rectangular	18/01/2016 17:36	Autodesk Revi
Columns_Rectangular_Timber	18/01/2016 17:36	Autodesk Revi
Columns_Round	18/01/2016 17:36	Autodesk Revi
Columns_Tuscan	18/01/2016 17:36	Autodesk Revi

File name: Columns_Metal_Clad

Files of type: All Supported Files (*.rfa, *.adsk)

C.Varied design methods

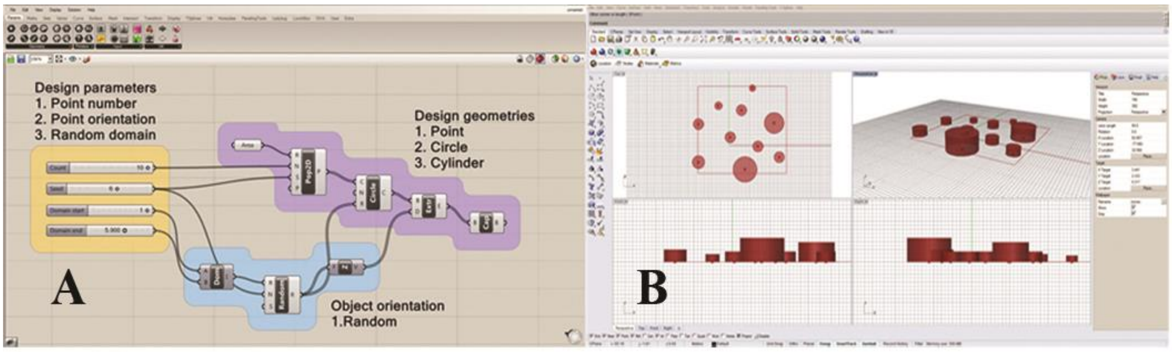
D.Varied design parameters

Source: Author reproduced/ Grasshopper/ Revit 2017

f) Algorithmic process – *Design expression*

This section investigates the design process of algorithmic design and exhibits the logical relationship within architectural expressions. Berlinski (2001) defined an algorithm ‘as a finite procedure, written in a fixed symbolic vocabulary, governed by precise instructions, moving in discrete steps, 1, 2, 3…, whose execution requires no insight, cleverness, intuition, intelligence or perspicuity, and that, sooner or later, come to an end.’ Parametric design is not revolutionary in that it does not create graphical entities out of mathematical functions and numerical series. The parametric design concept is formulated by interaction between numeric attributes (Fig.4.11.A) and geometries (Fig.4.11.B). Algorithms are able to construct those relations and demonstrate these with node diagrams. In other words, algorithms are understood as programs or programming languages for parametric design methods. All CAD works with scripting languages to create the design outcomes, normally consisting of a sequence of a language without a visible structure. Algorithms represent those structures inside the scripts (Woodbury, 2010). Terzidis (2003) suggested that the algorithmic process uses an inductive strategy which can encourage the designer to explore the generative activities or to expand his complex thinking process during the design development. These inductive algorithms are recognized as extensions of human thought and lead the design results into the unpredictable and unimagined potentials. He also stated that algorithmic design enables the role of architects or designers to change from architectural programming to programming architecture.

Fig.4.11 Algorithmic design process (Grasshopper + Rhino)

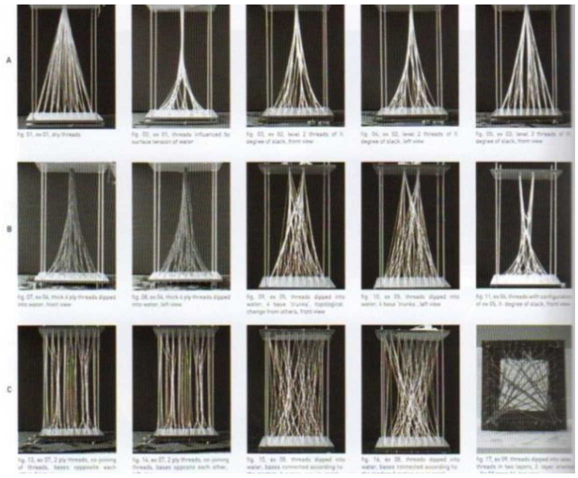


Source: Author reproduced/ Grasshopper/ Revit 2017

g) Population classification

The conventional design method, the nonparametric process, using conventional typology, offered designs through the observation of natural environments with biological inspiration. (Quatremere de Quincy, 1789). By contrast, in parametric studies, the idea of population thinking goes against typology thinking and it is also recognized as the proper explanation for parametric design methods. In a biological definition of population thinking, Mayr (1963) states: ‘What is true for the human species, that no two individuals are alike, is equally true for all other species of animals and plants…For the typologist, the type (eidos) is real and the variation an illusion, while for the populationist, the type (average) is an abstraction and only the variation is real.’ Typological thinking classifies objects by physical characteristics, on the other hand, population thinking indicates objects by their characteristic process. In building practices, architectural design is more about the relationship of geometries with design expressions such as compositions and scales. Population thinking, through a morphogenetic process, provides an understanding of those communications rather than focusing on a single geometry (Fig.4.12).

Fig.4.12 Morphogenetic process
As the population design thinking



Cited: MA Dissertation of Pavel Hladik, 2006

Besides, design by parameters creates a parallel connection between values of variable and structures through the design process (Barrios, 2004). Furthermore, the morphogenetic process of population thinking gives design variation in the early design stages. It can stimulate the evolution of concepts and produce multiple results, not just a single type (Trummer, 2011). In the architectural problem-solution process, the ‘wicked problem’ type (Rittel & Webber, 1973), Section 3.2.2, Chapter 03) caused investigation to become very complex and so a single solution could not easily be found. But the parametric design method using population thinking offers a comprehensive observation of this process and also provides various solutions. This explorative stage also helps architects to avoid being trapped in existing knowledge or typology and to extend their design thinking by understanding its context.

4.4 BIM design for architecture and creativity

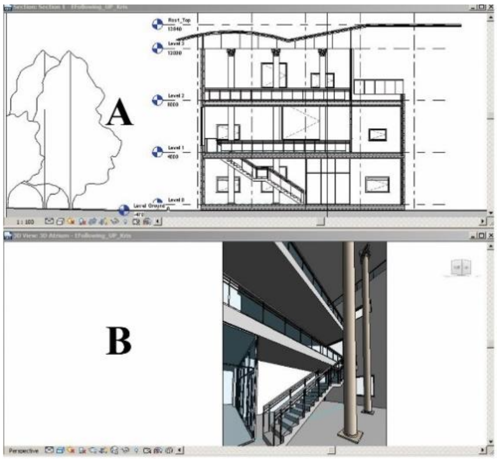
Parametric design methods have many related applications in the current architectural design industry. This section reviews the two most common parametric design approaches in both academia and practice: Building Information Modelling/Management (BIM) design, and algorithmic design to explore the influences on design creativity throughout the architectural design process. The review also gives relevant case studies of the particular parametric methods being used in different architectural practices.

4.4.1 BIM design

‘Building information modelling (BIM) is a design and documentation system that supports the design, drawing, and scheduling required for a building project. BIM delivers information about project design, scope, quantities and phases when you need it.’ (Revit User Guide, 2011).

In addition, the BIM design process covers the production of the visual outputs from a 2D design drawing (Fig.4.13-A) to 3D modelling (Fig.4.13-B) of the building construction, it is sometimes called ‘Visual Design and Construction’ (VDC), (Barnes & Davies 2015). BIM, like many other parametric design methods, consists of shared principles, but its function focuses particularly on the coordination of the building construction process rather than traditional CAD modelling techniques. The ideas of BIM have been applied to certain computer software packages such as Revit (the Autodesk product) and ArchiCAD (from Graphisoft); these generally perform the same functions as BIM design but have some differences in individual functions and operations.

Fig.4.13 Real-time 2D to 3D drawing



Cited: Revit 2017/ Author reproduced

4.4.2 BIM design creativity

BIM is a technology rather than a design tool that enables architects to design buildings through a pre-examined construction process. In contrast to traditional design methods on paper or through conventional CAD, BIM users can explore design creativity in a series of problem-solutions through its advanced coordination process. These activities have also been defined as ‘‘Little c’ (everyday) creativity: daily problem solving and ability to adapt to change’ (Beghetto & Kaufman,2007). There are three aspects of BIM design which offer design methods to enhance creative design thinking.

Firstly, BIM is a design process with digital modelling techniques which enables us to produce 2D drawings and 3D models at the same time. When compared with conventional 2D to 3D based design, designers usually realise the nature of possible design problems in the construction stage after they convert the drawing into 3D using a modelling process. 3D modelling provides a wide range of perspective views to help sort some critical angles and complex joints that can't be identified in two dimensional views. Abdelhameed (2004) indicated that 3D depictions enhance the design process without the false assumptions that often happen in 2D only design drawings. Moreover, there are multiple papers defining three main positive impacts of the transition from 2D to 3D design thinking: firstly the 3D design process increases the level of geometrical definition and abstraction, secondly the process enhances the coordination of geometric complexity and details, and finally the 2D to 3D process in the same CAD interface simplifies the design activities (Novitski,1991; Kaiser 7 Maller, 1993; Barreneche, 1996; Groh, 1997; Delaura, 1997; Cheng, 1999).

BIM technology allows the design activity to start with pre-set parametric geometries. Those parametric components provide material and adaptable shapes for the final design composition. For example, each of the building components contains editable information on materials and layers. Through the visual functions, architects are able to see the design visualization as well as the visible impact of material choice on aesthetic performance and the architectural message. Moloney & Issa (2003) observed that students thinking about materials in CAD design produced different spatial concepts, and using different materials also provided more creativity when designing form. Moreover, poor quality of design with mismatched design representation has a significant relation to the material used in the early design stage (Johnson, 1997).

Real-time visual based simulations offered by the BIM design process could allow testing of different architectural design situations. For example, lighting simulations with Autodesk Ecotect Analysis or solar exposure or thermal comfort perfection might affect building designs or window size or opening rates. Moreover, Autodesk Navisworks provides comprehensive project simulations for BIM design which include modelling crashes, structural simulation, cost and time calculation, and real-time building navigation.

4.5 Case study of creative BIM design hospital

Although the BIM design method has only been developed in the last few years, many hospital buildings have been completed using BIM methods. DiNardo (2014) states ‘BIM is one method that‘s been growing in popularity among the architecture, engineering and construction industries as healthcare projects continue to grow in size and complexity.’ Precisely-speaking, the BIM design method is described as the use of powerful CAD for a complex building project with an organized design system and advanced 3D modelling process, or real-time coordination between 2D drawing and 3D modelling (Eastman, Sacks, Teicholz and Liston, 2013). So, the following case study integrates literature from specific BIM designed hospitals as well as focusing mainly on three specific workflows relating to creativity of design in BIM: 3D modelling, Building Simulation and Project coordination.

4.5.1 Visual simulation – *Creativity in problem solutions in detail design for buildings*

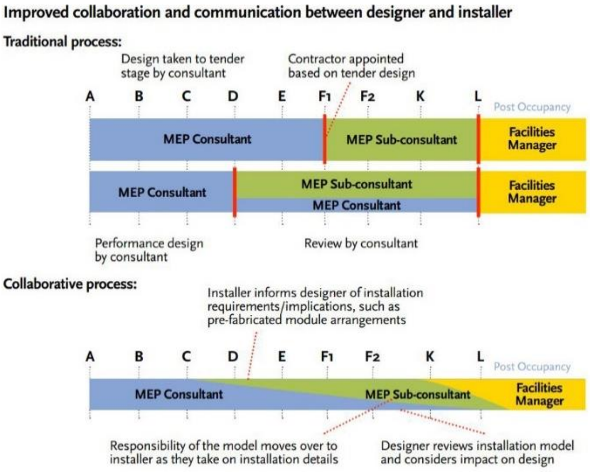
The use of BIM design for a new hospital in Bristol, UK (Fig.4.14) shows an excellent example of how the parametric design process optimized the building’s detailed planning as well as the changes in the design procedure from the traditional hospital design process to an innovative working environment (Fig.4.14-1). There are two important factors operating in the BIM design system and assisting the design optimization (Fig.4.14-2):

Firstly, all the design teams used the same software platform (Autodesk – Revit) and intensively shared design information (Fig.4.14-2.A). For example, in this project the architectural design team and engineering team could share the design parameters under the Revit system which means they could run their design model and discuss the design issues with the parametric based tables, drawing and models.

Fig.4.14 The Bristol royal infirmary

Cited: Robert, 2012/ smithmalney.co.uk

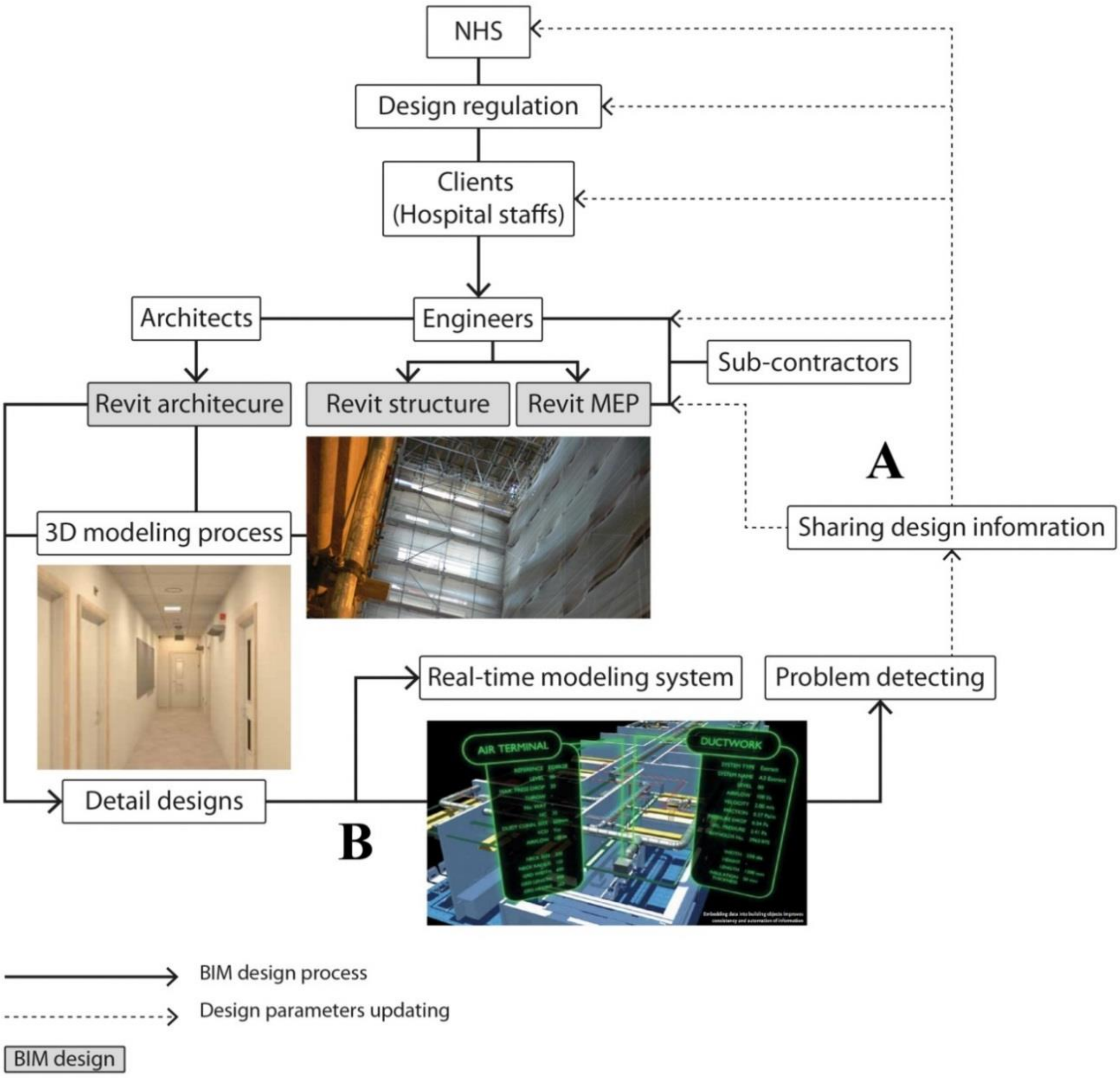
Fig.4.14-1 BIM optimization for hospital design process



Cited: Robert, 2012/ smithmalney.co.uk

Secondly, a strong function of the 3D modelling integration was that it assisted different design professionals to inspect and highlight design problems or faults from the early design stages, especially the design of building details (Fig.4.14-2.B). For instance, the architects could draw their design model with Architectural Revit, and the engineers could make the engineering design model of the structure with MEP (Mechanical, Electrical and Plumping) Revit. During the design process, the structural and mechanical engineers could involve their design proposal earlier and identify the design problems in the architectural design models (Roberts, 2012). As the senior mechanical engineer Lea (2012) stated on this project, 'BIM projects enable the team to consider fabrication requirements as the design model is being created; thus reducing the need for reworking after the detail design that occurs on a traditional project.' Thus, the above two aspects demonstrate how the parametric design process using BIM enhanced the problem-solution stage of the detail design, and also changed the traditional hospital design process through earlier involvement and communication with other design professions.

Fig.4.14-2 The BIM design process for the Bristol royal infirmary, UK



Cited: Photos-Robert, 2012/ Smithmalney.co.uk/ Diagram- author produced

4.5.2 Spatial Simulation – *Creativity in design using visualization technology*

Fig.4.15 Smart Eco hospital, Japan

Cited: www.Kitasato.ac.jp

A new project for a Smart Eco hospital proposed and approved by the Kitasato University, Japan (Fig.4.15) is their first BIM designed hospital using advanced visual-technology as well as parametric design functions. The hospital building is located in the city of Sagamihara, Kanagawa Prefecture, and contains a 14-storey building of 92,700 square meters. There are 757 ward beds and departmental services are shared with an existing healthcare centre. The design was fully conducted using a BIM process with Revit software, which demonstrated an ambitious plan for the design process. Because of massive building programs and functions, these were expected to slow down the design process. However, the results show that BIM not only helped the integration of internal design teams such as architects and engineers, but also demonstrated an optimized problem-solution process using the visual-technology in the Revit system for external participant involvement, that of the medical staff. Four aspects of visual technology were used in the BIM design proposal (Fig.4.15-1):

The first was 3D depiction as requested by the design team (Fig.4.15-1.A). When compared to traditional 2D design, the 3D modelling system provides multi-viewpoints in the design process which also can also be revised quickly, through the use of changed parameters. This function so improved communication that even someone not a specialist in the field of architectural design could voice opinions and suggestions on the design.

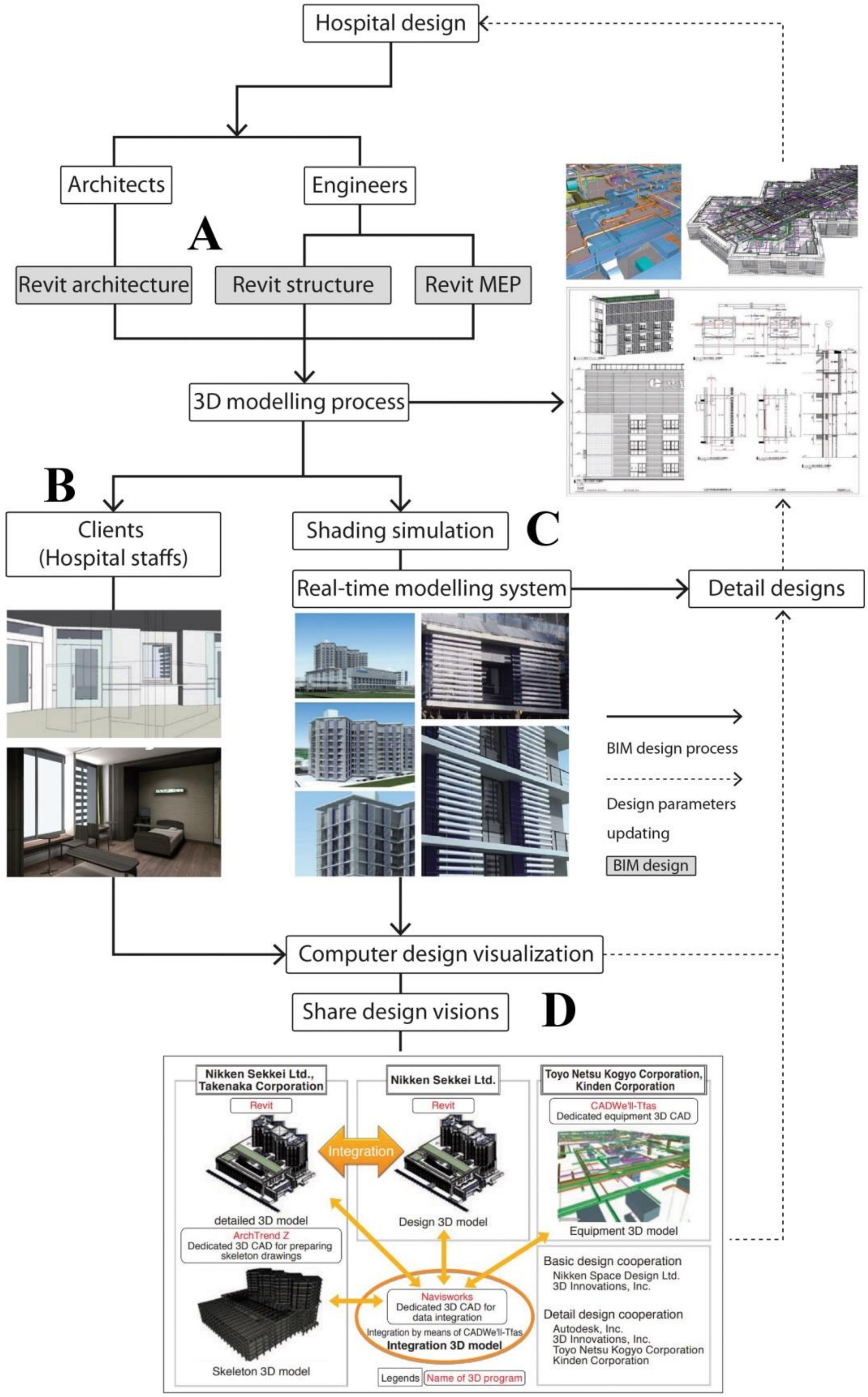
The second, involved determining the needs of hospital staff (Fig.4.15-1.B). The 3D modelling process created a design library sufficient to allow architects to exhibit their design layouts and discuss these with the nursing manager, which helped staff to identify the best design layout for their daily services. Moreover, changes in layout were connected with visible design parameters, so this also assisted group discussion and decision making on spatial arrangements.

The third, showed the potential of BIM for environmental simulation such as lighting and shade (Fig.4.15-1.C). During the design process, the Vice director of the Kitasato university hospital, Akitaka Shibuya, said of the simulation tech, ‘we could put individual hospital rooms in the locations with the most exposure to sunlight (using simulation data), and put the staff meeting rooms in the areas without such good access to sunlight'.

As to the last factor, BIM design can share vision of the hospital building design among participants (Fig.4.15-1.D). In this design project, the proposed design models were created with an animation video which was shown to the staff, which helped them understand how the new hospital would be, and to feel their ideas would be present as part of design project.

In conclusion, the parametric modelling process and the real-time visual technology of BIM have significantly improved the efficiency of conventional hospital design methods which rely more on massive design documentation. Also, the visual simulation helps discussion of the design problem-solving process allowing for idea exchange with and among expert medical practitioners from a variety of backgrounds.

Fig.4.15-1 The BIM design process of Smart Eco hospital



Cited: Photos-www.villagebim.typepad.com/ Diagrams -author produced

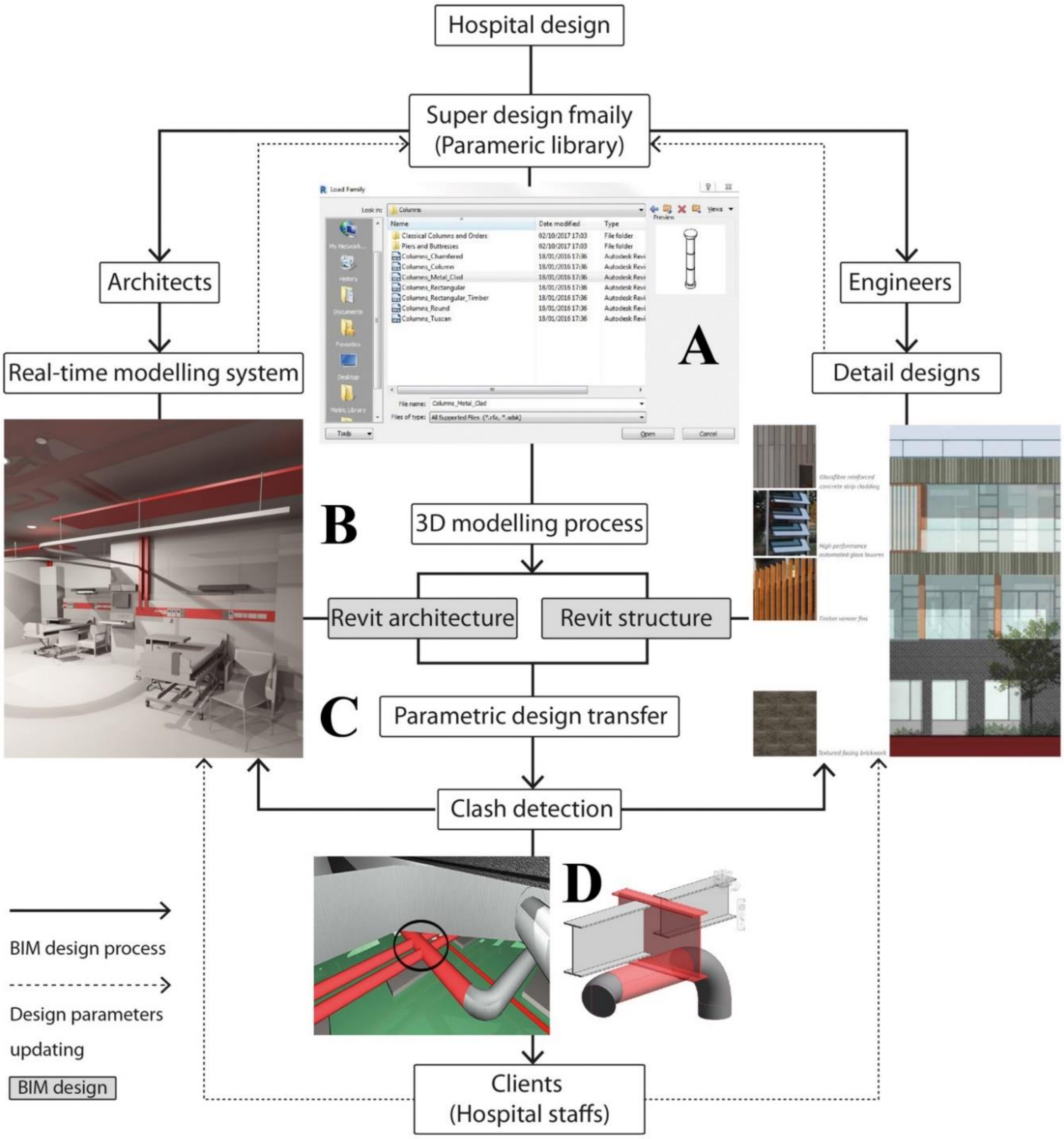
4.5.3 Project coordination – *Creativity in problem solution in multi-design communication*

Fig.4.16 The HCTH (Hospital), UK

Cited: Lewis, 2017

The Hampshire Critical Treatment Hospital (HCTH) (Fig.4.16) is a specialist healthcare building whose design was proposed to the NHS, North Waltham, UK. The project applied a parameter based design process using the Revit BIM design software, which demonstrated an innovative design procedure connected to one of the latest design functions, 'the super-family'(Fig.4.16-1). The super-family is a 3D modelling design method which is different from a normal digital library system (Lewis, 2017). It is a massive but structured parameter-based library. All the essential building components are created and stored using an identical coding reference (Fig.4.16-1.A). It includes not only the architectural design objects such as furniture or walls, but also mechanical facilities like pumping or other structural details. Utilising this super-family system, architects and engineers were able to communicate and make changes in the design development (Fig.4.16-1.B). Especially as each family based object could be freely exported from and imported to the current model, design changes could immediately update all projects without checking the coding structure, which is the most common problem for digital transfer between design objects (Fig.4.16-1.C). For example, if there were any revisions from the engineering side of ward layouts, the super-family could always update these new ideas and directly apply them to 300 bedrooms (Lewis, 2017). It also gave architects and engineers a better communication platform, accessing the same design library for their proposed ideas. This creative design process is hard to find in the conventional nonparametric design process. Besides that, the design process also employs a clash detection tool (Fig.4.16-1.D), such as Sobibri Model Checker, via the cloud. So, the design teams can evaluate problems at an early design stage and change the family system to avoid repeated problems arising from the same situation. In addition, in this project the BIM coordinator for the design office, Dean Hunt said, 'The client (hospital manager) will be able to see which consultants are liable for which objects, what level of details they should be achieving, at each stage of a project. It will make it easier to assess progress and how consultants are performing.' To sum up, the BIM design process provides a new idea for sharing design information or parameters and thus increasing design communication through the internal library system. It also upgrades the method for design problem-solving, which can be updated and stored in a system for design optimization in future hospital building (Fig.4.16-1.E).

Fig.4.16-1 The superfamily design and parametric library



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Columns_Column	18/01/2016 17:36	Autodesk Revi
Columns_Metal_Clad	18/01/2016 17:36	Autodesk Revi
Columns_Rectangular	18/01/2016 17:36	Autodesk Revi
Columns_Rectangular_Timber	18/01/2016 17:36	Autodesk Revi
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Columns_Tuscan	18/01/2016 17:36	Autodesk Revi

File name: Columns_Metal_Clad

Files of type: All Supported Files (*.rfa, *.adsk)

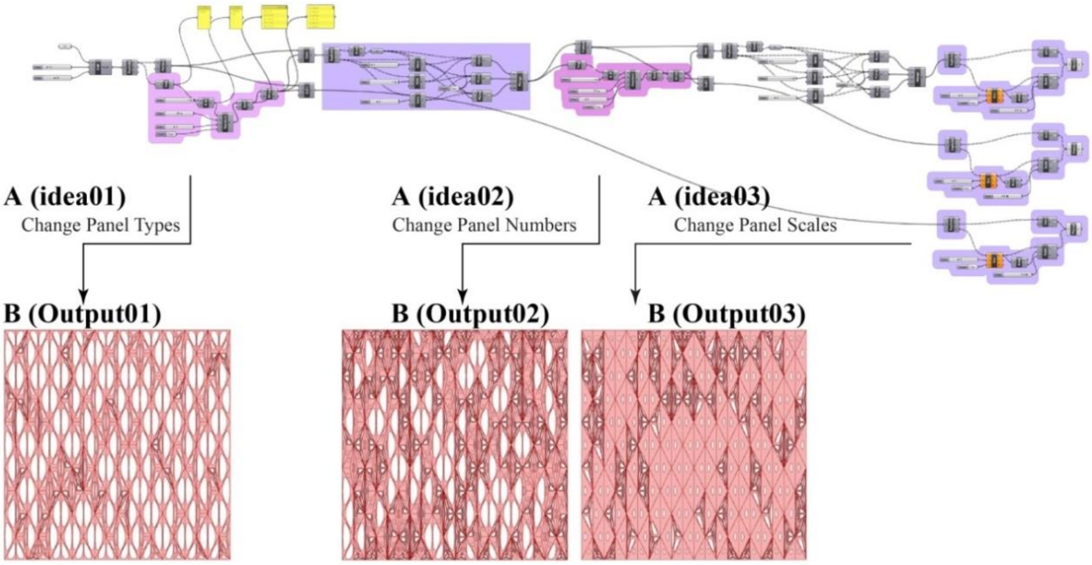
Cited: Photos-Lewis, 2017/ www.pad.basingstoke.gov.uk/ Revit2017/ Diagrams -author produced

4.6 Algorithmic CAD for architecture and creativity

4.6.1 Algorithmic CAD

In this section, algorithmic design is defined as a design which results from the computational interactions in the relationships in the architectural design process rather than just mathematical equations. 'An algorithm is a computational procedure for addressing a problem in a finite number of steps. It involves deduction, induction, abstraction, generalisation and structured logic.' (Terzidis, 2003). To compare it with the BIM design process, algorithmic design is a conceptual design process and shows virtually the design structure of the activities. On the other hand, BIM shows the defined concept, design coordination, but hides the design structure or relationships of the process forming or shaping an object. Algorithms allow the design process to be modified or changed, taking the underlying condition and generating different ideas (Fig.4.17.A). As a result, the algorithmic method can produce variable design solutions rather than the just a single one (Fig.4.17.B). Generally, an algorithmic design activity has been recognized as providing a strong contribution to the design problem-solution and the process has often been associated with conceptual and unpredictable outcomes. In addition, the above advantages of algorithmic design are often associated with a higher level or order of creative design behaviour (Terzidis, 2006).

Fig.4.17 Algorithmic design ideas and outputs



Source: Author produced

4.6.2 Algorithmic design creativity

Three creative activities are often associated with the study of algorithmic design. These are the generative algorithm, the emergent algorithm and algorithmic simulation.

The generative algorithm represents a structural process in design thinking. It works with defined algorithms and produces variable design relationships according to the pre-set parameters and steps. Lazzeroni, Bohnacker, Groβ and Laub (2009) define generative design as ‘a cyclical process based on a simple abstracted idea, which is applied to a rule or algorithm’. Abdelmohsen (2013) applied a design task to students with generative design instructions; he found the generative process of algorithms offered diverse concepts in the stage of finding the design solution. The generative process also helped student's exploration with many positive impacts on creativity of design. Finally, the learning outcomes showed that better design expression had a significant connection with the generative algorithm design process. Moreover, Agkathidis (2015) applied generative design techniques, a morphogenesis design method with a digital or physical form finding process involved, in undergraduate architectural education. 57 out of 230 students in a year were selected as his experimental group. After 12 weeks training and one year’s recording of their design experiences, he found students performed particularly well in variety of geometric explorations, volume of idea creativity, as well as good organisation of their design results. His spread-sheet analysis for ‘Considering the Freedom in Design Creativity’, showed generative algorithms represented 51.5% agreement as to improved creativity in design results with only 2.9% disagreeing. Also, the majority of students found that their design ability had been improved with respect to the criteria examined in the design investigation, design evidence and strategy as well as in aspects like 3D modelling skill and 2D drawing.

The emergent algorithm is generally associated with the Morphogenetic Design strategy which is a concept associated closely with mathematical and biological studies. This algorithmic design looks like a logical pattern of design thinking, not linear design thinking, but with an embedded and changeable process. Any design revision or re-development improves the paradigm or concept of the overall system design. It is defined as a dynamic and flexible process of evolving morphogenetic design (Hensel, Menges and Weinstock, 2010). The morphogenetic strategy is based on population thinking already identified as a parametric design concept. The emergent algorithm gives unexpected results in design outcome and extends the variety of thinking in design systems. This complex pattern-like thinking in design, through an evolutionary process, brings more potential creativity of design according to D'Arcy Thompson (1961). It used the emergent algorithms based on mathematical ideas to explore physical strength, then created a new design structure and pattern. Thompson suggested the emergent process helped generate design concepts linking geometric laws and external forces and encouraged his design creativity during the formulation process.

Algorithmic simulation aims to examine the design correlation between the performance of simulated elements and design concepts. The process is open-ended design, and the design concept normally is adaptable. As a result, algorithmic simulation normally can provide more than one correlation of the design activities. This is different from BIM simulations which are pre-defined programs with the data system hidden. Ahlquist & Menges (2011) used computational processes with algorithmic simulation exploring an optimized modelling process with the interaction of physical and material design behaviours such as gravity, bending, tension and inflation. They tested a tensile structure with computing meshes and controlled the structure with relative values or parameters. The simulation process was undertaken by the Particle System, a parametric simulation environment. This computing environment attempts to measure the design process by related simulation factors such as gravity and tension, producing the best degree of curvature, deformation and formulation in the final model. The algorithmic design process provides a comprehensive set of mathematically-based tools and techniques which serve as a live physical engine for interactive simulation of form finding and optimization.

4.7 Case study of creative algorithmic CAD building

The following case study section shows the three areas of creativity identified in Section 4.5.2, with algorithmic methods affecting the development of a design project: 1. The generative algorithm. 2. The emergent algorithm. 3. Mathematical or algorithmic simulation. However, there is currently no published hospital project which particularly mentions an algorithmic design process or similar methods in the building design. So Instead of giving hospital design projects citing algorithmic design, the following case studies introduce three architectural design offices who have specialist algorithmic design groups who can demonstrate creative design work on complex buildings, dominated by the use of algorithms. The definition of complex building design is referenced from the design training course on ‘Complex Building Programs’ at NTNU (Ntnu.etu, 2017), a Norwegian University. The definition indicates that complex building design normally contains different phases of design in its project stages and detail design. Also, the problem-solving stage should be concerned with different design aspects combining aesthetical, technical and economical solutions.

4.7.1 Generative algorithms – *Constructive design concepts for novel architectural shapes*

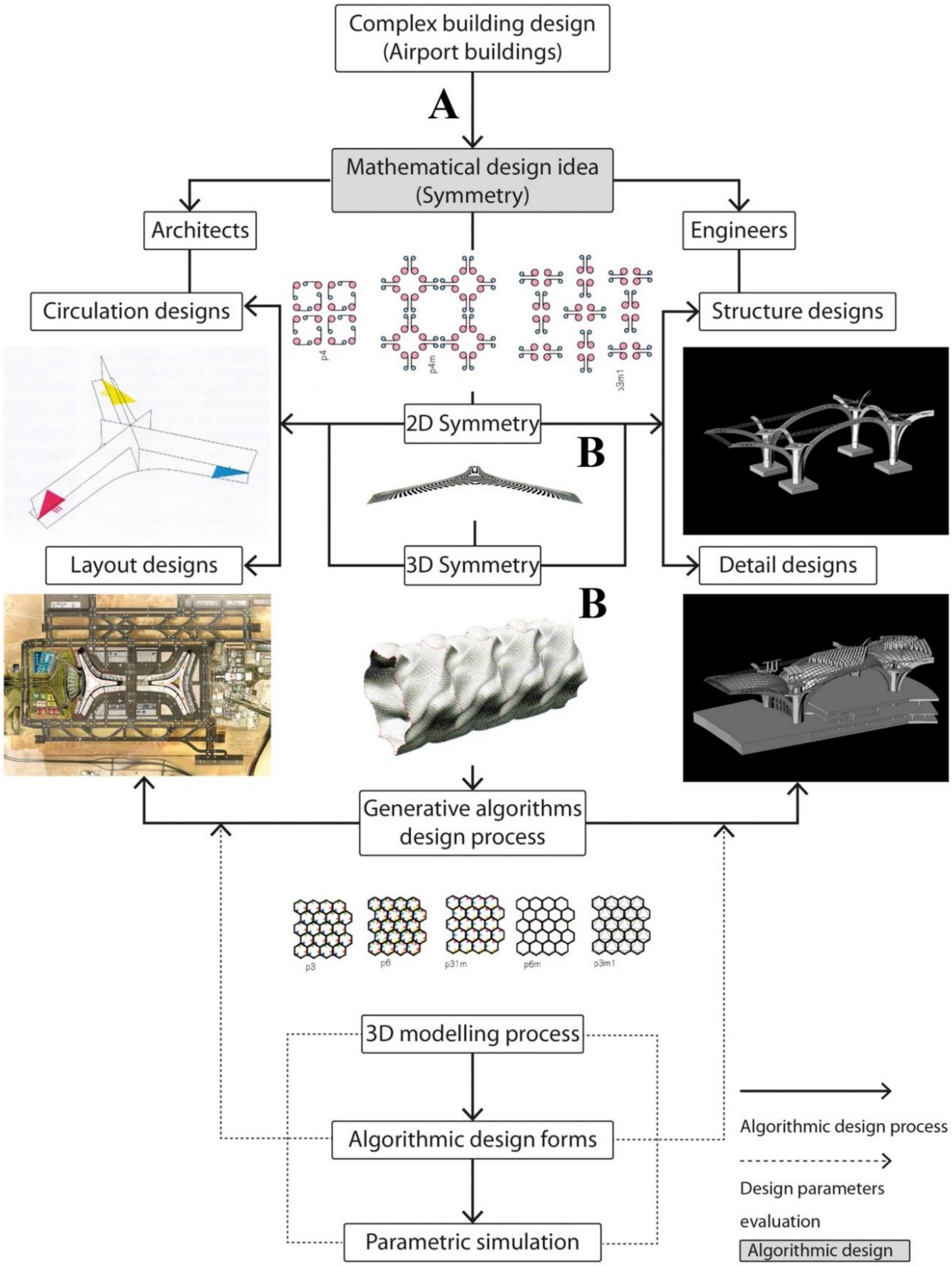
The SMG (Smart Geometry Group) in Foster + Partners was founded in 1998 and aims to explore the potential of computational design and sustainable environment proposals. The design group usually take ideas from different areas, such as mathematics, fine art, or engineering, and imports them into the generative process along with the environmental efficiency concept for generating the building prototype. For example, the Kuwait International airport (Fig.4.18), Kuwait, 2009, is a typical complex design project which contains many departments such as security, support, administration, etc. The design proposal used a mathematical concept (Fig.4.18-1.A), symmetry-encoded, to explore the design efficiency of the airport plans, in terms of a more compact floor plan design which is less prone to geometrical errors occurring during the construction design. Also, through a generative algorithm process, they found distinct design composition improvements by using discrete translations, rotations and mirroring to optimize the building

Fig.4.18 The Kuwait international airport by Foster+Partners

Cited: Foster+Partners architect

process with repeating design entities and by creating a symmetrical design system (Fig.4.18-1.B) (Castle,2013). The generative design process using algorithms offers architects a better vision of the varied design ideas as well as rationalization of the design concept connected with mathematical factors, which helps logical design development, especially in the problem-solving process (Josefsson, 2013).

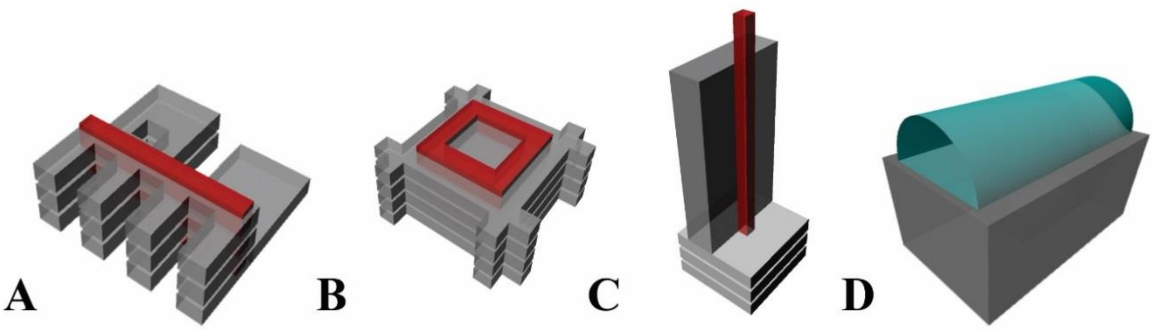
Fig.4.18-1 The algorithmic design for Kuwait international airport by Foster+Partners



Cited: Photos-Foster+Partners architect/ Catsle,2013/ Diagram-author reproduced

To compare this with traditional nonparametric design (Fig.4.18-2), in this the hospital architect normally adopts an existing type of hospital design such as Finger plan (Fig.4.18-2.A), Monoblock (Fig.4.18-2.B), Podium & Tower (Fig.4.18-2.C), Atrium (Fig.4.18-2.D), etc. These design shapes contain only very little mathematical reasoning so there is insufficient shape information which can be manipulated for further design development. Also, there are no associated design parameters which can be applied to other building design parts such as façade or structural design. However, the generative algorithm not only allows varied presentation of the building shapes, but it can also extend the design ideas and follow these up with other, different design aspects. That means that algorithmic design offers architects a flexible process of producing new design solutions for clients, in this case hospital staff, which could not be achieved by only following the existing design types with limited design innovations.

Fig.4.18-2 The traditional/ nonparametric design typology



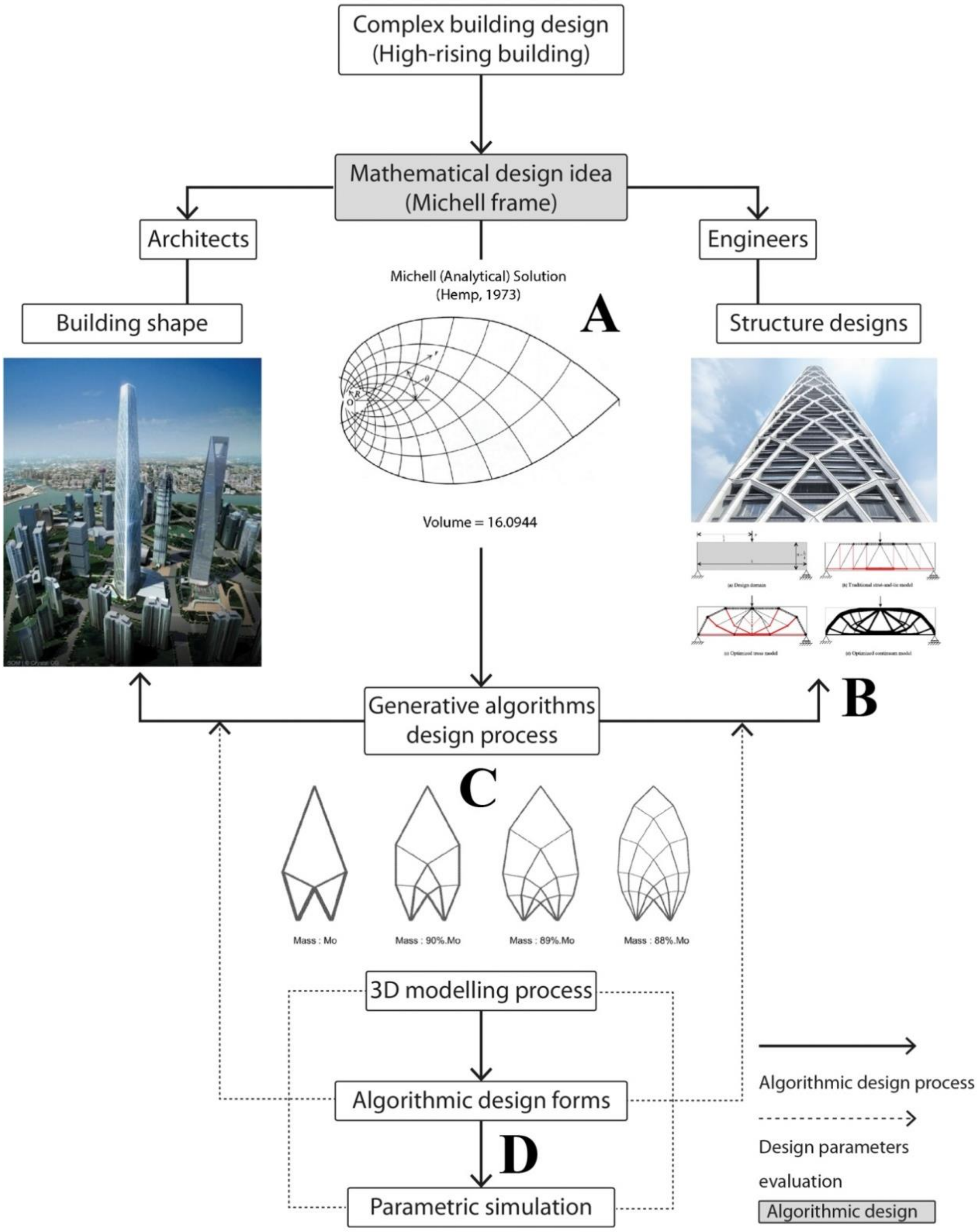
Source: Author reproduced

4.7.2 Emergent algorithms – *Optimized design solution for high-rising building design*

The FE algorithm or FE analysis software in SOM (Skidmore, Owings & Merrill LLP - architects) creates a parametric platform for the specialist engineering department and design department in terms of enhancing the structural design of high-rise buildings. The office normally proposes their ideas based on genetic algorithms and explores the most efficient structural design patterns for the project. To compare this with traditional high-rise building design, the latter mainly starts from the floor plans, with the design team studying the building envelope or façades. The façade design can cover the issue of structural supports, cladding materials and even building shapes. Then the façade can later improve the floor plan and mechanical layouts. In contrast to a traditional design of a façade system which uses grid, triangular and polygon shapes, SOM used an emergent algorithm to generate a pattern-like solution and imported this into a structural simulation to further adjust and determine the most efficient strength of supports (Fig.4.19). For example, in the Transit Center competition, San Francisco, California, 2010, the office designed the façade system with the Michell frame (Fig.4.19.A), a pattern from emergent algorithms, representing an optimal typology for a cantilever structure (Fig.4.19.B). This gradient-based emergent algorithm was proposed to identify the most efficient self-supporting design pattern for the façade and to establish a flexible and complex building profile (Fig.4.19.C). The emergent design algorithm focused on a conceptual structure and construction which reinforced the design ideation in the problem-solving process (Fig.4.19.D); in other words, this constantly iterative design thinking using synthesis and evaluation in quick succession increased creativity in idea generation (BEsserud,Katz and Beghini, Architectural Design, 2013).

High-rise hospital design aims to minimize land use but maximize building capacity (See the international style hospitals in the United States, Section 2.4.2-a, Chapter 02); thus the building needs to be developed vertically. So, this design decision has direct impact on some critical construction issues such as structures, materials and cost efficiency. But in the conventional nonparametric design process, structure and materials are planned separately in each individual stage. It is then very difficult to integrate the multiple aspects and produce an optimized solution. On the other hand, the algorithmic design process can provide support on most of design issues based on mathematical algorithms. Through the algorithmic process, the designers are not only able to discover the optimized design solution, but it also helps them to integrate or express the design languages in a coherent way.

Fig.4.19 The algorithmic design for high-rising building by SOM architects

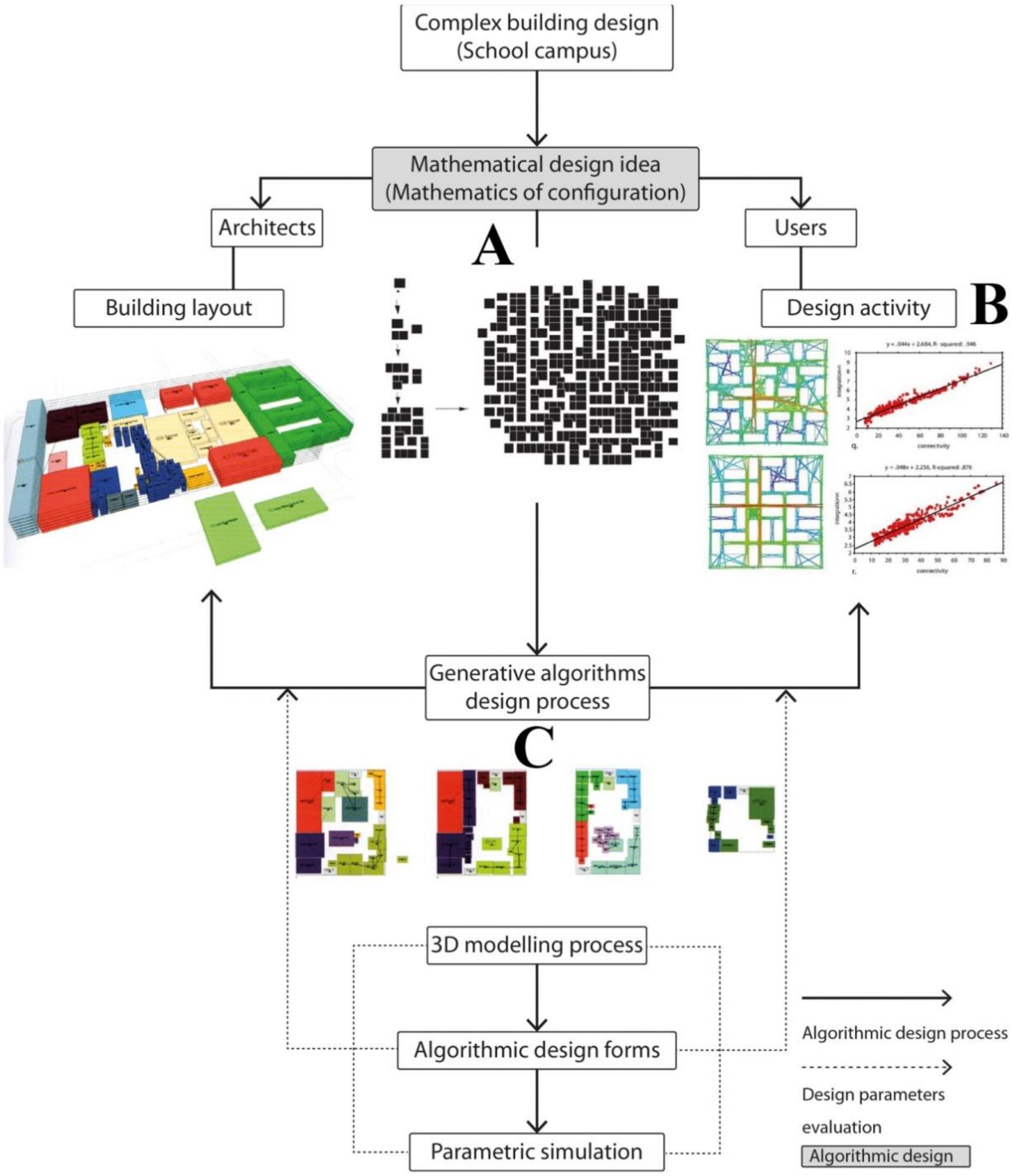


Cited: Photos-SOM architect/ paulino.ce.gatech.edu/ (Etienne Bouleau) Tools for structure/Diagram- Author reproduced

4.7.3 Algorithmic simulations – *Novel building layouts based on the results of computing algorithms*

The CRD (Computational Design and Research) group in Aedas|R&D focuses on the research of user behaviour and a perceptive occupant simulation for design computation of spatial configurations. They are specialists in the use of algorithmic research on complex space syntax. Their studies do not follow traditional methods of behavioural study with extensive protocol documentation such as paper-based or photographic records; instead, they apply generative systems based on algorithmic behaviour, which provide various maps for the prediction of occupancy so that architects can choose any one of these as a template for the final design proposal. For example, in Elasticity of Programme (Fig.4.20.A), 2009-11, the CRD proposed interactive site plans for a new proposed school campus design using a generative aided algorithm. The campus contains multiple buildings and functions which made it very complicated to find the best solution for the design. But the algorithmic design scheme allowed architects to propose a variety of site plans according to self-generated and physical simulations such as travelling distance or emergency evacuations (Fig.4.20.B). The results not only created economical campus layouts but also introduced better compatibility between building blocks and rooms (Fig.4.20.C). Algorithmic design simulation not only focuses on design evaluation of the building shapes, but also extends the design idea through a scientifically-based design process such as psychology or ethology. This parameter-aided design algorithm is described as a mathematical process which is used by mathematicians to answer the question of how to achieve creative idea optimization (Derix and Izaki, Architectural Design, 2013). For hospital design, the algorithmic design process could possibly be inspired by or simulate design ideas from different social science areas. For example, efficient nursing movements based on generative algorithmic ward design layouts or a departmental plan including safe design for emergency evacuation.

Fig.4.20 The algorithmic design for campus design by Aedas/ R&D



Cited: Photos-Derix and Izaki, 2014/ Hillier,2007/ Diagram-author reproduced

4.8 Discussion

Historical reviews of design tools and their impacts on architectural design indicate that the different tools are closely associated with their functional outputs and the design method is also significantly associated with mental processes and cognition in relation to design. For example, in traditional design by pencil and paper it is hard to present more than one type of design information, only sketches are produced. On the other hand, digital design tools are able to present more kinds of design information, such as materials and 3 dimensional objects (Woodbury, 2010). When it comes to modern architectural design, CAD tools dominate the architectural and engineering design sectors. Therefore, it is important to understand the potential of different CAD functions and the impact of their use on the architectural design process, especially for specific buildings like hospitals.

The comparison of parametric and nonparametric CAD has pointed to nonparametric CAD processes having limitations with respect to adding design information during the ideation process, as well as failing to produce variety in design expression. This is because the designed objects are independently created; there is no correlation between the generated objects (Tedeschi, 2016). Designers have to organize them in their minds and very often it is difficult to fully explain whether the project has involved complex issues. As a result each design output, in the nonparametric design process, is just a typical digital representation such as 2D drawing or 3D object. There is a weak connection between nonparametric design outputs; sometimes the thinking involved in this CAD type even blocks the designer's creative thought (Gregotti, 2007). On the other hand, parametric CAD is constructed using design parameters with algorithmic structures. It is a mathematically based design process which improves the logical thought of designers and defines problems with relevant design parameters. According to Jabi's (2013) definition of the four characteristics of the parametric design, he establishes four classes: object-orientated design structures, objects belonging to families, flexible design methods and a parameter-aided design process. These have huge potential in supporting design in modern architecture. In addition, parametric design increases the number of ideas in the problem-solution process which implies more divergent thinking and creative thought during the design process.

The last section discussed two types of parametric CAD, BIM and Algorithmic design. The obvious differences between these two design methods are in the flexibility of the design planning. BIM defines the design functions and makes them into semi-automatic programs. Architects are free to adjust the output through parametric manipulation of design attributes such as changing scales and rotations. Also, the design inputs and outputs are well-correlated under a parametric system and adjustable through adding further design information (Barnes & Davies, 2015). One criticism of the BIM design method is that it can be regarded as providing little creativity (Beghetto & Kaufman, 2007). This means it constantly operates as a repetitive problem-solving process rather than replacing a complete design plan or creating a major new and original idea for the design. By contrast, algorithmic CAD means creating different design relationships in the problem-solution process. This means that in progressing from the input of design information to the output of design objects, there could be a variety design processes and structures created under the algorithmic process (Terzidis, 2003). As a result, Beghetto & Kaufman (2007) describe this type of creativity as ‘big creativity’ which means bringing totally new ideas into the design process through a unique thought process.

The case studies of the two parametric CAD methods show that BIM design optimized the hospital design process with an organized design system as well as real-time 3D visualizations. The 3D modelling design process allowed architects and other design professionals, such as engineers or medical consultants, to communicate and be easily involved in design discussions and problem-solving activity. Also, Clash Detector, a plug-in, could predict design problems at the detailed design stage, which improved design efficiency without including misleading detail errors. In addition, a parameter based design library stored the latest design solution or data without repeating the use of old design templates, thus causing problems. To sum up, BIM design represents a powerful process for design coordination and an improved problem-solving process in hospital design projects that could be explained as ‘little c - everyday creativity’ (Section 3.5.1, Chapter 03) using the definition of Beghetto & Kaufman (2007). Although there is no specific hospital building designed by the algorithmic CAD method, case studies of other complex buildings, where algorithmic design methods were employed, indicate that algorithmic CAD can offer a generative design process with varied ideas which help discover alternative solutions in the design project. Also, mathematically based design optimization and simulation improve design quality with many creative aspects in areas such as space syntax design or optimized structure of building supports. Those ideas not only solve particular design problems but also create a new horizon for design thought which could be expounded as ‘the Big C – eminent creativity’ (Beghetto & Kaufman, 2007).

Part II/ Chapter 5 - Research design

This chapter presents my research plan, carries out a literature review and selects an appropriate study methodology to provide valid and reliable research findings. There are three parts to this research design planning process. First, the research hypothesis outlines the main direction of the study plan and then the research questions extend the research domain into specific study areas. Second, the pilot work makes an initial investigation of specific material and makes it possible to distinguish and decide on the most appropriate research method. The material investigation which contains initial observations of hospital design experts' interviews also combines these with the existing literature. After that a suitable research methodology is selected for this research plan. The last part plans the proposed research methodology and divides the content into sub-categories to explain the investigative work of the thesis including case-study selection, data handling, the analysis methods and other relevant information providing further details of the research design.

5.1 Research questions

The main research hypothesis can be stated as: *'Parametric design methodologies not only assist the architect in the management of design complexity but also increase the potential of creativity at the early stages of hospital design process'.* A comparative study of '*parametric'* and '*nonparametric*' Computer Aided Design (CAD) has been carried out in this research in order to gauge and understand different reactions to them as well as the potential creativity shown during these CAD processes in hospital design. The study was broken down into a series of research questions in order to investigate in depth the different aspects of the CAD methodologies from various perspectives. The following questions were derived from the available literature materials and are designed to be tested for confirmation or refutation by this research investigation: *To what extent do the different CAD methodologies influence the performance of the hospital design ideation process?*

1. *To what extent do the different CAD methodologies increase the creative potential of attributes such as material, shape and concept, for a complex design project, i.e., a hospital?*
2. *What is the correlation between the design activities in each of the two different CAD methods and how do these design behaviours promote more systematic design thinking?*
3. *In the design process, how can design cognition be influenced through applying different CAD methods and how do these different design cognitions influence the problem-solving process as well as providing divergent thinking in the design project?*
4. *How is empirical research into the measurement of design performance related to creativity?*

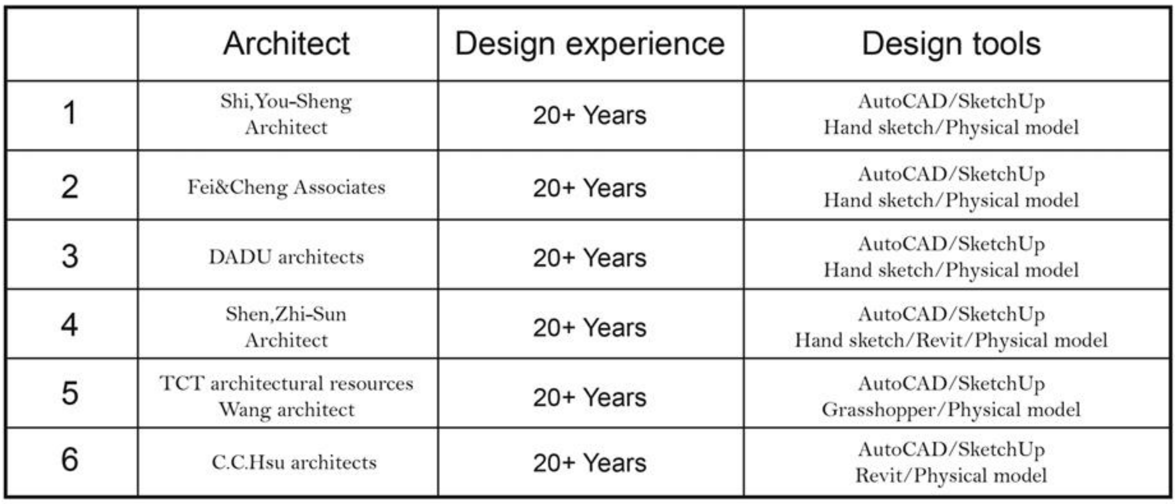
To answer these questions and to set up an appropriate research methodology to test the research hypothesis, this Ph.D. thesis provides the necessary framework for results to be based on: *1. Initial pilot work, 2. Specific literature reviews, 3. Main questionnaire survey, and 4. Main study of protocol analysis experiments.*

5.2 Initial pilot work

The interviewing of expert hospital design architects aims to provide an early pilot study on the views of practitioners of hospital design. The process was set up to be based on a presentation through open-ended discussion rather than asking solely for their judgments of the design project; the process was observed by the Ph.D. candidate and summarized into a few key points to inform the subsequent research directions. Six architects were selected from different Taiwanese hospital design firms (Table5.1). In meetings with them they were asked to provide one of their design projects and to explain their design process.

The interview material was classified into the four parts: design concepts, design planning, design process, and satisfaction with the design project.

Table5.1 Initial pilot – experts of hospital design Interviewees



	Architect	Design experience	Design tools
1	Shi,You-Sheng Architect	20+ Years	AutoCAD/SketchUp Hand sketch/Physical model
2	Fei&Cheng Associates	20+ Years	AutoCAD/SketchUp Hand sketch/Physical model
3	DADU architects	20+ Years	AutoCAD/SketchUp Hand sketch/Physical model
4	Shen,Zhi-Sun Architect	20+ Years	AutoCAD/SketchUp Hand sketch/Revit/Physical model
5	TCT architectural resources Wang architect	20+ Years	AutoCAD/SketchUp Grasshopper/Physical model
6	C.C.Hsu architects	20+ Years	AutoCAD/SketchUp Revit/Physical model

Source: Author reproduced

5.2.1 Design concepts for hospital buildings

Design ideas have to reflect a key aspect of hospital building in that functional requirements commonly overrule aesthetics and formal considerations. In addition, each hospital building has its own service capacity and plays a role in the regional health care system. However, divergent thinking is important; different types of hospitals might have different design considerations. For example, a children's hospital needs to think about interior colour, scale and shape, a medical centre needs to have some mixed-use space, and a geriatric hospital needs to consider disability design issues and avoid isolated spatial design. As a result, contemporary hospitals tend to lean toward specialized development but with multiple-functions added; their design concepts should be more flexible and also be able to cover different scenarios at the early stages of the design proposal.

5.2.2 Design planning for hospital buildings

The functional design planning of departments and facilities in hospital buildings is very important. In terms of departmental design, any kind of health care building should contain at least 2 or 3 large scale departments. Each department will have 2 types of medical service relationship; one is internal, the other is external. Problem solving for this complexity strongly depends on sound design planning. Especially in the early design stages, architects need to have a flexible planning direction which can be revised through the different stages of the design development. *Hsu*, one of the architects interviewed, stated, "*Wards in a* *maternity department normally need to be a large space in order to store facilities or transfer bed".*

In addition, the main circulation system of the building should be considered as central to the building design. Regardless of the medical service type, decisions on this could affect the building shape development and future expansion. *Shen*, one of the other architects, stated, "*A compact ring-road circulation system indicates that the building should lean toward a vertical shape rather than a horizontal design. If the ring-road circulation is located in an overextended horizontal building, such a design could weaken centralised medical services and could also easily cause loss of direction between the departments. On the other hand, a hospital street circulation design is more suited to a horizontal development and is better where growth is envisaged, as in a campus design, and would also be more physically attractive in terms of factors such as natural lighting, ventilation and external views".*

Mock-ups or other assessment applications are frequently required to test the feasibility of specific design planning issues. However, some architects prefer to base their design on medical teams' previous work experience. Because of this, their prototype design scheme helps to target certain design advantages and disadvantages and then finds appropriate design solutions. In addition, building notes are helpful in providing the necessary design knowledge and identifying the critical design points in advance. But the notes are just a design aid; there is still much practical knowledge and experience that needs to be tested in any design process.

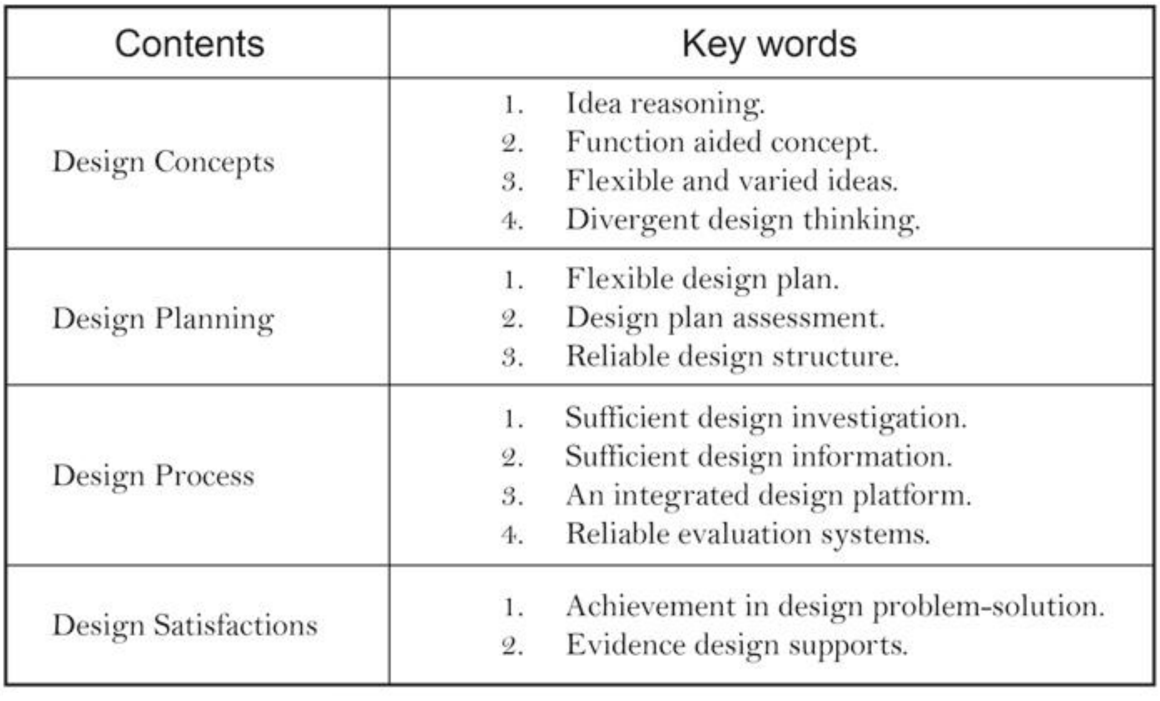
5.2.3 Design process for hospital buildings

There is not a single standard design process for hospital buildings, but the design project is big and complicated, so multi-disciplinary team work is usually required. In order to make successful workflow distributions, there are two early stage requirements for effective design development. The first is an open resource design library. If the office has varied experience and sufficient design materials, such as case studies and lists of requirements and design elements, this helps architects to apply a design template as well as make flexible choices for the design options at the earlier design stages. The second is a drawing management system. The architect *Shen* stated, "*A flexible drawing system facilitating the sharing of ideas and using the same design interface could reduce unnecessary time spent on internal team work".* Secondly, a valid design evaluation system should be employed during the design process for the assessment of program area volume, departmental distance and the structural feasibility of grids. These assessments should be considered at the early planning stage in order to standardize the design quality, avoiding chaos in the latter stages of the design development.

5.2.4 Design satisfaction with regard to hospital buildings

Some levels of satisfaction were observed while the architects explained how they solved design problems. But they did not feel the same level of satisfaction with their final design products i.e. the hospital buildings. Most of the architects said they were able to predict the design outputs from an early design stage, because the design ideas normally are similar; except with some small projects such as private hospitals or small clinic centres that can offer the testing of new ideas. However, a few architects mentioned that if they had better simulation and knowledge-based tools, they would have felt more confident about their design decisions or solutions and, in turn, they would have felt happier with their design process. Table5.2 summarizes the contents of the interview and puts key words in each section for the primary study directions.

Table5.2 The summary of hospital design experts' interview



Contents	Key words
Design Concepts	1. Idea reasoning. 2. Function aided concept. 3. Flexible and varied ideas. 4. Divergent design thinking.
Design Planning	1. Flexible design plan. 2. Design plan assessment. 3. Reliable design structure.
Design Process	1. Sufficient design investigation. 2. Sufficient design information. 3. An integrated design platform. 4. Reliable evaluation systems.
Design Satisfactions	1. Achievement in design problem-solution. 2. Evidence design supports.

Source: Author reproduced

5.3 Review of existing studies in this field

5.3.1 Existing hospital design research

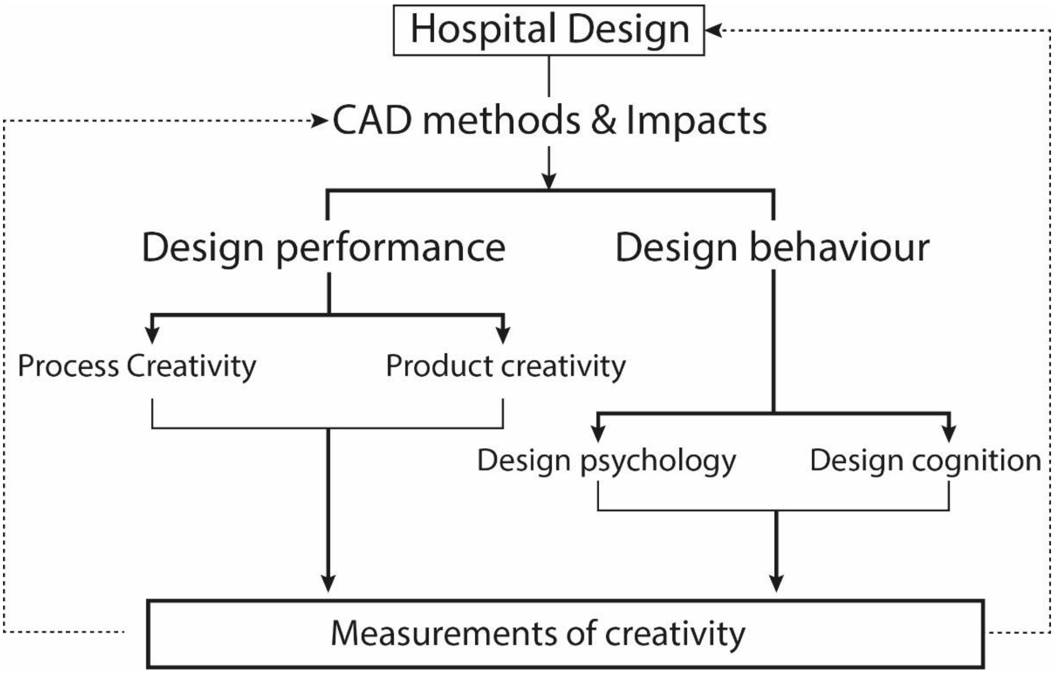
In Part 1 of this Ph.D. thesis, the literature reviews in Chapter 02 provide a historical review of changing hospital building design and ideas. Existing literature is mainly based on a few specific areas and comes from different sources. For example, some hardcopy material provides a general review of the history of healthcare design compared with modern practice, examples include: 'Changing hospital architecture (Prasad, 2008)', and 'Healthcare architecture in an era of radical transformation (Verderber and Fine, 2000)'. Another kind of text focuses on particular issues in hospital design such as 'Sustainable healthcare architecture (Guenther and Vittori, 2008)', 'Innovation in hospital design (Verderber, 2014)', and 'Specialized hospitals design and planning (Roberts, 2014)'. As for research journals/papers, from 1960 to the 1980s, the NHS provided a series of systematic hospital design projects as well as publishing a comprehensive list of Healthcare Building Notes (HBN). Regarding online and digital media, organisations such as The Nuffield Trust continually hold discussions on various issues regarding healthcare policy and healthcare ideas such as '50 years of ideas in health care building by Francis, Glanville, Noble and Scher, 1999'.

However, there is little specific research into hospital building design methods which provides a comprehensive view integrating the design ideation process, design cognition, Computer Aided Design (CAD) as well as creativity in design. So, the aim of this Ph.D. thesis is to highlight and emphasise the value of research into these areas of study, especially focusing on the aspects of originality and provisions based on an innovative view of the development of research.

5.3.2 The study of creativity in the field

This doctoral research focuses on the evaluation of the impact of creativity from the early design ideation process for hospital buildings using different CAD methods and related design technics. It is, therefore, imperative to establish the argument in the domain of process and product creativity as the study's main concept. To develop the research, the investigation of creativity is divided into two parts (Fig. 5.1). In the design ideation section, the study of creativity targets the measurement of the design process such as idea fluency, flexibility, and originality, as well as the evaluation of design output/product taking on board if innovation is applied in areas such as materiality, shape grammar, and the design layout. On the other hand, the study of design behaviour is based on the observation of on-going design activities, particularly with reference to time measurement, in order to discover the creative potential on design cognition between the different CAD activities.

Fig.5.1 The study of creativity in this research



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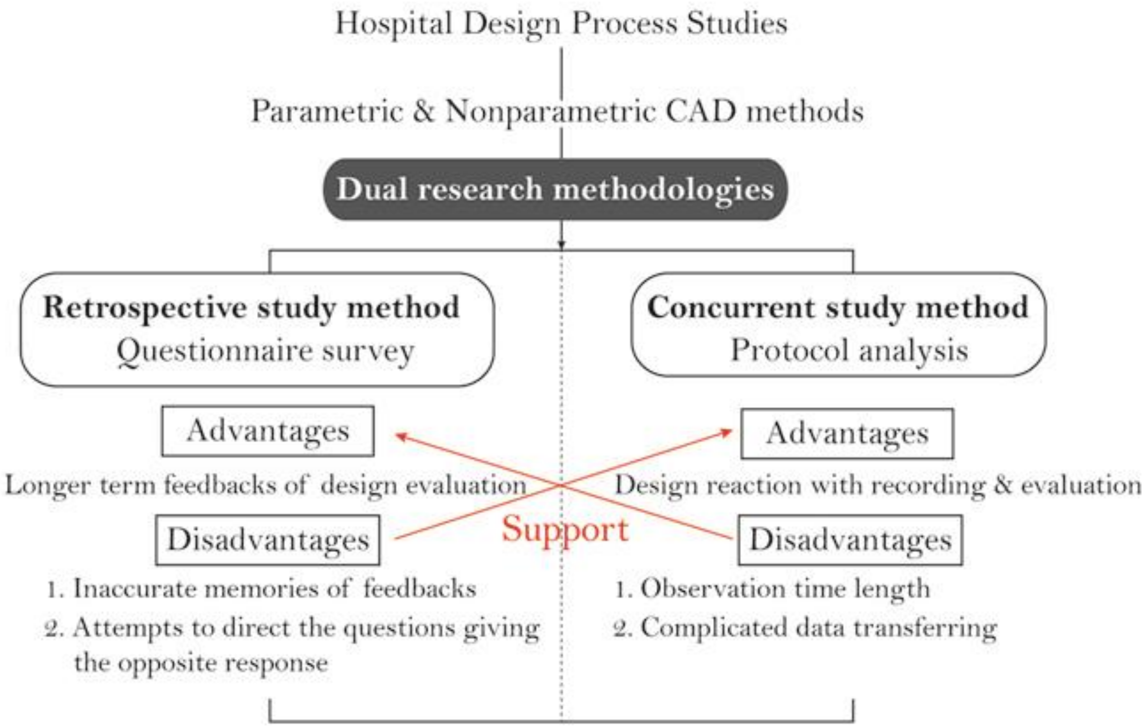
5.4 Dual research methodologies

The existing research methods in the field of hospital design are not empirical in nature and are not focused on the design process but rather on design outcomes, i.e. projects. This approach provides the reader with an easy understanding of the research into particular cases and establishes relevant information. However, this Ph.D. thesis focuses on investigating the hospital design process applying different CAD methodologies and extends this into a discussion on design cognition and creativity of design. This more elaborate research plan is more challenging than just providing a single case study.

Therefore, an empirical research method was needed to provide some evidence based objective judgments and arguments that may be useful and sufficiently deep to be relevant to in-depth investigations. This study seeks to measure the design impacts of applying two distinct CAD methodologies on design creativity and design cognition. So, the review of user performances was a vital factor in the design of the research. There were two kinds of method which were developed for the purposes of the research. The first was a retrospective approach which allows an evaluation through a questionnaire survey of architects' and CAD consultants' feedback on the impact of CAD on their hospital design performance. The second was a concurrent study method which involved some participants (architects) taking part in a small design task and applying a thinking-aloud (verbal utterances) technique called protocol analysis to express their design ideas. The reason for applying these two research methods was to explore creativity from two perspectives by collecting data on different reactions to the CAD methods used in the design process. The questionnaire evaluation focused on a longer-term feedback on the different CAD tools utilized, the protocol analysis further brought out psychological aspects associated with creativity and explored the architect's design reaction when applying a specific CAD methodology. The details of these dual research methods are explained more in the following chapters and are presented in Fig.5.2.

Fig.5.2 Dual research methodologies



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5.5 An Introduction to the questionnaire survey

The questionnaire survey was conducted to separately review the creativity of the hospital design process and final product perceived by different CAD user groups based on their work experience. This research aimed to redesign and direct the questionnaire to become more effective in testing the research hypothesis and to answer the research questions. Through analysis of the interviews of hospital design experts and of literature review materials, the investigation related hospital design variables to a core aspect of the research, namely design creativity, in some key sections of the questionnaire. Therefore, the questionnaire study was split into two sections with two groups. The first section and the group, this part on measurement of creativity in the hospital design process, referenced a golden standard of Torrance's (1966) creativity test, the TTCT, (See the literature review of the creativity study in Section 3.6.2.a, Chapter 3) and it involved asking hospital design architects to provide feedback on the use of different CAD methods and to what extent these assisted their ideation activity. The results would provide solid evidence, such as idea numbers and types, of the direct link between the CAD methodology and creativity in the hospital design process. The second part and the party, explored creativity through hospital judgments on final product (hospital building) applying the well know approach CAT (Amabile, 1982) (See the literature review of the creativity study in Section 3.6.2.b, Chapter 3). The collecting data includes feedbacks from the use of material selection, building form, design plan, etc. were identified from the feedbacks of selected CAD consultants.

Two different software types (parametric and nonparametric CAD), and three particular software products (AutoCAD, BIM and Grasshopper), were selected as the basis for comparison. The survey was carried out by the author in the offices selected and provided sufficient time for the questionnaire's completion and collection. Although there are many online questionnaire survey techniques and resources available, visiting design offices in person and directly providing the questionnaire along with an explanation helped minimise confusion or misconceptions regarding the survey questions. The participants had to answer the questions according to their personal CAD experience of a hospital design project. The survey technique followed the steps recommended by Oppenheim (1992) 'Questionnaire design, interviewing and attitude measurement'.

5.6 Target sample groups and questionnaires

5.6.1 Sample groups – *Selection of design software*

Computer Aided Design (CAD) and its related tools are significantly associated with contemporary architectural design practice. In recent years, the new trend of CAD, parametric design, and associated tools have created an innovative horizon for new architectural representation which has influenced both academic research and design practice. Hospital design demands an intelligent and integrated design process. So parametric CAD is considered as a potential tool for architects. According to 'Building a 2020 vision: Future health care environments (2001)', the future design of hospitals should focus on a creative and flexible design process, integrating design with other professions as well as standards and benchmarks for improving the quality of design. The CAD tools were divided into two categories for study, parametric and nonparametric tools, using three different software packages: AutoCAD, BIM and Grasshopper. The questionnaire survey focused on the design evaluation and idea formulation at an early design stage during the hospital design process.

AutoCAD (2D/3D) was selected as it is widely recognised as the most commonly used nonparametric CAD tool in architectural practice. Two parametric tools were selected for the study groups: the Building Information Modeling (BIM) system using Revit or ArchiCAD, and algorithmic CAD using Grasshopper (a plug-in to Rhinoceros). The reason for choosing BIM design is that the UK Government Construction Strategy published in 2011 required that fully collaborative 3D BIM should be used on all centrally procured UK Government construction projects by 2016 (Barnes and Davies, 2015). On the other hand, the use of algorithmic design allows designers to overcome the limitations of conventional CAD methods, achieving a higher level of design complexity and human manual ability which profoundly influences design creativity (Tedeschi, 2014).

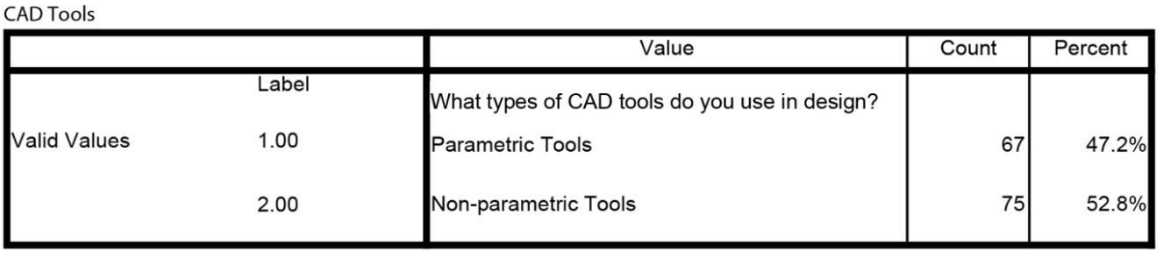
a-1) Sample background

The sample groups for this research study, hospital design firms and CAD consultants, were based in Taiwan, Asia. The reason for the choice of Taiwan for the study groups was based on two factors. First, the Taiwanese healthcare system is well organized and is often positively reported on by many international medical papers. The Daily Telegraph, UK (Roberts, 2014) showed the results of an international survey of high-quality and affordable healthcare services with the Taiwanese National Health Insurance (NHI) system ranked first. Also, Eastern Healthy Life (2015) reported Taiwanese healthcare as having the first position in Asia and being third in the world. Wu(MD), Majeed(MD) and Kuo(MD) (2010) suggest that the Taiwanese healthcare system (NHI) could be used as a bench-mark and as a reference for the NHS, UK in terms of development, good accessibility, service coverage, short waiting times and its national data collection system for healthcare supervision and research. Second, Computer Aided Design (CAD) in Taiwan has been used in sophisticated developments for specific markets. Taiwan is also a member of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA). Taiwanese architectural design in education (*Master of Science, The Graduate Institute of Architecture*, NCTU,2017) and practice (*BIM in Taiwan - Johan Hanegraaf*, 2016) shows a high percentage rate of using a variety of CAD tools in the design process, such as AutoCAD, 3DsMax, Rhinoceros, Revit, etc. In recent years, parametric design tools like BIM and algorithmic CAD have been promoted for use in architectural design and have been used in the completion of some innovative hospital design projects. For example, Nova, BIM(Taiwan) applied the latest BIM design technology in a new hospital construction in New Taipei city in San-Chong province, Taiwan in 2013 (Nova-hub.com., 2013). With the development of algorithmic CAD in the hospital design profession, TCT Architectural Resources, a Taiwan-based hospital design architects' office, has founded their specialized algorithmic design unit and it is currently engaged in new hospital design and construction projects.

a-2) Sample size of hospital design architects - *User Group 1*

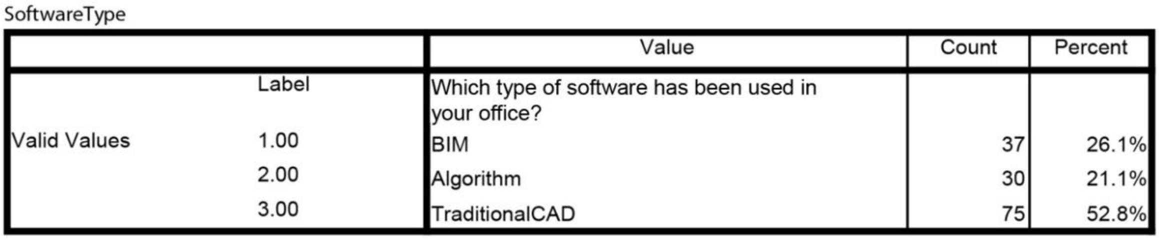
The sample size of the design process survey consisted of 142 respondents (Table5.3). Questionnaires were sent to 25 specialized hospital design offices with between 20 and 100 employees, of which only 15 (142 employees) responded, which represents a response rate of 47%. The number of participants in each software type was: 67 architects employing parametric tools, representing 47.2% of the overall sample size, and 75 architects employing nonparametric tools, or 52.8% of the total. Among the users of parametric tools, there were two user subgroups: BIM tool users with 37 users, representing 26.1% of the sample size, and Algorithmic tool users, composed of 30 users, representing 21.1% of the overall sample (Table5.4). As to the user experience of the overall samples: 25% of users identified 3.5 years' experience, 50% of users had 5.5 years' and 75% of users had 10 years' experience. The statistical mean for CAD user's experience was approximately 6.5 years. It showed the statistical average for most participants as being qualified in terms of experience, with over 6 years, and sophisticated in their use of CAD tools, and they could also demonstrate their benefits when testing design creativity. This user experience helps to make better comparisons of CAD performance in terms of design ideation and variation.

Table5.3 Sample size and CAD types



CAD Tools

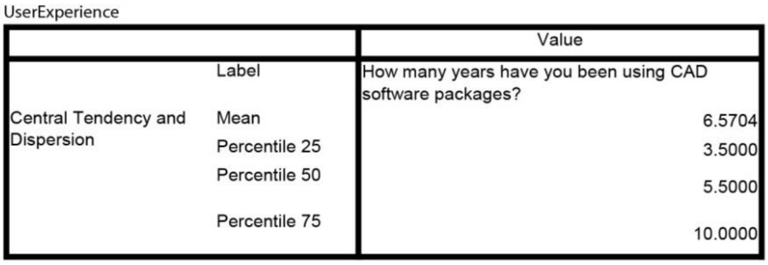
		Value	Count	Percent
	Label	What types of CAD tools do you use in design?		
Valid Values	1.00	Parametric Tools	67	47.2%
	2.00	Non-parametric Tools	75	52.8%



SoftwareType

		Value	Count	Percent
	Label	Which type of software has been used in your office?		
Valid Values	1.00	BIM	37	26.1%
	2.00	Algorithm	30	21.1%
	3.00	TraditionalCAD	75	52.8%

Table5.4 User experience



UserExperience

		Value
	Label	How many years have you been using CAD software packages?
Central Tendency and Dispersion	Mean	6.5704
	Percentile 25	3.5000
	Percentile 50	5.5000
	Percentile 75	10.0000

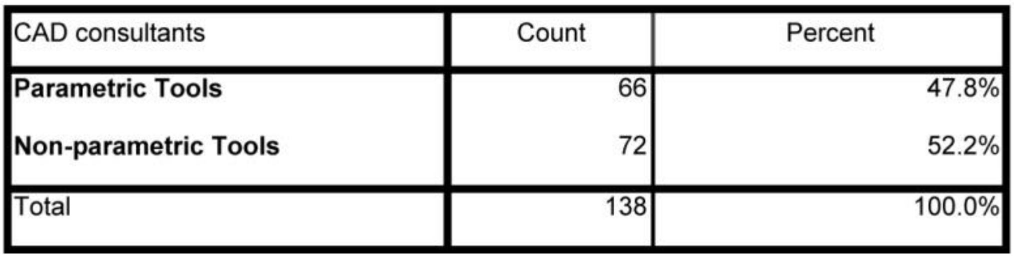
Source: Author reproduced

a-3) Sample size of CAD consultants - *User Group 2*

The CAD consultants were selected from those who had experience on hospital design projects. They were asked to focus their evaluation on building design aspects which were completed by architects. Each CAD consultant had more than 4 years' experience with the CAD method and was able to judge design performance according to the criteria provided from Amabile's creativity research (1982). Questionnaires were sent to 250 specialist CAD consultants of which 138 responded, which represents a response rate of 55%.

The number of participants in each software type (Table5.5) was: 66 consultants specializing in parametric CAD, representing 47.8% of the overall sample size, and 72 consultants specializing in nonparametric CAD, or 52.2% of the total. Among the parametric CAD participants, there were equal numbers in the user subgroups: BIM design, with 35 users representing 25.4% of the sample size, and algorithmic design, composed of 31 users representing 22.5% of the overall sample (Table5.5-1).

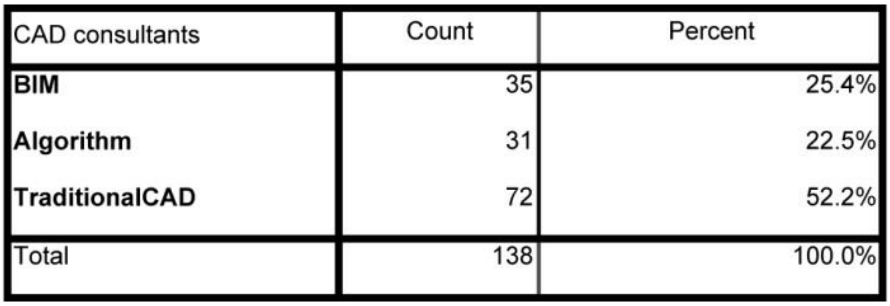
Table5.5 Sample of parametric and nonparametric CAD consultants



CAD consultants	Count	Percent
Parametric Tools	66	47.8%
Non-parametric Tools	72	52.2%
Total	138	100.0%

Source: Author reproduced

Table5.5-1 Sample size and CAD types



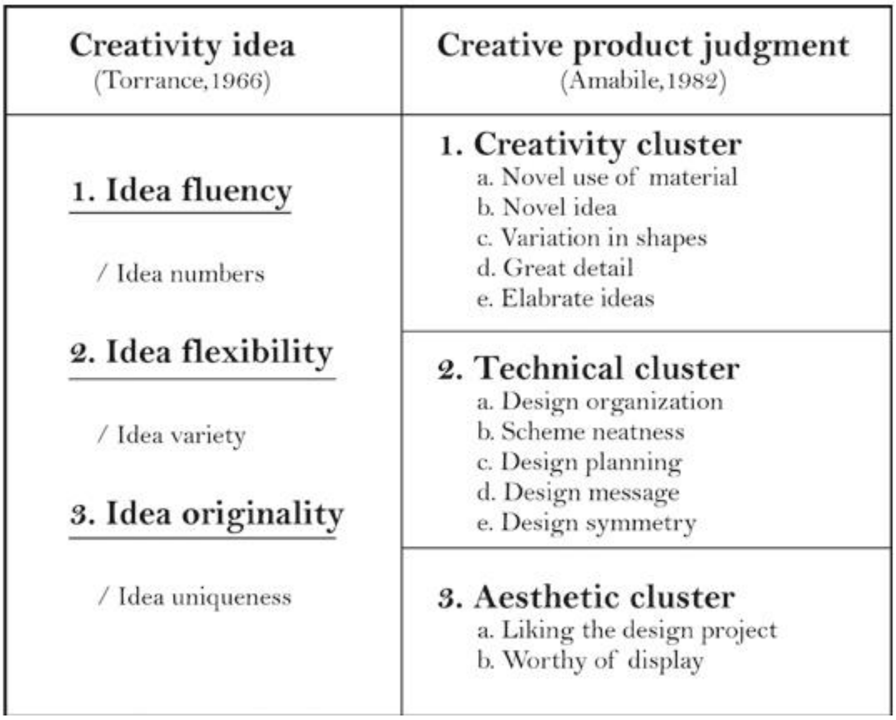
CAD consultants	Count	Percent
BIM	35	25.4%
Algorithm	31	22.5%
TraditionalCAD	72	52.2%
Total	138	100.0%

Source: Author reproduced

5.6.2 Question category

The question categories in Table5.6 aim to measure creativity when using CAD tools in the hospital design process. The first category includes three indicators of creativity in terms of ***Idea fluency*** *(idea numbers),* ***Idea flexibility*** *(idea variety) and* ***Idea originality*** *(idea uniqueness)* (Torrance, 1966). The second involves three judgements of product creativity in a ***Creativity cluster*** (*Novel use of material, Novel idea, Variation in shapes, Details and Complexity), a* **Technical cluster** *(Organization, Neatness, Planning, Symmetry and Expression of meaning) and* ***Aesthetic judgement*** *(Liking, Aesthetic appeal and worth displaying)* (Amabile, 1982).

Table5.6 Question category with creativity indicators



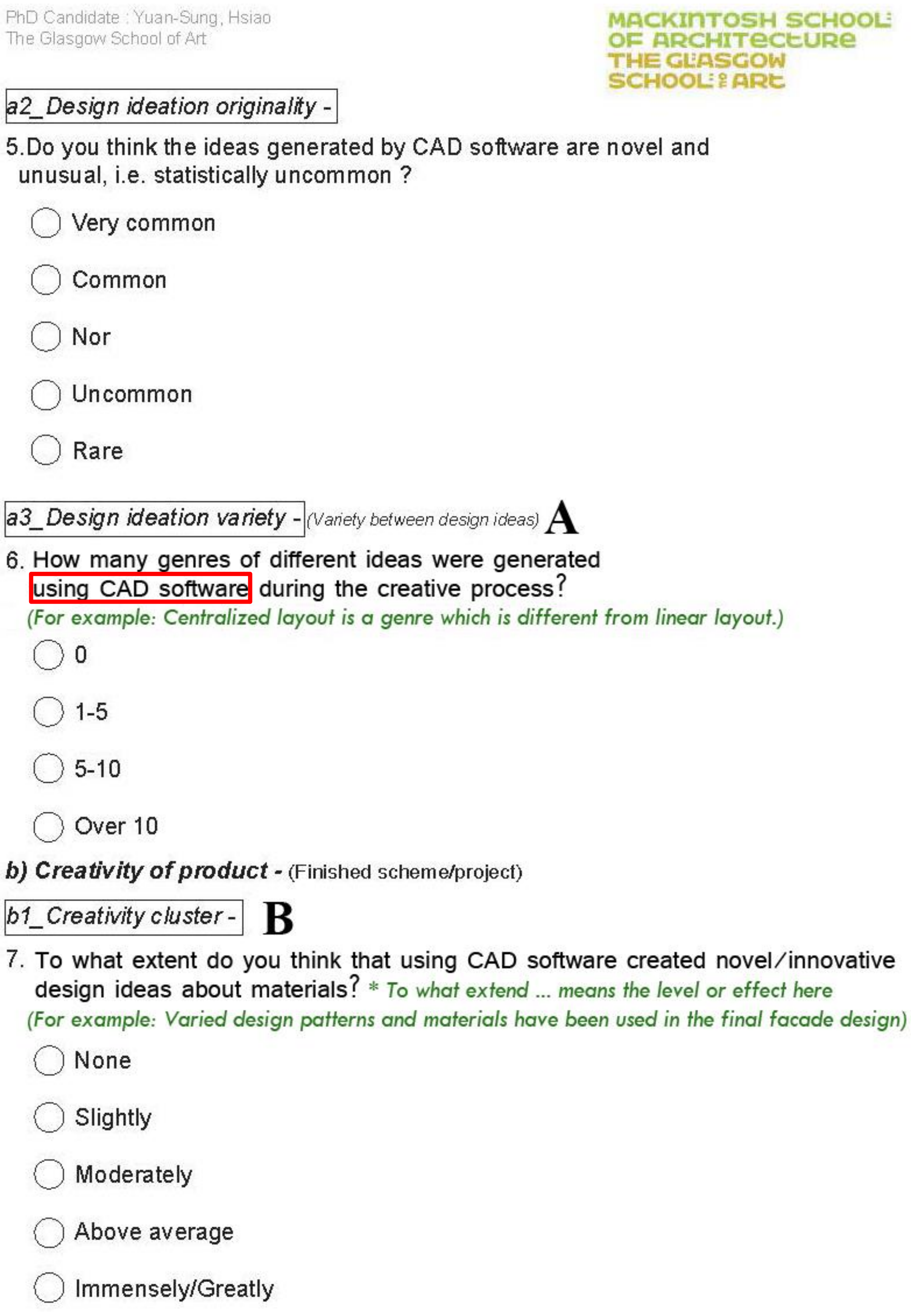
Creativity idea (Torrance,1966)	Creative product judgment (Amabile,1982)
1. Idea fluency / Idea numbers	**1. Creativity cluster** a. Novel use of material b. Novel idea c. Variation in shapes d. Great detail e. Elabrate ideas
2. Idea flexibility / Idea variety	**2. Technical cluster** a. Design organization b. Scheme neatness c. Design planning d. Design message e. Design symmetry
3. Idea originality / Idea uniqueness	**3. Aesthetic cluster** a. Liking the design project b. Worthy of display

Source: Author reproduced

a) Attitude measurements and data

The self-administrated questionnaire consisted completely of closed questions with two types of measurements. The first type of question was designed for a countable response (Table5.7-A), for example, the number of ideas generated during the design process. The second type, which accounts for the majority of questions, provided a ranking scale (Table5.7-B) for evaluation or feedback on the general view of the CAD performance. The questionnaire design followed the design procedures regarding semantics as outlined in Oppenheim's (1992) metric (approach) 'Questionnaire design, interviewing and attitude measurement'.

Table5.7-A-B Questionnaire sample



PhD Candidate : Yuan-Sung, Hsiao
The Glasgow School of Art

MACKINTOSH SCHOOL OF ARCHITECTURE
THE GLASGOW SCHOOL OF ART

a2_Design ideation originality -

5.Do you think the ideas generated by CAD software are novel and unusual, i.e. statistically uncommon ?

○ Very common

○ Common

○ Nor

○ Uncommon

○ Rare

a3_Design ideation variety - *(Variety between design ideas)* **A**

6. How many genres of different ideas were generated using CAD software during the creative process?
(For example: Centralized layout is a genre which is different from linear layout.)

○ 0

○ 1-5

○ 5-10

○ Over 10

b) Creativity of product - (Finished scheme/project)

b1_Creativity cluster - **B**

7. To what extent do you think that using CAD software created novel/innovative design ideas about materials? ** To what extend ... means the level or effect here*
(For example: Varied design patterns and materials have been used in the final facade design)

○ None

○ Slightly

○ Moderately

○ Above average

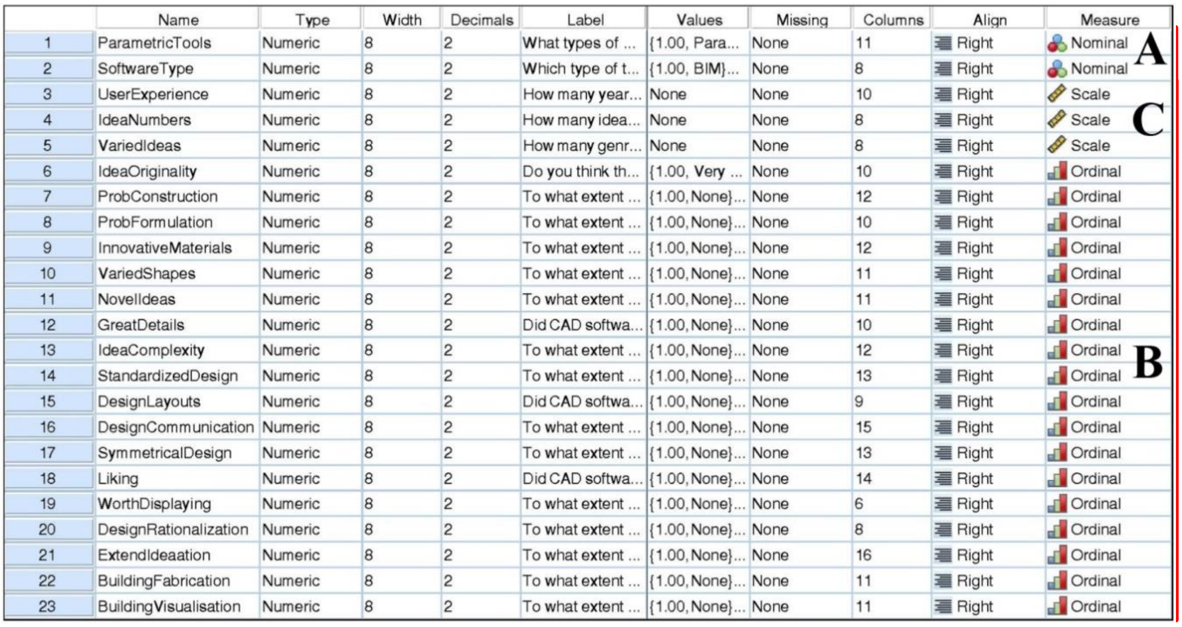
○ Immensely/Greatly

Source: Author reproduced

b) Interpreting and analysis

The survey responses were transferred into a data base for the structuring of concepts into different statistical variables. For example, the data form for the ranking scale was classified into a category type with either a nominal (Table5.8-A) or ordinal (Table5.8-B) variable.

Table5.8-A-B-C SPSS variable inputs



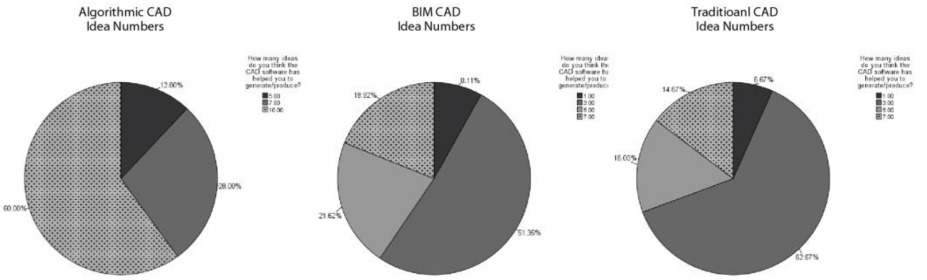
	Name	Type	Width	Decimals	Label	Values	Missing	Columns	Align	Measure
1	ParametricTools	Numeric	8	2	What types of ...	{1.00, Para...	None	11	Right	Nominal
2	SoftwareType	Numeric	8	2	Which type of t...	{1.00, BIM}...	None	8	Right	Nominal
3	UserExperience	Numeric	8	2	How many year...	None	None	10	Right	Scale
4	IdeaNumbers	Numeric	8	2	How many idea...	None	None	8	Right	Scale
5	VariedIdeas	Numeric	8	2	How many genr...	None	None	8	Right	Scale
6	IdeaOriginality	Numeric	8	2	Do you think th...	{1.00, Very ...	None	10	Right	Ordinal
7	ProbConstruction	Numeric	8	2	To what extent ...	{1.00, None}...	None	12	Right	Ordinal
8	ProbFormulation	Numeric	8	2	To what extent ...	{1.00, None}...	None	10	Right	Ordinal
9	InnovativeMaterials	Numeric	8	2	To what extent ...	{1.00, None}...	None	12	Right	Ordinal
10	VariedShapes	Numeric	8	2	To what extent ...	{1.00, None}...	None	11	Right	Ordinal
11	NovelIdeas	Numeric	8	2	To what extent ...	{1.00, None}...	None	11	Right	Ordinal
12	GreatDetails	Numeric	8	2	Did CAD softwa...	{1.00, None}...	None	10	Right	Ordinal
13	IdeaComplexity	Numeric	8	2	To what extent ...	{1.00, None}...	None	12	Right	Ordinal
14	StandardizedDesign	Numeric	8	2	To what extent ...	{1.00, None}...	None	13	Right	Ordinal
15	DesignLayouts	Numeric	8	2	Did CAD softwa...	{1.00, None}...	None	9	Right	Ordinal
16	DesignCommunication	Numeric	8	2	To what extent ...	{1.00, None}...	None	15	Right	Ordinal
17	SymmetricalDesign	Numeric	8	2	To what extent ...	{1.00, None}...	None	13	Right	Ordinal
18	Liking	Numeric	8	2	Did CAD softwa...	{1.00, None}...	None	14	Right	Ordinal
19	WorthDisplaying	Numeric	8	2	To what extent ...	{1.00, None}...	None	6	Right	Ordinal
20	DesignRationalization	Numeric	8	2	To what extent ...	{1.00, None}...	None	8	Right	Ordinal
21	ExtendIdeaation	Numeric	8	2	To what extent ...	{1.00, None}...	None	16	Right	Ordinal
22	BuildingFabrication	Numeric	8	2	To what extent ...	{1.00, None}...	None	11	Right	Ordinal
23	BuildingVisualisation	Numeric	8	2	To what extent ...	{1.00, None}...	None	11	Right	Ordinal

Source: Author reproduced

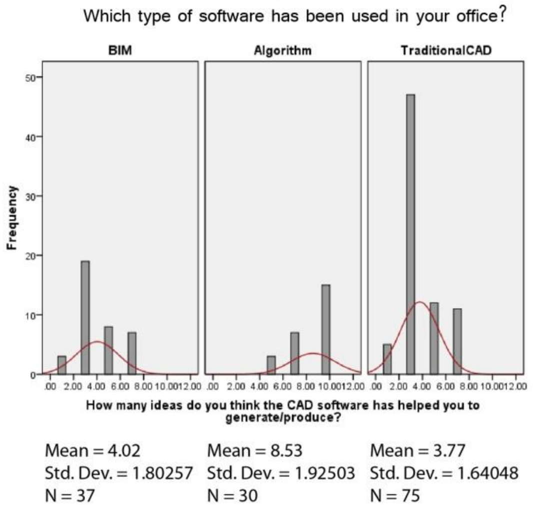
On the other hand, numerical data was defined as a continuous variable (Table5.8-C). Next the data was imported into statistical software called SPSS (Statistical Package for Social Science) and processed using the relevant analyses. Two types of statistical analysis were applied in the Ph.D. research, one was descriptive statistics (Fig.5.3) which is consistent with summarizing or reporting a sample through a figure, diagram or table. The other was inferential statistics (Table5.8-1) which is concerned with making correlations, deductions and associations from population data such as one-way analysis of variance or correlation computing. Statistical sources and technical studies were reviewed before engaging in the analysis, for example: ‘Statistics without tears’ (Rowntree, 1981), ‘Simple statistics’ (Clegg,1990), and ‘SPSS for introductory statistics’ (Morgan, Leech, Gloeckner and Barrett, 2004).

Fig.5.3 Descriptive statistics

(Pie-charts)

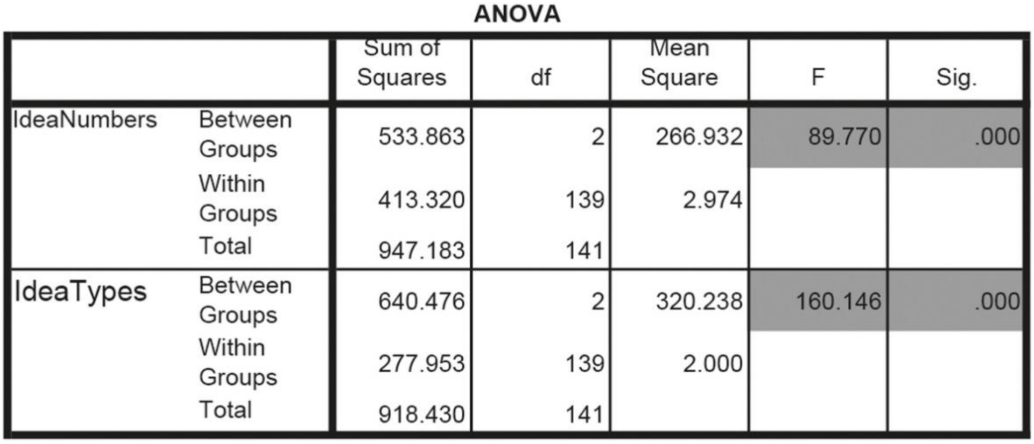


(Histograms)



Source: Author reproduced

Table5.8-1 Inferential statistics



ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
IdeaNumbers	Between Groups	533.863	2	266.932	89.770	.000
	Within Groups	413.320	139	2.974		
	Total	947.183	141			
IdeaTypes	Between Groups	640.476	2	320.238	160.146	.000
	Within Groups	277.953	139	2.000		
	Total	918.430	141			

Source: Author reproduced

5.7 An introduction to computer-based protocol analysis

The second investigation used represents a second research methodology – a computer-based protocol analysis. The aim of this research was to observe the on-going design behaviour when using different CAD methodologies for a pre-selected design task. The participants had to finish the same task using two different CAD methods. This investigation aimed to test the early design stages - the ideation process, rather than testing the entire design project.

The recorded transcripts were divided into four categories: *1. Design process, 2. Problem formulation, 3. Design cognition and 4. Form exploration*. Each category presented a different aspect of the design. Through comparison of the recorded behaviours and time-based investigation, the research further studied the impacts during the design process as well as discussing the relevant ideas which were found in the design task. The protocol process and associated approaches were developed and adapted from existing research papers, for example: 'Understanding the difference between how novice and experienced designers approach a design task (Ahmed, Wallace and Blessing, 2003)', 'An approach to the analysis of design protocols (Gero and Neill, 1998)', 'Descriptive models of creative design: application to an example (Cross, 1997)', and 'An investigation into the influence of free-form digital modelling on architectural designing (Niblock, 2012)'.

Variable idea generation was used in this study as an important indicator for the evaluation and measurement of design creativity. Participants were encouraged to create ideas for the planned design as much as they could, which meant detailed drawing was unnecessary. The investigation process was audio-visually recorded by a recording software application. The recorded materials included participants' verbal recordings and computer sketches.

5.8 Target sample groups and the design task

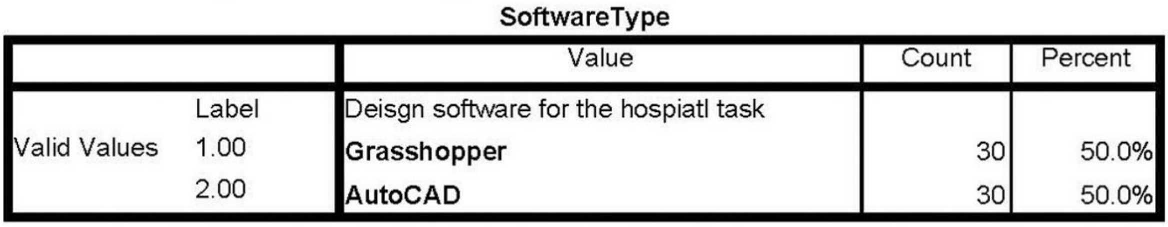
5.8.1 Sample groups – *Selection of design software*

The nonparametric CAD process employed AutoCAD which is the most common CAD tool using by hospital design offices. On the other hand, the parametric CAD platform selected used Grasshopper, an algorithmic CAD product (a plug-in to Rhinoceros). The reason for choosing algorithmic CAD and not BIM was because algorithmic CAD (Grasshopper) has a visually-based geometric design interface with visible data structures, node diagrams, which could provide easily observed study materials. This visual algorithm parametric design process is associated with 3D objects which can instantly show the changes in geometries as well as the design developments (Tedeschi 2014). In addition, Schumacher (2010) suggests "In principle any conceivable network of relations between a given set of attributes can be constructed." In other words, the flexible design process of algorithmic CAD provides a totally different approach to design providing various research profiles in contrast to the traditional nonparametric CAD process, especially with complex design projects as for hospital buildings.

a) Sample size and background

There were 30 participants selected for this computer-based protocol study. All participants had around 5 years' experience in hospital design and the use of CAD; the participants were working at the time in Taiwanese hospital design firms (Table5.9).

Table5.9 Sample size and CAD types



SoftwareType

		Value	Count	Percent
Valid Values	Label	Deisgn software for the hospiatl task		
	1.00	**Grasshopper**	30	50.0%
	2.00	**AutoCAD**	30	50.0%

Source: Author reproduced

b) Design task

The task asked participants to propose a concept design layout for an outpatient centre. The design requirements included functional features and spatial details to be prepared. The site selected was the new Fu-Jen Catholic University Hospital, Taiwan. This hospital was established as a medical centre providing education and medical services for the local region. The proposed design was to aim as much as possible at the conceptual design layouts rather than making detailed drawings, so the plan types and ideas were important; the output representations could be either 2D or 3D objects.

The following highlights the steps taken by the researcher in terms of the design brief and idea requests in order to make sure the participants would primarily focus on the ideation process rather than just working on the functional layouts.

b-1) Design brief

The participants were requested to propose a conceptual floor plan design for the ground floor outpatient department of the Fu-Jen Catholic University hospital, Taiwan. The reason of selecting an outpatient centre design task rather than an inpatient project aimed to test the CAD methodology for complex design integration and the user’s reaction during the design problem-solving process. The design guidelines used are shown below:

1. *Your design should contain the departments, rooms, and service space that the task requires. Centralized operating theatres and X-ray department are important, and please provide two separate entrances: one for the clinic hall, the other for the AandE department. Please consider an urban context for visitors and the departmental relationships for medical services.*
2. *Detailed drawings are not necessary, the aim of this task is to propose various types of design plans with relevant new ideas.*

b-2) Idea requests

The following instructions should be followed in verbal discussions during the design process:

1. *Describe the design idea, why do you think the idea is good for the task?*
2. *When you face a problem, please explain and suggest solutions.*
3. *Please try as much as possible to provide different ideas/shapes in the floor plan design*
4. *Please explain the spatial relationships following the design concept, what are the advantages? For example, efficient service or energy saving.*
5. *Please suggest a possible extendable design plan for your design proposal.*
6. *Please express your feelings about your design, how do you feel about the design outputs? What do you think can be improved?*

c) Protocol data Interpretation and analysis

c-1) Recording and Data transcription

The study interpretation was based on the time spent on the different design categories during each architect's design process; some overlapping design behaviours occurred in the same time period and they were always classified into different design categories. Each participant was asked to produce two separate design plans in two CAD environments (AutoCAD and Grasshopper). The task was limited to 45mins for each CAD process. All participants were also asked to follow the protocol rules for 'talking-aloud' and design sketches in the CAD interface as much as possible. This protocol process was recorded by software called HyberCam. This provided real-time recording (Fig.5.4-A) of the verbal materials or speech (Fig.5.4-B) as well as design behaviours or drawings (Fig.5.4-C).

Recorded materials were initially provided as transcriptions (in Word file format) and the summarized time data was imported into (Excel) and formatted according to the code list used. The data was further converted into representations (Excel files) for providing the descriptive statistics, for example, statistical graphs and diagrams (Table5.10).

Fig.5.4 Data recording and Transcription

(A) Real-time recording - HyberCam

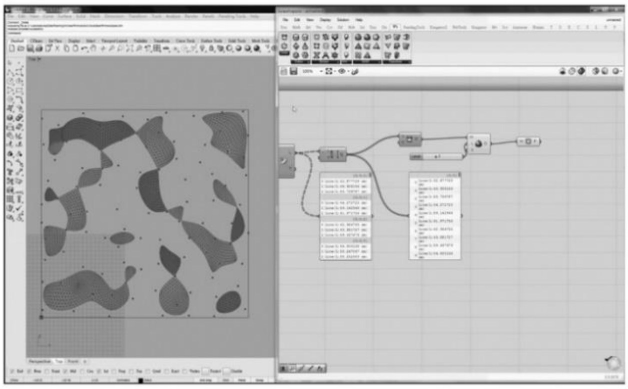
Start X 0 Start Y 0
Width 1600 Height 900

When recording:

☑ Show rectangle around recorded area
☐ make this rectangle blink
● Leave HyperCam Window Opened
○ Iconize HyperCam Window to the Task Bar
○ Hide HyperCam Window

☑ Capture layered/transparent windows (may slow down performance)

(C) Design drawings - Rhino5.0 + Grasshopper

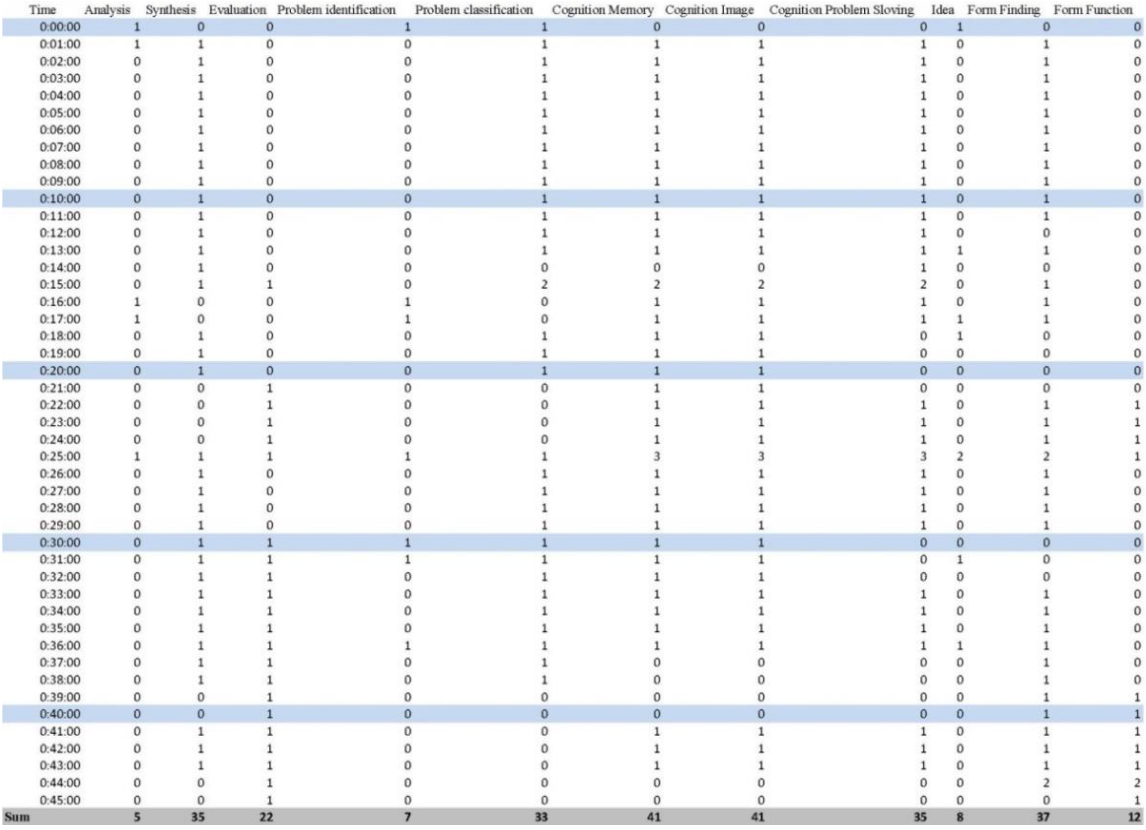


(B) Verbal materials - speech transcriptions

05:08
There is a little bit trouble, doesn't matter we can correct it.
09:04
Actually it have been done however in the opposite.
(We actually want the intersection of free form and the matrix,
but now look like trim the matrix with free form.)
09:50
If we bake it out, it seems complete half of it however not so clear.
Usually it is trim the matrix with free form. Actually we want the intersection.

Source: Author reproduced

Table5.10 Summarized data from the computer-based protocol analysis



Time	Analysis	Synthesis	Evaluation	Problem identification	Problem classification	Cognition Memory	Cognition Image	Cognition Problem Sloving	Idea	Form Finding	Form Function
0:00:00	1	0	0	1	1	0	0	0	1	0	0
0:01:00	1	1	0	0	1	1	1	1	0	1	0
0:02:00	0	1	0	0	1	1	1	1	0	1	0
0:03:00	0	1	0	0	1	1	1	1	0	1	0
0:04:00	0	1	0	0	1	1	1	1	0	1	0
0:05:00	0	1	0	0	1	1	1	1	0	1	0
0:06:00	0	1	0	0	1	1	1	1	0	1	0
0:07:00	0	1	0	0	1	1	1	1	0	1	0
0:08:00	0	1	0	0	1	1	1	1	0	1	0
0:09:00	0	1	0	0	1	1	1	1	0	1	0
0:10:00	0	1	0	0	1	1	1	1	0	1	0
0:11:00	0	1	0	0	1	1	1	1	0	1	0
0:12:00	0	1	0	0	1	1	1	1	0	0	0
0:13:00	0	1	0	0	1	1	1	1	1	1	0
0:14:00	0	1	0	0	0	0	0	1	0	0	0
0:15:00	0	1	1	0	2	2	2	2	0	1	0
0:16:00	1	0	0	1	0	1	1	1	0	1	0
0:17:00	1	0	0	1	0	1	1	1	1	1	0
0:18:00	0	1	0	0	1	1	1	0	1	0	0
0:19:00	0	1	0	0	1	1	1	0	0	0	0
0:20:00	0	1	0	0	1	1	1	0	0	0	0
0:21:00	0	0	1	0	0	1	1	0	0	0	0
0:22:00	0	0	1	0	0	1	1	1	0	1	1
0:23:00	0	0	1	0	0	1	1	1	0	1	1
0:24:00	0	0	1	0	0	1	1	1	0	1	1
0:25:00	1	1	1	1	1	3	3	3	2	2	1
0:26:00	0	1	0	0	1	1	1	1	0	1	0
0:27:00	0	1	0	0	1	1	1	1	0	1	0
0:28:00	0	1	0	0	1	1	1	1	0	1	0
0:29:00	0	1	0	0	1	1	1	1	0	1	0
0:30:00	0	1	1	1	1	1	1	0	0	0	0
0:31:00	0	1	1	1	1	1	1	0	1	0	0
0:32:00	0	1	1	0	1	1	1	0	0	0	0
0:33:00	0	1	1	0	1	1	1	1	0	1	0
0:34:00	0	1	1	0	1	1	1	1	0	1	0
0:35:00	0	1	1	0	1	1	1	1	0	1	0
0:36:00	0	1	1	1	1	1	1	1	1	1	0
0:37:00	0	1	1	0	1	0	0	0	0	1	0
0:38:00	0	1	1	0	1	0	0	0	0	1	0
0:39:00	0	0	1	0	0	0	0	0	0	1	1
0:40:00	0	0	1	0	0	0	0	0	0	1	1
0:41:00	0	1	1	0	0	1	1	1	0	1	1
0:42:00	0	1	1	0	0	1	1	1	0	1	1
0:43:00	0	1	1	0	0	1	1	1	0	1	1
0:44:00	0	0	1	0	0	0	0	0	0	2	2
0:45:00	0	0	1	0	0	0	0	0	0	0	1
Sum	**5**	**35**	**22**	**7**	**33**	**41**	**41**	**35**	**8**	**37**	**12**

Source: Author reproduced

c-2) Coding list

The data coding process was classified into four categories to correspond to the research questions on the design process using the different CAD methodologies. The following list provides detailed definitions of the categories:

Design Process (DP)

Markus (1969) and Maver(1970) propose an elaborate architectural design mapping system for the design process which contains a series of cyclical activities: design analysis, design synthesis, and evaluation. Lawson (1997) further defines the design process as follows:

1. *DPa- Analysis*
   The analysis involves the exploration of relationships, looking for patterns in the information available, and the classification of objectives.
2. *DPb- Synthesis*
   The synthesis is characterized by an attempt to move forward and create a response to the problem – the generation of the solution.
3. *DPc- Evaluation (appraisal)*
   The evaluation involves the critical appraisal of suggested solutions against the objectives identified in the analysis phase.

Problem Formulations (PF)

Hospital design is usually referred to as a complex design task. Lawson (1997) argues that the design complexity, and its scale, upgrades the level of design problems. Therefore, it is important to understand the problem formulation process in order to manage the complexity of hospital design.

1. *PFb- Classified design problems*
   Levin’s (1966) model of design problems suggests the primary step of ‘classified design problems’ as a diagrammatic pattern for further problem constructions.
2. *PFa- Identified design problems*
   Lawson (1997) suggests the ‘definition of design problems’ could be done in the ‘detail’ stage to help focus later on design problem evaluation.

Design Cognitions (DC)

Design cognition is associated with three cognition processes: memory, imagery and problem-solving

1. *DC(a)- Memory*

   Anderson (1983) proposes two kinds of memory in the cognition process: declarative memory and production memory. In this study, memory was associated with the selection of CAD functions such as drawing and editing options. Picking the relevant design options represented how the declarative instruction connected the user's, the architect's, mind with decision making during the cognition process.
2. *DC(b)- Imagery*

   Kosslyn and Schwartz (1977) present imagery as the 'deep representation' of the human brain. Our brain stores imagery as coded information, or symbols, and takes action on it on each different occasion with a related mental process. Because the study is based on a design layout process, so the imagery or coded information element in cognition was used to create design drawings such as 2D geometries or 3D spaces.
3. *DC(c)- Problem-solving*

   Hayes (1991) identifies cognitive problem-solving as a cyclical process, like a hill-climbing strategy. Each action brings us closer to the goal and necessary response to the cognitive process. This problem-solving cycle in the CAD process is shown by a series of design actions in response to the design proposal. For example, if the user wants to draw a large number of circles to fit a design plan, this involves the selection of the functional tool, progressively modifying the drawing and finally generating the proper result. This process is described as a problem-solving process.

Form Explorations (FE)

The investigation of form exploration involves a visual and geometry-based problem-solving process. This is a vital part of architectural design. Especially in hospital design, the types of building shapes can differ widely and in turn affect the medical proposals or service patterns for the hospital operations (Prasad, 2008). Two aspects influence this process:

1. *FFa- Form-finding*

   In this study, the form finding process means the use of CAD methods to explore the various design shapes and to attempt to seek a geometrical and appropriate design for building functions.
2. *FFb- Form Function*

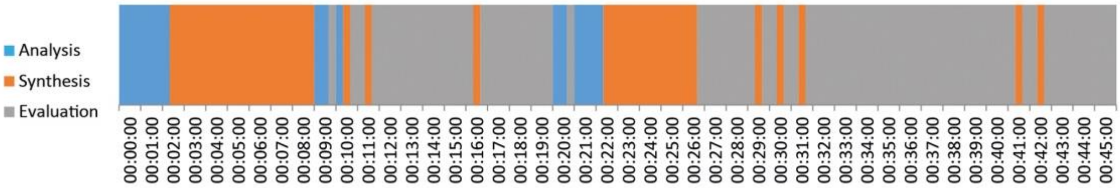
   This process is where architects relate the architectural function to a given design shape but with less emphasis on geometric considerations.

c-3) Analysis and representations

c-3-1) Descriptive analysis

The time-based graphs were selected to present observations of the study. A node diagram (Fig.5.5), a vertical bar graph, presented an interactive pattern of the design activities for each of the 45 minutes. In addition, related calculations were made to interpolate the result from the protocol analysis.

Fig.5.5 A node diagram for the computer-based study

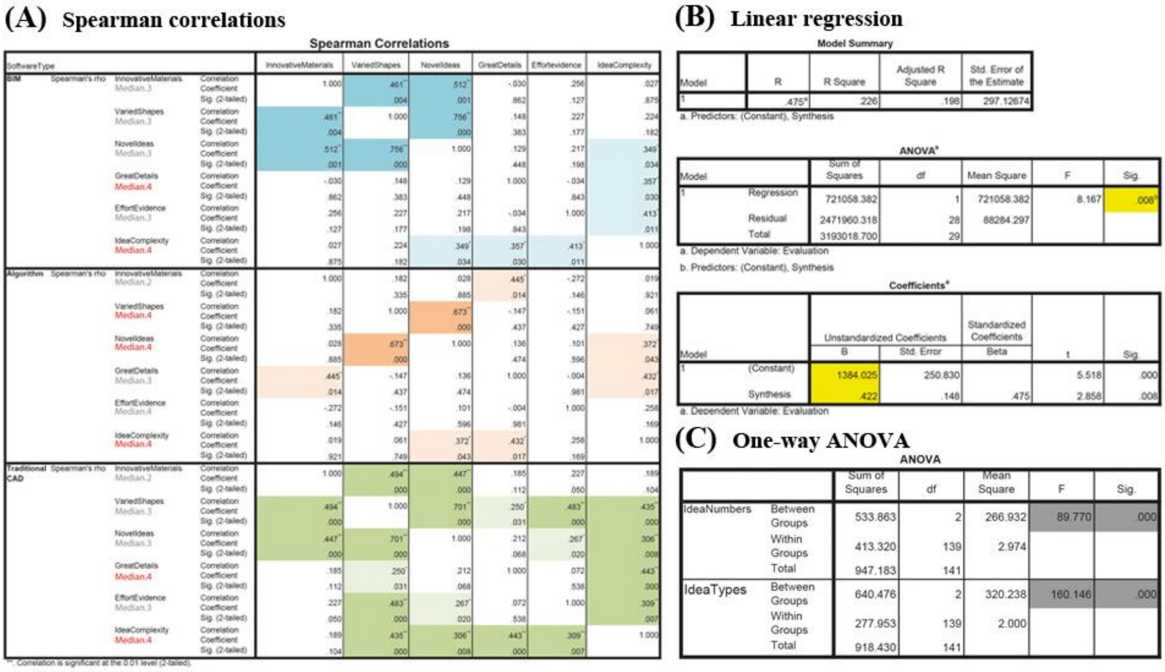


Source: Author reproduced

c-3-2) Inferential analysis

The protocol study was coded in a format and extended to a statistical analysis for in-depth investigation of the interrelations between different design categories. The statistical tests applied correlation (Table05.11-A), regression (Table05.11-B) and also included one-way ANOVA (Table05.11-C). The results were presented showing the computed coefficients.

Table5.11-A-B-C Inferential analysis - SPSS



(A) Spearman correlations

Spearman Correlations

SoftwareType				InnovativeMaterials	VariedShapes	NovelIdeas	GreatDetails	Effortevidence	IdeaComplexity
BIM	Spearman's rho	InnovativeMaterials Median.3	Correlation Coefficient	1.000	.461**	.512**	-.030	.256	.027
			Sig. (2-tailed)		.004	.001	.862	.127	.875
		VariedShapes Median.3	Correlation Coefficient	.461**	1.000	.756**	.148	.227	.224
			Sig. (2-tailed)	.004		.000	.383	.177	.182
		NovelIdeas Median.3	Correlation Coefficient	.512**	.756**	1.000	.129	.217	.349*
			Sig. (2-tailed)	.001	.000		.448	.198	.034
		GreatDetails Median.4	Correlation Coefficient	-.030	.148	.129	1.000	-.034	.357*
			Sig. (2-tailed)	.862	.383	.448		.843	.030
		EffortEvidence Median.3	Correlation Coefficient	.256	.227	.217	-.034	1.000	.413*
			Sig. (2-tailed)	.127	.177	.198	.843		.011
		IdeaComplexity Median.4	Correlation Coefficient	.027	.224	.349*	.357*	.413*	1.000
			Sig. (2-tailed)	.875	.182	.034	.030	.011	
Algorithm	Spearman's rho	InnovativeMaterials Median.2	Correlation Coefficient	1.000	.182	.028	.445*	-.272	.019
			Sig. (2-tailed)		.335	.885	.014	.146	.921
		VariedShapes Median.4	Correlation Coefficient	.182	1.000	.673**	-.147	-.151	.061
			Sig. (2-tailed)	.335		.000	.437	.427	.749
		NovelIdeas Median.4	Correlation Coefficient	.028	.673**	1.000	.136	.101	.372*
			Sig. (2-tailed)	.885	.000		.474	.596	.043
		GreatDetails Median.3	Correlation Coefficient	.445*	-.147	.136	1.000	-.004	.432*
			Sig. (2-tailed)	.014	.437	.474		.981	.017
		EffortEvidence Median.4	Correlation Coefficient	-.272	-.151	.101	-.004	1.000	.258
			Sig. (2-tailed)	.146	.427	.596	.981		.169
		IdeaComplexity Median.4	Correlation Coefficient	.019	.061	.372*	.432*	.258	1.000
			Sig. (2-tailed)	.921	.749	.043	.017	.169	
Traditional CAD	Spearman's rho	InnovativeMaterials Median.2	Correlation Coefficient	1.000	.494**	.447**	.185	.227	.189
			Sig. (2-tailed)		.000	.000	.112	.050	.104
		VariedShapes Median.3	Correlation Coefficient	.494**	1.000	.701**	.250*	.483**	.435**
			Sig. (2-tailed)	.000		.000	.031	.000	.000
		NovelIdeas Median.3	Correlation Coefficient	.447**	.701**	1.000	.212	.267*	.306**
			Sig. (2-tailed)	.000	.000		.068	.020	.008
		GreatDetails Median.4	Correlation Coefficient	.185	.250*	.212	1.000	.072	.443**
			Sig. (2-tailed)	.112	.031	.068		.538	.000
		EffortEvidence Median.3	Correlation Coefficient	.227	.483**	.267*	.072	1.000	.309**
			Sig. (2-tailed)	.050	.000	.020	.538		.007
		IdeaComplexity Median.4	Correlation Coefficient	.189	.435**	.306**	.443**	.309**	1.000
			Sig. (2-tailed)	.104	.000	.008	.000	.007	

**. Correlation is significant at the 0.01 level (2-tailed).

(B) Linear regression

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.475a	.226	.198	297.12674

a. Predictors: (Constant), Synthesis

ANOVAa

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	721058.382	1	721058.382	8.167	.008b
	Residual	2471960.318	28	88284.297		
	Total	3193018.700	29			

a. Dependent Variable: Evaluation

b. Predictors: (Constant), Synthesis

Coefficientsa

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1384.025	250.830		5.518	.000
	Synthesis	.422	.148	.475	2.858	.008

a. Dependent Variable: Evaluation

(C) One-way ANOVA

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
IdeaNumbers	Between Groups	533.863	2	266.932	89.770	.000
	Within Groups	413.320	139	2.974		
	Total	947.183	141			
IdeaTypes	Between Groups	640.476	2	320.238	160.146	.000
	Within Groups	277.953	139	2.000		
	Total	918.430	141			

Source: Author reproduced

5.9 Discussion

This chapter reviewed the research plan for this Ph.D. thesis which includes appropriate research questions, initial pilot work and research methodologies. Regarding hospital building design and relevant research areas, such as design cognition and creativity, existing literature, as identified in Chapters 1, 2 and 3, provides an overview of the research framework, and confirms the research direction. When compared with existing hospital design research, this (Ph.D.) thesis is not limited to investigating any specific project, its design idea and activity. Instead, the study explores the relationship between the creativity of the design in terms of ideation (fluency, variety and originality) and the differences in the creative process when using parametric CAD, which can be applied to any new hospital building design. Therefore, a comparative study of two CAD methods, parametric and nonparametric, was applied for the purpose of this investigation, as the different CAD methods present distinct and different functional tools and utilities. The main premise of this research is that it is believed that the use of CAD can affect the user's design performance as well as the process of design cognition (See Section 4.2.1, Chapter 04).

In the above explanation of the primary research plan, an empirical research method was required to discover evidence-based objective research findings. There were three stages in this research. First, the initial pilot work involved interviews with experienced hospital architects. These were arranged to establish a research focus based on objective professional factors rather than subjective personal judgements. The interview feedback was collected, summarised and then collated as important preparation for the next stages in the research. Second, the selection of dual research methodologies was designed to overcome any disadvantages of a single research method. Two methodologies were employed: 1. A retrospective questionnaire evaluation of design performance and 2. A computer-based protocol analysis of the on-going design process. On one hand, the closed questionnaire type and questions were carefully designed to provide different grades of response, in order to appropriately measure the participants' attitudes to their design experiences. On the other hand, in the computer-based protocol analysis, classifications of design behaviour and the use of digital recording software were applied to manage the process for the experimental design task and to generate essential data. Finally, all research data was input into a statistical analysis program (SPSS - Statistical Package for Social Science) where different statistical methods were used to produce reliable results to enable further research findings and discussion.

Part III/ Chapter 6 – Research findings 1

Case Study 1-2: Summaries of descriptive statistics from the survey on the use of parametric and nonparametric design methods in hospital design offices.

6.1 Introduction

The chapter presents the research findings from the questionnaire survey that was conducted to examine and gather evidence on the creative design performance of CAD architects with different work experience. Two different software types (parametric and nonparametric CAD), with three prevalent software packages (AutoCAD, BIM and Grasshopper) in practice were selected as the classification criteria for the comparative user groups. The participants were asked to answer the questions with reference to their own personal CAD experience in hospital design projects.

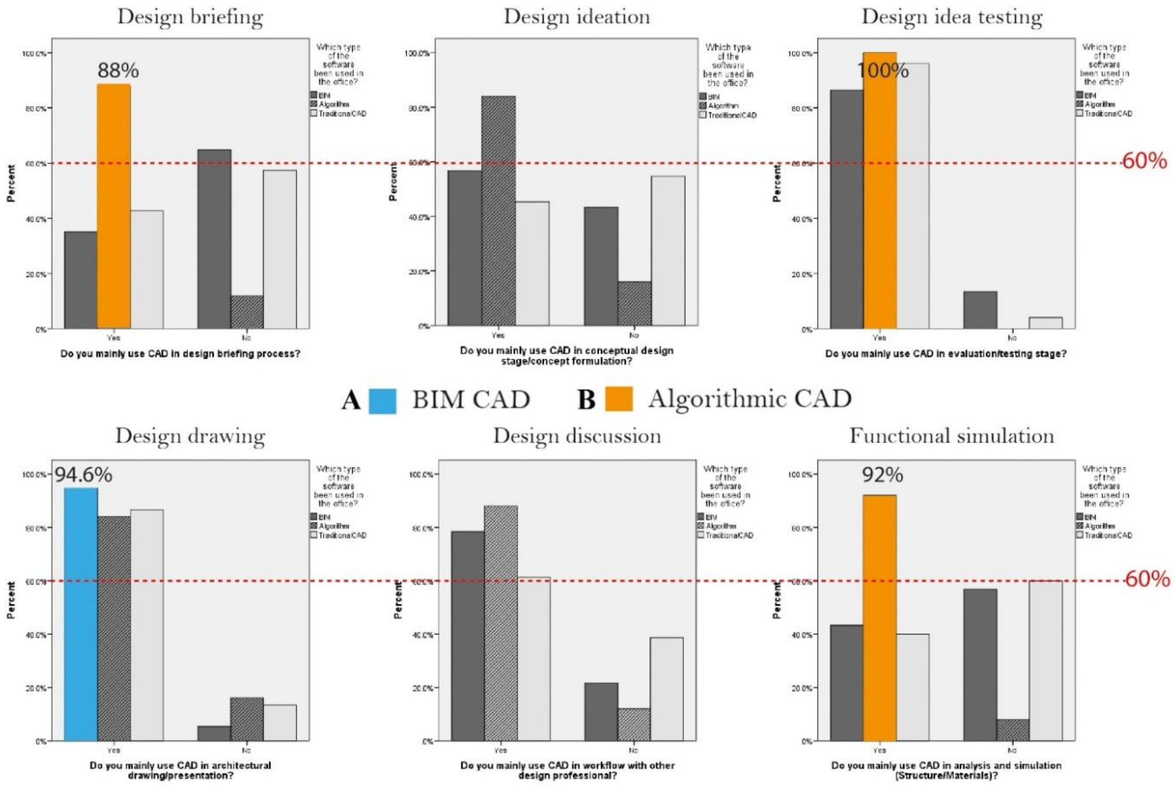
The content contains part of the research findings based on a summary of descriptive statistics using two techniques for measuring creativity when using CAD tools in the hospital design process. The first identifies three indicators for creativity in terms of fluency (idea numbers), flexibility (idea variety) and originality (idea uniqueness) (Torrance, 1971). The second involves judgements on product creativity in three clusters: a Creativity cluster comprising 'Novel use of material, Novel idea, Variation in shapes, Details and Elaborate ideas', a Technical cluster subdivided into 'Organization, Neatness, Planning, Symmetry and Expression of meaning' and Aesthetic judgement encompassing 'Liking, Aesthetic appeal and Worth displaying' (Amabile, 1982). In addition to the statistical summaries, the analysis results are discussed using relevant interview materials collected during the survey.

6.2 CAD tools and design process

Six design activities were selected as vehicles for an understanding of where the CAD tools were deployed in the design process: design briefing, concept formulation, concept testing, architectural drawing or presentation, discussion with other professions and functional simulation.

Overall, 60% of parametric CAD users agreed that CAD was used in all these aspects of the design process while 60% of nonparametric CAD users agreed that the CAD tool was used mainly in concept testing (drafting layout) and architectural presentation (Fig.6.1). When it came to parametric user groups, the BIM system users stated that the parametric modelling system improved work coordination particularly in 2D drawing and 3D presentation. BIM users (Fig.6.1-A) represented the highest percentage, 94.6% agreement with respect to where in design, i.e. which stage in the design process CAD was most useful, identifying drawing and presentations. This might be because the BIM system provides excellent integration between 2D drawing and 3D modelling, so architects found it easy to process their design developments within the same CAD environment and to detect design errors easily during the design process. In addition, the algorithmic CAD architects (Fig.6.1-B) also had a high percentage of respondents suggesting the tool was most useful during three design stages: design briefing (88%), design idea testing (100%) and functional simulation (92%). The algorithmic CAD architects identified that they integrated functional simulations such as lighting or solar testing in the design briefing stage to determine their design direction because they considered natural lighting as a very important factor in the design of wards. However, this general review of using CAD tools for hospital design provides only a descriptive overview of architects’ attitudes in relation to CAD tools but does not indicate any effects on design performance. The following sections aim to use statistical diagrams to explore the potential impact of using a particular CAD tool on design creativity.

Fig.6.1 The CAD methods & hospital design process



Source: Author reproduced/ SPSS outputs

6.3 Measurements of creativity in the hospital design process

This section uses different diagrams on descriptive statistics to summarise the research observations with reference to three creativity indicators based on Torrance’s (1971) research: fluency (idea numbers), flexibility (idea variety) and originality (idea uniqueness).

6.3.1 Idea fluency as a parameter of creativity

a) The generation of idea numbers

The following pie charts (Fig.6.2) show the proportional frequency for the different CAD users' thoughts on the impact of using the tool on idea numbers during the design process. The majority of traditional CAD users (62.67%) thought the tool had helped them to generate 3 ideas on average during the design process, and 16% of users were able to produce 5 ideas using the same tool in the design. Although only 51.35% of BIM users thought they had produced 3 ideas in the design, there were 21.62% of users, around 6% higher than with traditional CAD, who had generated over 5 ideas. 60% of algorithmic CAD users claimed a remarkable number of 10 design ideas created during the design process. Even so, the pie charts do not show any evidence as to how the specific CAD tools had influenced the design idea numbers, so the following sections show further tests conducted in this study using different statistical techniques to explore in greater detail the relationship between idea numbers and the use of the CAD tools.

Fig.6.2 The CAD methods & production of hospital design idea numbers

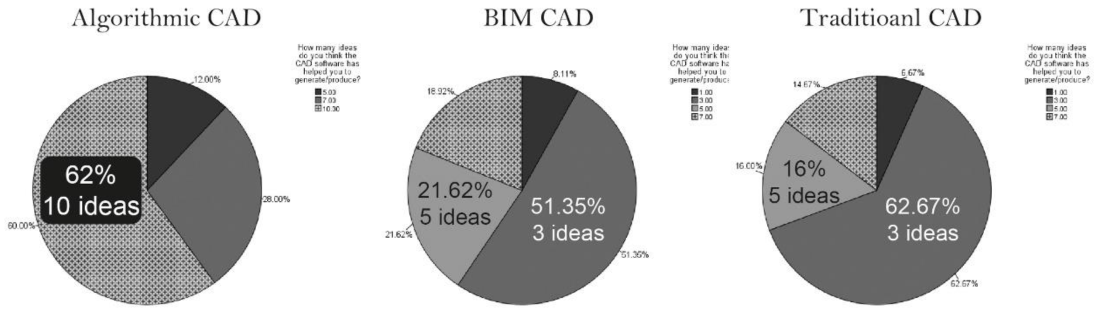


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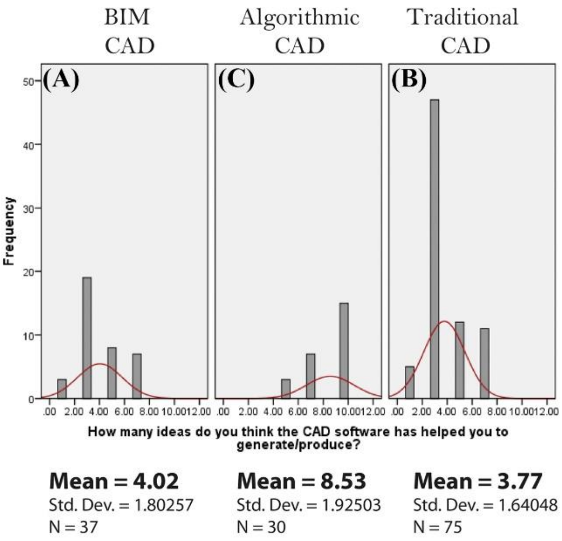
Fig.6.2-1 The CAD methods & hospital idea numbers



Source: Author reproduced/ SPSS outputs

Next, this study explores the statistical 'mean' of the data distribution (Fig.6.2-1). The mean shows the central tendency of data, or the average, in typical statistical observations. It presents a particular value instead of general groups' data. This representative value can provide easy inspection and understanding of the data bias. For example, the mean can help to find the average value for certain test groups such as average ages and numbers. The three diagrams show their means, and each presents a particular number of ideas that CAD users thought the tool had helped to generate in the design process. There are about 3-4 ideas for traditional CAD, 4 ideas for BIM and 8-9 ideas for algorithmic CAD. Clearly, the response suggests that algorithmic CAD generated almost twice as many ideas as the others.

Besides that, the histogram and its related curve (Fig.6.2-1) also define the relationship between CAD tools and idea numbers. Traditional CAD (Fig.6.2-1-A) and BIM (Fig.6.2-1-B) present a positively skewed form, which means the observed variables are close to the left side with approximately 4 ideas as the mean. On the other hand, algorithmic CAD (Fig.6.2-1-C) demonstrates a trend towards the right side, which is a negative skew with approximately 9 idea numbers as the mean. The skewed shape and the mean indicate the general tendency of the algorithmic CAD tool to help users to generate more ideas. Turning to the curve form, algorithmic CAD (Fig.6.2-1-C) presents a flat curve shape that goes against the normal bell-shaped curve. 'Normal distribution is used to describe a symmetrical, bell-shaped curve, which has the greatest frequency of scores in the middle with smaller frequencies toward the extreme' (Gravetter, Forzano and Wallnau, 1998). So, this flat curve means the values of ideas generated are distributed more extremely as opposed to normal distributions. In other words, algorithmic CAD had a significant tendency to generate high values of design ideas. In contrast, the results also confirm that traditional CAD (Fig.6.2-1-A) design methods did not have the potential to help produce a large number of design ideas.

Although BIM and algorithmic CAD are in the same category, i.e. parametric tools, algorithmic CAD performed better in idea production. The reason is that the algorithmic CAD tool offers an associated design information structure in the design process. It is a flexible and conceptual design process that encourages users to explore and vary their unique design ideation. During interviews, algorithmic CAD users said they normally design a process to produce ideas. Not using the traditional method of thinking of a particular type of design as a template for generating the 'idea' and then using CAD in the ideation process to draw it allowed them to produce a large number of ideas by simply inserting more values in the parametric slider; the algorithmic definition then created many more design options/solutions. The difference from the conventional CAD process is that this generative and associative design process helps architects to make their design thinking visible, isolates them from complicated hospital design regulations and enables them to concentrate on the construction of specific concept developments. Besides that, those design algorithms can always be modified according to varying design parameters. Terzidis (2003) argues the algorithmic design process is a computational procedure of design constructions; the process involves deduction, induction, generalisation, abstraction and organised logic regarded as extensions to human thinking. Runco (1986), Runco and Okuda (1991), and Chand and Runco (1995) compared implicit and standard instructions for design students during their learning. They highlight the importance of reducing functional fixedness and increasing flexibility during the ideation stages where standard instructions, such as pre-defined computer programs, might block the mental set (cognitive process) with less alternative thinking.

However, the conventional CAD users observed that the design interface was of no obvious help in creating design ideas. Because most of the drawing tools in AutoCAD offer only partial modelling functions under a pre-defined menu (Fig.6.3), architects must find existing geometric shapes for the design and then incrementally construct their ideas one by one. This process contains less flexible thinking and no visible structure for the design outputs, which play an important role in the idea exploration stage. For example, the architect wants to create the furniture layout in a waiting zone with a comfortable and random ambience. AutoCAD design can only manually arrange these objects with a 'random' feeling but cannot create an associated system defining the geometric relationships with random distances (Fig.6.3-1). But without mathematical support, humans cannot generate random numbers (Figurska, Stańczyk and Kulesza, 2008). As a result, the conventional design environment only provides instructional design options with less reliable and unclear design structures. On the other hand, the algorithmic design interface uses a more adaptable design process, but it is controlled by an identifiable mathematical process (Fig.6.3-2). Algorithmic CAD can produce a limitless computed randomness (Fig.6.3-2-A) and coordinate the furniture (Fig.6.3-2-B) with associated distances, and so creates evidence-based designs for hospitals.

Fig.6.3 AutoCAD design menu

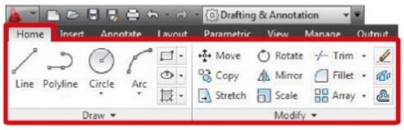


Fig.6.3-2 Mathematical arranged random layouts

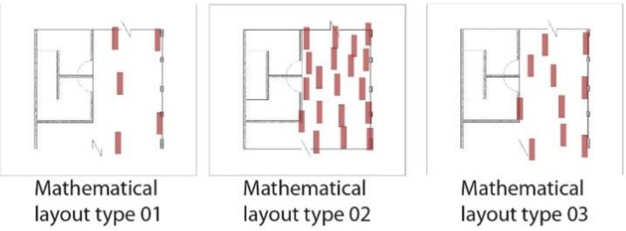


Fig. 6.3-1 Manually arranged random layout

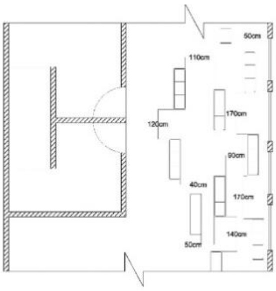
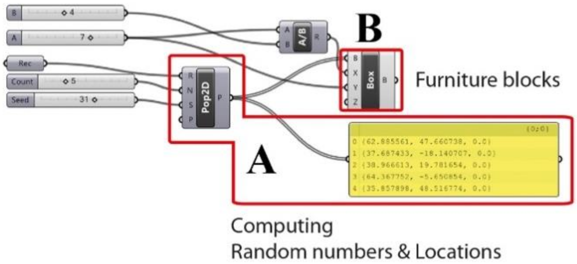


Fig.6.3-2-A-B Algorithmic randomness & object coordination



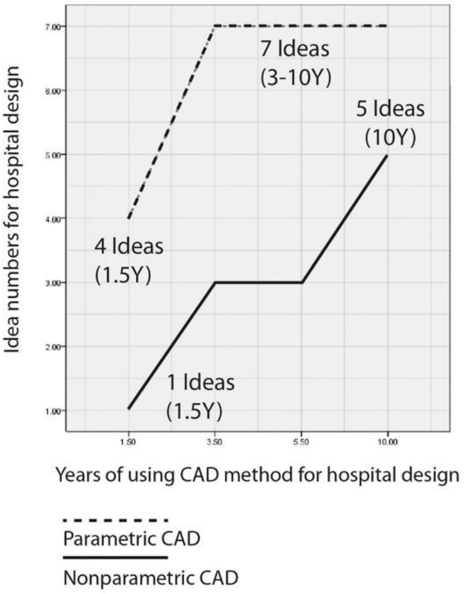
```
{0;0}
0 {62.885561, 47.660738, 0.0}
1 {37.687433, -18.140707, 0.0}
2 {38.966613, 19.781654, 0.0}
3 {64.367752, -5.650854, 0.0}
4 {35.857898, 48.516774, 0.0}
```

Source: Author reproduced/ AutoCAD/ Grasshopper

b) Idea numbers and User experiences

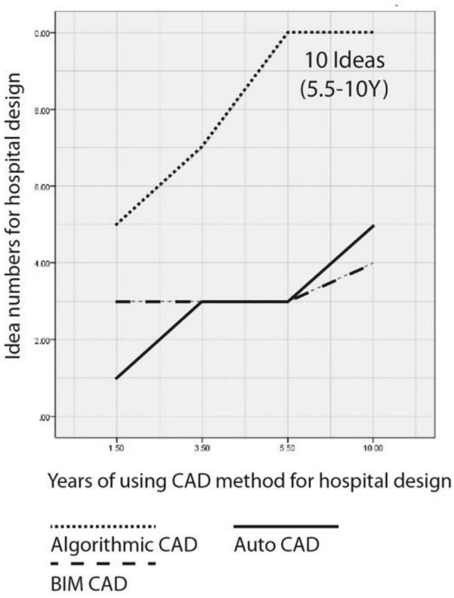
This section shows the connection between user experience and idea fluency as having important effects on creativity. The first line graph (Fig.6.4) shows that both parametric and nonparametric tools show increases in the number of ideas when designers have a longer experience with the tools. In the second diagram (Fig.6.4-1), the algorithmic CAD users showed a remarkable idea generation tendency with over 10 ideas when they had over 5.5 years CAD experience in hospital design. These algorithmic CAD users said that a longer experience in the use of CAD tools offers a better understanding of the algorithmic process, which can produce a large volume of design ideas. Especially when they are more familiar with hospital design regulations, they can apply the rules and design an algorithm rather than finding a certain shape as the concept's prototype or template. For instance, if the design is for a general district hospital (Fig.6.4-2-A), a multi-departmental design with associated distances could be important (Fig.6.4-2-B). The distance between service rooms can be transferred into an algorithm and a range of distances (Fig.6.4-2-C) for the design layouts can be computed (Fig.6.4-2-D).

Fig.6.4 The CAD experience & idea numbers



Source: Author reproduced/ SPSS outputs

Fig.6.4-1 The CAD experience & idea numbers

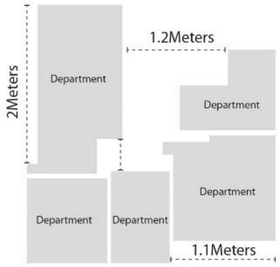


Source: Author reproduced/ SPSS outputs

By contrast, the traditional CAD users thought there was less of an impact when using the tool to explore design ideas. Because the CAD method just followed their thoughts in relation to the abstract concepts, there was no connection between the CAD tool and geometrical design. Consequently, they just used the CAD tools as drawing equipment. Most of their design ideas were based on other projects or were inspired by similar architectural types (Fig.6.4-3). For example, an analogy to hotel design (Fig.6.4-3-A) provides similar layout styles and levels of comfort, which are then applied to the design of inpatient wards (Fig.6.4-3-B). Reference to previous design projects can offer a safe zone for the design development and reduce unexpected design errors. Another example, a pavilion/finger style of inpatient layouts (Fig.6.4-4-A) might ensure that every ward has sufficient lighting and #better external landscape views (Fig.6.4-4-B).

Fig.6.4-2-A General district hospital layout

Fig.6.4-2-B Department layout & distances



Source: Author produced/ AutoCAD

Fig.6.4-2-C Algorithmic design for departmental distances

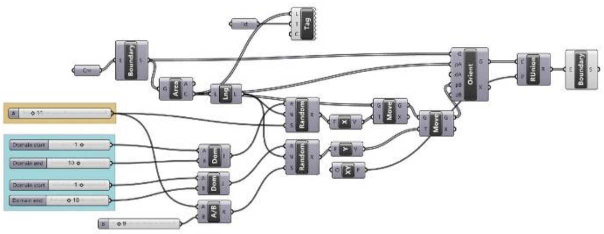
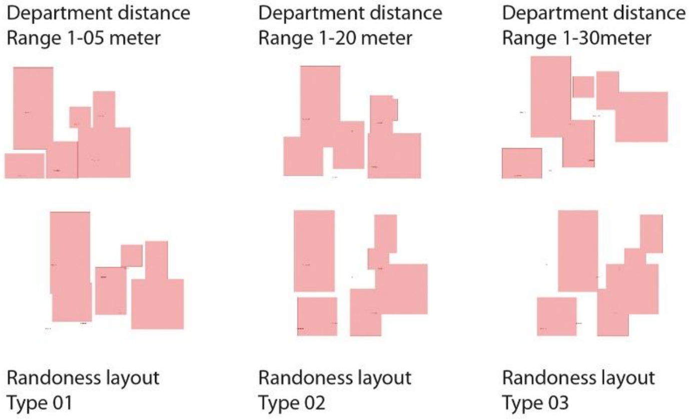


Fig.6.4-2-D Computed design layouts



Source: Author reproduced/ Grasshopper

Next in the analysis is the scatter diagram (Figure6.4-5), which explores the relationship between user experiences and ideation numbers through a mathematical function. This SPSS procedure produced a regression equation ($y = 1.65 + 0.29x$) that can predict the number of ideas resulting from years of experience in using CAD. Each trend uses a mathematical equation, which shows the relationship of user experience (X) to the numbers of ideas generated (Y). For example, for experienced nonparametric designers with 10 years' experience, the calculation shows they were able to generate 4 to 5 ideas according to the equation: $4.55(Y) = 1.65+0.29*10(X)$. When comparing individuals having the same experience with two different types of CAD, the parametric algorithmic CAD architects generated around 4 times more ideas than the nonparametric AutoCAD designers according to the calculation, $3.8=\frac{7.04+0.25*X1}{1.65+0.29*X2}$, where X1 = mean value from the parametric and X2 = mean values from the nonparametric. Woodbury (2010) argues that the conventional CAD environment creates independent objects as the design outputs; copy, cut and paste are applied for design revision and there is no relation between these design objects. In other words, the experience of working with conventional CAD might increase knowledge of design options, but those repeated actions do not directly help idea generation. On the other hand, parametric CAD is built to establish the relationship between design objects. The longer the user is involved with the parametric tools, the better they can learn how to organise the design relationships within the design parameters, as well as to develop associations and a structure on how to extend their idea exploration. As Woodbury said, 'The algorithms takes care of keeping design consistent with the relationships and thus increase designer ability to explore ideas by reducing the tedium of rework'.

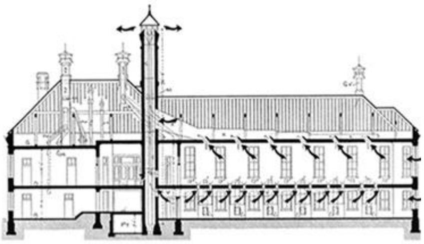
Fig.6.4-3-A Ward design
(Fremont Area Medical Centre)

Fig.6.4-3-B Hotel room design
(Neudahm hotel)

Cited: www.neudahmdesign.com/ www.rdgusa.com

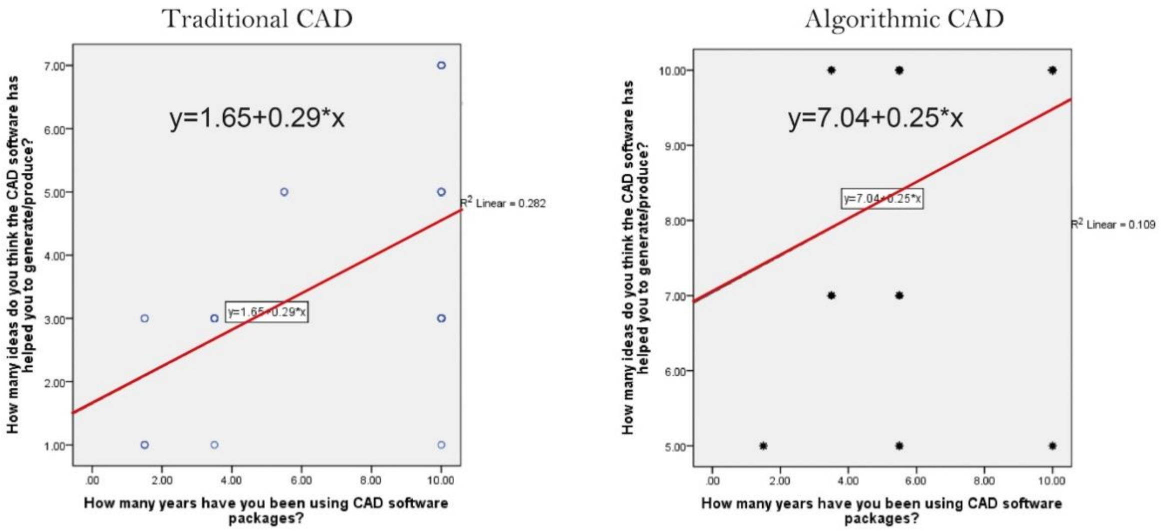
Fig.6.4-4-A Sufficient lighting
(Woolwich hospital)

Fig.6.4-4-B better ventilation
(John Hopkins hospital)



Cited: www.which.co.uk/ john Hopkins hospital

Fig.6.4-5 Idea numbers & user experience (Scatter)



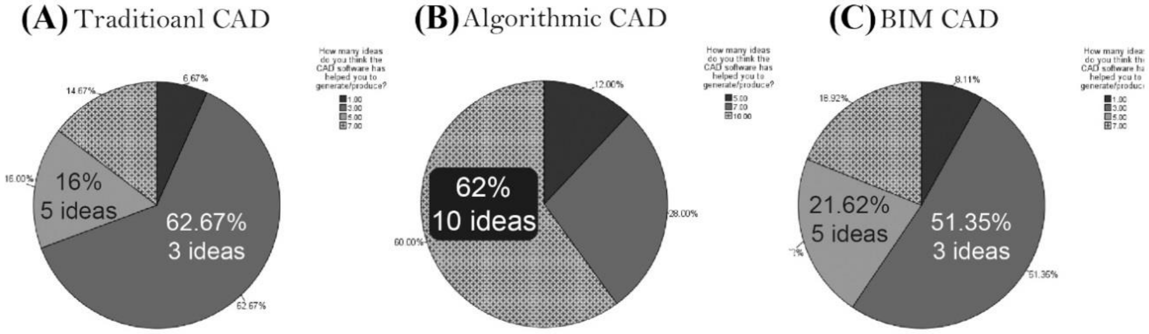
Source: Author reproduced/ SPSS outputs

6.3.2 Idea flexibility as a parameter of creativity

a) The generation of idea genres

The concept of idea flexibility means a variety of different idea types (Torrance, 1971). For example, a floor plan design based on energy improvements might be different from the one designed to improve the efficiency of the medical services through improved departmental circulation. The concept type often determines hospital building developments as well as their service systems. So, it is a very important design factor if architects can produce varied idea types during the design process. Three pie charts (Fig.6.5) summarise the results as to whether computer users thought the CAD tool had helped to produce more idea genres during the design process.

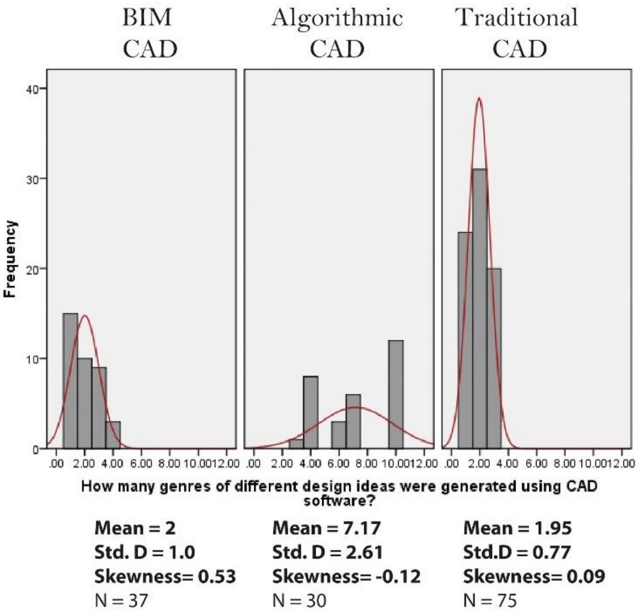
Fig.6.5 The generation of idea genres (pie chart)



Source: Author reproduced/ SPSS outputs

The majority (73.33%) of nonparametric CAD (traditional CAD) users (Fig.6.5-A) thought the tool had helped them to generate up to 2 idea types and only 26.67% of users were able to produce 3 idea types during the design process. In the parametric CAD category, for algorithmic CAD users (Fig.6.5-B), over 60% agreed that the CAD tool encouraged them to produce 7-10 different types of ideas. Although over 60% of BIM users (Fig.6.5-C) thought they had only produced 2 idea types for the design, over 20% of users had produced 3 to 4. On balance, these parametric CAD tool outcomes are generally better than for traditional CAD users.

Fig.6.5-1 The generation of idea genres (Histogram)

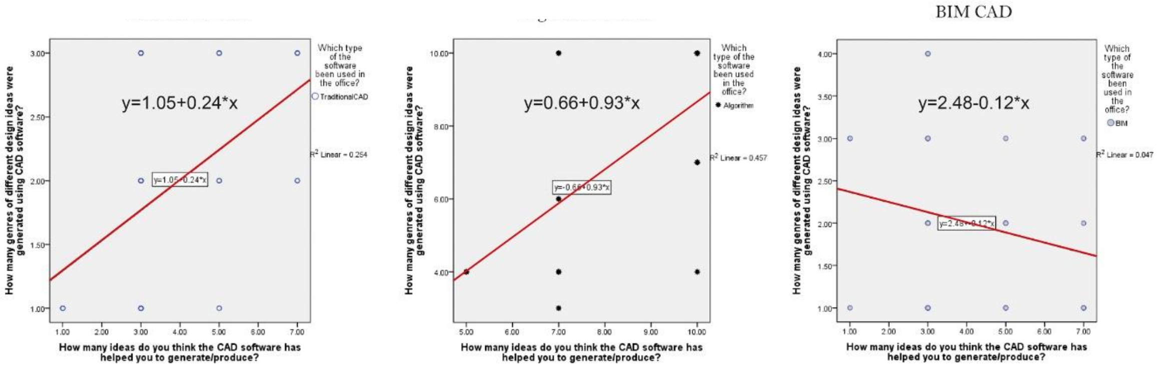


Source: Author reproduced/ SPSS outputs

The histogram in Figure 6.5-1 exhibits a frequency-based data distribution with the selected variable of the idea types. There are two ways used to present the study results. The first, the skewness and the skew's side on the histogram tell us that only algorithmic CAD presents a negative skewness (-0.12) with a skew to the right side. The mean value (7.17) and the majority of idea types are located at a higher range of values, between 8 and 12 idea genres. In other words, algorithmic CAD has helped produce a variety of design genres. By contrast, the traditional CAD tool shows a positive skewness (0.09) with a skew to the left side, the lower value side. The mean value of 1.95 and the variable distribution of idea types are close to a low value of 0 to 4 idea types. That is to say, the tool does not help to produce a large number of design types. In the second, the Standard Deviation (SD), the deviation from the mean value and curve shape, further explains the relationships between idea types generated and the type of CAD package used. The SD value indicates a variation in the data distribution; a small value means a close proximity between the variables and more coherence in the data and a large value means a great range of variety and data dispersion, hence the opposite. Algorithmic CAD provides a large SD with the mean 7.17; the SD is 3 times that of traditional CAD (SD=0.77) with a mean of 1.95. This also means that conventional CAD affected users' performance on the variety of ideas generated with the most common number agreed upon being only 2 types and there were only limited exceptions i.e. few outliers. By contrast, the higher SD value (2.6) of the algorithmic CAD method produced a larger range of idea types, with 3 to 10 types. Also, the curved shape of the histogram shows that algorithmic CAD presents a flat shape, which goes against the statistical norm of a bell-shaped curve. It means the variables, idea genres, have varied values, making this an abnormal distribution. In other words, the CAD method, algorithmic CAD, helped in creating a wide variety of design ideas and a higher overall value.

Besides that, the scatter diagram (Fig.6.5-2) explores the correlation between idea numbers (x) and genres (y) through a mathematical calculation and predicts a regression equation ($y = 1.05 + 0.24x$), linking the two in a linear function. While traditional CAD users generated 5 ideas, they could also produce 2 to 3 genres with the equation 2.25(Y) = 1.05+0.24*5(X). To compare this with algorithmic CAD users, the latter could possibly generate around 5 ideas and 5 types, 5.31(Y) = 0.66+0.93*5(X), which is an equal production of both numbers of ideas and types. Interestingly, only BIM users presented an opposite result from the calculation, 1.88(Y) = 2.48-0.12*5(X), which represented 5 ideas and only 2 types.

Fig.6.5-2 The generation of idea numbers & genres (Scatter)



Source: Author reproduced/ SPSS outputs

These findings indicate a problem with traditional CAD and BIM where the relational process for the design cannot be displayed; this blocks the user's flexible thinking mode and use of the method. In the design process, this hidden data structure for CAD functions in BIM also restricts the users' ability to create variety in design layouts, i.e. genres, during the design ideation process. Hospital design is very complex and is associated with multiple design disciplines. If the CAD users cannot fully see the structure of the design process with its associative geometry, they will feel less inclined to explore the design ideas and try out different concepts. When it comes to conventional CAD, producing the design idea relates to a specific type of design layout. For example, an atrium hall (Fig.5-3) is cognitively associated with having sufficient lighting in space, and monoblock (Fig.5-4) is identified with a compact/centralised design; this means, one type is related to one idea. By contrast, algorithmic CAD provides different idea definitions associated with changes in parameters, and the design outputs are ‘produced in mass’. Also, these algorithms can be added to and, consequently, more than one type of conceptual definition can be created. For example, randomly generated numbers or a series in computing (Fig.5-5) can be applied to layouts (Fig.5-5-A) and facades (Fig.5-5-B), as well as to any other kind of design entity. So, there are no limits for the number of compositions or genres that can be created in this process. The algorithmic design process is constructed by mathematics. As Jones (1970) states, ‘it is fair to say the mathematics is useful only for optimizing’, meaning that algorithmic CAD can not only produce a lot of design ideas but can also optimise the design idea with varied types. Also, in a comparison of the conventional design processes, Terzidis (2003) states that algorithmic design computes the design development and better exploits alternative choices of divergent thinking.

Fig.6.5-3 The atrium hall design hospital

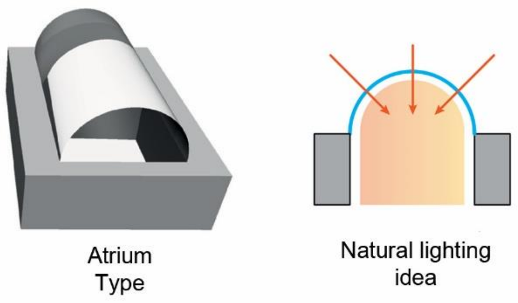


Fig.6.5-4 The monoblock design hospital

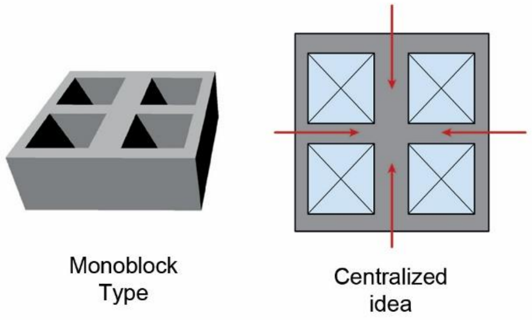
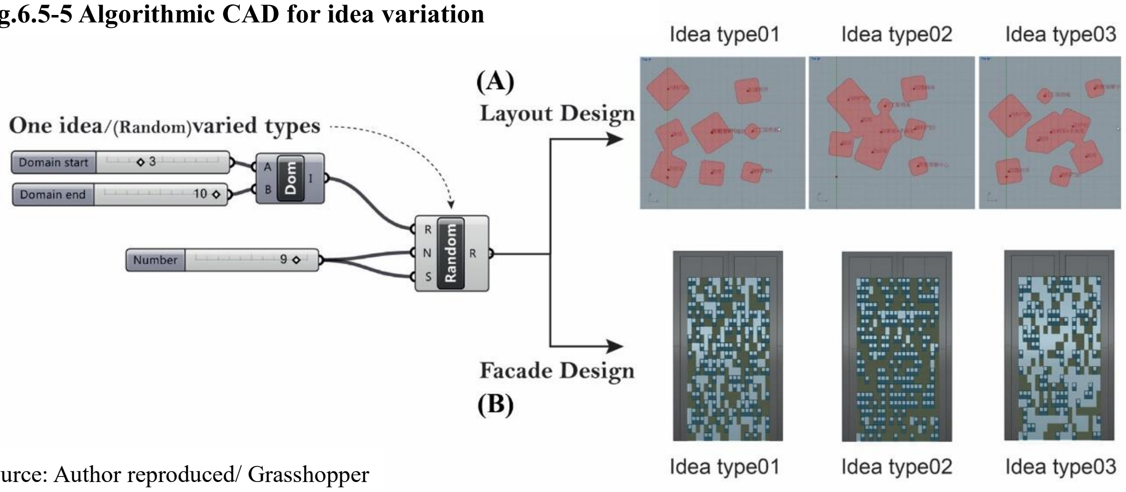


Fig.6.5-5 Algorithmic CAD for idea variation

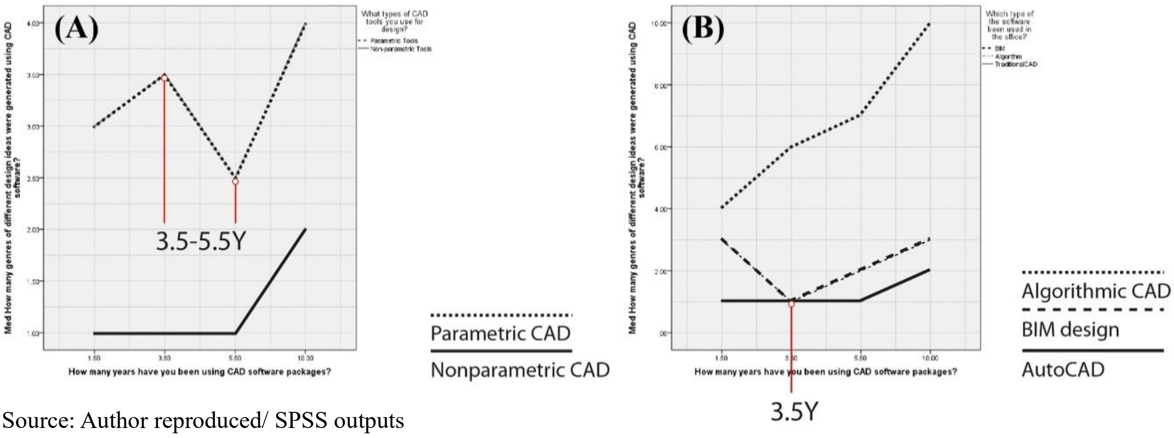


Source: Author reproduced/ Grasshopper

b) Idea genres and User experiences

This section compares the relationship between user experience and varied idea types. The line graph in Figure 6.6 shows that both parametric and nonparametric CAD helped architects to generate more idea types when they had more experience. The first graph (Fig.6.6-A) identifies that idea genres when using parametric CAD tools had a falling trend between 3.5 and 5.5 years of experience, but the overall values for idea types were higher than for nonparametric CAD. There were inconsistencies among BIM users that distorted the picture on parametric CAD when they were included. However, the second multi-line graph (Fig.6.6-B) displays an increase in the design variety among more experienced users in the case of both traditional CAD and algorithmic CAD. Only BIM users showed a falling value for creating idea genres when they had experience of fewer than 3.5 years.

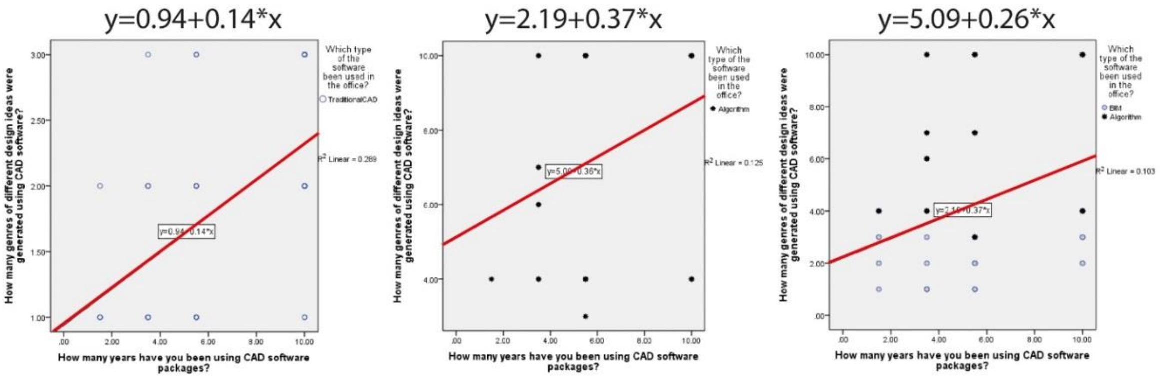
Fig.6.6 The idea genres & user experiences



Source: Author reproduced/ SPSS outputs

The scatter diagrams in Figure 6.6-1 further define this relationship of the user experience and ideation genres through a mathematical equation, ($y = mx + c$), generated using linear regression in SPSS. In this equation, user experience (X) can determine the number of idea types (Y). For example, in the case of a nonparametric designer, or AutoCAD user with 10 years' experience, the calculation tells us they were able to generate approximately 2 to 3 idea types according to the equation 2.34(Y) = 0.94+0.14*10(X). When comparing this with parametric CAD users (BIM and Algorithmic CAD users) with the same number of years of experience, they would generate around 2.5 times more idea types according to the calculation where X1 equals the mean value from the parametric and X2 equals mean values from the nonparametric, $2.5 = \frac{2.19+0.37*X1}{0.94+0.14*X2}$.

Fig.6.6-1 The idea genres & user experiences (Scatter)


y=0.94+0.14*x

AutoCAD users

y=2.19+0.37*x

BIM & Algorithmic CAD users

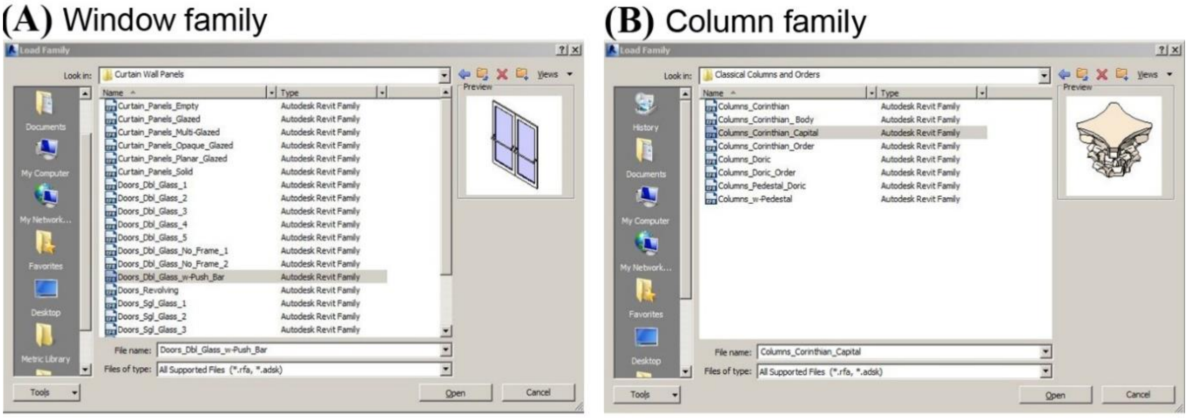
y=5.09+0.26*x

Algorithmic CAD users

Source: Author reproduced/ SPSS

Moreover, if we compare the performance of different software, the experienced algorithmic CAD users were able to produce 3.7 times more idea genres than traditional CAD users using the calculation, $3.7 = \frac{5.09+0.36*X1}{0.94+0.14*X2}$. For that reason, BIM architects argue that although the BIM software is a well-designed system with adaptable parameters, the design data structures are hidden, thus, it is difficult to redefine the algorithms. Users sometimes get lost navigating between different design functions, especially new users. If someone is not familiar with the interface, they must feel limited and find it difficult to construct design variations. In addition, all objects in BIM are pre-defined and belong to a particular family (Fig.6.6-2), such as the window family (Fig.6.6-2-A) and the column family (Fig.6.6-2-B). It is not easy to check the data structures in those pre-made objects; it is even difficult to understand the design algorithms and the resulting geometries. As a result, many new BIM users prefer to use and manipulate similar design types that they are familiar with in order to minimise getting lost during the design process.

Fig.6.6-2 BIM design families


(A) Window family

Look in: Curtain Wall Panels

Name	Type
Curtain_Panels_Empty	Autodesk Revit Family
Curtain_Panels_Glazed	Autodesk Revit Family
Curtain_Panels_Multi-Glazed	Autodesk Revit Family
Curtain_Panels_Opaque_Glazed	Autodesk Revit Family
Curtain_Panels_Planar_Glazed	Autodesk Revit Family
Curtain_Panels_Solid	Autodesk Revit Family
Doors_Dbl_Glass_1	Autodesk Revit Family
Doors_Dbl_Glass_2	Autodesk Revit Family
Doors_Dbl_Glass_3	Autodesk Revit Family
Doors_Dbl_Glass_4	Autodesk Revit Family
Doors_Dbl_Glass_5	Autodesk Revit Family
Doors_Dbl_Glass_No_Frame_1	Autodesk Revit Family
Doors_Dbl_Glass_No_Frame_2	Autodesk Revit Family
Doors_Dbl_Glass_w-Push_Bar	Autodesk Revit Family
Doors_Revolving	Autodesk Revit Family
Doors_Sgl_Glass_1	Autodesk Revit Family
Doors_Sgl_Glass_2	Autodesk Revit Family
Doors_Sgl_Glass_3	Autodesk Revit Family

File name: Doors_Dbl_Glass_w-Push_Bar

Files of type: All Supported Files (*.rfa, *.adsk)

(B) Column family

Look in: Classical Columns and Orders

Name	Type
Columns_Corinthian	Autodesk Revit Family
Columns_Corinthian_ Body	Autodesk Revit Family
Columns_Corinthian_Capital	Autodesk Revit Family
Columns_Corinthian_Order	Autodesk Revit Family
Columns_Doric	Autodesk Revit Family
Columns_Doric_Order	Autodesk Revit Family
Columns_Pedestal_Doric	Autodesk Revit Family
Columns_w-Pedestal	Autodesk Revit Family

File name: Columns_Corinthian_Capital

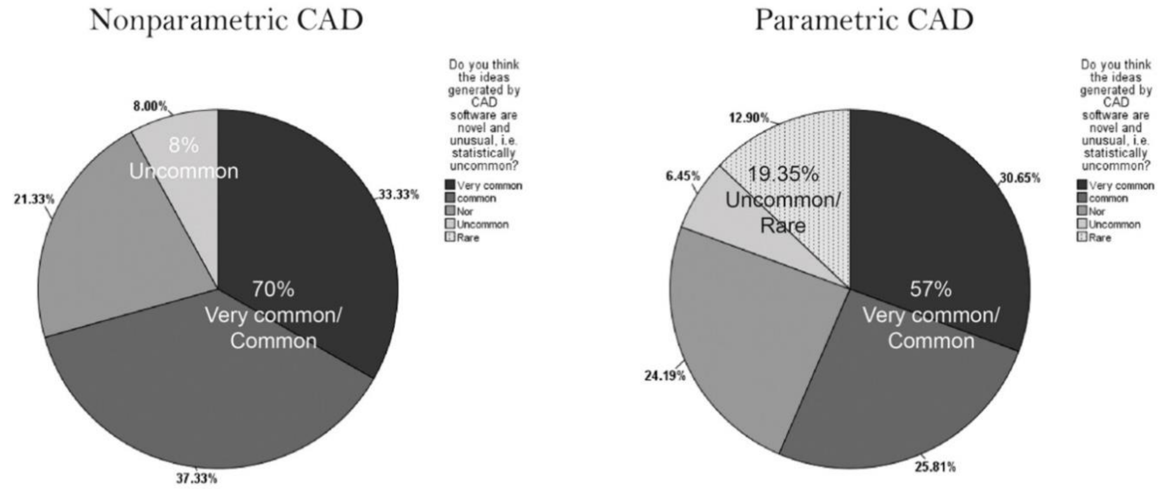
Files of type: All Supported Files (*.rfa, *.adsk)

Source: Author reproduced/ Revit2015

6.3.3 Idea originality as a parameter of creativity

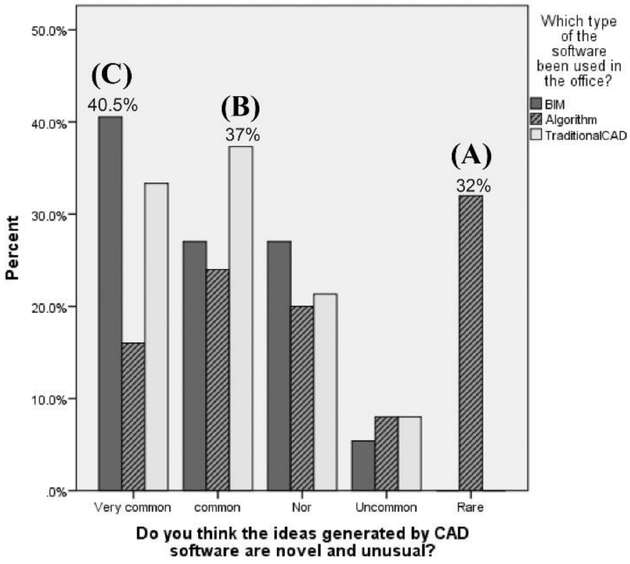
This last section on creativity measurement reviews users' opinions about the originality of their design ideas and types. Originality is an important aspect of the designed products of hospital buildings. It is also an important part of hospital building design in terms of the conceptual quality and innovation. Users were asked whether their generated ideas were 'novel' or 'unusual'. The responses to this question were divided into five categories: 1. Very common, 2. Common, 3. Either common or uncommon, 4. Uncommon and 5. Rare. Two pie charts in Figure 6.7 were used to summarise the percentages of observations. Nonparametric CAD users described originality in their design ideas as ‘very common’ and ‘common’ with results of about 70%; only 8% users thought their designs were novel or uncommon. By contrast, parametric CAD users showed 2.4 times more uniqueness idea production than nonparametric CAD users, with 19% uncommon and rare views regarding their original design.

Fig.6.7 Parametric & nonparametric CAD for idea originality



Source: Author reproduced/ SPSS outputs

Fig.6.7-1 Idea originality of CAD users



Source: Author reproduced/ SPSS outputs

The bar charts in Figure 6.7-1 display further analysis on the comparative results for the three CAD tools. The algorithmic CAD users stated that they perceived their original design ideas generated by the CAD tool as rare in 32% of cases (Fig.6.7-1-A), which was the highest percentage. Both BIM and traditional CAD users thought their design ideas were very common or common: 37% common in the case of traditional CAD (Fig.6.7-1-B), and 40.5% very common for BIM (Fig.6.7-1-C). The algorithmic CAD users stated that the idea construction process with an algorithmic activity was very different from the conventional design activity of just drawing ideas directly from their mind on the screen. Before the design algorithms were completed, they could not properly predict the design output, and the ideas produced often pleasantly surprised them. Most of the algorithmic CAD users said they enjoyed the uncertainty of this design process because it was a process that made them concentrate more on thinking about spatial design rather than on complex functions and regulations for the hospital design. By contrast, the traditional CAD and BIM users stated that they usually reference their design ideas from other design materials such as existing building shapes or layouts and transfer these ideas into the CAD interface; the design ideas are recycled and are thus normally predictable and appear fairly common. They also commented that these methods made them feel confident in the management of the entire design process with fewer technical challenges. Also, because hospital design programs are complex, if one can benefit from using existing design types, they believe this means that the concept should be achievable with both fewer challenges and design problems. Other traditional CAD users think that hospital design is a time-consuming process, as they need to constantly discuss and revise design ideas with departmental managers. Therefore, adopting pre-existing design templates helps them concentrate on the latter design stages of the project such as construction developments. However, the unpredictable design results from algorithmic CAD are built into the mathematical algorithm, which aims to produce design strategies but not design products. As Terzidis

(2003) said, ‘algorithmic form is not about perception or interpretation but rather about the process of exploration, codification and extension of the human mind’. In terms of the design process, ‘algorithms employ induction regression, randomness, etc. the outcomes of which are unknown, unpredictable and unimaginable’ (Terzidis, 2003).

6.4 Judging creativity in hospital building design

This section summarises the collected data on CAD consultants to judge creativity with regards to the ‘product’, i.e. design outcome of hospital buildings, and with respect to three particular clusters: Creativity (Novel use of material, Variation in shapes, Novel idea, Detail, and Elaborate idea), Technical (Organization, Neatness, Planning, Symmetry and Expression of meaning), and Aesthetics (Liking, Aesthetic appeal and Worth displaying). This evaluation provides not only a clear operational assessment and methodology such as using materials or profiles but also helps the production of reliable predictions from objective sources in the judgement of creativity.

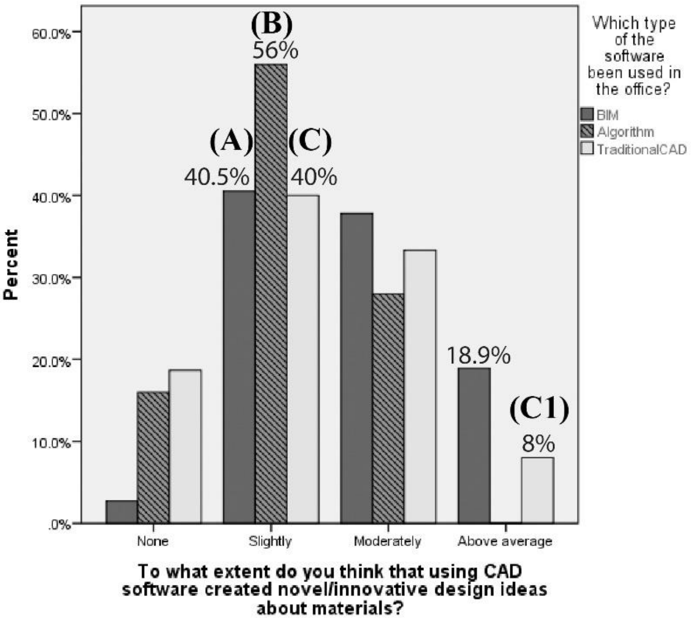
6.4.1 The creativity cluster for hospital building design concepts

The responses in the creativity cluster are divided and measured on a five-point scale, from the lowest to the highest: 1. None, 2. Slightly, 3. Moderately, 4. Good and 5. Immensely/Greatly. The answers from each CAD specialist group were measured and coded with variables using these ordinal rankings. The statistical summary focuses on the percentage or frequency of each group and uses the statistical median as a representation of each group’s opinions. The multi-bar charts demonstrate medians within the overall creativity cluster. The BIM and the traditional CAD experts stated that the tool had a good effect on generating a highly detailed and elaborate design idea with a median of 4 (good). The algorithmic CAD consultants presented slightly better results than the other two groups, stating that the tools had assisted their design projects in a good way with varied shapes, novel ideas, and elaborate design, all with a mean of 4 (good). However, these summaries of the statistical median only provide a general display of judgements in the creativity cluster. The following sections provide more detail and make better comparisons between the user groups.

a) Novel utilisation of materials

The CAD specialists were asked how far they thought the CAD tools had provided architects with help in exploring the innovative use of materials, such as mixed textures or new patterns of design for their hospital design projects. The bar charts (Fig.6.8) display that the majority of responses were located in the ‘slightly helps' category in all 3 cases with 40.5% recorded for the BIM group (Fig.6.8-A), the algorithmic CAD group registering 56% (Fig.6.8-B) and the traditional CAD group showing 40% (Fig.6.8-C). Only 8% of the traditional CAD experts (Fig.6.8-C1) agreed the tool had provided ‘good' help in creating innovative design materials.

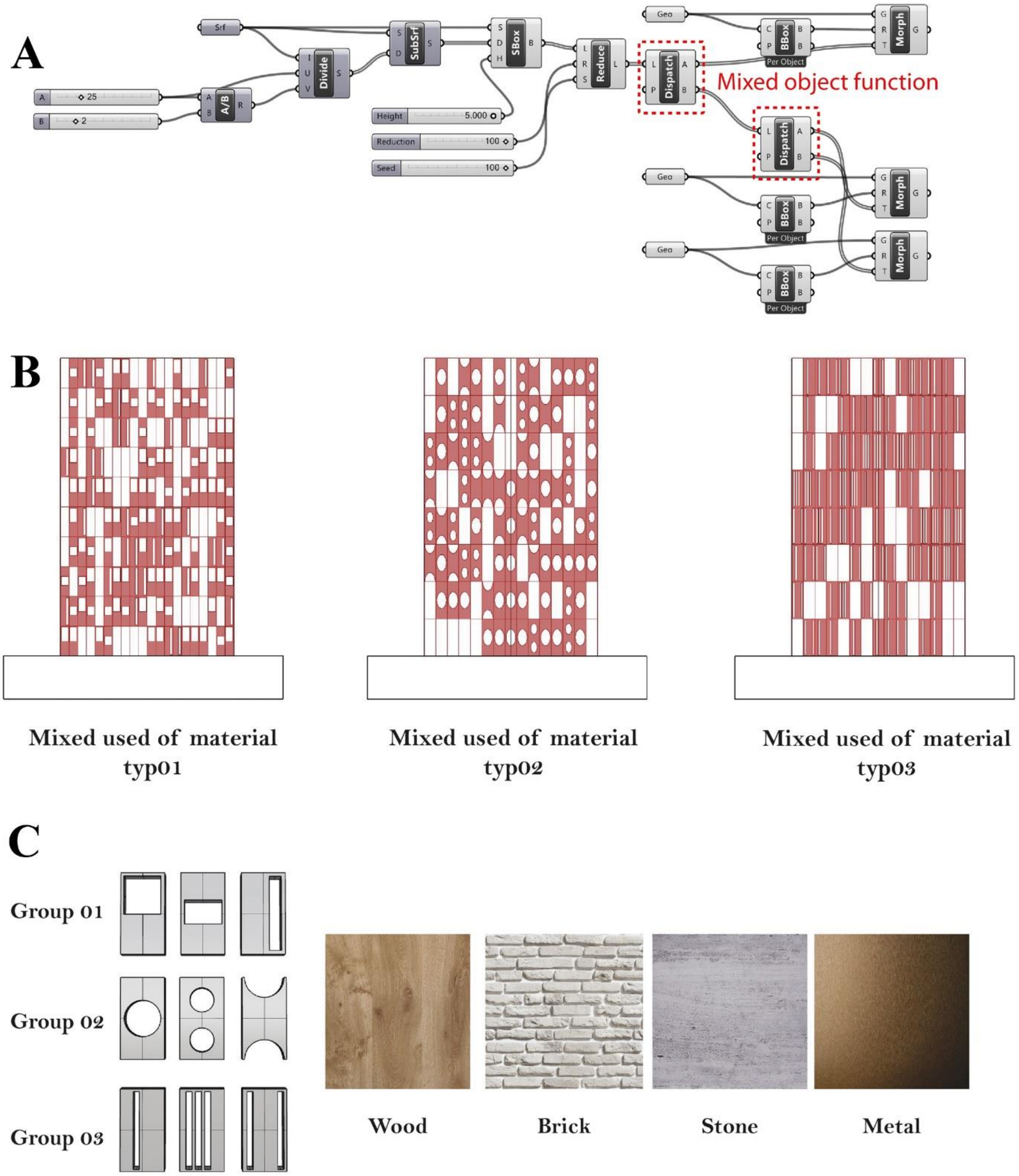
Fig.6.8 Novel utilization of materials



Source: Author reproduced/ SPSS outputs

This is because most hospital building materials are chosen and designed by subcontractors. The materials to be utilised might be specified by the hospital building notes and contained in the functional design for the medical space, which means the architects cannot easily change or invent building materials without professional consultations. For instance, the wall design of the X-ray room must employ a high-pressure lead boned material to prevent exposure to radiation. Partition cladding must be designed with 1mm to 3.5mm steel with plasterboard or plywood (raybloc.co.uk, 2017). In another example, the wall cladding system for hospitals should contain multi-functional design features such as thermal retention, low pollution, fire resistance, water resistance and ease of installation, as in the case of the Dow chemical company’s XPS thermal system (www.dow.com, 2017). Before a project starts, the architect and the client, in this case, the hospital manager, must decide the building design functions, and the architect chooses the associated subcontractors for material supplies. If the client decides their hospital building needs better energy efficiency, the architect needs to find energy saving solutions such as solar panels, a smart shading system or energy recycling machinery. There are limited design interpolations from the architects' side other than the material contractors to be selected. Moreover, most of existing design sources, such as material details, are created and embedded in AutoCAD files when using traditional CAD. Some might occur in BIM models, but they are not produced in algorithmic models. However, the algorithmic CAD specialists stated that parametric aided design using algorithms (Fig.6.8-1-A), such as parametric design patterns or facades (Fig.6.8-1-B), could support the mixed use of materials (Fig.6.8-1-C); however, this might need to be approved by a professional team who can evaluate the possibilities available.

Fig.6.8-1 Algorithmic design for mixed used materials

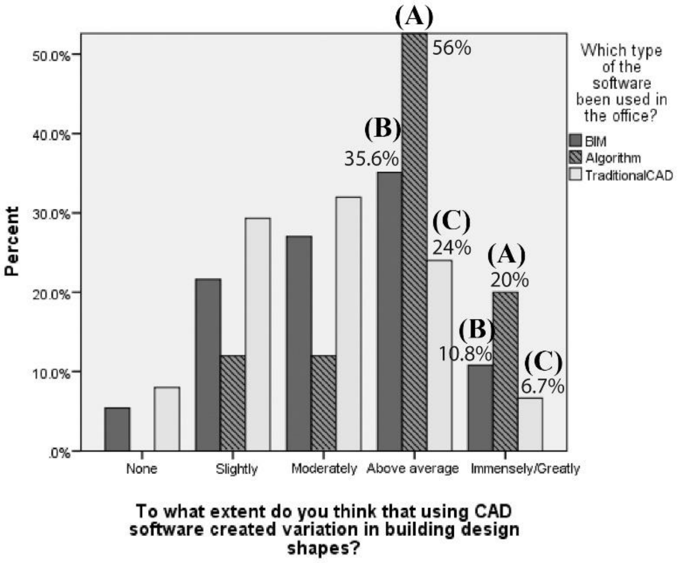


Source: Author reproduced/ Grasshopper

b) Varied shape design

Under the above heading, a question asks about how the CAD tools supported architects in designing buildings using a variety of shapes. The algorithmic CAD consultants (Fig.6.9-A) stated that the CAD tools provided good (56%) and great (20%) help in designing different shapes in over 76% of cases. The BIM design consultants (Fig.6.9-B) agreed that the tool provided 'good' (35.6%) or 'immense help' (10.8%) in generating their building shape design in 46% of cases. Only 30.7% (24% + 6.7%) of the traditional CAD consultants (Fig.6.9-C) thought the tool performed well in this respect.

Fig.6.9 Varied shape design



Source: Author reproduced/ SPSS outputs

The traditional CAD experts said there are commonly two difficulties when designing different shapes for hospitals. First, it is difficult to try a new design type for hospital buildings because most clients, hospital managers or departmental coordinators, have their own preferences about the building layouts. Spatial design priorities are based on efficient operations and medical services. Hospital design architects usually prefer not to try new layouts, so architects feel there is no need to introduce new or different shapes. Second, it is very important that the building should be compact and fully utilised to achieve the most economical layout. There should not be any unnecessary spaces, especially in the outpatient centre. Traditional CAD only provides predefined design menus (Fig.6.9-1-A); users can only use the functions and drawing entities provided and are unable to create new design ideas. As a result, traditional CAD architects prefer to apply the same design layouts, which are grid-based (Fig.6.9-1-B) or rectangular/square in plans (Fig.6.9-1-C). On the other hand, algorithmic experts said algorithmic CAD can rather construct a design system (Fig.6.9-2-A) and produce many spatial compositions (Fig.6.9-2-B) for clients. Clients are able to choose their preferred space, and then architects finalise the result and produce the best design solution. They stated it is very important to offer clients such choices because clients are the main users of the space. Only they know what the professional requirements for their services are and which type of design can best match their operations. With this comparison, we can conclude that conventional CAD picks a shape by typology, but algorithmic CAD provides a strategy for producing forms (See the literature review of typology design in Section 4.3.2.c, Chapter 4). In other words, the algorithmic CAD method upgrades architects' design thinking from the traditional designer's 'solution focused' approach to thinking in a scientific way through a 'problem-focused' mode of thinking (Lawson, 1990). The problem-focused approach in design thinking can be easily linked to strategic planning which, as has been mentioned, should be a leading factor in future healthcare and its associated architecture (Nuffield Trust, 2001).

Fig.6.9-1 Traditional CAD form-finding process

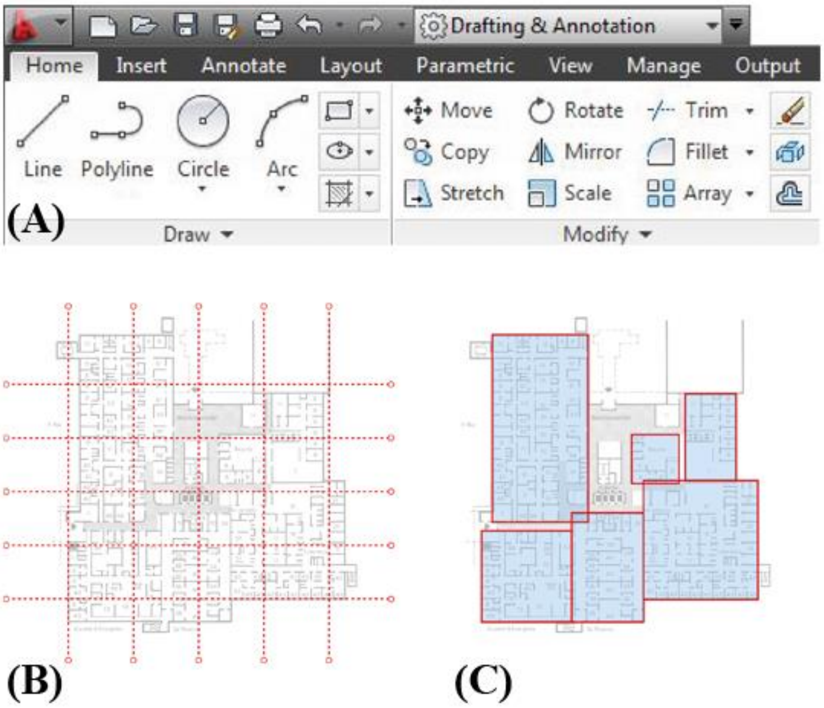
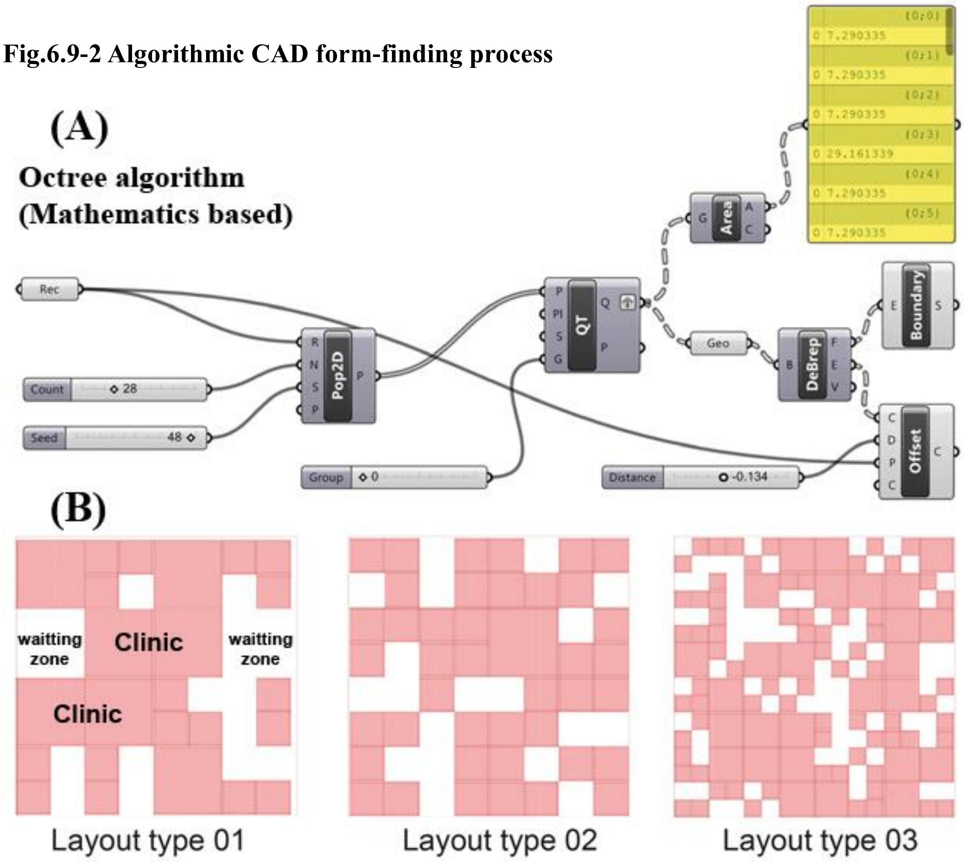


Fig.6.9-2 Algorithmic CAD form-finding process

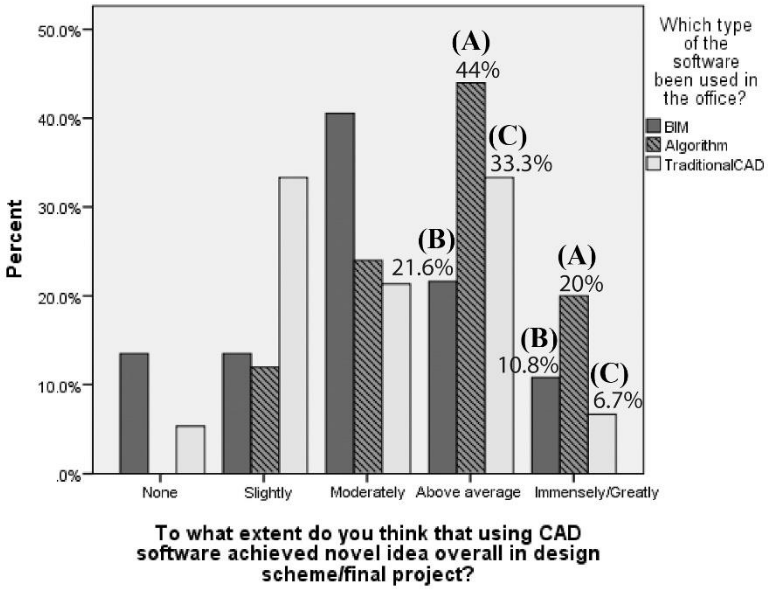


Source: Author reproduced/ AutoCAD/ Grasshopper

c) Novel design ideas

Guilford (1950) argues that novel ideas are associated with personal thinking behaviour with uncommon yet acceptable novelty in responses to issues. Furthermore, 'in conjunction with some of the fluency tests, there may be opportunities to obtain some indications concerning flexibility'; alternatively, flexibility means varied ideation (Torrance, 1971). So, a novel design idea is related to intensive ideation activities. When it comes to hospital design, architects normally discuss ideas with clients during the design briefing. So, a large number of ideas is produced quickly through sketches or diagrams, which are the common methods used during this process. The algorithmic experts showed in 64% of cases that the tool was of 'good' (44%) and 'great help' (20%) in creating novel ideas (Fig.6.10-A). The results were nearly twice as high in this section as in the other two groups – 40% in the traditional CAD group (Fig.6.10-B) and 32% in the BIM group (Fig.6.10-C).

Fig.6.10 Novel design ideas



Source: Author reproduced/ SPSS outputs

The BIM experts presented the lowest percentage as to the software providing great help when compared with the other two groups. Because the (BIM) modelling system uses drawing functions with built-in 3D building components (Fig.6.10-1), it cannot easily make abstract design drafts. For example, to draw a line in BIM means to create a 2D and 3D wall (Fig.6.10-1-A); to draw a rectangular shape automatically generates a 2D and 3D floor plan or a roof (Fig.6.10-1-B). If BIM users want to quickly sketch the design idea for building profiles, they need to build the structure, floor plans, walls, etc. It is a very time-consuming and long procedure. Therefore, quick drawings and producing many ideas for discussion when creating novel ideations are almost impossible processes when using the BIM tool. By contrast, traditional CAD can easily produce single lines in any design views such as floor plans, elevations and section diagrams (Fig.6.10-2). This fast CAD function provides more chances for discussions with clients and helps in design ideation or creating novel ideas. On the other hand, algorithmic CAD helps the architects create many design types and many ideas in an abstract/conceptual form rather than creating a solid image (Fig.6.10-3). Those ideas are presented just as a prototype and can encourage discussion with different professions to upgrade the ideas formed into complete and innovative outputs. As the hospital design process is a multi-disciplinary design activity, it is believed sufficient discussion with different professions can improve design quality and achieve innovative ideas in hospital design (Verderber, 2010).

Fig.6.10-1 BIM design discussion for novel idea development

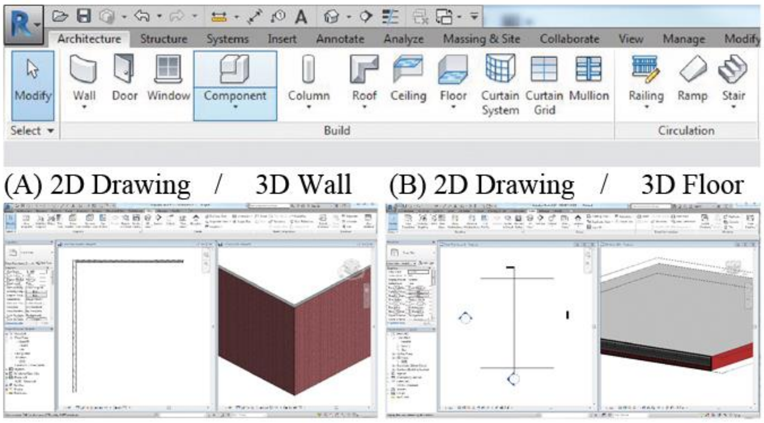


Fig.6.10-2 Traditional CAD (AutoCAD) discussion for novel idea development

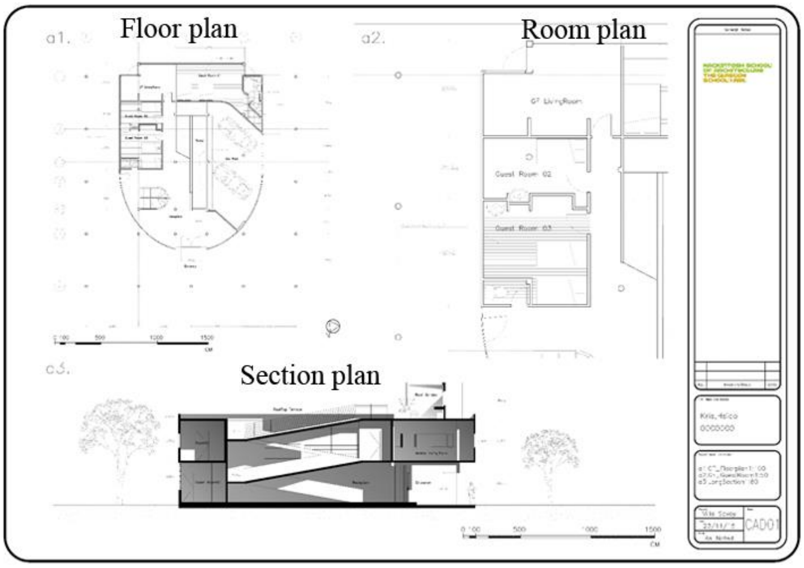
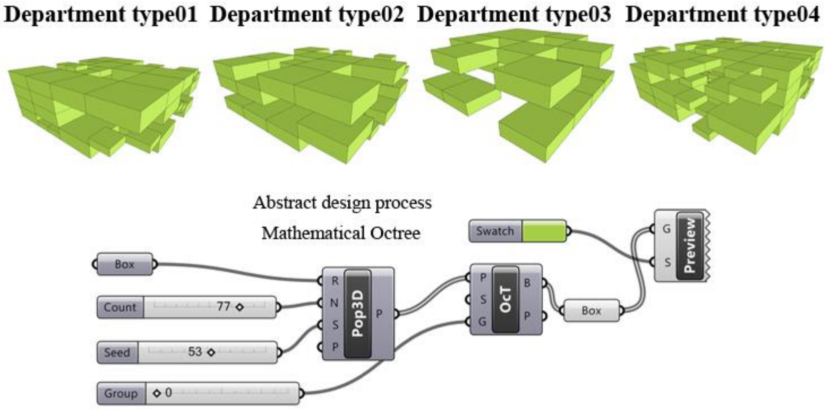


Fig.6.10-3 Algorithmic CAD discussion for novel idea development

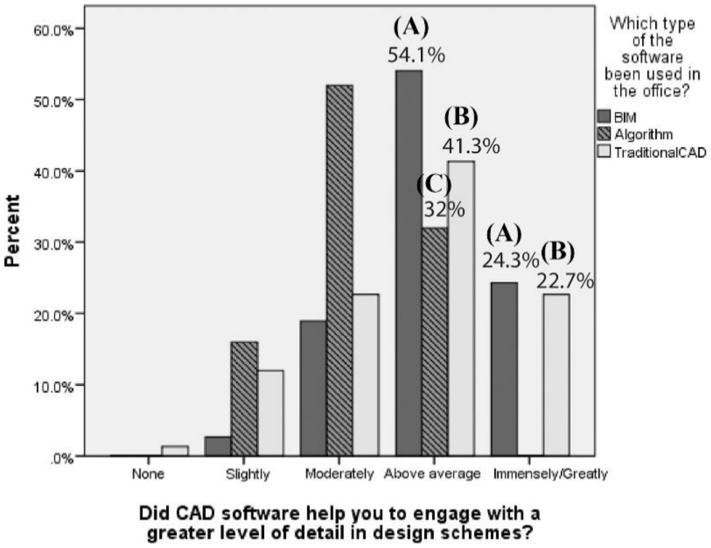


Source: Author reproduced/ AutoCAD/ Grasshopper/ Revit

d) Detailed design of building components

The design detail includes building components or functional facilities, such as cladding or building mechanical systems. For hospital buildings, façade details have a significant relationship with the interiors, like inpatient departments, and mechanical design details are determined by the service pattern. The majority of the BIM design specialists, about 78.4%, stated the method provided 'good' (54.1%) performance or 'greatly helped' (24.3%) in the detailed design for the design project (Fig.6.11-A). 64% of the traditional CAD specialists thought the design methods performed well for the detailed layout (Fig.6.11-B). On the other hand, only 32% of the algorithmic CAD specialists stated that the design methods provided good help for design details (Fig.6.11-C).

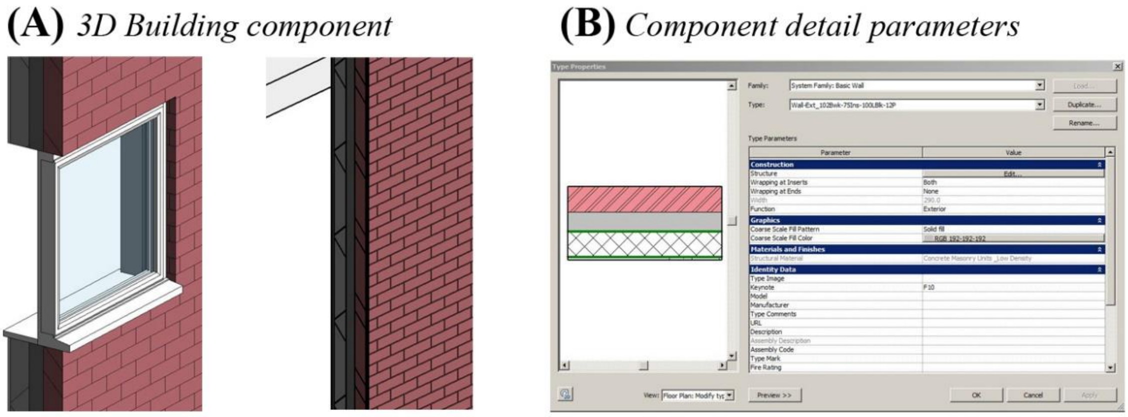
Fig.6.11 Detailed design of building components



Source: Author reproduced/ SPSS outputs

The BIM design consultants said that the computer interface contains a highly functional library system including lots of building components (Fig.6.11-1-A) and details (Fig.6.11-1-B). So, architects could simply apply those pre-made objects during the design process. For example, if the hospital design requires energy to be saved in the façade design, from the library, the BIM architect can choose the most suitable energy-saving glass as the curtain wall system. In traditional CAD, the architects produce 2D drawing blocks (Fig.6.11-2-A). Each block includes a detailed design drawing and material instructions (Fig.6.11-2-B), so traditional CAD architects apply those 2D drawing blocks to help their design details. When compared with the algorithmic CAD, the general algorithmic design method does not provide such a library system. Also, building in new components (Fig.6.11-3-A) might take too much time and make the algorithms become very complex, slowing down the computer (Fig.6.11-3-B). As a result, algorithmic CAD architects usually avoid presenting details in their design drafting stage.

Fig.6.11-1 BIM design details



(A) *3D Building component*

(B) *Component detail parameters*

Type Properties

Family: System Family: Basic Wall

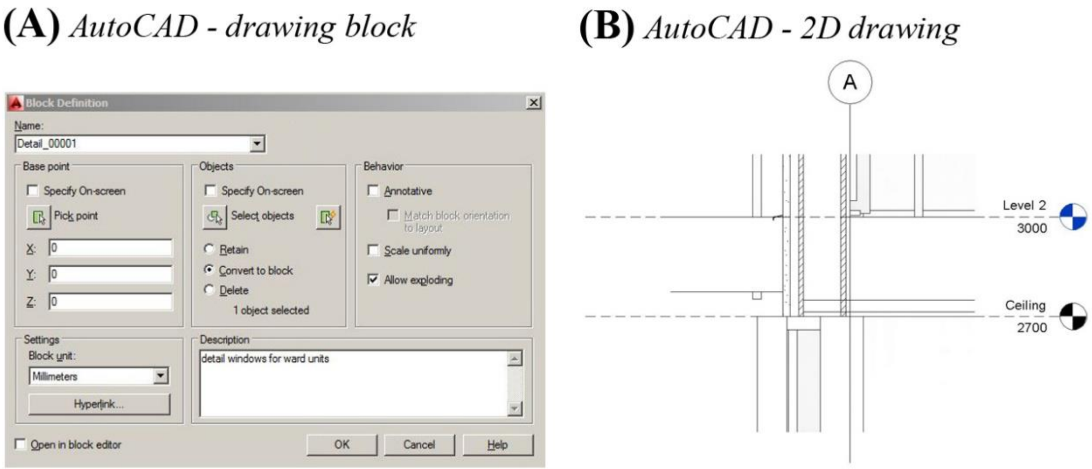
Type: Wall-Ext_102Bwk-75Ins-100LBlk-12P

Type Parameters

Parameter	Value
Construction	
Structure	Edit...
Wrapping at Inserts	Both
Wrapping at Ends	None
Width	290.0
Function	Exterior
Graphics	
Coarse Scale Fill Pattern	Solid fill
Coarse Scale Fill Color	RGB 192-192-192
Materials and Finishes	
Structural Material	Concrete Masonry Units _Low Density
Identity Data	
Type Image	
Keynote	F10
Model	
Manufacturer	
Type Comments	
URL	
Description	
Assembly Description	
Assembly Code	
Type Mark	
Fire Rating	

View: Floor Plan: Modify typ

Fig.6.11-2 Traditional CAD details



(A) *AutoCAD - drawing block*

(B) *AutoCAD - 2D drawing*

Block Definition

Name: Detail_00001

Base point
☐ Specify On-screen
X: 0
Y: 0
Z: 0

Objects
☐ Specify On-screen
○ Retain
● Convert to block
○ Delete
1 object selected

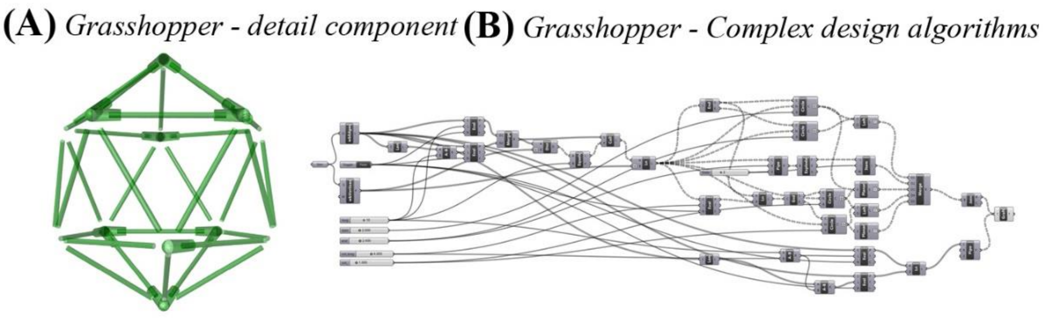
Behavior
☐ Annotative
☐ Match block orientation to layout
☐ Scale uniformly
☑ Allow exploding

Settings
Block unit: Millimeters

Description: detail windows for ward units

☐ Open in block editor

Fig.6.11-3 Algorithmic CAD details



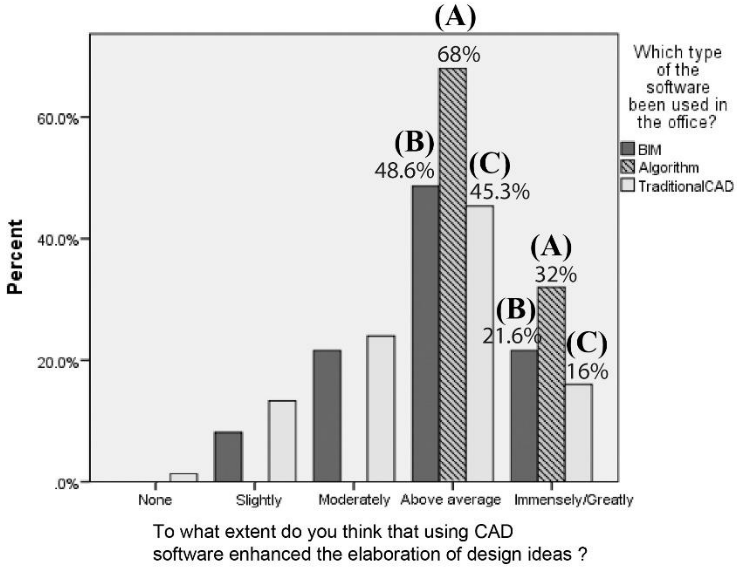
(A) *Grasshopper - detail component* (B) *Grasshopper - Complex design algorithms*

Source: Author reproduced/ AutoCAD/ Grasshopper/ Revit

e) Elaboration of design ideas

Elaboration of design ideas means the progression or development of the design idea. It includes the ability to ‘reframe’ design problems to create solutions. So, the question asked to what degree the CAD methods enhance the elaboration of ideas demonstrated in hospital building design, for example, how is façade design associated with interior ventilation or lighting or to what extent are interior layouts related to service efficiency? The algorithmic CAD consultants showed 'good’ (68%) and 'great' (32%) performance from the tool in 100% of cases (Fig.6.12-A). About 70% of the BIM design consultants (Fig.6.12-B) also indicated the tool provided 'good' (48.6%) or 'immense’ (21.6%) help to the elaboration of design ideas. This was slightly lower in the case of traditional design approaches but there were still 61% (45.3% + 16%) of traditional CAD consultants (Fig.6.12-C) who thought the tool optimised the complexity of design ideas.

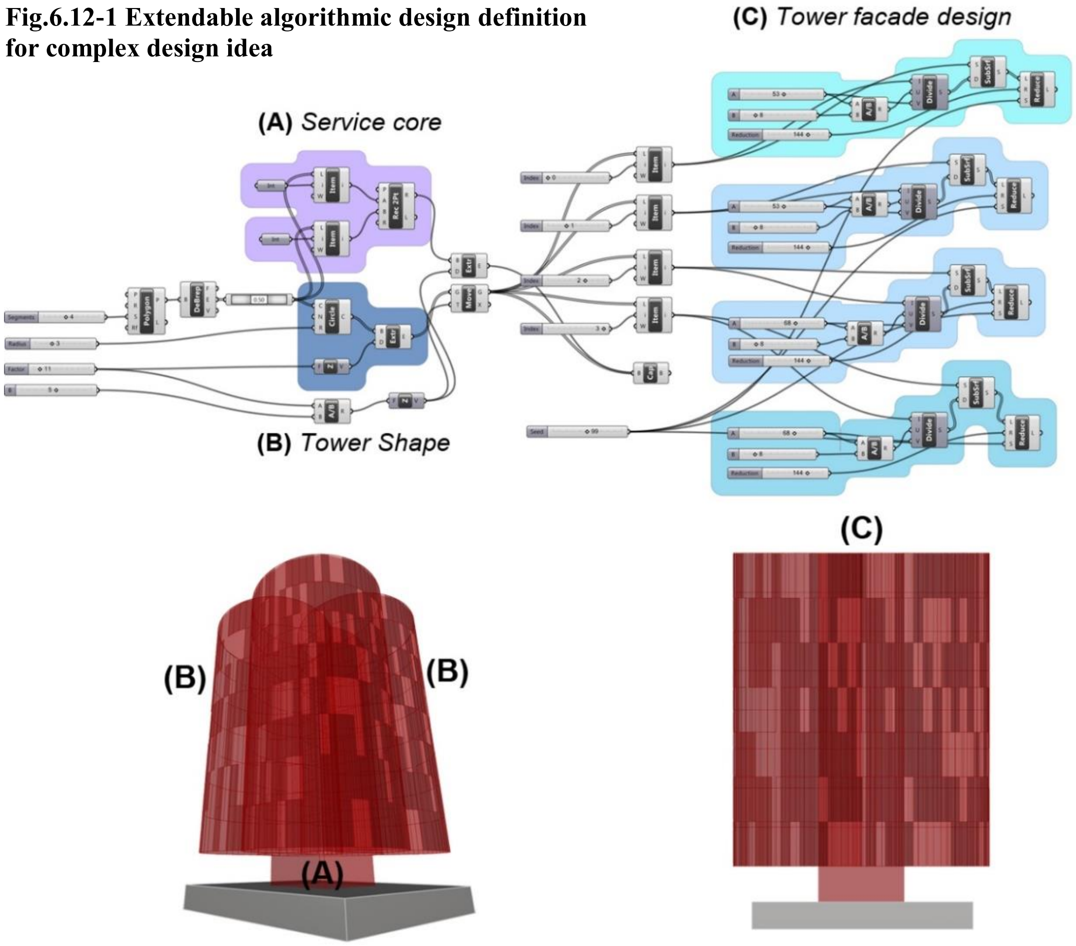
Fig.6.12 Elaboration of design ideas



Source: Author reproduced/ SPSS outputs

Although the results indicated all CAD experts significantly agreed that the tools enhanced elaboration in their design ideas, each CAD user group applied different degrees of integration when working with the tools. For example, the traditional CAD experts preferred to break down the design idea into several design components such as layouts, façade, and site planning. Because conventional CAD can only handle one design aspect at a time, the CAD method does not allow converting more than one design function. For example, 2D drawing for layouts has no direct correlation to the 3D modelling process. It is quite hard to consider a complex design idea within the same design period. However, some sophisticated designers could organise the different design components according to their individual design experience like drawing in 2D while still imagining the resultant 3D shape. But their design process was internalised and thus unique to their own mental process, which means it was not possible to share this step with other design team members; there is no support for this within the CAD method. On the other hand, the parametric CAD methods, especially algorithmic CAD software such as Grasshopper, could add and organise different design aspects or ideas within an algorithmic definition. The design definition (Fig.6.12-1) is explicit and could always be changed or extended (Fig.6.12-1-A-B-C) according to input from different design disciplines. Therefore, if some of the algorithmic architects did not have enough hospital design experience, they were able to get experienced designer’s support in the elaboration of design ideas through adding different algorithmic definitions. Jabi (2013) states that the algorithmic design process allows users to encapsulate the design ideas including methods into an object aided function. Each object is stored in the parametric classes and allows it to be associated with or included in further design development. Furthermore, this extendable design idea process is often referred to as group brainstorming, which can be effective in generating creative ideas according to Brown and Paulus’s (2002) research.

Fig.6.12-1 Extendable algorithmic design definition for complex design idea



Source: Author reproduced/ Grasshopper

6.4.2 The creative technical cluster for the design of hospital buildings

The responses to questions on the technical cluster were divided into five levels, from the lowest to the highest: 1. None, 2. Slightly, 3. Moderately, 4. Good and 5. Immensely/Greatly. Once again, the answers to questions each contained a single variable, and responses from each of the three different categories of software groups were measured using these ordinal rankings. The statistical summary focuses on the percentage of each group and uses the statistical median as an indicator of the group's opinions. The BIM experts thought the tool provided 'good' help to them in all the 4 criteria measured in the technical cluster with a median of 4 or 'good'. The traditional CAD experts also presented similar results, but the technical judgement of how well the tool helps idea expression only gave a median of 3 or 'moderate' help in expression. By contrast, the algorithmic CAD experts demonstrated low comparative values with medians of 2 or 3 and agreed that the tools only helped them 'moderately' or 'slightly' in the technical aspects of good connection in design, 2D planning, and symmetry in design. Only in 'help towards good idea expression' did a median of 4 or 'good' appear. However, this median summary just provides a rough comparison of the technical judgements on creativity when using different CAD tools. The following provides a more detailed comparison of each assessment by the three different CAD user groups.

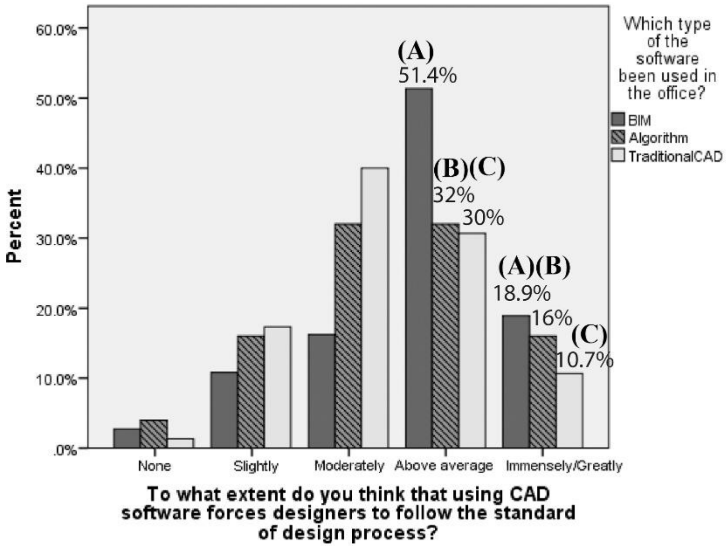
a) Organisation and neatness of the functional programs

Hospital design includes many functional spatial areas such as clinics, operating theatres, emergency centres, wards, kitchens, storage areas, etc. Without a well-organised design process, it would not be possible to express and organise this in a logical design order and with precise design ideas. The question on the technical aspects of organisation and neatness asked what the CAD consultants thought about the impact of the CAD tools on the improvement of the organisation and neatness in the design process. The BIM design consultants showed in over 70% of cases that the impact was 'good' (51.4%) or 'excellent' (18.9%) (Fig.6.13-A). The algorithmic CAD and traditional CAD consultants only showed responses of 40% (Fig.6.13-B) to 45% (Fig.6.13-C) for 'good' and 'excellent 'help from their computer design tools.

The BIM architects stated they used a CAD function called 'project browser' (Fig.6.13-1-A) to standardise their design production. It is a very organised interface and can manage all design outputs including 2D and 3D representations in a systematic list.

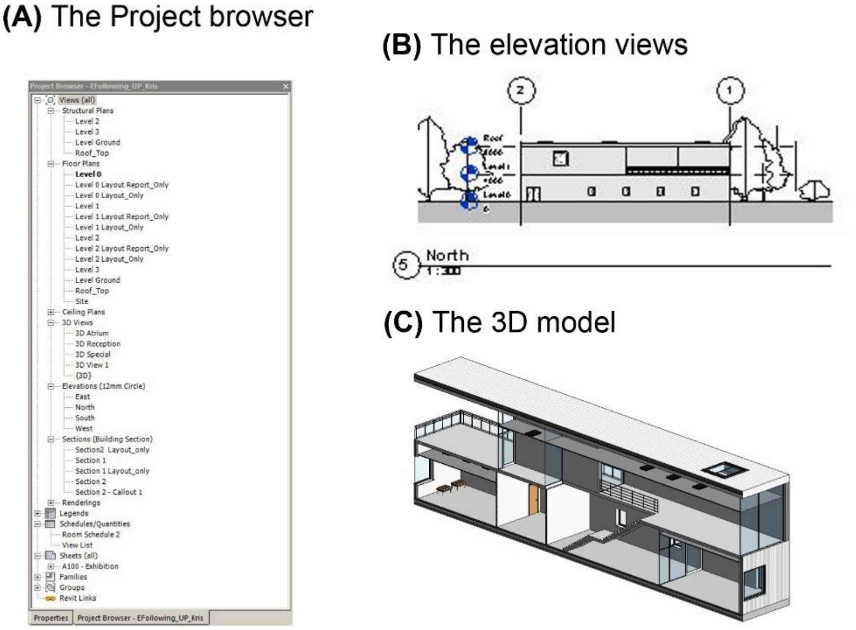
The project browser is parameter based, and the list follows the architectural design development such as standardised floor plans, elevation, 3D views and detailed constructions. While architects produce floor plans, the system immediately creates elevation views (Fig.6.13-1-B) and 3D models (Fig.6.13-1-C). When it comes to traditional CAD, it has a 'layer-manager' (Fig.6.13-2), which can also organise but does not automatically generate different design/drawing views in multiple layers. However, this function does not use a parametric interface; architects need to organise those manual drawings into different layers or to self-manage the design list. As a result, this manual work sometimes causes failures following poor organisation such as wrong layer naming or missing files; this happens more often when architects are dealing with complex building designs, like hospitals. To compare file management systems between parametric (BIM) and nonparametric CAD, the real-time file updating system of BIM design presents an instant evaluation of both 2D and 3D outputs. This function indicates important creative potential through intensive design evaluation and synthesis in the design process (Lawson, 1990). For the algorithmic CAD group, although there was no standardised design list supplied with the software, the architects could create their design development with a series of algorithms. The algorithmic CAD architects said that those self-designed algorithms were organised neatly by several mathematical processes (Fig.6.13-3). Those algorithms may not have fully managed drawings as a design list for the building construction, but they provided a form of excellent organisation for the formulation of design ideas.

Fig.6.13 Organization of the functional programs



Source: Author reproduced/ SPSS outputs

Fig.6.13-1BIM design function & coordination



(A) The Project browser

Project Browser - EFollowing_UP_Kris

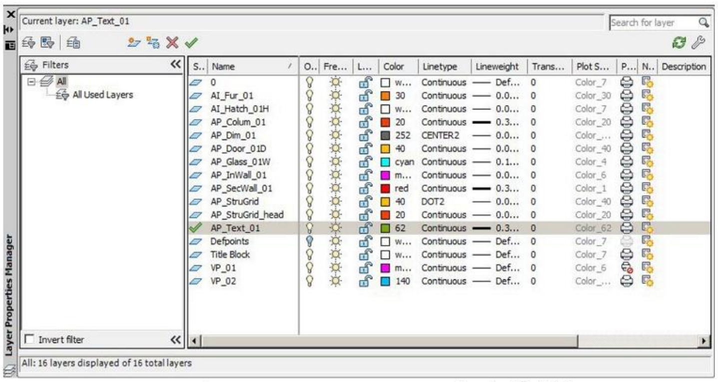
- Views (all)
  - Structural Plans
    - Level 2
    - Level 3
    - Level Ground
    - Roof_Top
  - Floor Plans
    - **Level 0**
    - Level 0 Layout Report_Only
    - Level 0 Layout_Only
    - Level 1
    - Level 1 Layout Report_Only
    - Level 1 Layout_Only
    - Level 2
    - Level 2 Layout Report_Only
    - Level 2 Layout_Only
    - Level 3
    - Level Ground
    - Roof_Top
    - Site
  - Ceiling Plans
  - 3D Views
    - 3D Atrium
    - 3D Reception
    - 3D Special
    - 3D View 1
    - {3D}
  - Elevations (12mm Circle)
    - East
    - North
    - South
    - West
  - Sections (Building Section)
    - Section2 Layout_only
    - Section 1
    - Section 1 Layout_only
    - Section 2
    - Section 2 - Callout 1
  - Renderings
- Legends
- Schedules/Quantities
  - Room Schedule 2
  - View List
- Sheets (all)
  - A100 - Exhibition
- Families
- Groups
- Revit Links

Properties | Project Browser - EFollowing_UP_Kris

(B) The elevation views

(C) The 3D model

Fig.6.13-2 Traditional CAD function & coordination



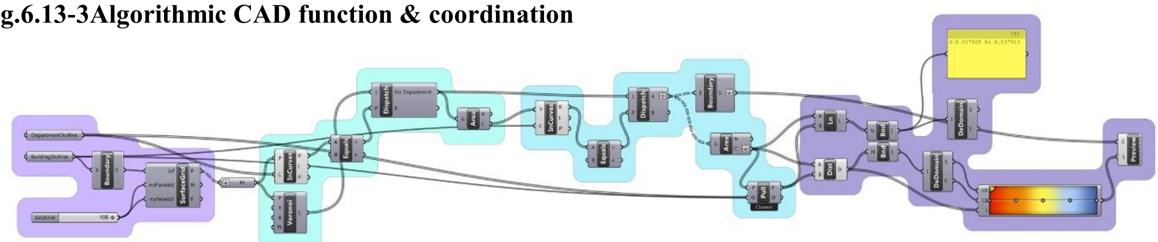
Current layer: AP_Text_01

S..	Name	O..	Fre...	L...	Color		Linetype	Lineweight	Trans...	Plot S...	P...	N..	Description
	0				☐	w...	Continuous	Def...	0	Color_7			
	AI_Fur_01				■	30	Continuous	0.0...	0	Color_30			
	AI_Hatch_01H				☐	w...	Continuous	0.0...	0	Color_7			
	AP_Colum_01				■	20	Continuous	0.3...	0	Color_20			
	AP_Dim_01				■	252	CENTER2	0.0...	0	Color_...			
	AP_Door_01D				■	40	Continuous	0.0...	0	Color_40			
	AP_Glass_01W				■	cyan	Continuous	0.1...	0	Color_4			
	AP_InWall_01				■	m...	Continuous	0.0...	0	Color_6			
	AP_SecWall_01				■	red	Continuous	0.3...	0	Color_1			
	AP_StruGrid				■	40	DOT2	0.0...	0	Color_40			
	AP_StruGrid_head				■	20	Continuous	0.0...	0	Color_20			
✓	AP_Text_01				■	62	Continuous	0.3...	0	Color_62			
	Defpoints				☐	w...	Continuous	Def...	0	Color_7			
	Title Block				☐	w...	Continuous	Def...	0	Color_7			
	VP_01				■	m...	Continuous	Def...	0	Color_6			
	VP_02				■	140	Continuous	Def...	0	Color_...			

All: 16 layers displayed of 16 total layers

Layer-managmer - AutoCAD

Fig.6.13-3Algorithmic CAD function & coordination



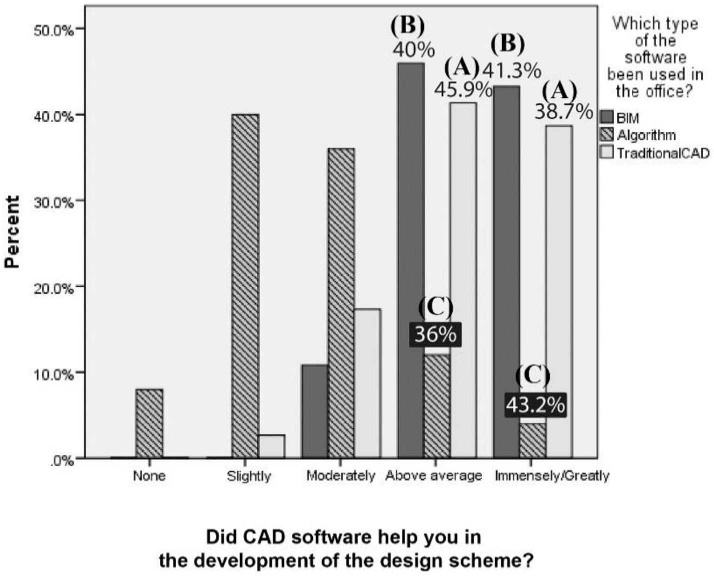
Mathematical design process - Grasshopper

Source: Author reproduced/ AutoCAD/ Grasshopper/ Revit

b) A design scheme: the development of design

The design scheme means to make different plans following the design idea and to optimise the process for the development of the design. The traditional CAD and the BIM design experts returned a very high percentage for 'good' and 'great help' from the CAD tools with 80% in the case of traditional CAD (Fig.6.14-A) and 89% for BIM (Fig.6.14-B). The majority of the algorithmic design experts, about 76% (Fig.6.14-C), thought the software did not provide much help. However, the nature of algorithmic software is such that it is designed mainly to create shapes and 3D forms through engaging with mathematical processes and higher order optimisation function and knowledge-based systems such as the Voronoi, Delaunay, Triangulations and Galapagos, the last of which is an algorithmic function of ‘Evolutionary computing’ based on Darwin’s principles (Darwin and Francis, 1859) of ‘fitness’ and ‘criteria’ for fitness.

Fig.6.14 A design scheme: the development of design

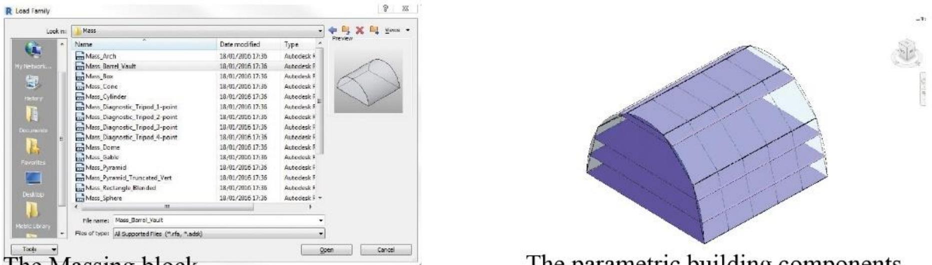


Source: Author reproduced/ SPSS outputs

Conventional CAD and BIM basically utilise non-mathematical notions of geometry aided design. This means that all design plans start with the selection of a design geometry, which is also a small piece in the’ form-finding’ process; the form determines the design idea and design development. For example, in the BIM method, architects modified the design scheme by inserting a massing block in advance (Fig.6.14-1-A). The geometric block was used to construct other parameter-based building components (Fig.6.14-1-B), so the building design development could be linked to the same parametric design system. This process established that the design scheme followed the form selection and then built up the rest of the design functions. Similar views were also found among the conventional CAD architects; they thought that form-finding (Fig.6.14-2-A) was an economical design process for the scheduling of design planning as well as helping to formulate the design layouts (Fig.6.14-2-B). Without form determination in advance, it was hard to focus the design strategy in such complex design project of hospital building.

By contrast, the algorithmic CAD architects tended to explore the design relationships (Fig.6.14-3) with a varied horizon rather than focus on any particular form selection process in the design development. So, the algorithmic CAD experts did not think the algorithmic process helped the efficiency in the production of design plans, but they agreed the CAD method helped exploration of the design when formulating design strategies. Although it was a time-consuming process when engaging in the preparation of the design plans, they believed the generative algorithm involved helped divergent thinking and, in turn, the creativity of design.

Fig.6.14-1BIM design development



(A) The massing family - Revit

(B) Geometric block & building scheme

Name	Date modified	Type
Mass_Arch	18/01/2016 17:36	Autodesk F
Mass_Barrel_Vault	18/01/2016 17:36	Autodesk F
Mass_Box	18/01/2016 17:36	Autodesk F
Mass_Cone	18/01/2016 17:36	Autodesk F
Mass_Cylinder	18/01/2016 17:36	Autodesk F
Mass_Diagnostic_Tripod_1-point	18/01/2016 17:36	Autodesk F
Mass_Diagnostic_Tripod_2-point	18/01/2016 17:36	Autodesk F
Mass_Diagnostic_Tripod_3-point	18/01/2016 17:36	Autodesk F
Mass_Diagnostic_Tripod_4-point	18/01/2016 17:36	Autodesk F
Mass_Dome	18/01/2016 17:36	Autodesk F
Mass_Gable	18/01/2016 17:36	Autodesk F
Mass_Pyramid	18/01/2016 17:36	Autodesk F
Mass_Pyramid_Truncated_Vert	18/01/2016 17:36	Autodesk F
Mass_Rectangle_Blended	18/01/2016 17:36	Autodesk F
Mass_Sphere	18/01/2016 17:36	Autodesk F

The Massing block

The parametric building components

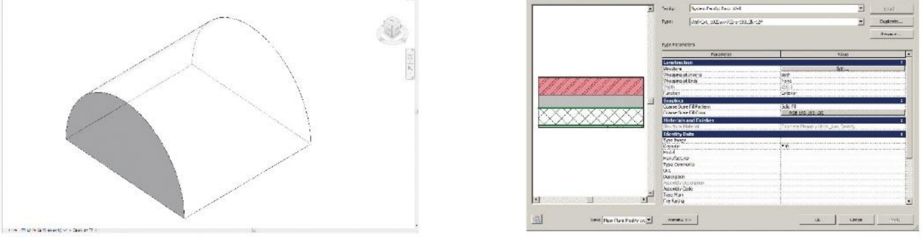


Fig.6.14-2 Nonparametric CAD design development

(A) The form-finding in AutoCAD design

(B) Form-finding design layout
(Central Kansas Medical Center,USA)

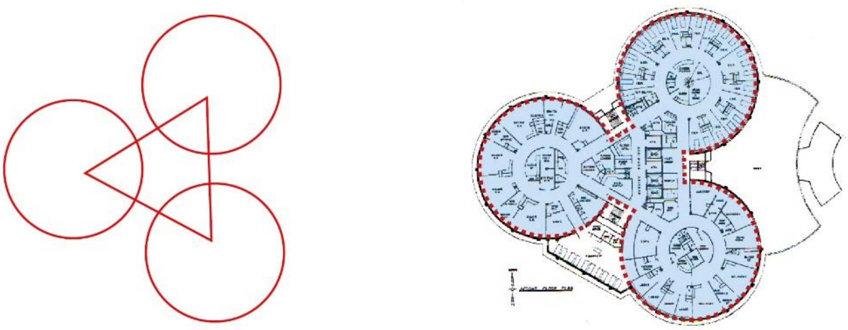
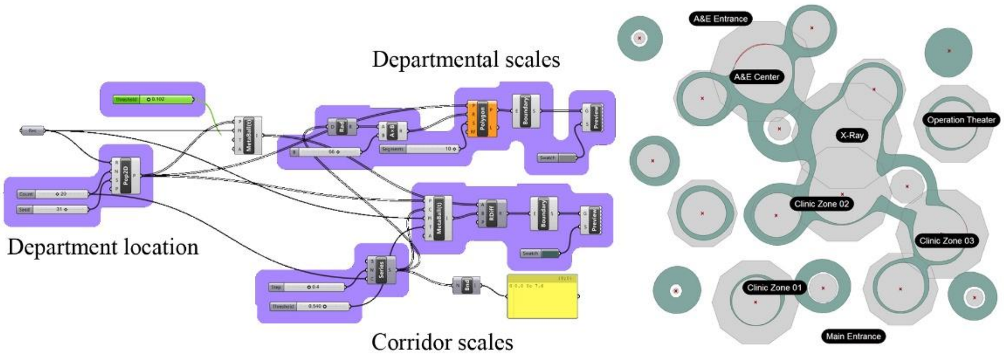


Fig.6.14-3 Algorithmic CAD design development

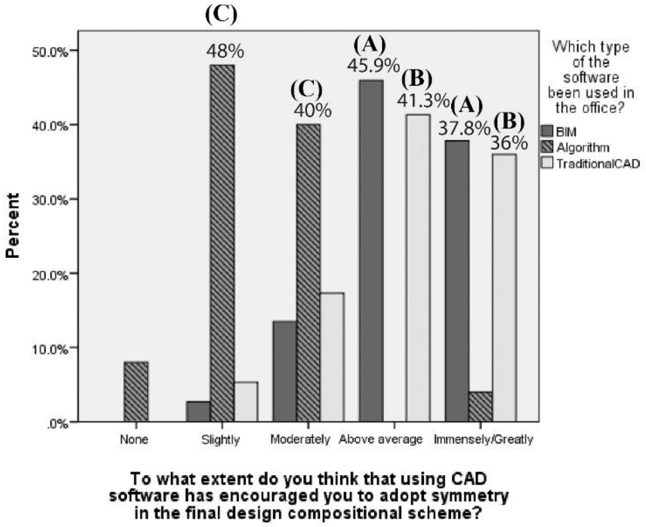


Source: Author reproduced/ AutoCAD/ Grasshopper/ Revit

c) Symmetrical design methods in the allocation of space

Symmetrical design means a parallel and mirror-like design composition along either a horizontal or vertical axis or both, or along a diagonal axis for the design outputs rather than an asymmetrical design combination. Both BIM and traditional CAD architects showed a very high percentage of 'good' and 'greatly helped' responses indicating that the computer tools significantly assisted the symmetrical design of buildings, with 83% of BIM (Fig.6.15-A) and 77% of traditional CAD users (Fig.6.15-B) showing these positive responses. For example, wards usually follow symmetrical layouts to make sure the longest walking distances from the nurses' stations to the wards are equidistant in two building wings (Fig.6.15-1). Drawing functions provided symmetrically designed modifications such as offset, mirror, align, etc. With BIM CAD, the ‘smart tracking’ system allowed architects to define the space equally with more accurate dimensions.

Fig.6.15 Symmetrical design methods in the allocation of space



Source: Author reproduced/ SPSS outputs

On the other hand, the majority of algorithmic CAD architects, over 88%, indicated that the tools only 'slightly' or 'moderately' helped with this symmetrical/ mirror-like design approach (Fig.6.15-C). The algorithmic architects argued the methods they used for design were closer to the definition of a mathematical function for design symmetry, not just the use of simple parallel or aligned objects. They did not accept mirror-like design drawings as the only option for creating efficient layouts; they explored form from a logical definition of this symmetrical representation. For example, if there was a group of rooms requiring equal walking distances, they could use an algorithmic function called ‘Voronoi’

(Fig.6.15-2) to organise the circulation design and process the calculations for the equal distances (Fig.6.15-2-A) in departmental rooms. The Voronoi pattern, in fact, achieved better solutions in terms of efficient design layouts when compared to traditional mirror-like shapes. In addition, the algorithmic CAD architects described a computing calculation and optimisation function called ‘Galapagos’ (Fig.6.15-3), which computes pre-set design conditions (Fig.6.15-3-A) such as scale, length or volume and discovers the most-optimised design layouts (Fig.6.15-3-B). Although such algorithmic design proposals, such as a Voronoi diagram, do not look like a mirrored form, the composition is still mathematically harmonious. Bosia (2011) argues that computer algorithms enhance the architect’s design thinking in a nonlinear way, stating ‘this is a matter of learning from nature’s revolutionary and nonlinear processes rather than mimicking them’. In other words, this nonlinear design thinking explores divergent thought in the design process, which indicates the creativity of design.

Fig.6.15-1 Nonparametric CAD for symmetrical layout (Inpatients)

(Typical racetrack plan pioneered by Gordon Friesen)

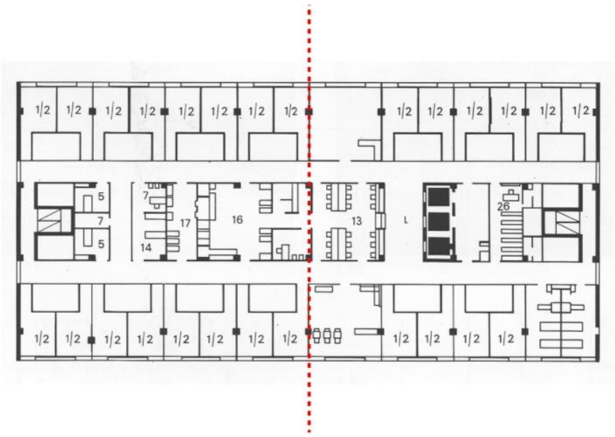
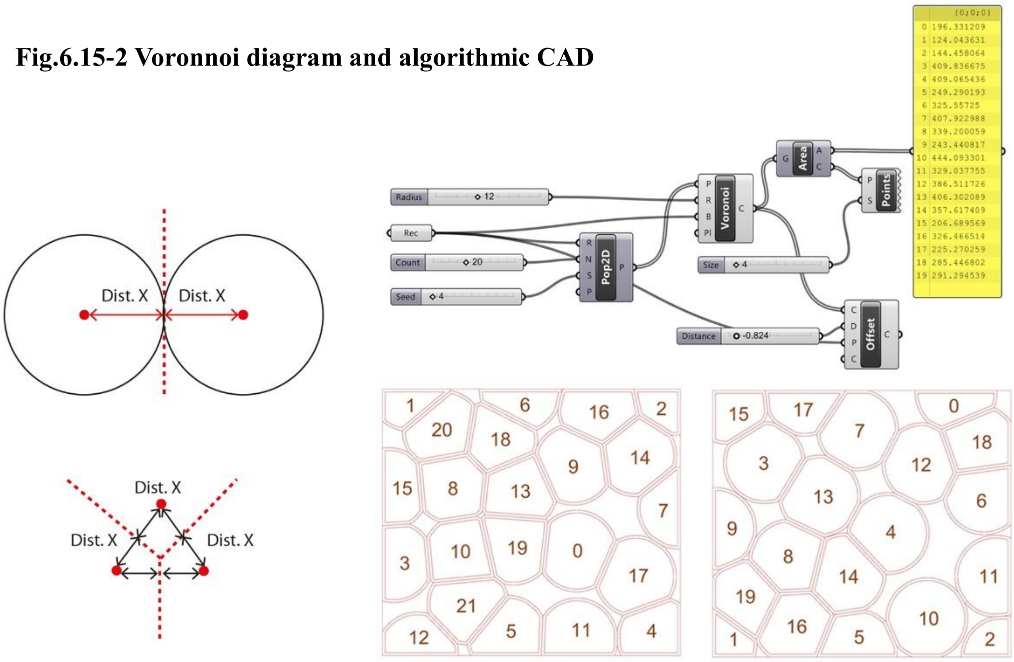
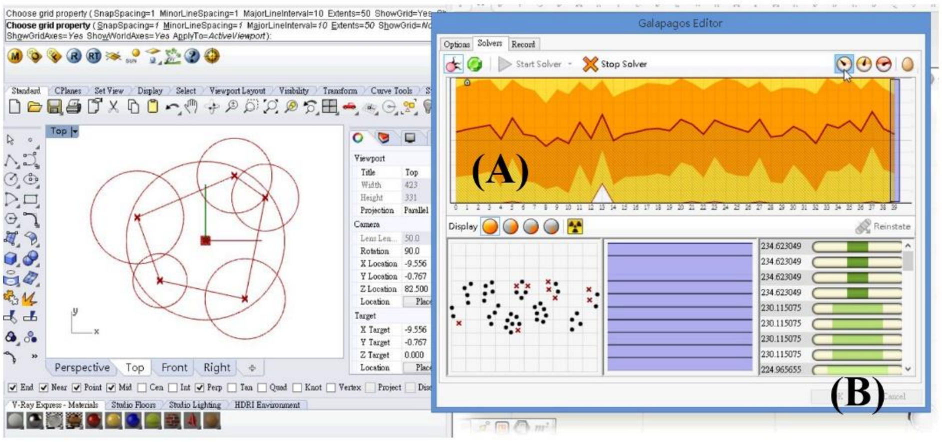


Fig.6.15-2 Voronnoi diagram and algorithmic CAD



```
0 196.331209
1 124.043631
2 144.458064
3 409.836675
4 409.065436
5 249.290193
6 325.55725
7 407.922988
8 339.200059
9 243.440817
10 444.093301
11 329.037755
12 386.511726
13 406.302089
14 357.617409
15 206.689569
16 326.466514
17 225.270259
18 285.446802
19 291.294539
```

Fig.6.15-3 Galapagos for computing revolutionary (algorithmic CAD)



```
Choose grid property ( SnapSpacing=1  MinorLineSpacing=1  MajorLineInterval=10  Extents=50  ShowGrid=Yes
Choose grid property ( SnapSpacing=1  MinorLineSpacing=1  MajorLineInterval=10  Extents=50  ShowGrid=No
ShowGridAxes=Yes  ShowWorldAxes=Yes  ApplyTo=ActiveViewport ):
```

Viewport
Title Top
Width 423
Height 331
Projection Parallel
Camera
Lens Len... 50.0
Rotation 90.0
X Location -9.556
Y Location -0.767
Z Location 82.500
Target
X Target -9.556
Y Target -0.767
Z Target 0.000

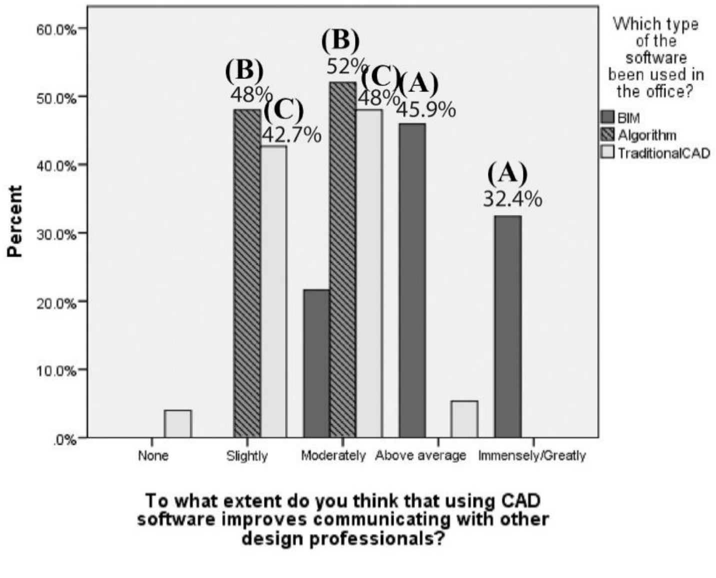
234.623049
234.623049
234.623049
234.623049
230.115075
230.115075
230.115075
230.115075
224.965655

Source: Author reproduced/ AutoCAD/ Grasshopper

d) Expression of the design message

As already stated, hospital design is complex and requires coordinating the work of many design professions such as construction professionals, layout designers, engineers and facilities suppliers. The meaning of the design and its expression needs to be shared between those functional disciplines. If the architectural message can be expressed fluently in the workflow, this optimises design efficiency. So, the design question asked how the CAD specialists thought the methods improved this aspect of design during the working process. Surprisingly, over 78% of the BIM design experts showed responses that the software provides 'good' or 'immense' help in design expression (Fig.6.16-A). The vast majority of algorithmic CAD (100%) (Fig.6.16-B) and traditional CAD experts (90%) (Fig.6.16-C) said the software only 'slightly' or 'moderately 'helped. The BIM experts stated the positive influence on the expression of meaning is because all design teams can use the software for communication, including other design professionals such as structural and mechanical engineers.

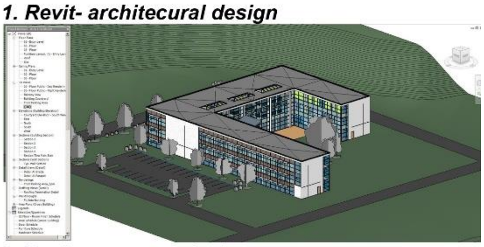
Fig.6.16 Expression of the design message



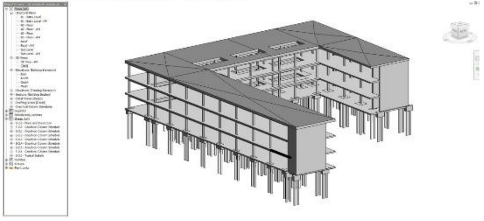
Source: Author reproduced/ SPSS outputs

Fig.6.16-1 BIM design communication by software integration

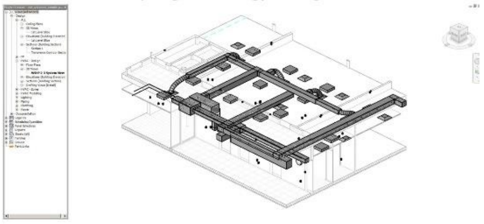
1. Revit- architecural design



2. Revit- structure design



3. Revit- MPE (engineering)design



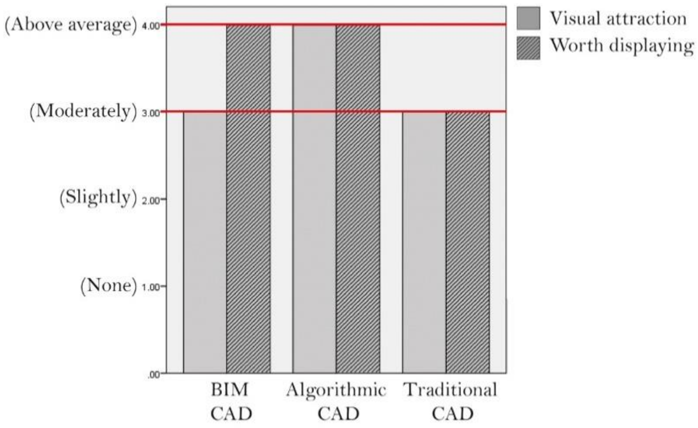
Source: Author reproduced / Revit

For example, the BIM software, Revit, provides three kinds of design interfaces (Revit-architecture, Revit-structure, and Revit-MPE) for architects and engineers (Fig.6.16-1). They can share the same computer work environment and the design outputs are all based on the same parametric structure. This coordinated system can apply design changes and transmit these in the same parametric platform. This platform helps different design professionals to find design problems through working with each other. By contrast, traditional CAD method does not have this integrated design platform. Although different professionals, like engineers, might use this same type of software for discussion, the files produced are not coordinated in a parametric system. In other words, the design files are independent, and there is no integrated system to offer a communication tool. As a result, there might be errors in the design expression caused by failures in transmission. Corss (2011) defines creativity as creating a ‘bridge’ to connect the design problem and solution. If BIM design, as has been widely agreed, provides an excellent platform for design message expression to different design teams, this indicates it has great potential for creating innovative designs.

6.4.3 Aesthetics judgements on hospital building appearances

The aesthetic cluster is based on two judgements: visual attraction and worth displaying. There were again five levels of response used in this assessment; 1. None, 2. Slightly, 3. Moderately, 4. Good, and 5. Immensely/Greatly. The first bar chart (Fig.6.17) shows the median values for those two judgements. Only the algorithmic CAD group showed a median of 4 or ‘good’ in both visual attraction and worth displaying for the design outcomes. The BIM group stated the design results have a median of 4 for worth displaying only. By contrast, the results for the traditional CAD group did not show a strong tendency for either visual attraction or worth displaying for the design outputs.

Fig.6.17 Aesthetics judgments (Bar chart)



Source: Author reproduced / SPSS

The pie charts in Figure 6.18 summarise the feedback as a percentage in each of the CAD reviews. For the results on worth displaying, there was a very high percentage of responses where 96% of algorithmic CAD experts thought the architects should display their created project using the software. The BIM experts also presented 73% of 'good' and 'great help' results showing the software significantly helped the architects to produce projects worthy of display. Only 44% of the traditional CAD experts thought the CAD tools generated projects worth displaying. These positive reviews, in fact, also indicated design satisfaction particularly on the challenges in the problem solving process. As hospital architecture is one of the complex design types, the challenges and achievements have important links to design satisfaction. The parametric CAD architects applied their design software and the methodology used offered them a better design environment, especially in the parametric modelling system. Each design problem has an associated design parameter which can be extended or discussed with different professions to give a better design suggestion.

Parametric CAD makes these challenges or problems visible and accountable (Fig.6.18-1), so architects felt encouraged to explore the design problem-solution process. When it comes to visual attraction (Fig.6.18-2), the algorithmic CAD experts also presented over 68% of 'good' and 'greatly help' responses indicating the positive impact of the software on generating attractive building appearance. The BIM and the traditional CAD experts showed a comparatively lower percentage for the same responses with 46% for BIM and 26% for traditional CAD. The algorithmic design process offers dynamic design algorithms with parametric inputs encouraging architects to explore new ideas during the design process. Also, the mathematical calculations give a unique sense of design appearance (Fig.6.18-3), which is more distinctive than the general visual representations in the ideas created by traditional CAD. As Steele (2011) argues, ‘Mathematics in architectural design is not only in the accomplishments of their form, beauty or material realization, but also their willingness to take on directly the challenges of reinventing the very language and numbers lying hidden behind their surface’. In other words, mathematically based aesthetics and visual attraction promote the notion of designing into becoming a meaningful source for aesthetics in hospital building rather than just producing abstract imagery or iconic status.

Fig.6.18 Worth displaying (Pie chart)

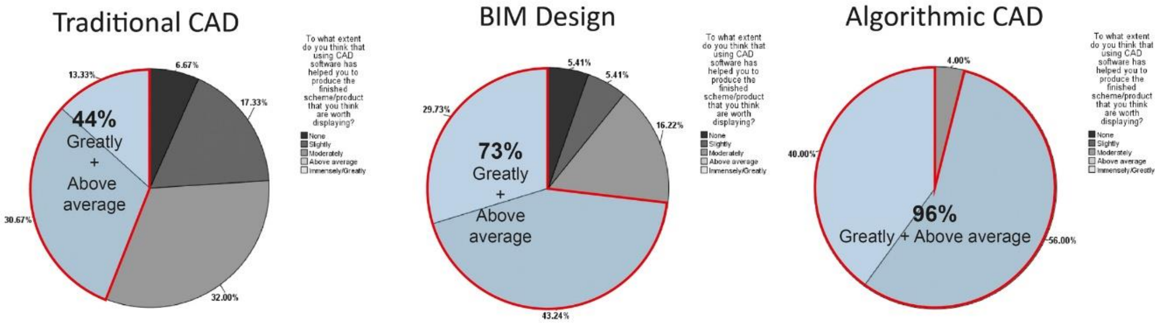
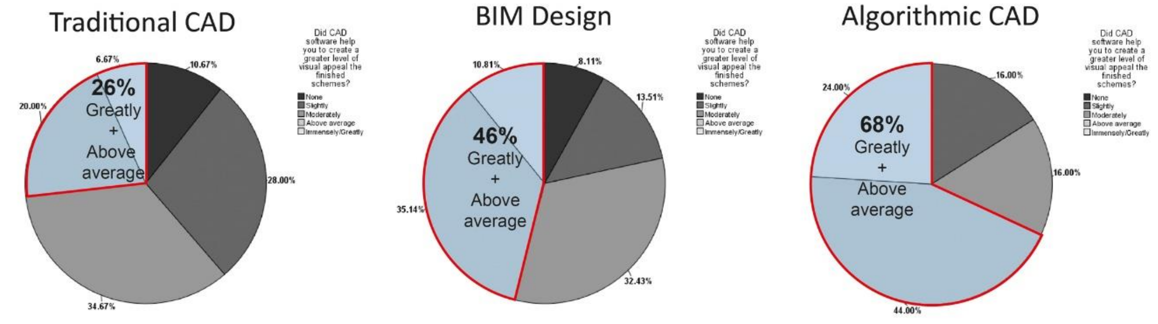
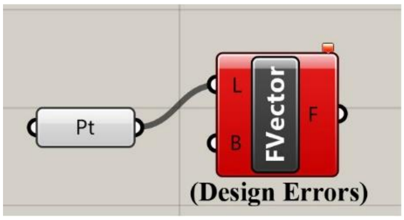


Fig.6.18-2 Visual attraction (Pie chart)



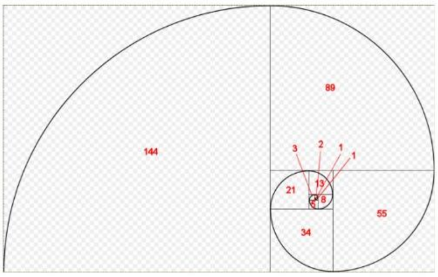
Source: Author reproduced / SPSS

Fig.6.18-1
Algorithmic design problem



Cited: Grasshopper3d.com

Fig.6.18-3 Beauty of mathematics



Cited: Grasshopper3d.com

6.5 Discussion

This chapter used descriptive statistics to summarise a survey questionnaire of hospital design practice in terms of three creativity design measurements: idea fluency, flexibility, and originality. The users of parametric tools, especially algorithmic CAD, presented very impressive results for these measurements. By contrast, nonparametric tools showed lower values than parametric tools regarding the general production of design ideas, genres and originality. Parametric design, especially algorithmic CAD provided a design process with an organised structure and turned design problems into a series of finite steps followed by generated solutions. This activity produced a design strategy rather than separately dealing with each design problem-solution, which is similar to some design methodologies such as shape grammar and generative design. In this intensive brainstorming by a series of algorithmic processes, a high volume of design ideas was generated. This productive design activity only achieved the required indicators for creativity in the hospital design process. The outcomes do not conclude whether it is better or not to use particular CAD tools for hospital design. Many algorithmic practitioners state that although they agree the CAD tool shows a very productive generation of new ideas, types, and uniqueness, some of the software design concepts are still experimental and might not be approved for certain medical services and practices in hospital design. In general, medical staff have their own working template regarding circulation or space design; the idea of new layouts may not be easily accepted by them. Consequently, algorithmic designers cannot always guarantee that their designs will be more widely accepted.

However, the algorithmic CAD architects' responses suggest that they enjoy and feel excited while they are engaging with the CAD tools at the early stages of the design process. On the other hand, traditional CAD users have very low ambitions for CAD performance. Most of the designers talk about their design ideas for hospitals as developing through 'know-how' rather than through the creation of conceptual exploration or integration with CAD performance. They feel trying out new design testing is unnecessary because they think CAD tools are just tools for drawing. On the other hand, traditional CAD designers agree on the importance of introducing new and creative design ideas for future hospitals; many of them agree that new ideas in hospital design might help the performance of medical services. They also say that more idea numbers and types generated will indeed improve the overall design quality and that combining these with greater idea uniqueness might give hospitals a more innovative vision for their healthcare services.

Regarding the judgements on creativity in the designed product, i.e. the hospital building, each CAD tool optimises a different aspect of design. Algorithmic CAD produced some impressive reviews regarding design variation, complexity, and innovation. BIM and traditional CAD also performed well in design development (floor plan drawing) and design management (organised drawings). In particular, the BIM architects stated that a function of the software, the real-time modelling system and internal-library, really helped in managing design developments such as 2D drawing, 3D modelling, and detailed components. Regarding aesthetic evaluation, algorithmic CAD provides different design algorithms and can generate significant amounts of mathematically based forms. The algorithmic process challenges architects involved with the idea and the unpredictable results dramatically demonstrate the beauty of mathematics. However, while the above judgements summarised feedback on the performance of different CAD types with simple descriptive statistics, there was no direct evidence pointing to the existence or presence of correlation between these judgements. Therefore, the next chapter will explore the correlation of those design opinions with the use of inferential statistics and will give further interpretations of the CAD functions relating to design creativity.

From the above results, it is obvious that this chapter focused particularly on the performance of different CAD applications in hospital design. It not only gave a summary of an evaluation of creativity in terms of different design aspects such as idea generation or innovative materials used, but it also indicated some distinctions on how each specific CAD method helped architects in their design process. Through the discussion of creativity of design, including the numbers of ideas produced and idea quality, this chapter has profoundly explored whether design ideas can drive and trace the relationship between hospital and healthcare buildings and their medical services, as well as exploring the building's relationship to the entire healthcare system (The Nuffield Trust, 2001). These relationships are like forces shaping and underlining both architects' and healthcare clients' intentions.

Part III/ Chapter 7 – Research findings 2

Case Study 1-2: Discussion of the effects on the creativity of design and other variable effects of parametric (BIM design and Algorithmic CAD) and nonparametric (Traditional CAD) design methods in hospital design.

7.1 Introduction

Chapter6 identified the research findings from the descriptive statistics. It presented the feedback from three different CAD user groups in terms of measurements of creativity in the hospital design process. The descriptive statistics, shown in Chapter5, confirmed that there were differences in design performance, particularly in the discussion of creativity indicators, when using different CAD methods during the hospital design process. However, regarding the effects on design activity, no connection between design creativity and these CAD methods has yet been defined. So, this chapter employs inferential statistical analysis to further discover the impact of the use of the different CAD methods with emphasis on the influence of the parametric design process on the creativity aspect of hospital building design.

The chapter content is divided into three parts:

The first part discusses the correlation between creativity criteria (Torrance, 1970) in the hospital design process, these being: the number of ideas (fluency), their types (variety), and their originality (uniqueness), as well as exploring their interrelationship with architects' CAD experience.

The second part considers correlations between judgements on creativity (Amabile,1982) in the final product, the hospital building. The study also considers complex building design projects undertaken using alternative CAD methods, discusses and suggests how parametric CAD can improve on conventional or nonparametric CAD and achieve design optimisation, such as through new concept formulation or intelligent design affecting the future development of hospital buildings.

The final part conducts a factor analysis to redefine and aggregate the creative design factors from the questionnaire survey. The results organise the factors into components and present loadings to show how each was influenced by each individual CAD method.

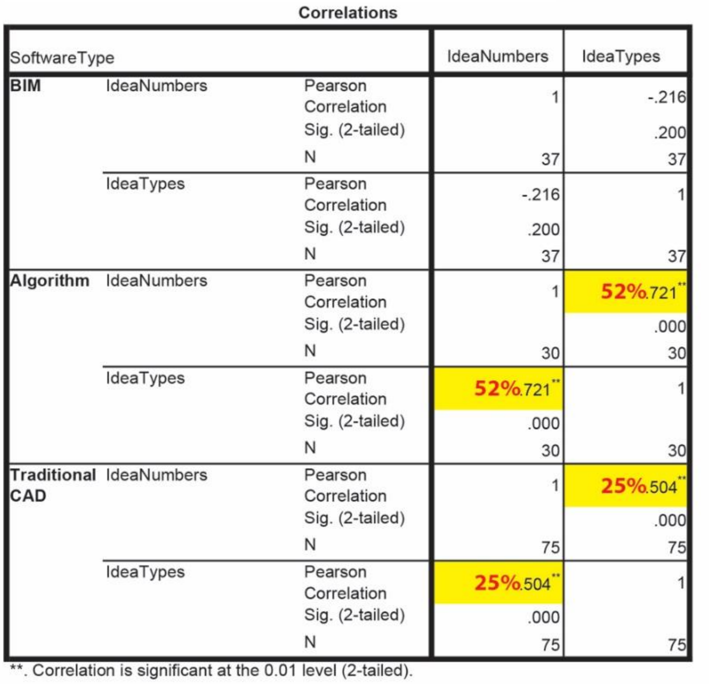
7.2 Comparative studies on the CAD methods and the measurement of creativity in the hospital design process

Runco (1999) and Hocevar (1981) suggested the score relating to idea originality and flexibility is closely associated with the score for idea numbers (fluency). Guilford (1950) stated that idea fluency is associated with productivity, and idea flexibility is apparent in the variety of ideas. In Chapter6, the scatter diagram shown stated a linear correlation between idea numbers and types. This section, however, seeks to investigate any significant correlation between the impact on idea numbers, types, originality and the user experience of the three alternative CAD methods when they are used in hospital design. Two analysis methods in SPSS were used to examine the relationship between the three CAD methods in terms of their performance in relation to idea fluency (numbers) and flexibility (genres). The first was the 'Pearson correlation', which defined the correlation between idea fluency and flexibility across the CAD methods. The second method employed variance testing (ANOVA) to examine the significant difference in creativity measurements caused by using each CAD method.

7.2.1 The relationship of Idea numbers, idea types and CAD methods

The Pearson correlation analysis was applied to compute the strength and direction of the linear relationship between two variables (idea numbers and idea types). The table (Table 7.1) highlights the Pearson correlation coefficients (r) value in the two groups: the algorithmic CAD architects and the traditional CAD architects. Statistically, there is a significant difference of 0.01 (2-tailed) in terms of idea numbers and types between the two groups. According to the guidelines provided by Cohen (1988), he suggests the r value (-1.00 to 1.00) can be interpreted with three different levels of strength: small (r= 0.10 to 0.29), medium (r= 0.30 to 0.49) and large (r = 0.50 to 1.0). In the case of the algorithmic CAD group, the relationship between idea numbers and idea types showed a strong, positive correlation, with the coefficient between the two variables shown as r = 0.72, n= 30, P= 0.00< 0.05.

Table7.1 The Pearson correlation analysis



Correlations

SoftwareType			IdeaNumbers	IdeaTypes
BIM	IdeaNumbers	Pearson Correlation	1	-.216
		Sig. (2-tailed)		.200
		N	37	37
	IdeaTypes	Pearson Correlation	-.216	1
		Sig. (2-tailed)	.200	
		N	37	37
Algorithm	IdeaNumbers	Pearson Correlation	1	52%.721**
		Sig. (2-tailed)		.000
		N	30	30
	IdeaTypes	Pearson Correlation	52%.721**	1
		Sig. (2-tailed)	.000	
		N	30	30
Traditional CAD	IdeaNumbers	Pearson Correlation	1	25%.504**
		Sig. (2-tailed)		.000
		N	75	75
	IdeaTypes	Pearson Correlation	25%.504**	1
		Sig. (2-tailed)	.000	
		N	75	75

**. Correlation is significant at the 0.01 level (2-tailed).

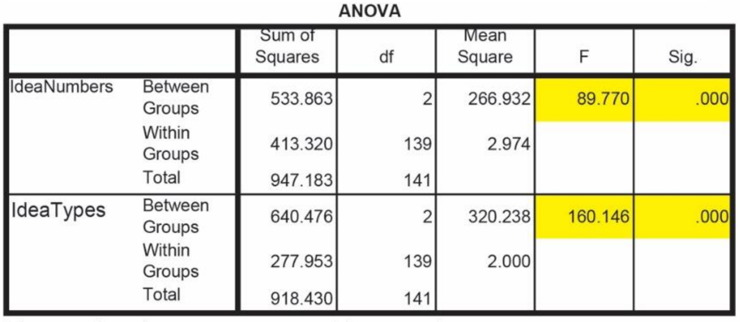
Source: Author reproduced/ SPSS outputs

For the traditional CAD group, the result also showed a strong positive correlation between the two variables: r = 0.50, n= 75, P=0.00<0.05. To further identify the correlation coefficient as an impact percentage, the calculations (y%=100*r^2) were applied and they show that the idea numbers influenced nearly 52% of the idea types where architects used algorithmic CAD in the design project. One possible interpretation of this relationship could be that if there were more ideas, then the probability that these ideas have variations in type would normally be greater.

In addition, a variance test – ANOVA was used to test the differences between two or more means. The table (Table 7.1-1) confirms there was also a statistically significant difference across the three CAD methods: F = 89.77, P = 0.00 <0.05 for idea numbers and F = 160.15, P = 0.00 <0.05 for idea types. The results confirm that when using different CAD methods, there was a significant difference in the production of idea numbers and types. Moreover, the actual difference (Table 7.1-2) in mean scores between the groups was quite large. The size of the effect was calculated using eta squared where $Eta\ squared = \frac{\text{Sum of squares between groups}}{\text{Total sum of squares}}$. According to Cohen (1988), effect sizes are classified as: 0.01=small effect, 0.06=moderate effect, and 0.15=large effect. The effects identified in this investigation were 0.56 for idea numbers and 0.69 for idea types.

Furthermore, the ANOVA comparison between groups showed that there was a statistically significant difference between the algorithmic CAD group and the other two CAD groups, BIM and traditional CAD, in idea numbers: F = (2,139) = 171.06, P =0.00 >0.05, and idea genres: F = (2,139) =310.6, P = 0.00 >0.05.

Table7.1-1 The variance test of idea numbers & types



ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
IdeaNumbers	Between Groups	533.863	2	266.932	89.770	.000
	Within Groups	413.320	139	2.974		
	Total	947.183	141			
IdeaTypes	Between Groups	640.476	2	320.238	160.146	.000
	Within Groups	277.953	139	2.000		
	Total	918.430	141			

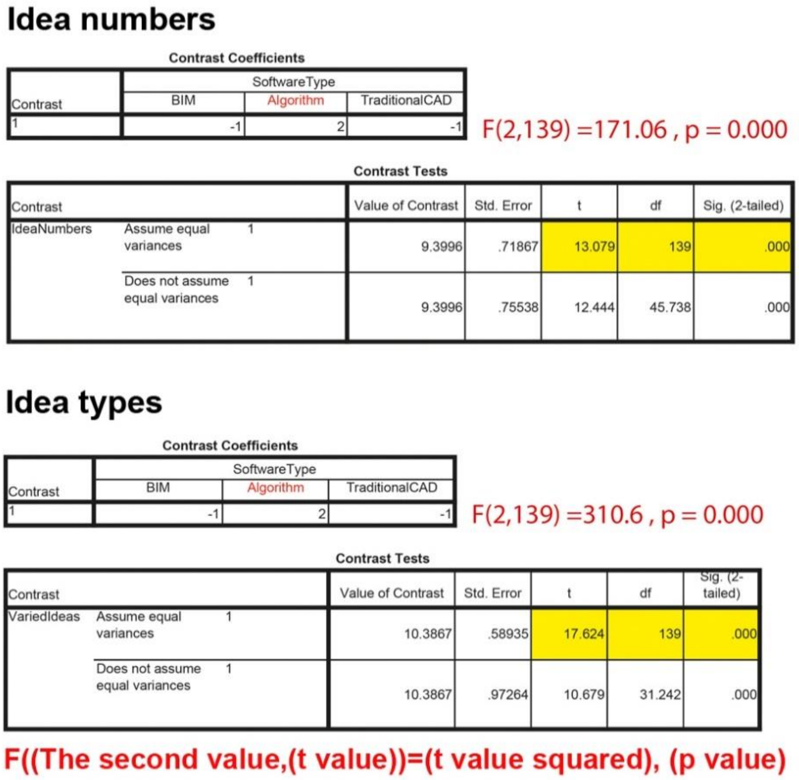
Idea numbers between groups: Eta squared = 0.56 (Large Effect)

Idea types between groups: Eta squared = 0.69 (Large Effect)

Source: Author reproduced/ SPSS outputs

From the above results, we can state there was a significant difference when using the algorithmic CAD method, as there was a production of high volumes for both idea numbers and genres. Also, there was no significant difference in idea production between the BIM and the traditional CAD groups. Terzidis (2003) states that what distinguishes algorithmic design is its abstraction of a process and its sequential patterns of finite steps during the design task; it is similar to the design methodology used in shape grammars, mathematical models, topological properties, and genetic systems, to name a few. Algorithmic CAD performs as a design system, and it is able to productively create idea numbers then form the design variations. Additionally, Jabi (2013) states ‘Algorithmic thinking allows designers to rationalize, control, iterate, analyse, and search for alternatives within a defined solution space’. In its vision for future hospital design, the British government has suggested a need for ‘strategic design planning’ able to link the healthcare system with varied plans for the building layout as well as producing different ideas relating to both the hospital design and the wider environment (Nuffield Trust, 2001).

Table7.1-2 The variance test of idea numbers & types (between CAD groups)



Idea numbers

Contrast Coefficients

Contrast	SoftwareType		
	BIM	Algorithm	TraditionalCAD
1	-1	2	-1

F(2,139) =171.06 , p = 0.000

Contrast Tests

Contrast			Value of Contrast	Std. Error	t	df	Sig. (2-tailed)
IdeaNumbers	Assume equal variances	1	9.3996	.71867	13.079	139	.000
	Does not assume equal variances	1	9.3996	.75538	12.444	45.738	.000

Idea types

Contrast Coefficients

Contrast	SoftwareType		
	BIM	Algorithm	TraditionalCAD
1	-1	2	-1

F(2,139) =310.6 , p = 0.000

Contrast Tests

Contrast			Value of Contrast	Std. Error	t	df	Sig. (2-tailed)
VariedIdeas	Assume equal variances	1	10.3867	.58935	17.624	139	.000
	Does not assume equal variances	1	10.3867	.97264	10.679	31.242	.000

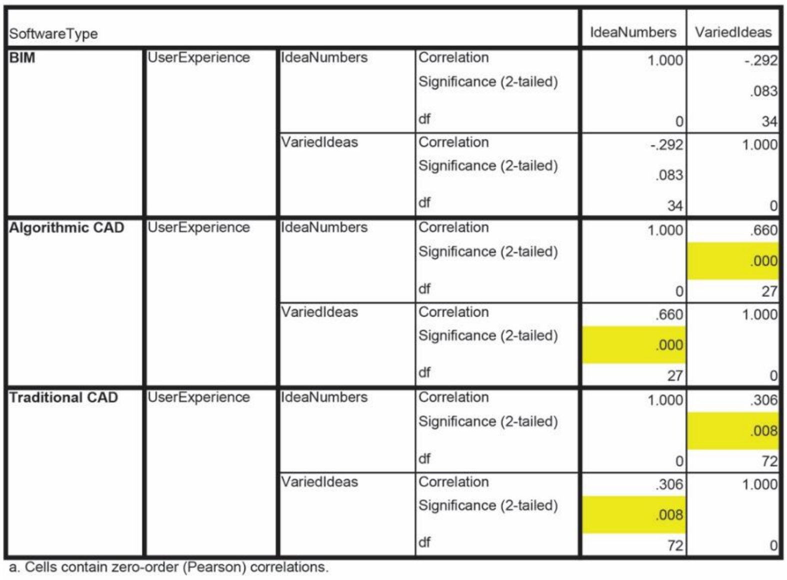
F((The second value,(t value))=(t value squared), (p value)

Source: Author reproduced/ SPSS outputs

7.2.2 Idea numbers, types and user experience in the use of CAD

Guilford (1950) states ‘No creative person can get along without previous experience or facts’. Hanna (2013) suggests the length of time a computer has been used in design has a statistical correlation with idea production. Thus, this section contains a statistical comparison used for the correlation testing between idea production (numbers and types) and user experience in years of CAD usage. In the testing of partial correlation, Table 7.2 tells us that in the case of the algorithmic CAD group there was a strong, positive, partial correlation between idea numbers and idea types, influenced by user experience: r = 0.66, n = 27, P= 0.00<0.05. The traditional CAD group showed a slightly lower significance (0.008>0.000) and thus a smaller but still strong correlation value (0.306<0.660) between idea numbers and types affected by user experience: r = 0.306, n = 72, P=0.00<0.05.

Table7.2 The partial correlation analysis of user experience & ideas



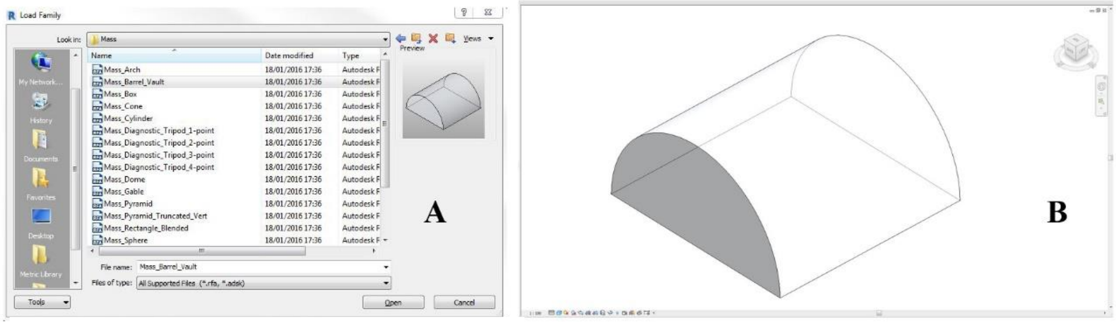
SoftwareType				IdeaNumbers	VariedIdeas
BIM	UserExperience	IdeaNumbers	Correlation	1.000	-.292
			Significance (2-tailed)		.083
			df	0	34
		VariedIdeas	Correlation	-.292	1.000
			Significance (2-tailed)	.083	
			df	34	0
Algorithmic CAD	UserExperience	IdeaNumbers	Correlation	1.000	.660
			Significance (2-tailed)		.000
			df	0	27
		VariedIdeas	Correlation	.660	1.000
			Significance (2-tailed)	.000	
			df	27	0
Traditional CAD	UserExperience	IdeaNumbers	Correlation	1.000	.306
			Significance (2-tailed)		.008
			df	0	72
		VariedIdeas	Correlation	.306	1.000
			Significance (2-tailed)	.008	
			df	72	0

a. Cells contain zero-order (Pearson) correlations.

Source: Author reproduced/ SPSS outputs

On the other hand, the partial correlation indicates there was a weak and negative correlation between idea numbers and types influenced by user experience in the BIM group: $r = -0.292$, $n = 34$, $P=0.08<0.05$. The negative r value also indicates the BIM users did not increase their design ideas and types as a result of their greater experience. In the BIM design interface, such as in Revit (Autodesk), a limited number of geometric design options or families are provided. The parametric library (Fig.7.1-A) only offers a few types of geometries, and architects must use these to build their conceptual schemes (Fig.7.1-B). Although an import function allows new geometries to be integrated into the application, some complex geometries, such as curved walls, could slow down the processing speed of the software and are not desirable in construction due to cost and technical challenges. Also, the hidden data structure (scripts) and the pre-produced parametric design components could restrict the architect's thinking when creating new ideas.

Fig.7.1 The BIM design library and building prototype



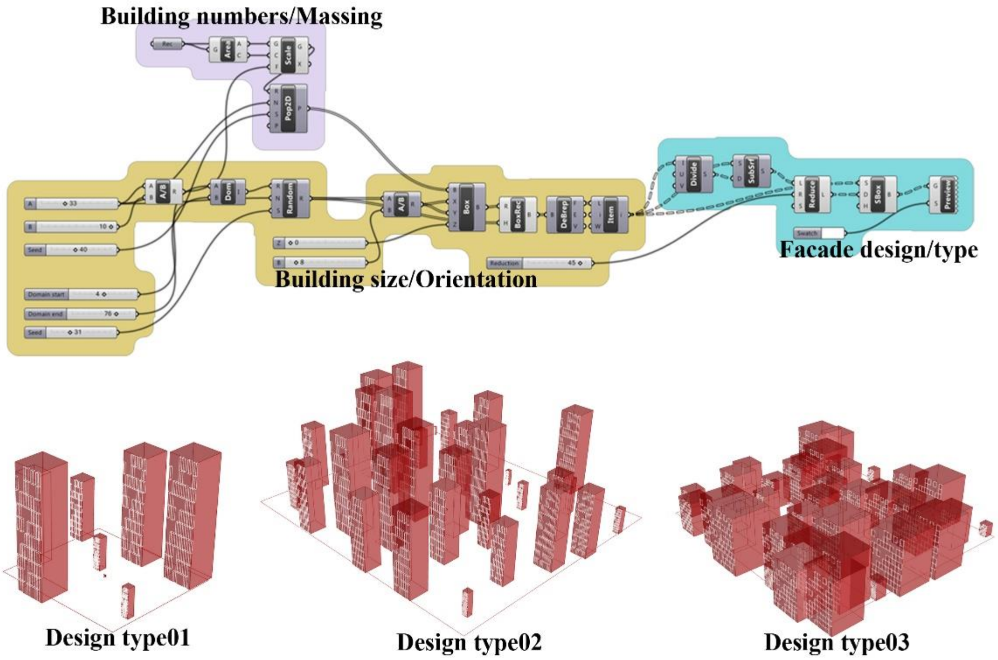
Name	Date modified	Type
Mass_Arch	18/01/2016 17:36	Autodesk F
Mass_Barrel_Vault	18/01/2016 17:36	Autodesk F
Mass_Box	18/01/2016 17:36	Autodesk F
Mass_Cone	18/01/2016 17:36	Autodesk F
Mass_Cylinder	18/01/2016 17:36	Autodesk F
Mass_Diagnostic_Tripod_1-point	18/01/2016 17:36	Autodesk F
Mass_Diagnostic_Tripod_2-point	18/01/2016 17:36	Autodesk F
Mass_Diagnostic_Tripod_3-point	18/01/2016 17:36	Autodesk F
Mass_Diagnostic_Tripod_4-point	18/01/2016 17:36	Autodesk F
Mass_Dome	18/01/2016 17:36	Autodesk F
Mass_Gable	18/01/2016 17:36	Autodesk F
Mass_Pyramid	18/01/2016 17:36	Autodesk F
Mass_Pyramid_Truncated_Vert	18/01/2016 17:36	Autodesk F
Mass_Rectangle_Blended	18/01/2016 17:36	Autodesk F
Mass_Sphere	18/01/2016 17:36	Autodesk F

File name: Mass_Barrel_Vault
Files of type: All Supported Files (*.rfa, *.adsk)

Source: Author reproduced/ Revit

Furthermore, in interviews, even experienced BIM architects said they felt they were less flexible when proposing new ideas or trying out different idea types. By contrast, the algorithmic design method, which is a ‘bottom-up’ rather than a ‘top-down’ method, allowed architects to create a design strategy with many possible ideas or solutions, like a complete design plan (Fig.7.2), rather than a separately occurring single idea as the only design option (See the literature review of parametric architectural design ideation and expression in Section 4.3.4.a, Chapter 4). Therefore, the algorithmic architects were able to produce a larger number of ideas once they had learned the required skills in the algorithmic design method. This behaviour can also be found among experienced chess players; they prefer to store and use different kinds of strategies, engaging with the game process more than novice players (Chase and Simon, 1973).

Fig.7.2 The algorithmic CAD plan & outputs



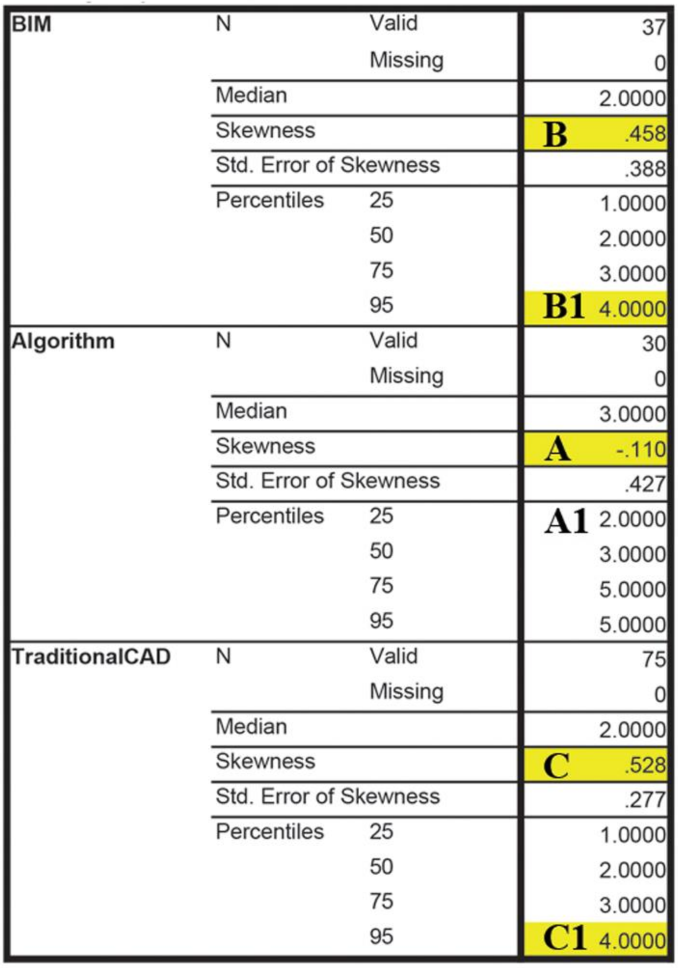
Source: Author reproduced/ Grasshopper

The above findings highlight two parts of the results in relation to the two design variables - design experience and design ideas. In the first, the algorithmic design process could lead to effective production in the design ideation process, including both idea numbers and types, when compared with a similarly experienced user in the other CAD groups, traditional CAD and BIM design. In the second, although both BIM and algorithmic CAD belong to the parametric design method, a more visible and adaptable design structure in algorithmic CAD helped to learn how to produce design concepts. In other words, if architects can see and construct the design process, it improves their design learning and, in turn, enhances their ability on the generation of idea numbers and types, all of importance in the hospital design ideation process. The Nuffield Trust (2001) suggests that a design idea is a force that can shape and coordinate the thinking of architects and clients, enabling them to work in a close relationship and thus develop better healthcare architectural design. Thus, if architects employ algorithmic CAD for idea generation, it can help them produce a sufficient number of ideas or suggestions for better hospital design discussions.

7.2.3 Idea originality from the use of different CAD methods

The descriptive statistics (Table 7.3) show two analyses of variable distributions. The first is skewness and the second shows the percentiles. First, the skewness value gives an indication of the data distribution. If it is a positive value, it means the variable presented is a left side skew (toward the lower values 1 and 2). On the other hand, if it is a negative value, it means the variable presented is skewed to the right (toward the higher values 4 and 5). The table gives a negative score for the algorithmic CAD group, -0.11 (Table 7.3-A) with the median value 4. This means the variable distribution shows a right-side skewness between the value of 4 and 5, where idea originality is uncommon or rare (Fig.7.3). This suggests that while the dependent variable, design originality, has been influenced by the independent variable, the algorithmic CAD methods influenced the level of idea originality in uncommon and rare cases only. Comparing this with the other two CAD methods, BIM and traditional CAD, both skewness values, BIM:0.458 (Table 7.3.B) and traditional CAD:0.528 (Table 7.3-C), show positive scores with a median value of 3, indicating that idea originality is not common or special. This means the variable distribution presented is skewed to the left side and falls between the values 1 and 2. This result confirms that the BIM and traditional CAD groups were affected by the use of their CAD methods and produced ideas that were described as ‘common’ and ‘very common’.

Table7.3 The variable distribution of idea originality in CAD for hospitals



BIM	N	Valid	37
		Missing	0
	Median		2.0000
	Skewness		**B** .458
	Std. Error of Skewness		.388
	Percentiles	25	1.0000
		50	2.0000
		75	3.0000
		95	**B1** 4.0000
Algorithm	N	Valid	30
		Missing	0
	Median		3.0000
	Skewness		**A** -.110
	Std. Error of Skewness		.427
	Percentiles	25	**A1** 2.0000
		50	3.0000
		75	5.0000
		95	5.0000
TraditionalCAD	N	Valid	75
		Missing	0
	Median		2.0000
	Skewness		**C** .528
	Std. Error of Skewness		.277
	Percentiles	25	1.0000
		50	2.0000
		75	3.0000
		95	**C1** 4.0000

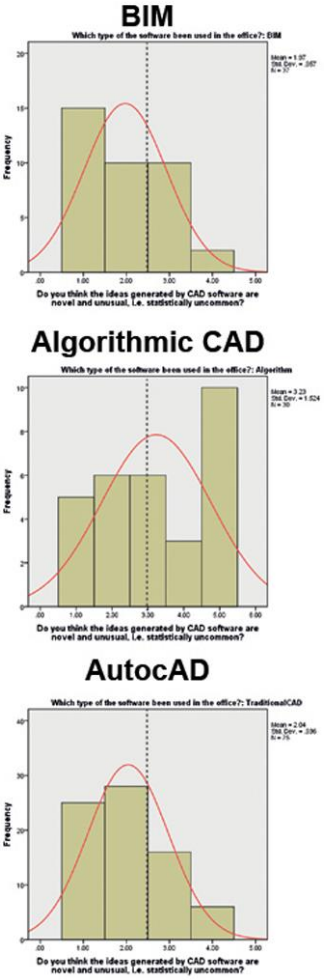
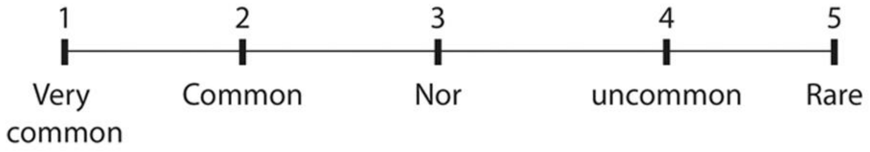
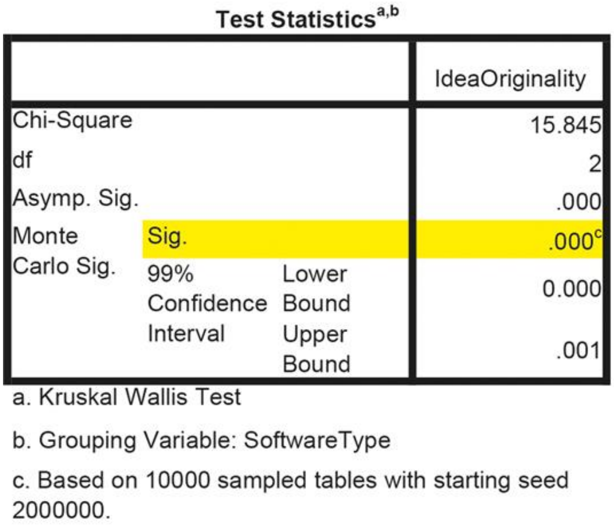


Fig.7.3 The ranking scales of idea originality in CAD process for hospitals



Source: Author reproduced/ SPSS outputs

Table7.4 The KW-Test of idea originality



Test Statistics[a,b]

			IdeaOriginality
Chi-Square			15.845
df			2
Asymp. Sig.			.000
Monte Carlo Sig.	Sig.		.000[c]
	99% Confidence Interval	Lower Bound	0.000
		Upper Bound	.001

a. Kruskal Wallis Test

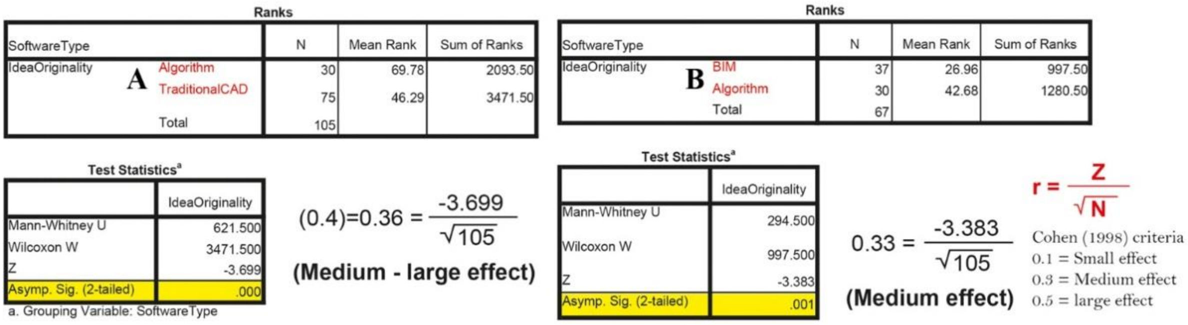
b. Grouping Variable: SoftwareType

c. Based on 10000 sampled tables with starting seed 2000000.

Source: Author reproduced/ SPSS outputs

In the second part showing percentiles, the table shows that for the algorithmic CAD group, 25% of the architects (Table 7.3-A1) identified their design idea as rare, with a value of 5. Alternatively, only 5% of the BIM (Table 7.3-B1) and traditional CAD (Table 7.3-C1) considered their design idea as uncommon, with a value of 4. The next section calculates the influence or significance of using different CAD methods on idea originality; the Kruskal-Wallis (KW-Test) for 3 independent groups (Table 7.4) was applied in this section. The statistical differences in the effects on idea originality are shown for the three CAD methods: BIM, n= 30, algorithmic CAD, n=75, traditional CAD, n= 37, χ_2 (2, n=142) = 15.85, P = 0.00 <0.05. The results suggest there was a significant difference in the impact on idea originality across the three CAD methods. Also, the Mann-Whitney test (U-test) was used to further investigate the three CAD groups and compare their significant differences. The table (Table 7.4-1) also confirms there was a significant difference regarding idea originality between the algorithmic CAD group and the traditional CAD group (Table 7.4-1-A): U = 621.5, Z = -3.699, P = 0.00 < 0.05. In addition, the effect on idea originality (r=0.4) for algorithmic CAD and traditional CAD was greater than a medium value and close to a large effect (Cohen's criteria, 1988). For the algorithmic CAD and the BIM groups (Table 7.4-1-B), the test also suggested the same significant difference with U = 294.5, Z = -3.83, P = 0.00 < 0.05; the effect size ($r = \frac{Z}{\sqrt{N}} = 0.3$) also showed a medium effect.

Table7.4-1 The U-Test of idea originality with different CAD groups



Ranks

SoftwareType			N	Mean Rank	Sum of Ranks
IdeaOriginality	A	Algorithm	30	69.78	2093.50
		TraditionalCAD	75	46.29	3471.50
		Total	105		

Test Statistics[a]

	IdeaOriginality
Mann-Whitney U	621.500
Wilcoxon W	3471.500
Z	-3.699
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: SoftwareType

$$(0.4)=0.36 = \frac{-3.699}{\sqrt{105}}$$

(Medium - large effect)

Ranks

SoftwareType			N	Mean Rank	Sum of Ranks
IdeaOriginality	B	BIM	37	26.96	997.50
		Algorithm	30	42.68	1280.50
		Total	67		

Test Statistics[a]

	IdeaOriginality
Mann-Whitney U	294.500
Wilcoxon W	997.500
Z	-3.383
Asymp. Sig. (2-tailed)	.001

$$0.33 = \frac{-3.383}{\sqrt{105}}$$

(Medium effect)

$$r = \frac{Z}{\sqrt{N}}$$

Cohen (1998) criteria
0.1 = Small effect
0.3 = Medium effect
0.5 = large effect

Source: Author reproduced/ SPSS outputs

These results suggest that by using algorithmic CAD in the hospital design process, users could achieve idea uniqueness, and this would have a more significant effect when compared with using other software such as BIM or traditional CAD. To explain this study's result, algorithmic CAD creates a design idea out of a series of mathematical functions (See the literature review of parametric concept in Section 4.3.4.a, Chapter 4). Each represented algorithm has both a mathematical process and connection with another algorithm. Thus, before these algorithmic design relationships have been completed, architects cannot easily predict the outcomes. In hospital design, this mathematically based design optimisation can not only present unique design ideas but also provides an evidence-based design process and effective decision making. Jabi (2013) points out that the algorithmic design process allows the designer to apply different mathematically based conditions responding to the design situation, such as equality (=), inequality (≠), greater or less than (> or <), etc. (Fig.7.4). These functions give a credible, flexible but logical process for the development of design ideation.

Fig.7.4 The mathematical design functions

Source: Author reproduced/ Grasshopper

7.3 Comparative studies of the CAD methods and the judgment of creativity in hospital design optimisation.

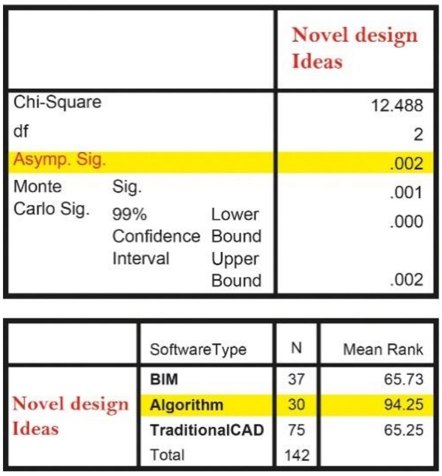
Chapter6 summarised feedback based on Amabile's creativity judgements (1982) and gave relevant interpretations from the three CAD user groups, BIM, algorithmic CAD, and traditional CAD. This section aims to select some aspects of these creativity judgments and to investigate the correlation of the use of the different CAD methods. In addition, the discussion extends the findings to other current innovative design projects of complex buildings and makes suggestions on different aspects of design optimisation as references and suggestions for future hospital design development.

There were two statistical analyses applied for the study. First, the Kruskal-Wallis test (KW-Test) compared the performance of each design category across the three CAD groups and computed the significance of it. Second, the Mann-Whitney (U-test) further compared the significance for two particular groups and checked the size of the statistical effect between the groups using Cohen’s criteria (1988): 0.1=Small effect, 0.3= Medium effect, and 0.5= Large effect.

7.3.1 Novel design ideas

‘Building a 2020 vision for future health care design environments’ (2001), a publication by the Nuffield Trust, mentions the importance of strategic design thinking with innovation in design and delivery of healthcare building environments. So, it is suggested that novel ideas should be an essential part of a unique design strategy which can influence building design developments and directions, such as a new compact design approach integrating hospital departments or one introducing an energy efficient floor plan. As to the CAD performances, the KW-test results (Table 7.5) identify that there was a significant difference between the three CAD systems in terms of the impact on the generation of novel ideas across the three CAD user groups: BIM, n=37, algorithmic CAD n= 30, and traditional CAD, n=75, χ_2 (2, n=142) = 12.488, P = 0.002 <0.05. The largest mean rank of 94.25 indicates that algorithmic CAD helped significantly in this regard. Thus, the U-test (Table 7.5-1) investigated the comparison between the BIM and the algorithmic CAD groups (Table 7.5-1-A), and the calculated statistics yielded a significant statistical difference with the values: U = 331.5, Z = -2.926, P = 0.003 < 0.05, showing a large effect r=0.4. A similar result was exhibited in the comparison between algorithmic CAD and traditional CAD (Table 7.5-1-B) where there was also a significant difference between the two: U= 666, Z = -3.396, P = 0.001 < 0.05, with a big impact $r = \frac{Z}{\sqrt{N}} = 0.3$.

Table7.5 The KW-Test of Novel design ideas

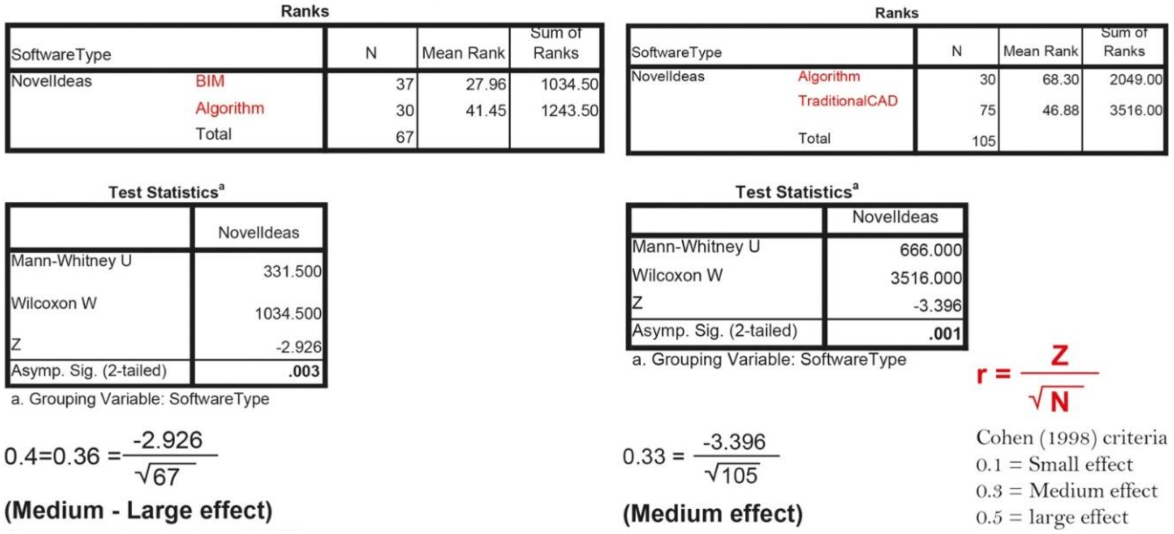


			Novel design Ideas
Chi-Square			12.488
df			2
Asymp. Sig.			.002
Monte Carlo Sig.	Sig.		.001
	99% Confidence Interval	Lower Bound	.000
		Upper Bound	.002

	SoftwareType	N	Mean Rank
Novel design Ideas	BIM	37	65.73
	Algorithm	30	94.25
	TraditionalCAD	75	65.25
	Total	142	

Source: Author reproduced/ SPSS outputs

Table7.5-1 The U-Test of novel design ideas with different CAD groups



Ranks

SoftwareType		N	Mean Rank	Sum of Ranks
NovelIdeas	BIM	37	27.96	1034.50
	Algorithm	30	41.45	1243.50
	Total	67		

Test Statistics[a]

	NovelIdeas
Mann-Whitney U	331.500
Wilcoxon W	1034.500
Z	-2.926
Asymp. Sig. (2-tailed)	**.003**

a. Grouping Variable: SoftwareType

$$0.4=0.36 = \frac{-2.926}{\sqrt{67}}$$

(Medium - Large effect)

Ranks

SoftwareType		N	Mean Rank	Sum of Ranks
NovelIdeas	Algorithm	30	68.30	2049.00
	TraditionalCAD	75	46.88	3516.00
	Total	105		

Test Statistics[a]

	NovelIdeas
Mann-Whitney U	666.000
Wilcoxon W	3516.000
Z	-3.396
Asymp. Sig. (2-tailed)	**.001**

a. Grouping Variable: SoftwareType

$$0.33 = \frac{-3.396}{\sqrt{105}}$$

(Medium effect)

$$r = \frac{Z}{\sqrt{N}}$$

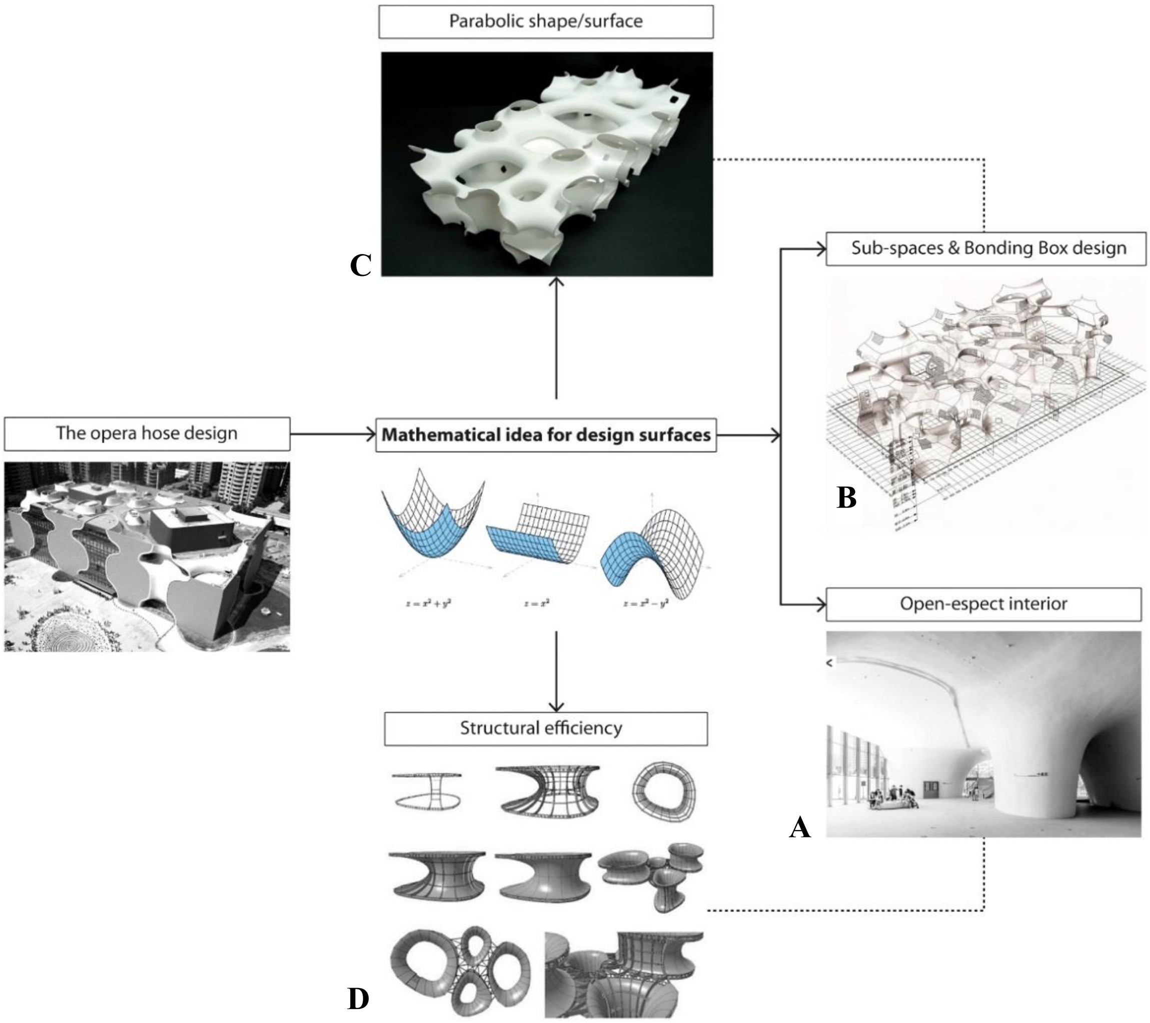
Cohen (1998) criteria
0.1 = Small effect
0.3 = Medium effect
0.5 = large effect

Source: Author reproduced/ SPSS outputs

The results suggest that if traditional CAD or the BIM architects switched their design method to algorithmic CAD, the architect could experience a large positive influence on the generation of creative design ideas, i.e. an increase in the ‘volume’ of ideas. This is because algorithmic CAD offers design strategies during the design ideation process. As Terzidis (2003) states, ‘This process, algorithmic design, presents abstract (mathematical) thinking to formalize the design problem and proper solutions but does not directly move to a particular solution. Therefore, the design idea is normally very different from a typical idea and gives more opportunities for the production of creative results’.

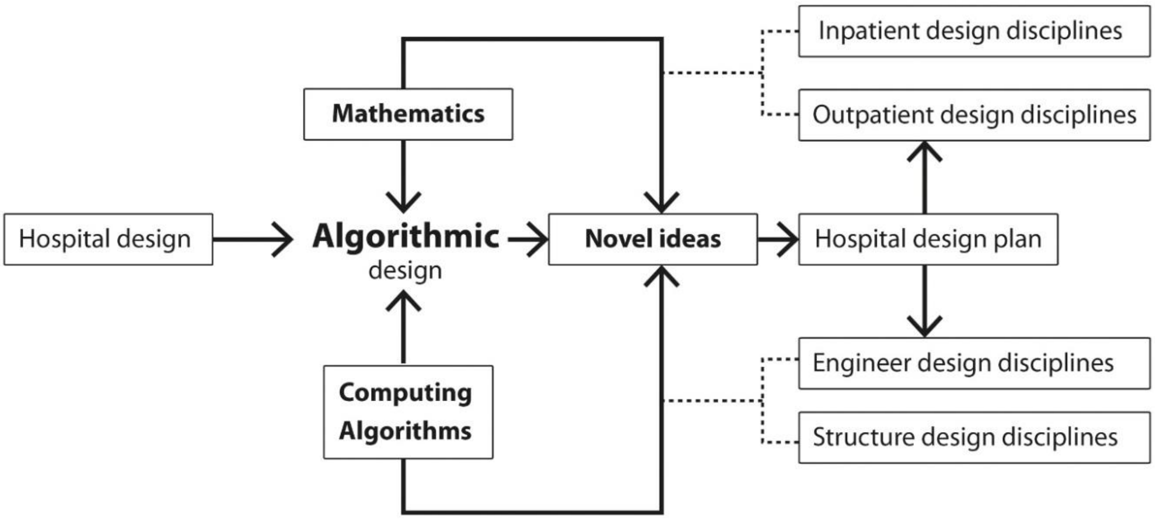
For instance, the national Taichung Opera House (2016) (www.metalocus.es) (Fig.7.5) contains complex architectural programs that include different functions such as performance spaces, administration, exhibition and education areas. The challenge for the design proposal was to make a design strategy integrating those functional spaces but also enabling good circulation and an open-aspect interior design (Fig.7.5-A). Therefore, the design office, Toyo Ito and Associates, proposed a continuous mathematically-designed surface that was able to formulate and integrate sub-spaces within a bounding box (Fig.7.5-B). This connected surface design was based on the idea of parabolic shape design (Fig.7.5-C), which breaks away from conventional spatial design such as columns, beams and floor plans, and shows continuous and infinite space experiences including better visual extension and structural efficiency (Fig.7.5-D). It is not possible for this design idea to be applied without algorithmic CAD because only the computed algorithms could apply this mathematical concept widely extending it into multiple design aspects such as building shape, layout and structural construction. When it comes to conventional, nonparametric hospital building design, there are limited design possibilities because the CAD method cannot easily manipulate mathematical design ideas and provide structural design plans; architects normally restrict their design thinking to existing building prototypes. Those existing design types, or design solutions, act like pre-existing ‘design templates’ and make it hard to escape from their cognitive influence and develop novel design ideas. If architects apply the use of the algorithmic CAD method (Fig.7.5-1), they can possibly improve their design idea through producing the mathematics or algorithm-based design plan (Fig.7.5-1-A) rather than adhering to any specific existing design model. Besides the creation of innovative design ideas, it is important that the architect can formulate their own design strategy (Fig.7.5-1-B) in the early design stages of complex building designs like hospitals. Once the architect forms the design idea through mathematical concepts and parametric algorithmic thinking, they can make design changes to accommodate the different opinions or involvement of clients and engineers.

Fig.7.5 The Algorithmic CAD process of novel design idea



Source: Author reproduced/ www.metalocus.es

Fig.7.5-1 The Algorithmic CAD optimization for innovative hospital design ideas

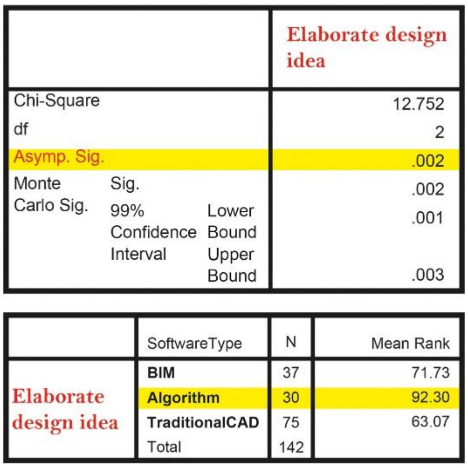


Source: Author reproduced

7.3.2 Elaborate design ideas

Verderber (2010) states that a hospital is not an isolated island. It possesses multiple functions and roles in our society such as leadership in an environmental context, a role in local communities, being part of city infrastructures, and roles in social care and charity sponsorship. Therefore, these complexities should be recognised from the earliest stages of design ideation. More particularly he says that producing 'elaborate' design means developing or progressing further detailed design information or involving much more carefully arranged design considerations in the design proposal.

Table7.6 The KW-Test of Elaborate design ideas



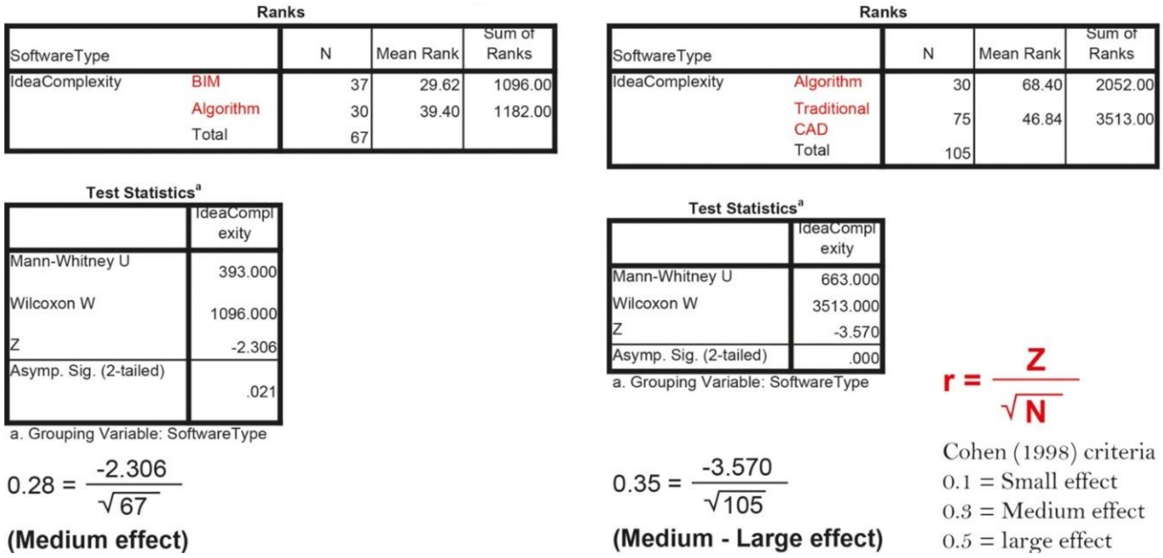
			Elaborate design idea
Chi-Square			12.752
df			2
Asymp. Sig.			.002
Monte Carlo Sig.	Sig.		.002
	99% Confidence Interval	Lower Bound	.001
		Upper Bound	.003

	SoftwareType	N	Mean Rank
Elaborate design idea	BIM	37	71.73
	Algorithm	30	92.30
	TraditionalCAD	75	63.07
	Total	142	

Source: Author reproduced/ SPSS outputs

Making a statistical analysis comparison, the KW-test results (Table 7.6) show there was a significant difference in the complex production of ideas across the three CAD user groups: BIM, n=37, algorithmic CAD, n= 30, and traditional CAD, n=75, χ_2 (2, n=142) = 17.134, P = 0.002 <0.05. Algorithmic CAD architects showed a value of 92.30, the highest value of the mean rank presented in this respect. The U-test was applied to compare the differences between the three CAD groups. For the BIM group and algorithmic CAD (Table 7.6-1-A), there was a significant difference between the values: U = 393, Z = -2.306, P = 0.021 < 0.05, with a medium effect size $r = \frac{Z}{\sqrt{N}} = 0.3$. In addition, the testing of the comparison between algorithmic CAD and traditional CAD (Table 7.6-1-B) also yielded a significant difference: U= 663, Z = -3.57, P = 0.000 < 0.05, a large effect size $r = \frac{Z}{\sqrt{N}} = 0.4$. The results suggest that if conventional CAD architects switched their design method to algorithmic CAD, they could experience a large effect on an improved process to elaborate and develop ideas in their design. The algorithmic design process largely relies on a disciplined knowledge of mathematical parameters; the design problems are formulated within this parametric system which can provide flexibility and can be extended or modified according to demands (See the literature review of the parametric concept in Section 4.3.4.a, Chapter 4).

Table7.6-1 The U-Test of elaborate design ideas with different CAD groups



Ranks

SoftwareType		N	Mean Rank	Sum of Ranks
IdeaComplexity	BIM	37	29.62	1096.00
	Algorithm	30	39.40	1182.00
	Total	67		

Test Statistics[a]

	IdeaComplexity
Mann-Whitney U	393.000
Wilcoxon W	1096.000
Z	-2.306
Asymp. Sig. (2-tailed)	.021

a. Grouping Variable: SoftwareType

$$0.28 = \frac{-2.306}{\sqrt{67}}$$

(Medium effect)

Ranks

SoftwareType		N	Mean Rank	Sum of Ranks
IdeaComplexity	Algorithm	30	68.40	2052.00
	Traditional CAD	75	46.84	3513.00
	Total	105		

Test Statistics[a]

	IdeaComplexity
Mann-Whitney U	663.000
Wilcoxon W	3513.000
Z	-3.570
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: SoftwareType

$$0.35 = \frac{-3.570}{\sqrt{105}}$$

(Medium - Large effect)

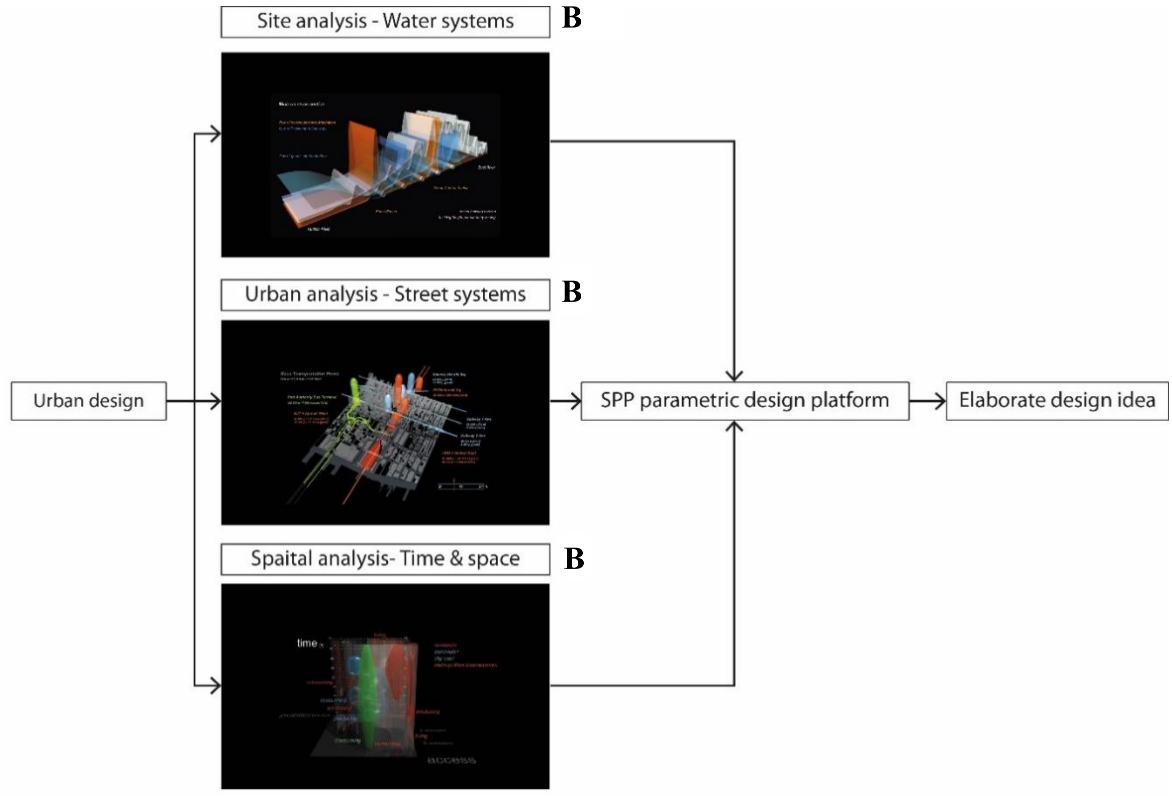
$$r = \frac{Z}{\sqrt{N}}$$

Cohen (1998) criteria
0.1 = Small effect
0.3 = Medium effect
0.5 = large effect

Source: Author reproduced/ SPSS outputs

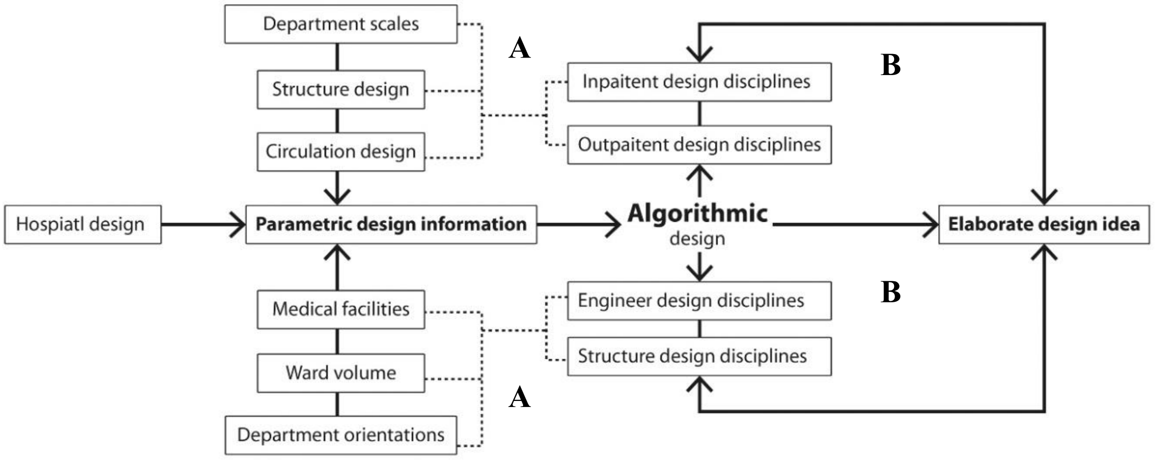
As a design project example, the UN studio has a specialised parametric design group applying the latest algorithmic CAD method – The Smart Parametric Platform (SPP). SPP is not just a conventional modelling system; it contains many complex algorithmic programs with disciplines and processes that use non-geometric parameters such as economic, political, materials, etc. An example of one of their design projects was the IFCCA Design of Cities Competition (USA,1999) (Fig.7.6). This SPP (Fig.7.6-A) provided many conceptual diagrams including complex relations between time, flow, structure, and economics within relevant spatial programs (Fig.7.6-B). This design information system increased the elaboration of the design idea and improved the quality of the design proposal. For hospital design (Fig.7.6-1), architects can apply this advantage of algorithmic design and collect complex design parameters to make a disciplined system, like spatial volume and scale, orientation, to name a few (Fig.7.6-1-A). If more design information is input, the algorithmic definition becomes complete and is then able to check design development in a multi-design process (Fig.7.6-1-B). Bosia (2011) argues that computer algorithms and scripting provide the designer with a nonlinear way of processing the design being developed; this learns from nature's evolutionary process and avoids the design falling into a replicated activity. As the NHS suggests (Nuffield Trust, 2001), the design idea means a platform is created for architects and healthcare professionals and this potentially improves the quality of healthcare buildings. Therefore, the design idea could increase its elaboration to intensify the different design aspects. This should enable the building of better design considerations for future healthcare architecture.

Fig.7.6 The Algorithmic CAD process of design elaboration



Source: Author reproduced/ www.unstudio.com

Fig.7.6-1 The Algorithmic CAD optimization for complex hospital design ideas



Source: Author reproduced

7.3.3 Organisation and neatness of the functional programs

It is suggested in ‘Building a 2020 vision for future health care design environments’ (2001) that modular design will be part of future hospital building design, particularly the aspect of construction as a manufacturing process. The inclusion of modular design aims to unify the quality of the design, control the budget and gain from previous projects’ feedback. However, this proposal means establishing an organised design that refers to the coordination of the conceptual design stages including modelling management, the use of a file browser, and the import and export of design files. When it comes to the statistical analysis of the effect of the CAD method on design organisation, the KW-test results (Table 7.8) also confirm there was a significant difference in the effects on standardised design across the three CAD user groups: BIM, n=37, algorithmic CAD, n= 30, and traditional CAD, n=75, χ_2 (2, n=142) = 22.84, P = 0.000 <0.05. The U-test further compared the groups; between the BIM and the algorithmic CAD groups (Table 7.8-1-A), there was a significant difference between the values: U = 180, Z = -4.964, P = 0.00 < 0.05, and a large effect size $r = \frac{Z}{\sqrt{N}} = 0.6$. When comparing algorithmic CAD and traditional CAD (Table 7.8-1-B), there was also a statistically significant difference: U= 595.5, Z = -3.884, P = 0.000 < 0.05, and a large effect size, $r = \frac{Z}{\sqrt{N}} = 0.4$ indicating a good effect.

Table7.8 The KW-Test of neatness of the functional programs

			Organisation and neatness of the functional programs
Chi-Square			22.836
df			2
Asymp. Sig.			.000
Monte Carlo Sig.	Sig.		.001
	99% Confidence Interval	Lower Bound	.000
		Upper Bound	.002

	SoftwareType	N	Mean Rank
Organisation and neatness of the functional programs	BIM	37	84.39
	Algorithm	30	41.35
	TraditionalCAD	75	77.20
	Total	142	

Source: Author reproduced/ SPSS outputs

Table7.8-1 The U-Test of Organization of the functional programs

Ranks

SoftwareType		N	Mean Rank	Sum of Ranks
DesignCo ction **A**	BIM	37	44.14	1633.00
	Algorithm	30	21.50	645.00
	Total	67		

Test Statistics[a]

	DesignConnection
Mann-Whitney U	180.000
Wilcoxon W	645.000
Z	-4.964
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: SoftwareType

$$0.6= \frac{-4.964}{\sqrt{67}}$$

(Large effect)

Ranks

SoftwareType		N	Mean Rank	Sum of Ranks
DesignCon ion **B**	Algorithm	30	35.35	1060.50
	TraditionalCAD	75	60.06	4504.50
	Total	105		

Test Statistics[a]

	DesignConnection
Mann-Whitney U	595.500
Wilcoxon W	1060.500
Z	-3.884
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: SoftwareType

$$0.4= 0.37= \frac{-3.884}{\sqrt{105}}$$

(Medium - Large effect)

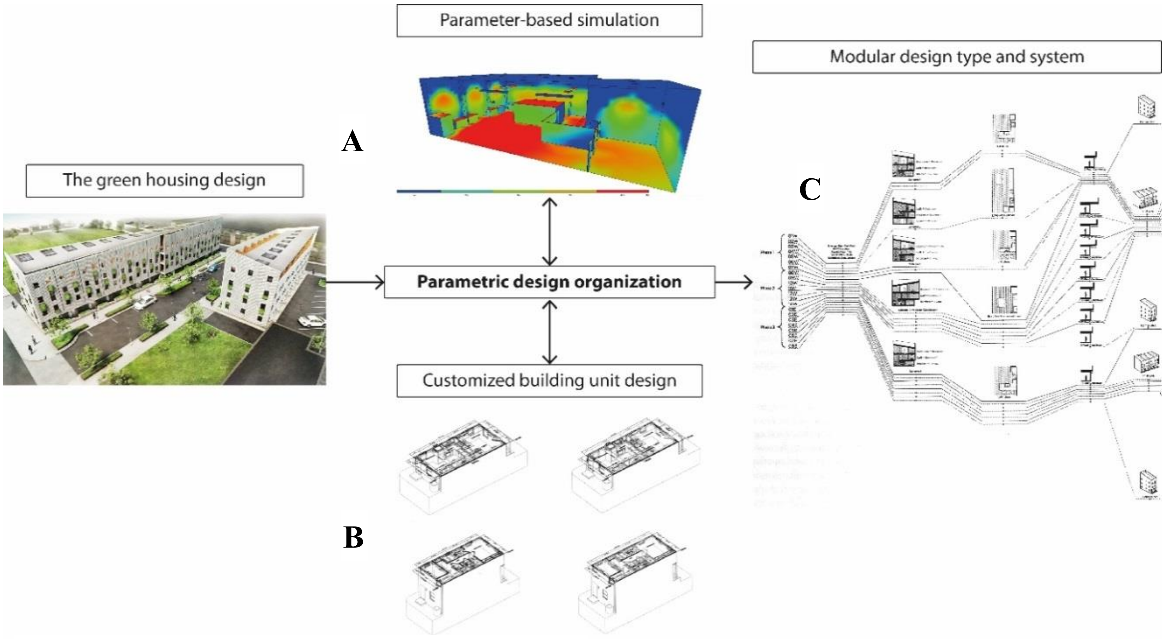
$$r = \frac{Z}{\sqrt{N}}$$

Cohen (1998) criteria
0.1 = Small effect
0.3 = Medium effect
0.5 = large effect

Source: Author reproduced/ SPSS outputs

The above results indicate that BIM design performed better in terms of design organisation and improved the neatness of the functional programming process. The design system especially contains many functions for project coordination such as a project browser and a collaborative working platform. Large-scale projects, like hospital design, require a large volume of design drawings and file coordination and BIM provides very good performance in this respect. Additionally, because BIM design could create a standard format for design components and files, those design sources could be more easily delivered or exchanged between different design teams and combined together in the final proposal. For example, the GRO architects, Jackson Green Housing, Jersey City, New Jersey, 2012-14 (Fig.7.7) proposed 22 units of residential housing in a design project with a modular design assembly system. The BIM system was employed to organise different parts, such as design simulation, modular design variation, modular fabrication and budgetary control (Fig.7.7-A). Those design sections were formed into a simulation process and optimised to fit the design concept – an eco-friendly modular design. At the same time, the output information was constructed using the same filing approach; for instance, the building mass and orientation were decided by a lighting simulation that also responded to detailed design issues by specifying the different changes to be applied to some special units (Fig.7.7-B). Also, the parameter-based design of 2D to 3D translation functions helped communications and saved a great deal of time and money in the problem prediction process between the module prefabrication and design teams. The final design produced 14 different types of housing units (Fig.7.7-C) based on energy consumption indicators. These had the same modular system but provided variety in the design details such as roof materials, rear decking, hot water supply, etc. This type of workflow exhibits the BIM parametric design process optimising design management from the aspect of flexible design coordination, economic construction and standardised design criteria. Architects, in particular, could consider those design issues at the early design stages and then allocate different design problems to individuals before bringing them together to make final adjustments.

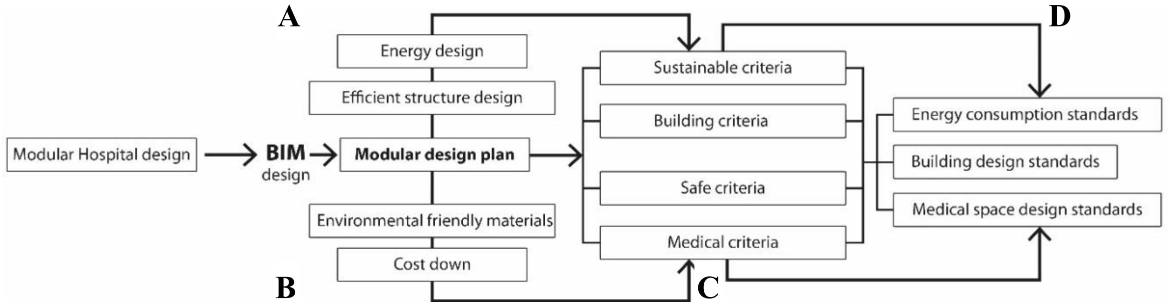
Fig.7.7 The BIM design process of design organization



Source: Author reproduced/ www.groarc.com

When comparing this with the early modular design hospitals, such as the Harness and Nucleus hospitals, these modular hospitals largely relied on conventional CAD methods and 2D outputs, which could not easily create such a flexible design system, especially when discussing the design problems across different building professions like plumbing or structural engineers. For example, the design of the Harness hospital was based on a long span structure, the 15mX15m cruciform, causing difficulties for plumbing design and adding considerably to costs. Therefore, greater expense and more limited types of modular design were consequences in this more traditional design process. If the BIM workflow can be applied to modular hospital design (Fig.7.7-1), it may then be possible to improve the design variety and efficiency of the design planning process (Fig.7.7-1-A) and also potentially improve design optimisation by predicting (Fig.7.7-1-B) design errors as well as addressing the criteria (Fig.7.7-1-C) of better healthcare design standards (Fig.7.7-1-D).

Fig.7.7-1 The BIM design optimization for hospital design organization

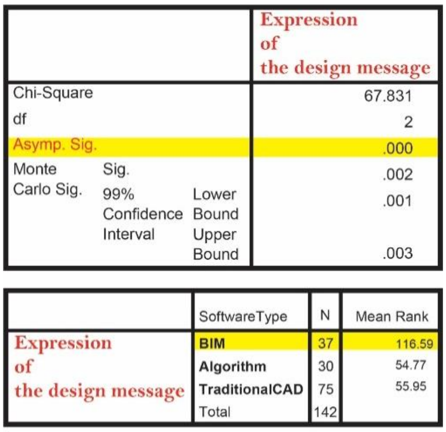


Source: Author reproduced/ www.groarc.com

7.3.4 Expression of the design message

In the hospital design process, Moss (1974) suggests that before the design project starts, training in design message expression could help to ensure work teams including architects, medical professionals and engineers share the same design image in the communication of the hospital design development. When it comes to considering the CAD methods used, CAD expression refers to the representation of design ideas which includes 3D models and digital visualisations. Within the design process, an accurate and fluent design expression also helps to reduce design mistakes arising in communication with and between other design professionals such as structural engineers or design technicians, and then helps to integrate the resulting information to accurately deliver the designed products i.e. the buildings. The BIM group had the highest review scores showing great support from this CAD method in this respect. The KW-test (Table 7.9) further states there was a significant difference in the impact on design communication across the three CAD user groups: BIM, n=37, algorithmic CAD, n= 30, and traditional CAD, n=75, χ_2 (2, n=142) = 67.831, P = 0.000 <0.05.

Table7.9 The KW-Test of expression of the design message



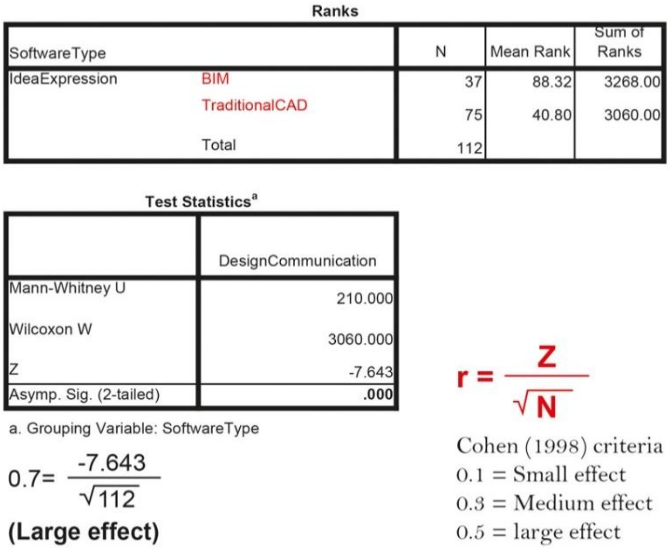
			Expression of the design message
Chi-Square			67.831
df			2
Asymp. Sig.			.000
Monte Carlo Sig.	Sig.		.002
	99% Confidence Interval	Lower Bound	.001
		Upper Bound	.003

	SoftwareType	N	Mean Rank
Expression of the design message	BIM	37	116.59
	Algorithm	30	54.77
	TraditionalCAD	75	55.95
	Total	142	

Source: Author reproduced/ SPSS outputs

In evaluating how the effects varied between the use of BIM parametric CAD and nonparametric or traditional CAD (Table 7.9-1) in the hospital design process, the results show that there was also a significant difference: U= 210, Z = -7.643, P = 0.000 < 0.05. Regarding the effect size, $r = \frac{Z}{\sqrt{N}} = 0.7$ indicated a very large effect. The reason for these results is because BIM computer design is based on a parametric modelling interface and 3D outputs, which are easily usable by most of the

Table7.9-1 The U-Test of expression of the design message



Ranks

SoftwareType		N	Mean Rank	Sum of Ranks
IdeaExpression	BIM	37	88.32	3268.00
	TraditionalCAD	75	40.80	3060.00
	Total	112		

Test Statistics[a]

	DesignCommunication
Mann-Whitney U	210.000
Wilcoxon W	3060.000
Z	-7.643
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: SoftwareType

$$0.7 = \frac{-7.643}{\sqrt{112}}$$

(Large effect)

$$r = \frac{Z}{\sqrt{N}}$$

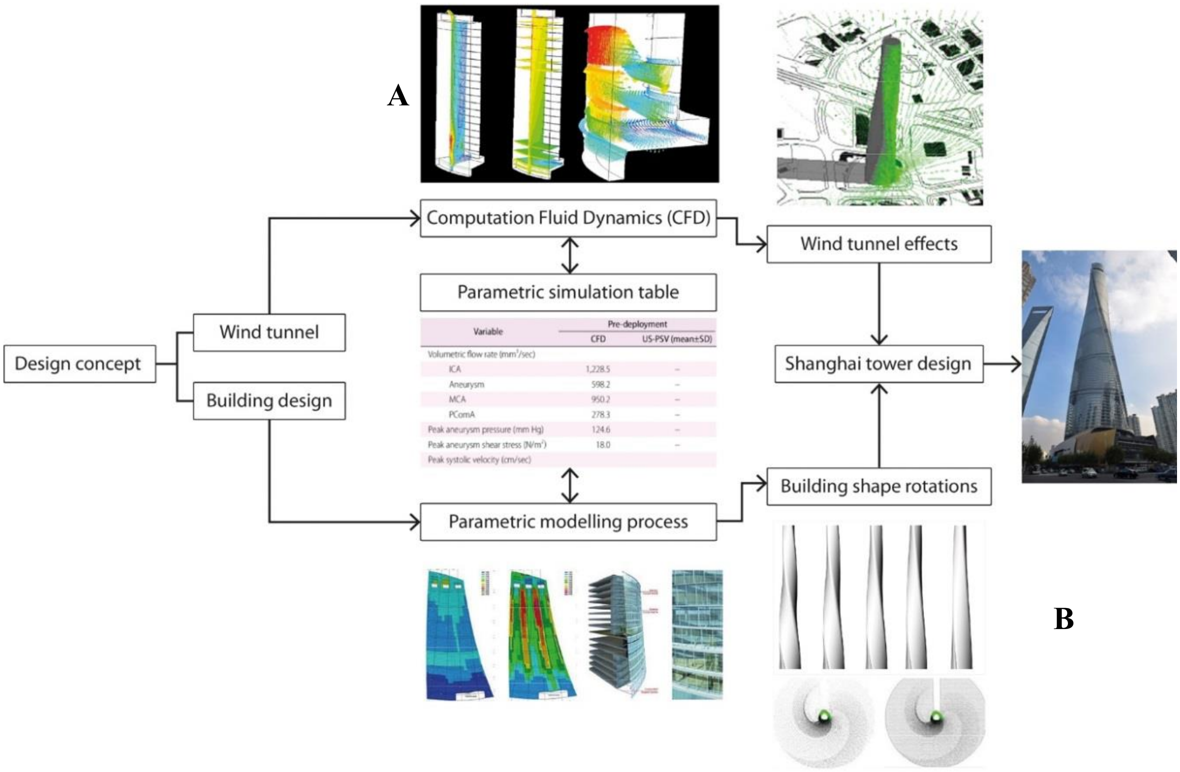
Cohen (1998) criteria
0.1 = Small effect
0.3 = Medium effect
0.5 = large effect

Source: Author reproduced/ SPSS outputs

design team, including engineers and hospital consultants. This parameter based geometric design system enhances the understanding of the design message through the building design representation, with a direct association between certain design entities and 3D objects, which are not just being explained through abstract ideas (See the literature review of taxonomy of parameters in Section 4.3.4.b, Chapter 4). Therefore, architects and other design professionals can fluently exchange the design options using the same design interface, discussing the visible design outputs, and reducing any misconceptions or misleading ideas.

One design example, the Shanghai Tower, Shanghai, China, 2008-14 (Fig.7.8) designed by Gensler, employed the BIM design method and successfully overcame the design challenges of how to respond to the local climate. Taking climate into consideration when designing buildings is complicated because there is no common language to connect these two topics. Therefore, the design team translated the available environmental data into a parameter-based system and adjusted the 3D modelling system including site contexts and building blocks. They then employed Computation Fluid Dynamics (CFD) (Fig.7.8-A), which simulated the local climate and predicted wind impacts on the tower shape design. During the simulation process, extensive physical parameters and analytical data were constantly exchanged and adjusted for the discussion on building shape optimisation. The resulting building rotation design (Fig.7.8-B) not only produced an aesthetically elegant form but also included a mass scientific justification for the design proposal in that it responded to the environmental issues. In the hospital design process, an intensive exchange of design information is necessary (Fig.7.8-1). Unfortunately, architects and engineers do not have the same approach to their thinking on design outputs. For example, architects work on design drawings, but engineers produce analysis reports (Fig.7.8-1-A). Very often, their discussions lack the ability to make real-time or immediate changes and cause some mistakes in the later stages despite the fact they normally take up a large amount of time in the design process. In other words, it is a problem that could affect design efficiency and cost more money. If the CAD method can and does build a connection to support idea exchange at an early stage and to efficiently transfer discussion results into a digital process (Fig.7.8-1-B), design coordination certainly can be optimised, ensuring a better quality of design outcomes.

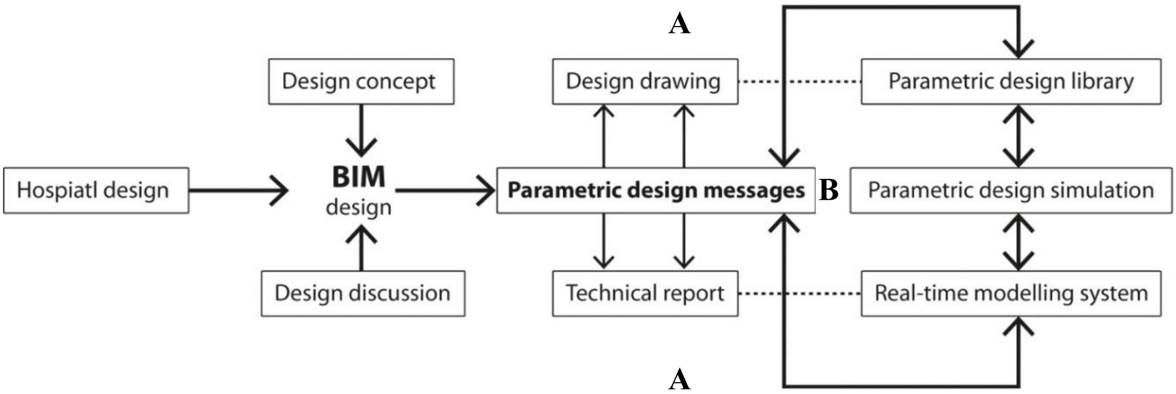
Fig.7.8 The BIM design process of design message expressions



Variable	Pre-deployment	
	CFD	US-PSV (mean±SD)
Volumetric flow rate (mm^3/sec)		
ICA	1,228.5	–
Aneurysm	598.2	–
MCA	950.2	–
PComA	278.3	–
Peak aneurysm pressure (mm Hg)	124.6	–
Peak aneurysm shear stress (N/m^2)	18.0	–
Peak systolic velocity (cm/sec)		

Source: Author reproduced/ www.slideshare.net

Fig.7.8-1 The BIM design optimization for hospital design expression



Source: Author reproduced

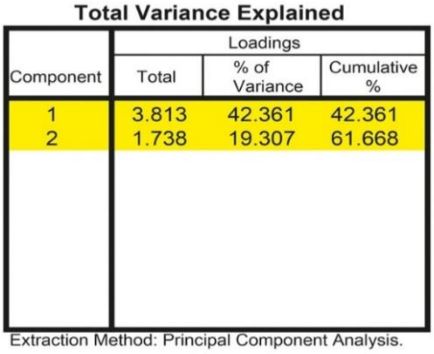
7.4 Statistical factor analysis across the CAD groups

Factor analysis is a statistical procedure used for exploring the interrelationship of variables in individual groups. In this section, the percentage of variance was explained in the Principle Component Analysis (PCA) which summarised the information in a correlation matrix. The loading of factors represented in the different design methods and design performances in terms of the creativity measurements. The variable of each component also gives a calculated coefficient according to the factor group or component, then squares the coefficient value, indicating the loaded percentage of the component.

7.4.1 Factor analysis for BIM design

The PCA of factor analysis (Table 7.10) calculates the total creativity variances explained by the main extracted factors and their individual and combined loading on creativity; over 61% of the variance was found to be caused by the two components. Component 1 (Table 7.10-A), responsible for 42% of the variance, mainly consisted of building design evaluations such as varied form making, new material utilisation and the enjoyment of design. Component 2 (Table 7.10-B), representing 19% of the variance, contained mostly technical design processes such as good detail, schematic design and design elaboration (See the literature review of the measurement of product creativity in Section 3.6.2.b, Chapter 3).The first component, with a loading value of 42%, indicates that the design factors from the product's evaluation of the BIM design activity had more influence on the creative potential, for example, considering the design aspects of assessing hospitals' novel idea, varied shapes, the liking of design and worth of displaying. The percentage value of these four factors shows over 60 as the sub-loading, which means the creative design was significantly determined according to unique ideas (73%), varied shapes (73%), the liking of design (72%) and worth of displaying (64%).

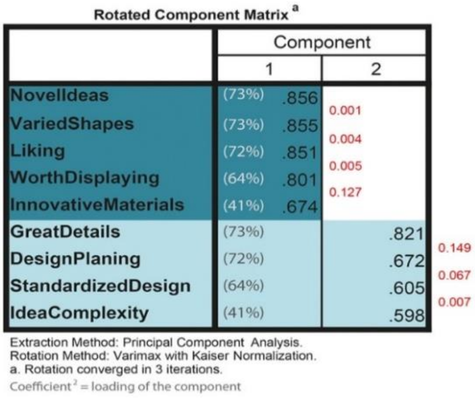
Table7.10 The factor analysis for the BIM design



Total Variance Explained

	Component	Loadings		
		Total	% of Variance	Cumulative %
A	1	3.813	42.361	42.361
B	2	1.738	19.307	61.668

Extraction Method: Principal Component Analysis.



Rotated Component Matrix[a]

	Component		
	1	2	
NovelIdeas	(73%) .856	0.001	
VariedShapes	(73%) .855	0.004	
Liking	(72%) .851	0.005	
WorthDisplaying	(64%) .801	0.127	
InnovativeMaterials	(41%) .674		
GreatDetails	(73%)	.821	0.149
DesignPlaning	(72%)	.672	0.067
StandardizedDesign	(64%)	.605	0.007
IdeaComplexity	(41%)	.598	

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 3 iterations.
Coefficient^2 = loading of the component

Source: Author reproduced/ SPSS outputs

In addition, the closed coefficient difference between those four factors was around <0.01 (1%) and confirmed that a closed relationship enhanced the BIM design creativity.

It is interesting that the BIM design method frequently identifies the intelligence with the programming function for detail design or file integration (Fig. 7.9). However, the statistical results confirm that a majority loading in the idea-making process had more creative impacts than the project management or detail drawing (Fig.7.9-1). For instance, more building design shapes could help to determine innovative design layouts and detailed designs. The nature of the parametric design activity is about how the parametric modelling system maximises the output from the design problem-solving process and influences real-life counterparts such as the structural force or materials behaviour. Also, parametric design geometries are, in essence, formulated by the design intention or logic rather than just through a form proposal (Jabi, 2013). This means an innovative idea developed by parametric design methods and algorithmic design thinking could well have been supported by the BIM design process rather than only focusing on technical aspects such as project integration or modelling management when applying the BIM design process to hospital buildings. Therefore, it is important to redirect the BIM design function as a parametric evaluation process, such as geometry exploration or material innovation, which can increase the potential influences helping hospital architects increase the creativity of their ideas in design development.

Fig.7.9 The BIM design and general building design

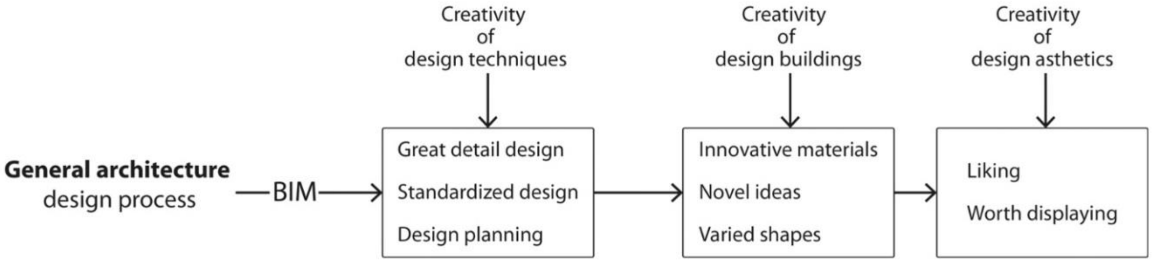
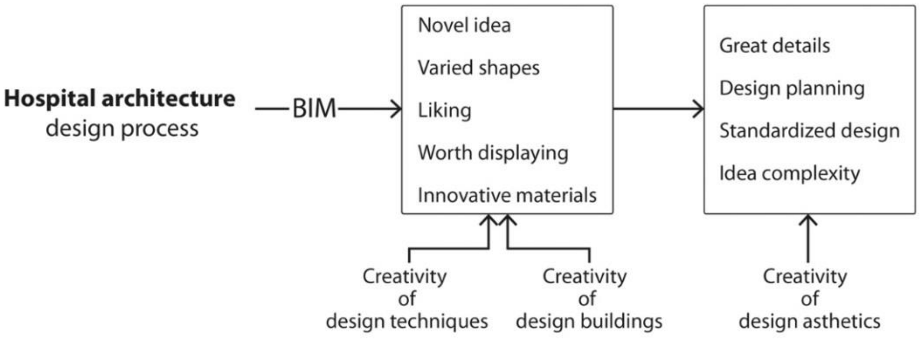


Fig.7.9-1 The BIM design and hospital building design



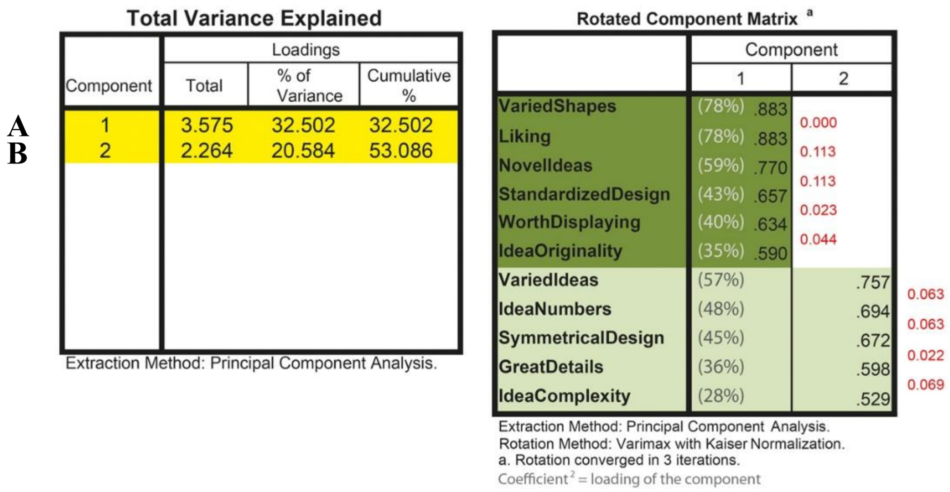
Source: Author reproduced

7.4.2 Factor analysis for Algorithmic CAD

The table (Table 7.11) shows there are two factors representing the 53% of the overall loading variance in the PCA with the correction matrix. The two components demonstrate only 10% difference in the loading variance with 32.5% in factor 1 and 20.6% in factor 2. In these results, both components indicate that the important influence of algorithmic design creativity appear in the ideation process (idea numbers, variety, and uniqueness), product ideas (varied shapes, novel ideas, idea complexity and others), and a few concerns such as the technical factors of the product (standardised design and symmetrical design).

In Component 1 (Table 7.11-A), varied shapes and enjoyment of the design had the same loading, around 78%, and the coefficients indicated no difference between the two variables. This means, when using algorithmic CAD, the exploration of design diversity helped make design enjoyable. This relationship is cited as an important factor in Torrance's creativity testing (Fig.7.10-1-A) (See the literature review of measuring creativity as an idea process in Section 3.6.2.a, Chapter 3). For the variables of novel ideas (59% of the component loading) and standardised design (43% of the component loading), the coefficient difference is about 0.1 (10%). This shows that novel ideas created by the algorithmic design method were based on an organised design procedure, namely, a series of design algorithms (Fig.7.10-1-B). Jabi (2013) identifies that algorithmic thinking allows designers to rationalise, control, iterate, analyse, and search for alternatives within a defined solution space.

Table7.11 The factor analysis for the Algorithmic CAD



Total Variance Explained

	Component	Loadings		
		Total	% of Variance	Cumulative %
A	1	3.575	32.502	32.502
B	2	2.264	20.584	53.086

Extraction Method: Principal Component Analysis.

Rotated Component Matrix [a]

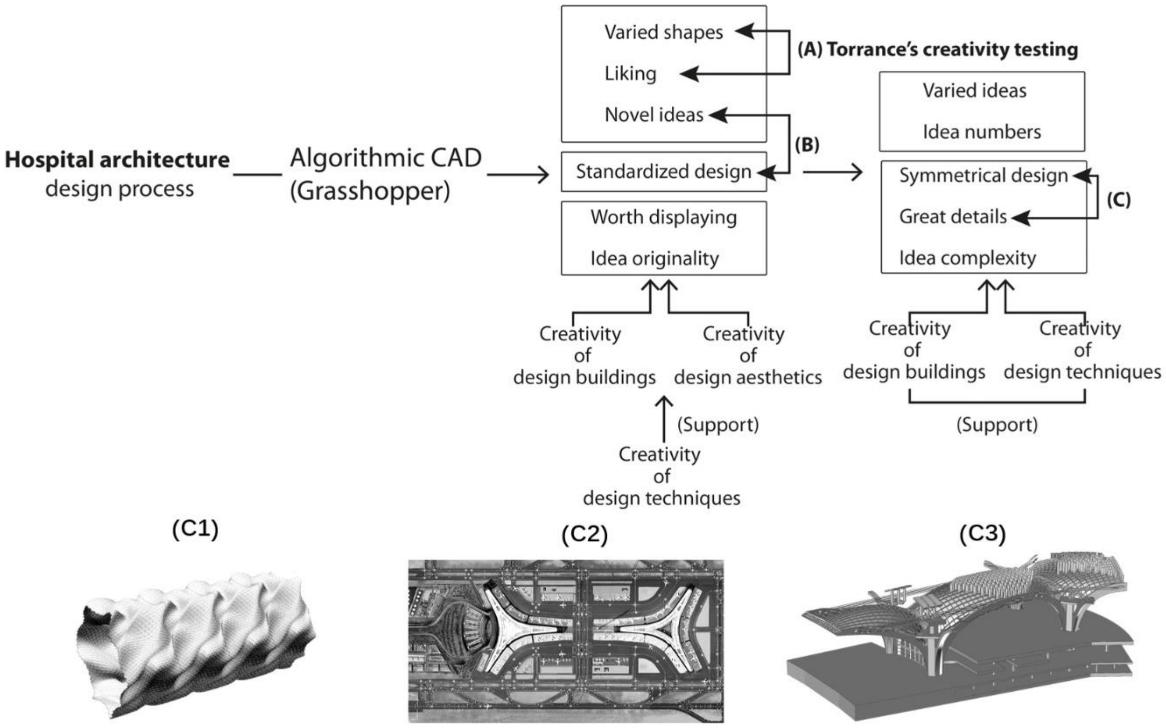
	Component		
	1	2	
VariedShapes	(78%) .883	0.000	
Liking	(78%) .883	0.113	
NovelIdeas	(59%) .770	0.113	
StandardizedDesign	(43%) .657	0.023	
WorthDisplaying	(40%) .634	0.044	
IdeaOriginality	(35%) .590		
VariedIdeas	(57%)	.757	0.063
IdeaNumbers	(48%)	.694	0.063
SymmetricalDesign	(45%)	.672	0.022
GreatDetails	(36%)	.598	0.069
IdeaComplexity	(28%)	.529	

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 3 iterations.
Coefficient^2 = loading of the component

Source: Author reproduced/ SPSS outputs

In Component 2 (Table 7.10.B), the five variables showed different loadings, but the coefficient differences were very small, under 1%. This means those variables might represent a grouped body of design interactions. For example, between the variable of symmetrical design (45% of the component loading) and great detail (36% of the component loading), the coefficient difference was only 0.022 ≤0.1 (10%). This means the algorithmic CAD architects considered that the symmetrical design process was closely associated with a highly detailed design method (Fig.7.10-1-C). This result makes the interesting point that the mathematical design's symmetrical harmony in the algorithmic method can actually produce an improvement in detail and enhance the overall quality of the design. For example, the Kuwait International Airport project by Foster + Partners applied a design concept – triple rational symmetry (Fig.7.10-1-C1). The idea of design creativity, based on a mathematical algorithmic ideation process, created a generative building design in shape (Fig.7.10-1-C2), layout (Fig.7.10-1-C2) and structure (Fig.7.10-1-C3), which were impossible to produce using traditional nonparametric CAD methods. In addition, the 3D symmetrical design and its detailed design scheme also improved the operational efficiency of the airport services (See the literature review of the Kuwait International airport, Section 4.7, Chapter 4). This advanced harmonic shape was due to the functionality of the algorithmic CAD process which is very different from the traditional nonparametric focus on design symmetry. The CAD can formulate design information with a computation process through mathematical algorithms and integrate these theoretical frameworks to support a design idea from virtual to physical existence through the development of different information (Ahlquist and Megens, 2011).

Fig.7.10 The Algorithmic CAD for hospitals

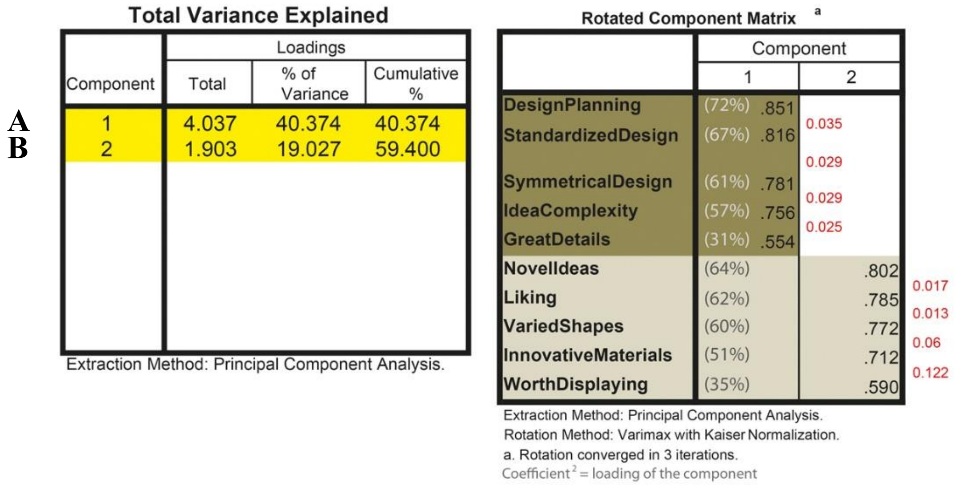


Source: Author reproduced/ www.fosterandpartners.com

7.4.3 Factor analysis for traditional/Nonparametric CAD

The PCA summary (Table 7.12) indicates that two factors represented a 59% overall loading variance on creativity in the correlation matrix. The content of Component 1 (Table 7.12-A) included the major factors in the development of the design’s technical process (40% of the loading) and had more influence than the traditional CAD design creativity. By contrast, in Component 2 (Table 7.12-B), which only contains half the overall loading (19% when compared with 40% for Component 1), the factors involved in the process of ideation in design are the use of new materials and creating varied forms; producing new ideas or design enjoyment had less impact than the CAD innovation performance.

Table7.12 The factor analysis for the traditional CAD



Total Variance Explained

	Component	Loadings		
		Total	% of Variance	Cumulative %
A	1	4.037	40.374	40.374
B	2	1.903	19.027	59.400

Extraction Method: Principal Component Analysis.

Rotated Component Matrix[a]

	Component	
	1	2
DesignPlanning	(72%) .851	
StandardizedDesign	(67%) .816	
SymmetricalDesign	(61%) .781	
IdeaComplexity	(57%) .756	
GreatDetails	(31%) .554	
NovelIdeas	(64%)	.802
Liking	(62%)	.785
VariedShapes	(60%)	.772
InnovativeMaterials	(51%)	.712
WorthDisplaying	(35%)	.590

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 3 iterations.
Coefficient^2 = loading of the component

Source: Author reproduced/ SPSS outputs

Component 1 shows that the sub-loading of the top four design factors are considerably high, about 60% and over, for example, the design planning with 72% of the component loading, standardised design with 67% of the component loading, symmetrical design with 61% of the component loading, and idea complexity with 57% of the component loading. These factors indicate that the conventional CAD method relied on a standardised drawing template/plan and included making parallelised design shapes to elaborate on the design development (Fig.7.11-A). The traditional CAD software does not produce connecting design functions, thus, in complex design projects like hospital design, the architect has to manually set up design guidelines and follow a parallelised drawing approach such as a modular system or copy-and-paste drawing template; these reference materials help architects move their ideation into a more elaborate mental process. In other words, the nonparametric CAD architects tend to focus on technical design (Fig.7.11-B1), controlling the design situation rather than exploring design innovation in the process (Fig.7.11-B2). The use of design templates or modules is similar to traditional craftsmen using a ruler or compass in their design process. Jones (1970) argues that those design tools help the designer coordinate their design perceptions and plot the trajectories of any changes between the different stages of the design, but there is no guarantee that those design templates give better innovative ideas.

However, there is only a small loading (19% of factors) shown in Component 2. The factors include that novel ideas, liking the design and varied shapes have over 60% of the component loading with a coefficient difference of ≤ 0.02 (2%).These factors came into play after the large loading of Component 1, which meant the unique ideas, shape variety, and design enjoyment were certainly less influential on the traditional CAD process compared with the technical development, such as the drawing scheme or design standards. This result may well explain why the early systematic hospital design projects (Fig.7.11-1-A) run by the NHS, UK, emphasised a standard design procedure (Fig.7.11-1-B), a parallelised modular design (Fig.7.11-1-C), and a documentary plan (See the harness and nucleus hospitals in Section 3.3.1.b, Chapter 3). Without these technical designs, traditional CAD architects could not easily adapt their ideas and ensure the quality of the design project.

Fig.7.11 The nonparametric/traditional CAD for hospitals

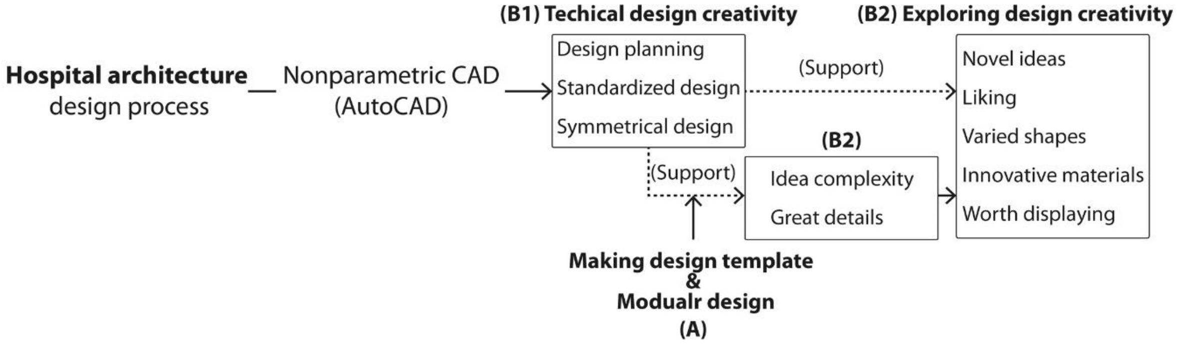
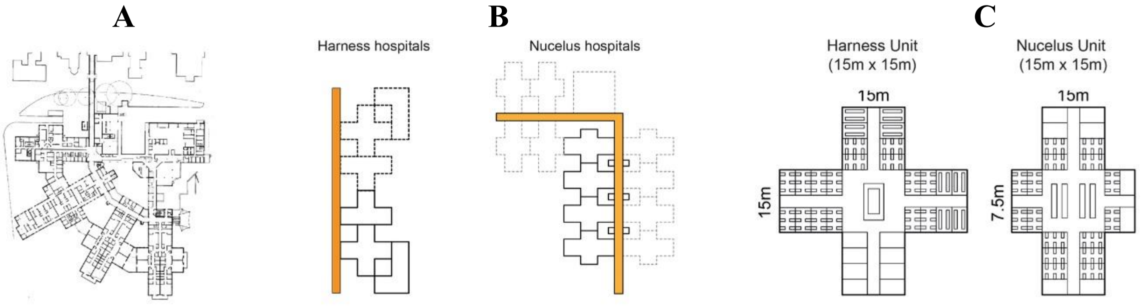


Fig.7.11-1 The nonparametric/traditional CAD of NHS systematic hospitals



Source: Author reproduced/ NHS

7.5 Discussion

7.5.1 Discussion of creativity measurement in the hospital design process

The statistical analysis demonstrated there were certainly significantly different performances when using different CAD methods in hospital design ideation, such as idea numbers, types, and originality of ideas. Regarding the design ideas produced and their variation, algorithmic CAD presented the highest score and gave outstanding impacts compared with the other two CAD groups, BIM and traditional CAD. In terms of a hospital design project, a function focused design remains the main design approach. The conventional CAD architect could only generate a few design ideas and genres, which they used as a design guide, such as building notes or certain design case studies, in their design ideation. On the other hand, algorithmic CAD develops designs through a mathematical system and process which can be organised and flexibly edited by different design inputs. It means the algorithmic CAD method can turn functional design conditions into a design strategy with varied solutions. Unlike seeking a universal design plan through the conventional design method, algorithmic CAD methods give architects a better ideation or brainstorming approach in the making of conceptual development. As the Nuffield Trust (2001) cites, ‘a strategic, systematic and flexible design process is essential for the development of future healthcare architecture in order to provide varied design options to adapt to different design conditions’.

With respect to the length of user experience, only algorithmic CAD users indicated that a longer length of time involvement with the design methodology could help significantly enhance the number of both idea generation and variety. As to idea originality, the majority of the algorithmic CAD architects perceived their design ideas as unique and uncommon. Hospital design relies on the experience of making a plan to connect complex program functions. When comparing conventional CAD with the algorithmic CAD design process, the conventional CAD architects stored their design strategies as memories; the design software just performed as a tool to complete their design plan. By contrast, the algorithmic CAD architects employed design algorithms to help construct their conceptual development, which involved a series of visual design processes and complex modelling processes using mathematical discipline (See the literature review of parametric concept in Section 4.3.4.a, Chapter 4). Therefore, in that design process, design outcomes were usually unexpected and unique.

7.5.2 Discussion of creative product judgements and hospital design optimisation

The results showed there were significant differences between judgements on the creativity of the product and the hospital building across the three CAD groups. Each group had particular areas influenced by the CAD methods. For example, compared to the BIM and traditional CAD groups, algorithmic CAD presented the highest scores and gave outstanding impacts in the creativity cluster in areas such as the design of new ideas and complex concepts or elaborate ideas. On the other hand, BIM claimed the majority of better performances in the building's technical sections in terms of design organisation and design message expression.

Algorithmic CAD had better scores in form and idea exploration. This was because the method menus provide a wide range of mathematical and geometry-based design functions such as points (Vector), surface (NURBS) and mesh creation facilities. Those basic geometric elements can be further connected with mathematical algorithms and operate with associated design parameters in the shape calculations. This process does not limit the discovery of the design concept, especially during the form finding process, and the design outputs can never be easily predicted before the design algorithm is completed (See the literature review of parametric architectural design ideation and expression in Section 4.3.4 Chapter 4). This flexible but well-defined design activity helped the architects to concentrate on the ideation process without engaging with complicated information in the form of hospital building data, which may limit their ideas. Laiserin (2008) suggests 'Form-making, loosely defined, is a process of inspiration and refinement (form precedes analysis of programmatic influences and design constraints) versus form-finding as (loosely) a process of discovery and editing (form emerges from analysis)'. Besides that the case studies using algorithmic CAD showed how the mathematically aided design process could improve design innovations, as in the case of a form finding design using a mathematical idea and algorithm application (Toyo, Ito: mathematically-based design surfaces) and complex design information to enrich design ideas (UN Studio, an information platform for design ideation). These examples demonstrate well how advanced algorithmic design ideas have inspired complex building design and acted as good references to support and inform future hospital design proposals. On the other hand, the case studies of BIM design projects show the impressive design organisation experienced when applying the parametric design system to certain complex design projects and how those parametric workflows improved modular design coordination with instant access to a visually-based modelling system, which could also adjust design requirements through given suggestions (The Jackson Green housing design project). Moreover, the BIM design system not only creates a standard for improving design working efficiency but also helps to express and exchange design information between different design professionals (the Shanghai Tower design project). These two case studies provided different suggestions for hospital design optimisation. They not only made a statement on how to create design standards for future hospital building but also showed how to deploy parametric design to enhance creativity in the context of complex building design.

Kocatürk (2009) highlights that the parametric design method provides a development design process that could reinforce architects' reactions to different design situations or phases which, in effect, means better design involvement. Also, the algorithm and parameter-based design environments assist architects to rationalise their design intentions and developments from the early conceptual design stage. This means they understand the potential and limitations arising from the use of their design tools and then they can optimise the design production and structure efficiently for complex design projects, such as hospital buildings. The above findings, arrived at through this PhD research, have not been identified in any current hospital design literature.

7.5.3 Discussion of the factor analysis

The factor analysis with its 2 components gathered information on the interrelationships of two creativity domains in each of the CAD user groups: measurement of the creativity of design process and creativity judgements on final products. Each CAD group presented a different pattern of these design factors.

The algorithmic CAD method evidenced most of the design creativity in the exploration of the design process. These results not only affected the design ideation but also the evaluation of the building design. Despite the lower loading on technical design factors, the algorithmic process was carried out with absolute methodical logic, which helped the architects develop their unique design techniques or algorithms (Jabi, 2013). Moreover, the algorithmic CAD method is associated with design parameters, mathematical ideas and geometries; this information enriches the design process allowing the building of comprehensive design thinking among architects. In other words, the design method enables the role of the designer to shift from architecture programming to programming architecture, or the associated architecture (Terzidis, 2003).

The major point on creativity about BIM in architectural design is surprisingly focused less on the outcomes produced by the building design techniques, such as standardised design or design planning, and is more concerned with the ideation process itself. The factor loading shows a large effect on the ideation assessment but not the technical aspects of the design development. It could be that the parametric and visual 3D modelling system provides architects with an instant problem correction process. Through applying different design parameters, the geometries can accurately respond to the design problems and can be extended, providing design solutions and gradually producing a logically based design idea. Kocatürk (2009), in her study of new digital approaches to architectural design and production and design cognition, notes 'Emerging design knowledge, influenced by CAD methods, should not only facilitate 'data exchange', but also provide the means for collaborative and innovative production and utilization of the design knowledge'. On the other hand, in traditional CAD, the main design creativity is based on technical design factors like making design guidelines rather than on evaluating the ideation process. The technical factors mainly provide the design rule of targeting design solutions before returning to problem identification. This is because traditional CAD does not provide a clear association between tool functions and idea developments. The conventional CAD creativity factors can only be discovered from focusing on the making of the design scheme and follow a template to make the design. This method could be referred to as the 'Primary Generator' (Darke, 1979) design method, which helps the designer to be able to solve complex design problems happening in the design process (See the literature review of systematic thinking of design behaviour in Section 3.5.1, Chapter 3).

In conclusion, the results provide some important information on managing each individual CAD method and its perceived impact on creativity in hospital design. For example, as to the parametric CAD methods, if architects wish to challenge new design ideas for a hospital project, then algorithmic CAD could be effective in this aspect of design ideation, including making varied shapes as well as producing novel ideas and large idea numbers. On the other hand, if architects wish to try out new workflows with specific building designs, they could use BIM design, which holds the highest scores for the production of ideas using materials in a creative way and creating an organised and efficient design scheme. However, these research findings represent an original contribution to knowledge as they have not been examined in any previous hospital design studies or research materials.

Part III/ Chapter 8 – Research Findings 3

Case Study 2-1: A computer-based protocol study of parametric and nonparametric design behaviour in hospital design

8.1 Introduction

The previous two chapters (Chapters 6 and 7) presented the research findings of the retrospective study method using a questionnaire survey. This chapter continues the investigation through a second research technique – a computer-based protocol analysis. The target of this examination was to observe the on-going design behaviour when using different CAD methodologies for a pre-selected design task. Through observing architects 'talking aloud' at the same time as carrying out the design activities, we were able to explore how each CAD method influenced their designs as well as the design cognition processes. Further research design details of this computer-based protocol analysis and the planned research can be found in Chapter 5.

The main body of this chapter is divided into the following research design's categories: 1. Design process, 2. Design problem formulation, 3. Design cognition, and 4. Form exploration. In the first section, the CAD processes including design analysis, design synthesis and design evaluation, were focused on the research of design interaction. The second section discovers the effects of a CAD method on the process of design problem-solving activity. The third part records the CAD activities and studies cognitive reactions such as the use of cognitive memory and the cognitive problem-solving process. The last part discusses the relationship of different CAD methods to the form-finding process as well as the functional design.

The discussion section summaries the findings from this chapter and extends the arguments to associated hospital design topics. These supporting materials and subsequent discussion are employed to reinforce the main research arguments and to provide the essential knowledge and evidence for the development of findings in the next chapter.

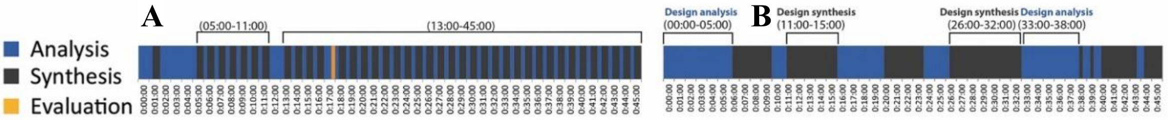
8.2 The protocol study of the CAD in the hospital design process

The study of the ***Design Process (DP)*** was based on three aspects of design behaviour: ***1. Design analysis, 2. Design synthesis, and 3. Design evaluation*** (See the research design of coding list in Section 5.8.1.c-2, Chapter 5). These three design sections were especially focused on the interaction during the design was in progressing and gave relevant discussions of them.

8.2.1 Nonparametric CAD design process

The overall study of the nonparametric CAD (AutoCAD) process presented two types of design interaction. The first related to frequently occurring design actions between analysis and synthesis (Fig.8.1-A). The second was spending a considerable length of time on the design analysis stage before moving to design synthesis but never progressing to design evaluation (Fig.8.1-B).

Fig.8.1 Nonparametric CAD process



Source: Author reproduced/ Excel outputs

However, these repeated design interactions did not provide the architects with better design organisation, such as the making of a sound design strategy or sound design logic. Besides that, many design decisions were found hard to identify the design reasoning under this nonparametric design process. In the first type of design interaction, the AutoCAD architects carefully analysed their design idea and then found associated CAD tool processing with their editing activity. Unfortunately, there is no associated CAD function/tool, such as parametric design algorithm, for the developing of design ideas in the AutoCAD design menus; the architects had to manually check the design tools and then constructed their conceptual drawings. The design analysis and synthesis, therefore, were applied intensively to idea revisions. Normally, this revision work was like a ‘trial-and-error’ process based on finding form and re-making them; at times, it was even necessary to restart a new design plan.

For instance, in case 10 (Fig.8.1-1), the difference in time spent on design analysis and design synthesis is about 1.125 (45 mins on design analysis and 40 mins of design synthesis). This shows the synthesis actions heavily depended on the analysis activities. In the design process, the architect wished to propose an idea of a centralised layout system (Fig.8.1-1-1-A). After the analysis work to select a cruciform design plan, the architect applied the accident and emergency centre (AandE) in the centre and surrounded it by the rest of the departments. After some work on design layouts exploring the functional relations between those departments, he realised there were big problems caused by this layout shape, such as bad connections for building circulation and the AandE entrance being too far from the central zone (Fig.8.1-1-1-B). However, he could not realise this issue before he processed the layout design. He had to return to the very beginning of his departmental drawing and correct his drawings step-by-step as well as figure out replacements for the design problem (See the transcription in Appendix 8.1).

Fig.8.1-1 Nonparametric CAD process of the architect 10

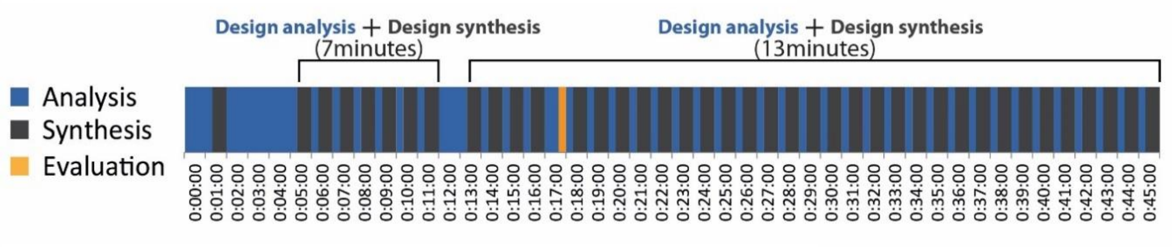
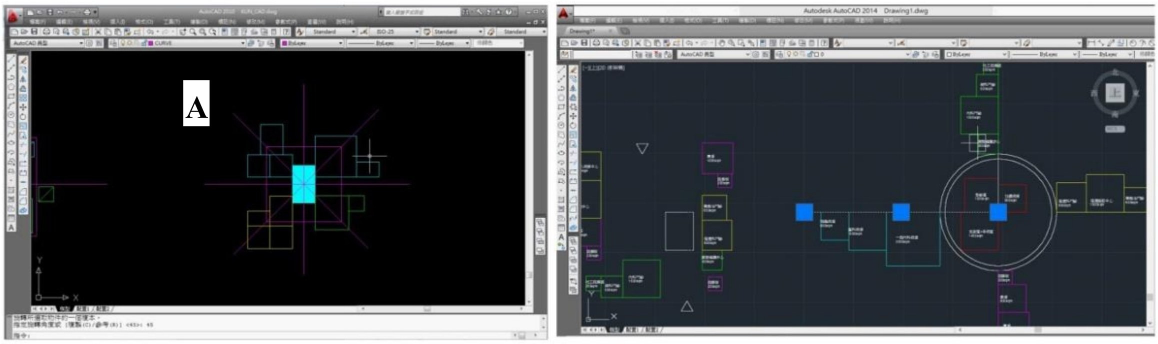


Fig.8.1-1-1 Architect 10: design with AuotoCAD



Source: Architect no.10 produced/ AutoCAD

Regarding the time occupied in the second type of design interaction, the study found some architects spent a lot of time between design analysis and design synthesis. No design evaluations were discovered to idea testing. For example, in case 04 (Fig.8.1-2), there were only 6% differences in time spending on the design analysis and design synthesis: 56% time spending on design analysis ($0.56 = \frac{25\text{mins (design analysis)}}{45\text{mins (overall design process)}}$ and 62% time spending on design synthesis ($0.62 = \frac{28\text{mins (design synthesis)}}{45\text{mins (overall design process)}}$. The architect started with 6 minutes of design analysis following by 3 minutes of design synthesis (Fig.8.1-2-A), and then he spent another 4 minutes on repeated design synthesis and 4 minutes on design analysis (Fig.8.1-2-B).

Fig.8.1-2 Nonparametric CAD process of the architect 04

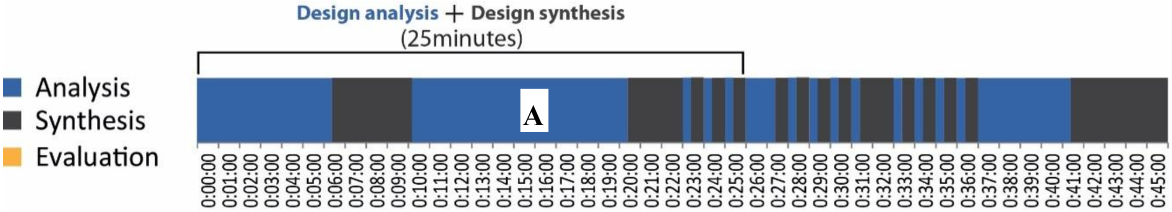
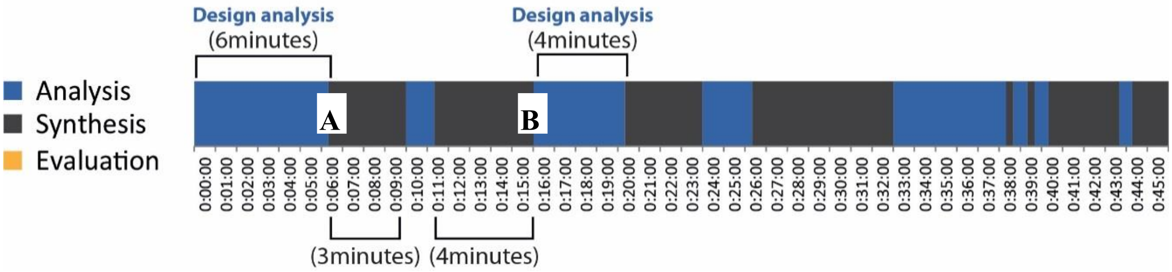


Fig.8.1-3 Nonparametric CAD process of the architect 05



Source: Author reproduced/ Excel outputs

Although the interactions of these two design stages, the design analysis plus the design synthesis, were intensively involved in the ideation process, the results only showed little progress on the decision-making for the spatial prototype of the floor plan design (Fig.8.1-2-1-A). In another case, architect 05 (Fig.8.1-3) spent nearly 25 minutes, including 19 minutes on design analysis plus 6 minutes on design synthesis (Fig.8.1-3-A), completing the making of program boxes only (Fig.8.1-3-1-A) (See the transcription in Appendix 8.1).

Fig.8.1-2-1 The architect 04 design with AuotoCAD

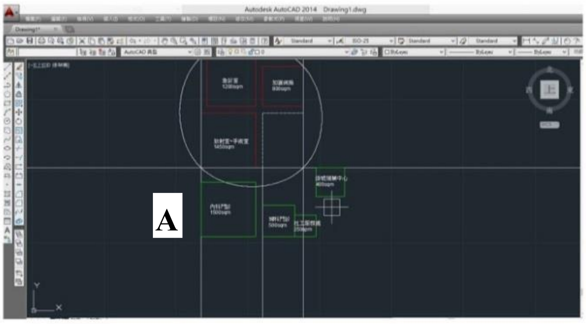
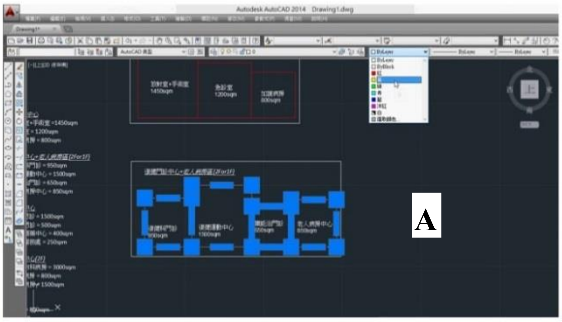


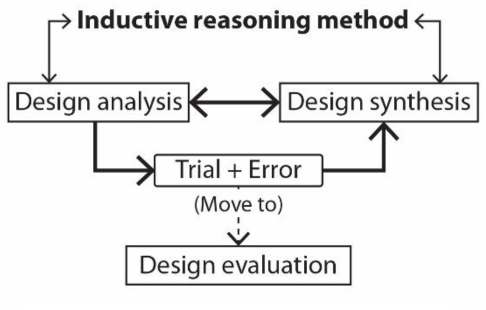
Fig.8.1-3-1 The architect 05 design with AuotoCAD



Source: Architect 04 and 05 produced/ AutoCAD

The lengthy design analysis and synthesis in the design process could be because the architects tended to use an induction technique to reach their design decisions. For example, during the inspection process, the AutoCAD architects frequently presented uncertain verbal data as a temporary summary of the design intention such as ‘I think here *could be*….’, ‘this circular form might help…’ or, ‘there might be enough space…’. This hesitation or uncertainty in idea expression or lack of confidence in presentation displays that the nonparametric architects utilised a lot of ‘inductive reasoning’ (Fig.8.2) in design determination or problem definition. Thus, we can deduce that the delays in the nonparametric CAD design process were caused by the predominant use of design inductions. However, Newell (1968) suggests induction is a weak method of design problem-solving because it requires the given design information to predict the design result; if the current design information is incomplete, the resulting objective could be lost, creating more problems.

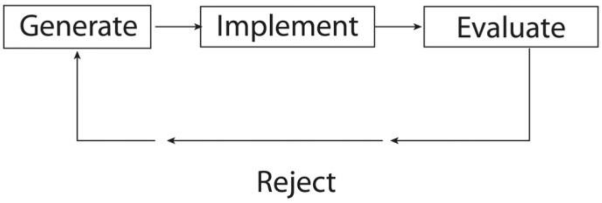
Fig.8.2 Nonparametric CAD process and Inductive reasoning method



Source: Author reproduced/ Newell,1968

To conclude, there were some interesting discoveries in these two types of design interactions. Regarding the aspect of architects’ performance during the design process, although the participants all had 3 to 5 years’ experience in hospital design, their design thoughts/behavioural patterns were identified as having similar problems to those of novice designers, such as less confidence in the design development or being focused on certain design details and ignoring the design planning (Novice designers’ approach to a design task) (Ahmed, Wallace and Blessing, 2003) (Fig.8.3). Other evidence was found such as delays in the decision-making process (the freshmen engineering designer) (Atman, Cardella, Bursic and Nachtman, 1999) and a long deduction process during design analysis and synthesis (the case of studying novice designer) (Lloyd and Scott, 1994).

Fig.8.3 Nonparametric CAD process shows novice designers’ approach



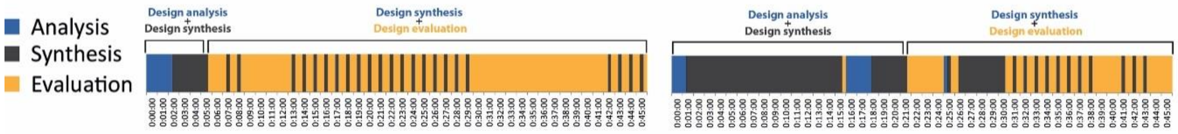
Source: Ahmed,Wallace and

In terms of the hospital building design process, the participants showed a very similar approach to the nonparametric CAD (the AutoCAD) process: making program boxes, applying a design template, separating the design area into independent layouts, etc. Also, the architects were following some existing examples of building types, such as pavilion plan, multi-courtyards plan, and atrium plan. In other words, this universal design process showed no creativity and no clear design ambition (novel design proposal) that could be discovered from the case studies. As Guilford (1950) argues, the more time they spent going over the same actions and design decisions, the less design creativity could be explored during the design process.

8.2.2 Parametric CAD design process

Parametric CAD methodology using the algorithmic tool: Grasshopper involves two types of design interactions – the first one is a short design analysis and synthesis and then a long process focusing on constant design integrating and testing (Fig.8.4-A); the second is about spending half the time on design synthesis and the other half on design evaluation (Fig.8.4-B).

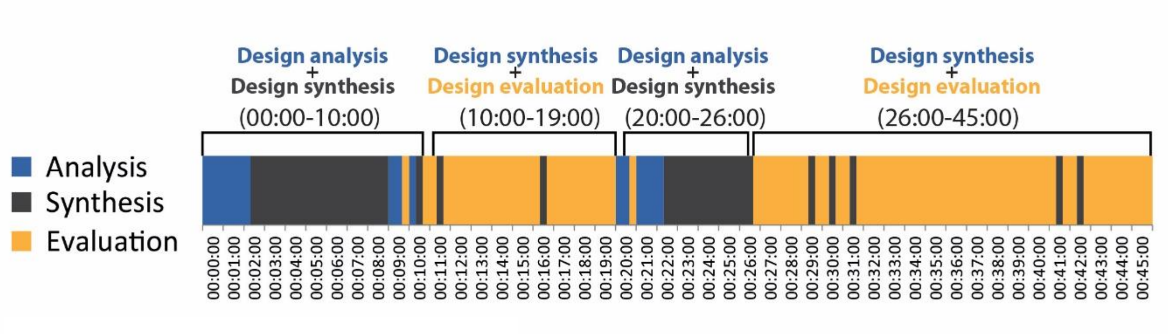
Fig.8.4 Parametric CAD process



Source: Author reproduced/ Excel outputs

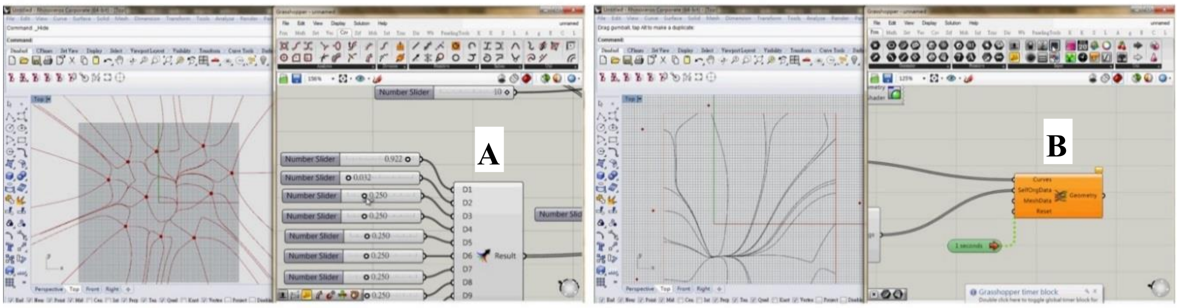
As an example of the first type of design interaction, in case 01(architect 01), (Fig.8.4-1) the interaction between design analysis and design synthesis exhibited 35% ($0.35 = \frac{\text{16mins (analysis+synthesis)}}{\text{45mins (overall design process)}}$) time spending on the entire design process. On the other hand, the interaction between design synthesis and evaluation showed 67% ($0.67 = \frac{\text{30mins (design evaluation)}}{\text{45mins (overall design process)}}$) of time spending on the entire design process. When it comes to the design observation, the architect wished to challenge design thought on building circulation but not following the conventional method of designing spatial blocks. So, the design idea was presented in an in-depth planning system based on a streamlined shape (Fig.8.4-1-1-A). In the nonparametric/traditional CAD process, the CAD tools only allowed architects to manually create one circulation plan at a time and each pattern had no associated geometrical connection. However, for this architect using algorithmic CAD, he only had a primary analysis of the design situation and then decided his design strategy – the streamlined circulation. He then constructed a design algorithm for the layout process. He produced one functional design algorithm and could generate various circulation patterns, which were associated with the same geometrical principle. In addition, the design synthesis was engaged while he applied different parameter inputs such as points, numbers and vectors; the computer subsequently exhibited this integrated result as varied streamlined shapes. The architect then moved the design process rapidly to more complex design synthesis and evaluation by using another design algorithm called 'CUBRA – a computerised self-organised application for optimisation of streamlines'. The CUBRA helped the architect to solve complex geometrical configuration and discovered appropriate solutions for his layout proposal (Fig.8.4-1-1-B) (See the transcription in Appendix 8.2).

Fig.8.4-1 Nonparametric CAD process of the architect 01



Source: Author reproduced/ Excel outputs

Fig.8.4-1-1 The architect 01 design with Grasshopper



Source: Architect 01 produced/ Grasshopper

Another example of the first design interaction type, architect 03 (Fig.8.4-2), the interaction between design analysis and design synthesis only occupied 10% ($0.1 = \frac{5\text{mins (analysis+synthesis)}}{45\text{mins (overall design process)}}$) time spending on the entire design process. On the other hand, the interaction between design evaluation occupied 89% ($0.89 = \frac{40\text{mins (synthesis+evaluation)}}{45\text{mins (overall design process)}}$) of time spending on the entire design process. The architect wanted to create a mathematically-based distance design for combining the departmental spaces. Traditional spatial combinations like the late 60s cluster design for inpatient wards (See the design of layouts in Section 1.5.1.d, Chapter 1) were designed referencing the architects' experience, which meant employing a manual design without software support. In this case, at the outset, the architect suggested multiple circles as the proposed departmental prototypes. Next, he chose a design algorithm – Metaball (mathematically-based spatial combination/design) (Fig.8.4-2-1-A) for the computerised design layouts that includes essential design information such as merged distance and areas.

Fig.8.4-2 Nonparametric CAD process of the architect 03

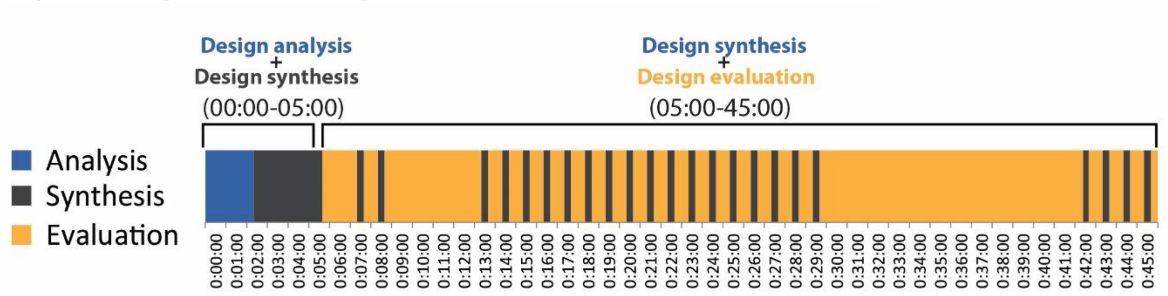
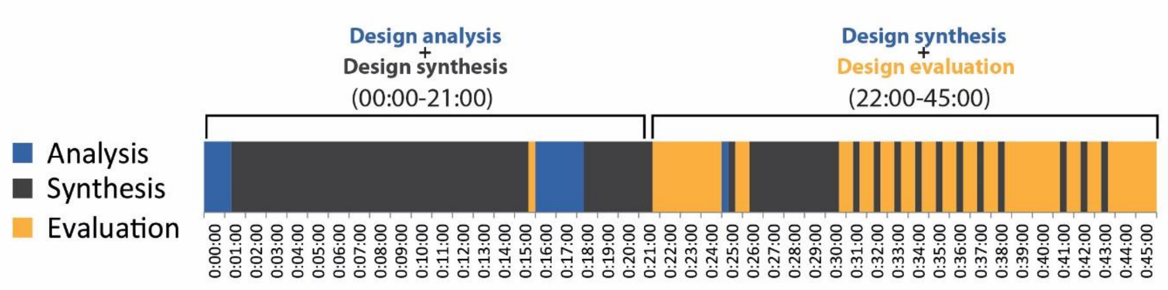


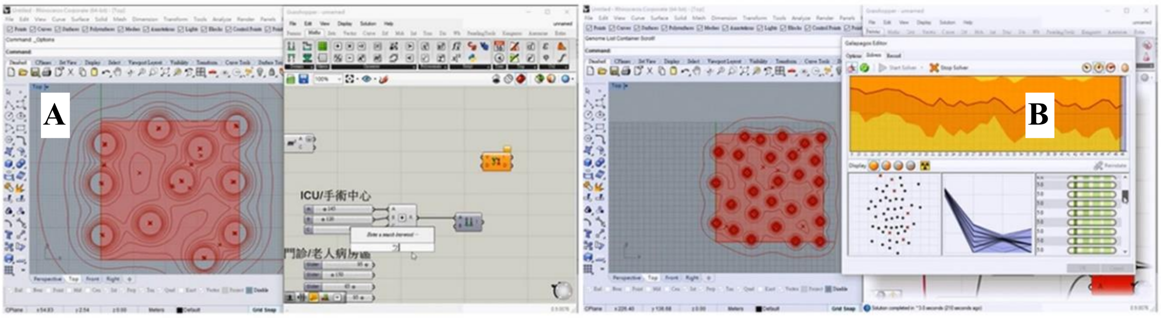
Fig.8.4-3 Nonparametric CAD process of the architect 06



Source: Author reproduced/ Excel outputs

Next, an algorithmic evaluation – Galapagos (Fig.8.4-2-1-B) was applied to optimise the fitness of the shortened distance between those merged spaces, and the architect only applied his experience of design layout to select the best result. In addition to directly applying a mathematical function as the design algorithm, the second type of the parametric CAD activity exhibits the use of design data (parameters) and ‘a two-state computed argument’, like ‘Boolean true or false’, ‘item index’ and ‘dispatch data’ to support the design decision-making process.

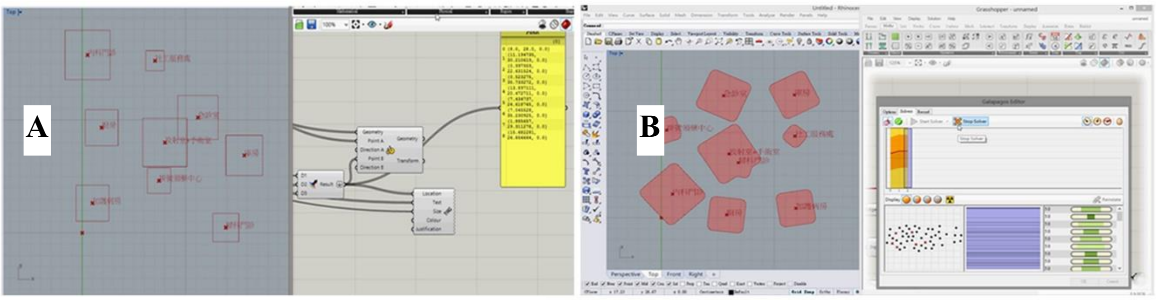
Fig.8.4-2-1 The architect 03 design with Grasshopper



Source: Architect 01 produced/ Grasshopper

On the other hand, the type of second design interaction’s pattern, architect 06 (Fig.8.4-3), had spent a similar time occupation on the design interaction between the group of design analysis and synthesis: 60% $(0.6 = \frac{\text{27mins (design synthesis)}}{\text{45mins (overall design process)}})$, and the design synthesis and evaluation: 57% $(0.57 = \frac{\text{26mins (design evaluation)}}{\text{45mins (overall design process)}})$. Unlike the conventional CAD process, the algorithmic CAD architect did not follow his intuition or design experience – he ran carefully series of algorithmic function to examine the design relationship of the spatial scales and functions through a scientific measurement. He first built the mathematical equation for making program rooms (Fig.8.4-3-1-A) because he needed to understand how the program scale and function might affect the space and the circulation design. Next, the architect thought about the environmental and natural lighting issues and how he could be influenced by room orientation, especially the large department. So, he computed the space sizes, which only allowed the spaces requiring lighting to be selected and he then rotated the space to match a pre-set daylight direction. Finally, the architect employed the Galapagos (computing evolution) technique (Fig.8.4-3-1-B) to simulate the design layout and provide a wide range of appropriate solutions such as the shortest distance between the departments (See the transcription in Appendix 8.2). This mathematical design process allowed the architect to analyse spatial information and integrate them into the algorithmic framework. The mathematical thinking also helped them to easily target their design problems with radical conditions and then connect associated design issues, such as daylighting, space size and the orientation. Thus, the design synthesis could be closely linked with an evidence-based evaluation process.

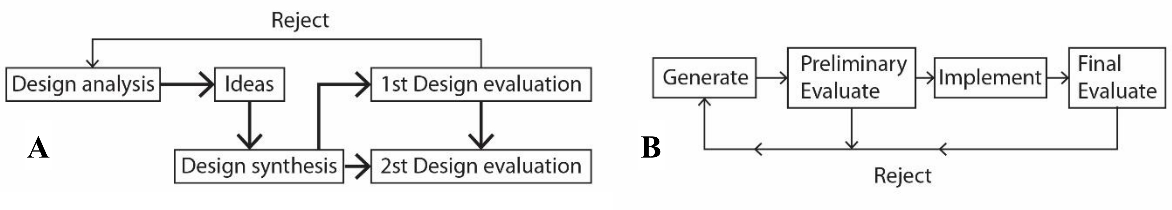
Fig.8.4-3-1 The architect 06 design with Grasshopper



Source: Architect 06 produced/ Grasshopper

To sum up, the interactive design process of algorithmic CAD architects frequently uses synthesis and evaluation to gain the optimum design solutions (Fig.8.5-A). Such a pattern of design activities was identified in Ahmed’s (2003) research into experienced designers (Fig.8.5-B). The information-based algorithmic component provides related design information which helps architects to quickly target design problems without a long analysis process. Proposed design ideas in parametric CAD must be rationalised through mathematical logic (See the literature review of parametric architectural design ideation and expression in Section 4.3.4.a, Chapter 4). Every algorithm is consistent with mathematical knowledge; for instance, random numbers, Voronoi, and Octree. Thus, design synthesis and evaluation always come after a knowledge-based thought and the provision of potential mathematically-based solutions. This reliable design process enables architects to easily target the design goal with a ‘problem scoping’ method. This helps them produce better design results as suggested by a senior engineering designer, Atman and her colleagues’ research (1999).

Fig.8.5 Parametric CAD process shows experienced designers’ approach



Source: Author reproduced/ Ahmed,Wallace and Blessing,2003

When it comes to the hospital design process, the NHS established pen and paper-based or conventional CAD traditional/nonparametric systematic designs aimed at a document-based method of collection and analysis of design information but very little of this could be used to inform the evaluation process. It meant this design data was independent of the design process and was only presented as documentary records. For this reason, parametric CAD based on the algorithmic process can not only improve the connection of design information but also helps architects to apply strategic thinking in their design ideation (See the literature review of taxonomy of parameters in Section 4.3.4.b, Chapter 4). According to the future design guidelines for healthcare buildings (The Nuffield Trust, 2001), a new healthcare system that responds to social care needs will be required in the UK. For example, systematic services with a variety of associated building facilities will also be required in this new system. Therefore, strategic planning is essential at the beginning of each design project. This concept includes covering the planning, design, operation and disposal of healthcare buildings. These factors should also be discussed during the design process (See the future healthcare architecture design and expectations in Section 1.6, Chapter 1).

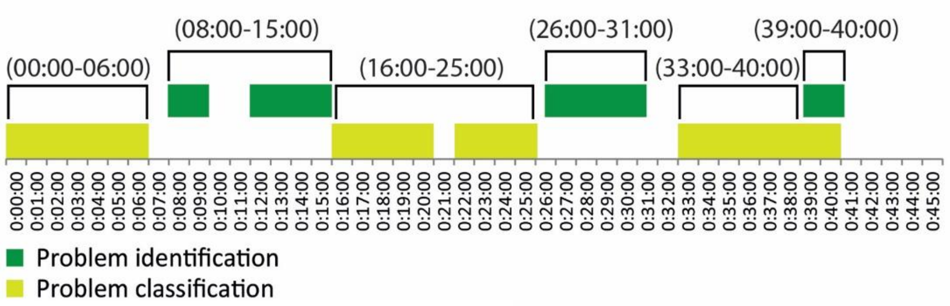
8.3 The protocol study of the CAD problem formulation in the hospital design process

The design problem of hospital buildings relates to the scale of the circulation, facility and the environmental context. Those issues increase the level of complexity in design problems. Therefore, this section aims to understand the relationship between two problem categories - ***Problem Identification*** and ***Problem Classification***, when using the different CAD methodologies and their perceived impacts on the design process (See the research design of coding list in Section 5.8.1.c-2, Chapter 5).

8.3.1 Nonparametric CAD problem formulation process

The observation of nonparametric CAD process found that there was a close interrelationship between the problem classification and problem identification. These two stages of problem formulation supported each other while nonparametric CAD users/architects discovered the design problems. For example, in case 07 (Fig.8.7), the architect classified the design factors and associated spatial problems as 4 parts.

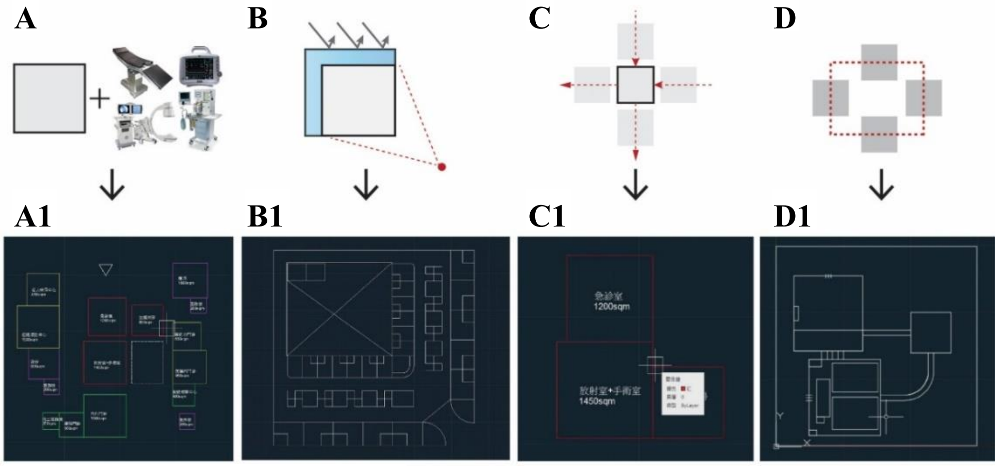
Fig.8.7 Nonparametric CAD problem formulation of the architect 07



Source: Author reproduced/ Excel outputs

The first, medical facility supply and department scale (Fig.8.7-1-A). The second environmental issues, such as noise interruption and visibility and clinic layout (Fig.8.7-1-B). The third, service efficiency and departmental phasing (Fig.8.7-1-C). The fourth, circulation design and space orientation (Fig.8.7-1-D). After the problem classification, he identified these problems by making program boxes big enough to ensure enough space for medical supplies then he immediately attempted solutions (Fig.8.7-1-A1), moving the clinical departments right next to the reception (Fig.8.7-1-B1), locating X-ray or operating theatres in the central part of the layout (Fig.8.7-1-C1), and setting up a ring road design (circular shape) as the layout template (Fig.8.7-1-D1) (See the transcription in Appendix 8.3).

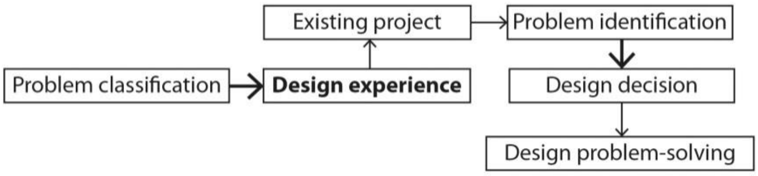
Fig.8.7-1-1 Design problem classification by the AutoCAD architect



Source: Architect 07 produced/

The problem formulation process, in fact, is more like experience-based design decision making rather than providing any reference for design problem-solving (Fig.8.8). This is because the nonparametric CAD method does not provide visible design algorithms limiting the ability of the designer to formulate design problems with associated geometries or spaces (See the literature review of design by drawing in Section 4.3.2.b, Chapter 4).

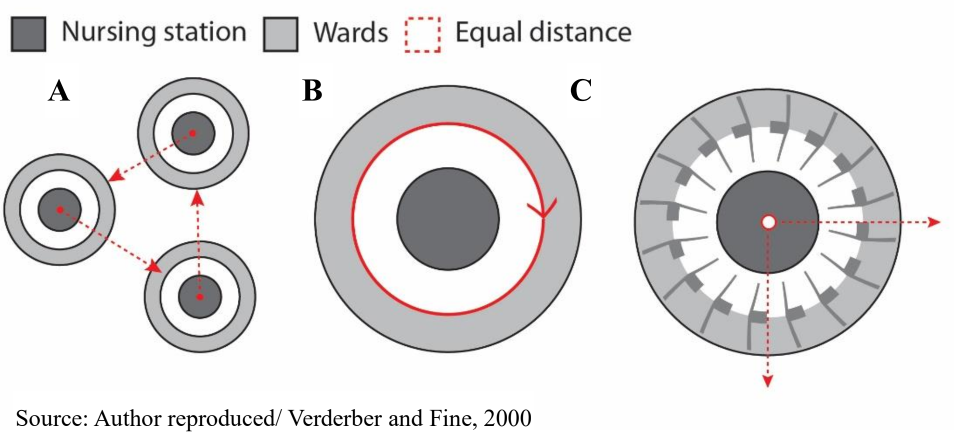
Fig.8.8 Experience-based design problem formulation



Source: Author reproduced

The architects in the study found it difficult to systematically observe the design issues and match these with appropriate design solutions, so continuously applying their experience became the only way to solve these design problems. It is a risk of only relying on old design experience during the problem formulation process in the hospital building solution, because it could block our mind without fully exploring other potential design problem. For example, a circular design floor plan was employed to manage service efficiency in the Central Kansas Medical Center plan (Fig.8.8-1), 1964, USA. This was because of the geometrical advantage that ward units were equally accessible (Fig.8.8-1-A) to and from the central nursing station. Unfortunately, such a reference-based (experience) design problem formulation is not always correct. Other design problems were soon discovered such as the frequent loss of direction (Fig.8.8-1-B) and the lack of privacy in wards (Fig.8.8-1-C). Moreover, these retrospective memories of design experience without support from a structured system often cause another problem in design development such as inaccurate memories or misleading information. Because only the senior architect knows the rationale behind his design experience, the problem decision-making lacks an objective approach and cannot easily be discussed.

Fig.8.8-1 Central Kansas Medical Center plan



Source: Author reproduced/ Verderber and Fine, 2000

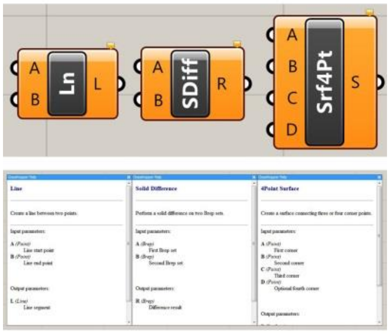
In addition, it is possible that the design process cannot deal with unpredictable factors and ‘crooked’ problems, which makes it impossible to manage certain types of design problems, referred to as ‘wicked problems’ (Rittel and Webber, 1973) and ‘ill-structured problems’ (Simon, 1973) (See the literature review of unpredictable design problems and design process in Section 3.3.3, Chapter 3). Such an experience-based design problem-solving process is described as a ‘black box’ approach (Jones, 1970) (Fig.8.8-2), meaning one experienced person takes complete responsibility for all the important design decisions and sorts out the critical design problems.

Fig.8.8-2 Black box method of design problem-solving

Source: Author reproduced/ Jones, 1970

8.3.2 Parametric CAD problem formulation process

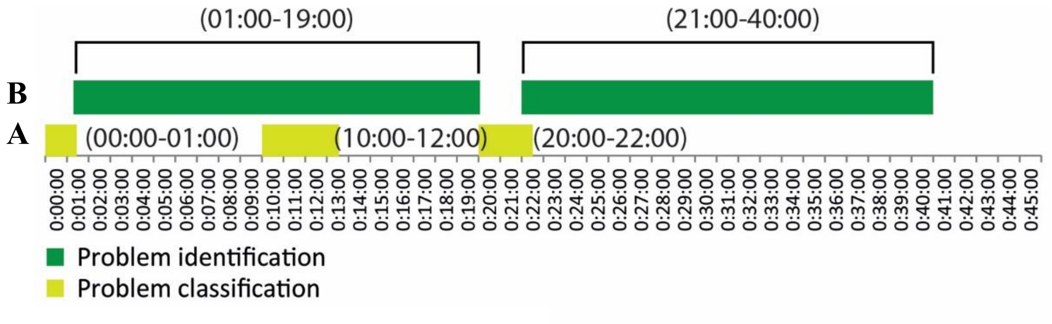
Fig.8.9 Algorithmic design functions



Source: Grasshopper

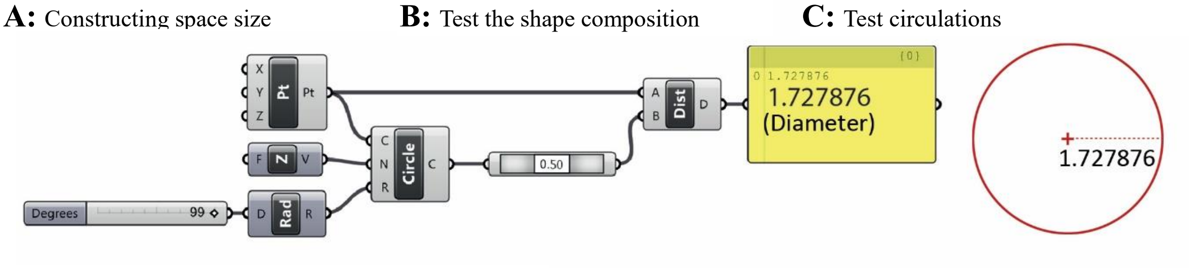
The problem formulation process in algorithmic CAD demonstrated only a minor process of problem classification but large amounts of the time were spent on problem identification. The comparison of time spent on problem identification and classification is about 2 times; $2.05 = \frac{39\text{mins (problem identification)}}{19\text{mins (problem classification)}}$. The reason might be associated with the algorithmic design method employing mathematical design functions that help architects to recognise design problems with mathematical problem classification and thus they are able to concentrate on the identification of attempted directions for problem-solving. In other words, before the architects requested the design actions in the problem-solving process, they were guided to a functional manual (Fig.8.9) and found a design algorithm which presented a primary classification for those design problems. For example, in case 06 (Fig.8.9-1), the architect indicated only three short time periods spent on the choice of design algorithms for problem framing (Fig.8.9-1-A): constructing a mathematical equation from the algorithmic design manual for space's size calculation (Fig.8.9-1-1-A), grouping departmental areas by selecting a function for shape interactions, and using Euclidean transformation to rotate the design spaces for testing the shape composition (Fig.8.9-1-1-B). Then, he spent the rest of his time on problem elaboration (Fig.8.9-1-B): identifying space scales and service types for grouping layouts and finding department design clusters by rotation of sub-rooms and testing the circulation for those departments (Fig.8.9-1-C) (See the transcription in Appendix 8.3).

Fig.8.9-1 Parametric CAD problem formulation of the architect 06



Source: Author reproduced/ Excel outputs

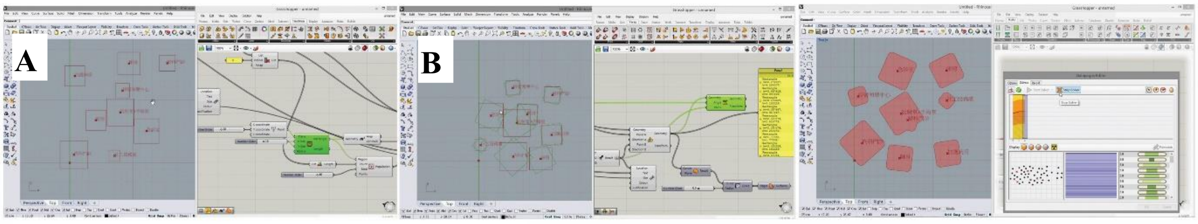
Fig.8.9-1-1 Design problem identification by the Grasshopper architect


A: Constructing space size **B:** Test the shape composition **C:** Test circulations

Source: Architect 06 produced/ Grasshopper

These longer periods of problem identification, in fact, assisted the architects to understand the relationship between those functional algorithms (Fig.8.9-2-A) and design geometries (Fig.8.9-2-B). The algorithmic rules for constructing design geometries such as determining the geometric relationships: scale, angle, length, rotation, etc. were thought of as the design reasoning behind the design problem construction.

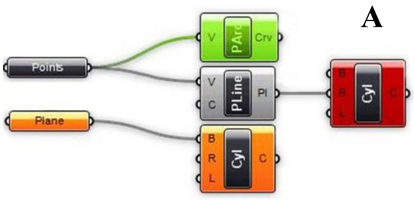
Fig.8.9-2 Functional algorithm and design geometry



Source: Author reproduced/ Grasshopper

As a further explanation of how algorithmic CAD (Grasshopper) supports architects in design problem formulation, two points can be identified. Firstly, node-diagrams (Fig.8.10) help architects better understand the relationship between design steps and more easily organise the design problems. Secondly, the algorithmic process is absolutely correct and follows a mathematical logic. If any error appears due to a wrong mathematical definition, the component is flagged or turns red (Fig.8.10-A) to inform architects there is a logical error in the input. So, architects never lose sight of or are misled by any logical problems that might affect the problem formulation activities. When compared with traditional/nonparametric hospital design which closely follows design guidelines, algorithmic design using Grasshopper provides better visual inspection of problem management; for example, when applying 'Isovist' (Fig.8.10-1) (a visibility testing plug-in for Grasshopper) to show the visible distance between nursing stations

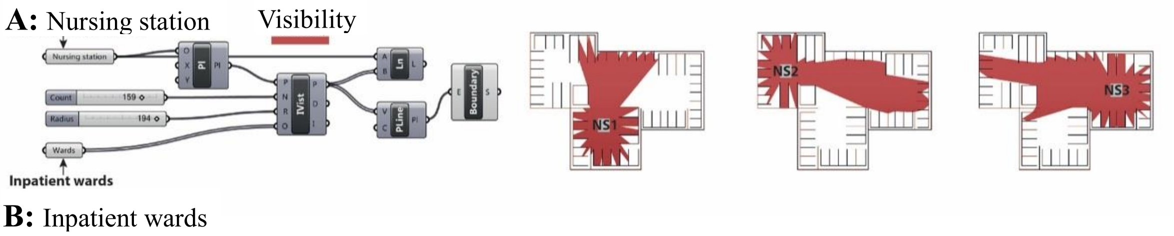
Fig.8.10 Note design diagram and Logical error



Source: Grasshopper

(Fig.8.10-1-A) and wards (Fig.8.10-1-B). The majority of design ideas can be constructed and saved as algorithmic definitions which can then be recalled to solve different design problems. The algorithmic definitions are also offered in 3D design interfaces such as Rhinoceros, which allows architects to visually check the problem-solving process rather than literally checking off a document-based (nonparametric) design list, such as the building notes.

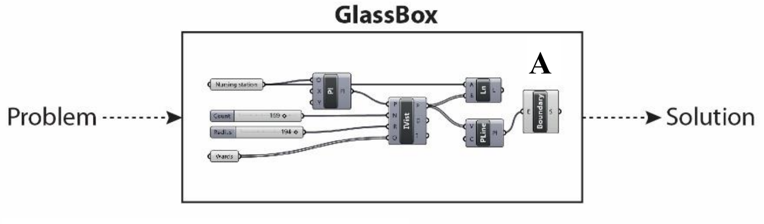
Fig.8.10-1 Visual inspection of problem management in algorithmic CAD process



Source: Author reproduced/ Grasshopper

Secondly, the problem formulation processes are entirely transparent. This is described as a ‘Glass box design activity’ (Fig.8.11) (Jones, 1970) and is the opposite of the ‘black box’ approach found in the conventional problem formulation process. This process has the following benefits: the glass box includes a design standard with an objective variable and a pre-defined structure; the algorithmic CAD and its analysis process is completed and corresponds to the solution; evaluation is structured and logical and there is an operating strategy-aided process (Fig.8.11-A). The diagrammatic design structure helps architects to recognise the problem context and predict further potential problems. They are then able to discuss these with different design professionals to establish the future design and construction of the next generation of envisioned healthcare buildings (The Nuffield Trust, 2001); this ‘pre-assembly’ is a measurable process for design integration with an early specialist involvement.

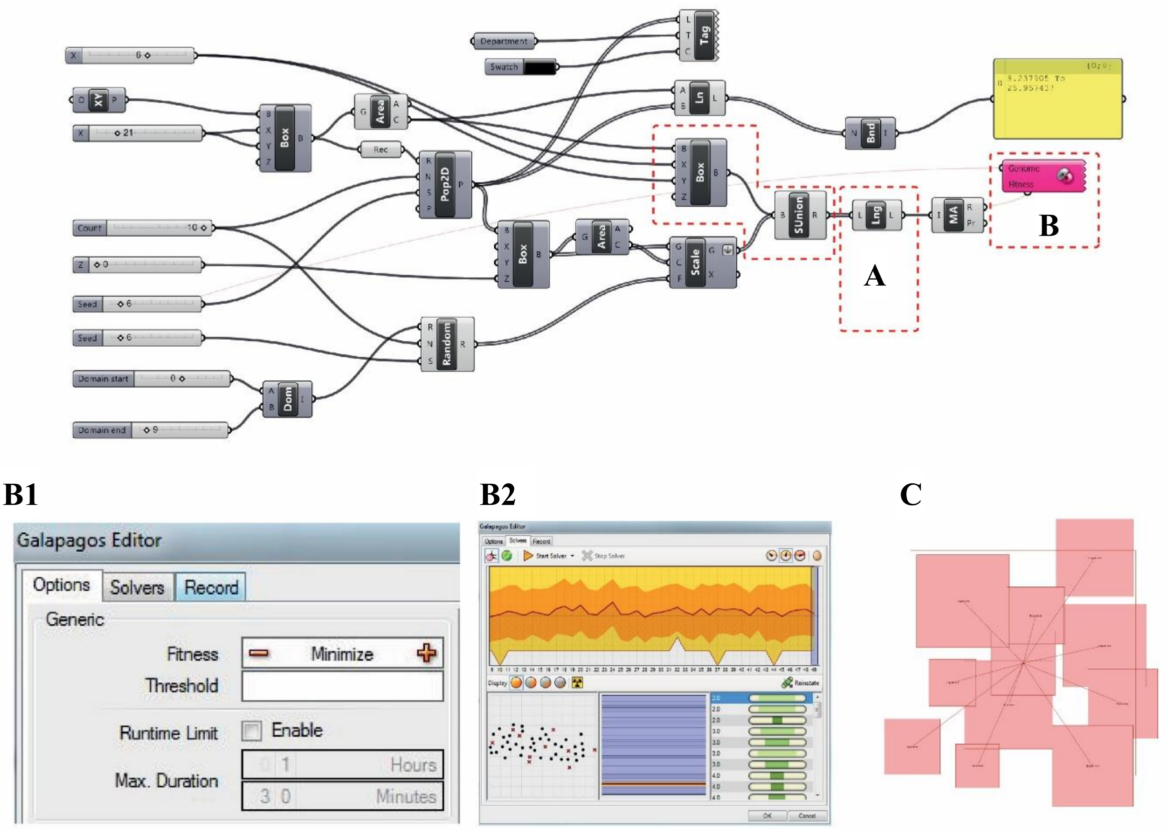
Fig.8.11 Glass box method of design problem-solving



Source: Author reproduced/ Jones, 1992

Lastly, an algorithmic process encourages architects to consider design problems with informed evidence such as scale, length, angle, etc. Next, this design information is turned into finite steps and relationships, built using functional geometries to map onto design problems; for example, a design of cluster departments (Fig.8.11-3), the length of distance ('List length' from the Grasshopper design function) (Fig.8.11-3-A) required to achieve optimised circulation efficiency/minimised travel distance (Fig.8.11-3-B1) ('Galapagos' from the Grasshopper design function), and scale calculation (Fig.8.11-3-B2) for determining the final required service pattern (Fig.8.11-3-C). This design association is supported by Alexander and Poyner's (1967) research findings on the 'tendencies' of geometric design and environmental responses (See the literature review of architectural design problems in Section 3.3.2, Chapter 3). Besides that, this parameter-based design evidence directly supports the concept of 'modular design', 'standardisation' and 'customisation' processes, which have been identified as important issues in hospital design development planning for next-generation healthcare architecture (The Nuffield Trust, 2001).

Fig.8.11-3 Finite steps for the design optimization of the clustering layout



Galapagos Editor

Options | Solvers | Record

Generic

Fitness: Minimize

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Max. Duration: 1 Hours, 30 Minutes

Source: Author reproduced/ Grasshopper

8.4 The protocol study of the CAD cognition in the hospital design process

Study of design cognition provides an important knowledge of understanding how architects process their design thoughts. As Akin (1986) sates 'Information processing theory provides us with an abstract symbolic medium within which we can represent, measure, and understand the cognitive strategies associated with human problem-solving behaviour'. This section considers the study of three cognition stages: ***Memory, Imagery*** and ***Problem-Solving*** in the design process. The results compare the two CAD methodologies and provide the basis for discussion in the sectional reviews.

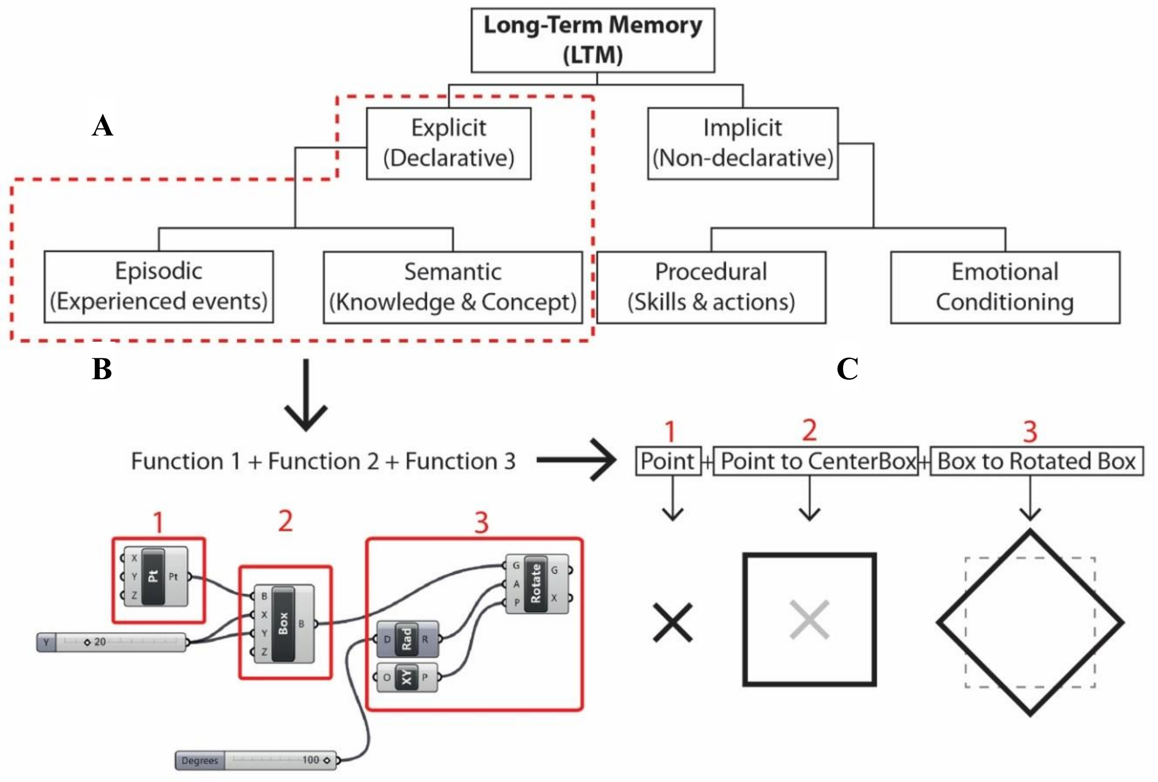
8.4.1 Cognitive memory and imagery in different CAD processes

a) Cognitive memory

In the CAD process, one could argue that memory involves remembering how to use the functional tools and imagery is what is present in the drawing geometries. In this study, both CAD methods show a close mind process between cognitive memory and imagery, but the mental activity affecting design behaviour shows some differences between the two CAD methodologies. The memory process in parametric CAD (Grasshopper) was found to be similar in type to Long-Term Memory – LTM (Newell and Simon, 1972) (Fig.8.12). These LTMs correlated with algorithmic design functions and created an unlimited and flexible learning process (Fig.8.12-A). Once architects have learned the algorithmic function, they can always recall this design knowledge (Fig.8.12-B) and produce a lot of geometrical outputs (Fig.8.12-C) using the LTM process.

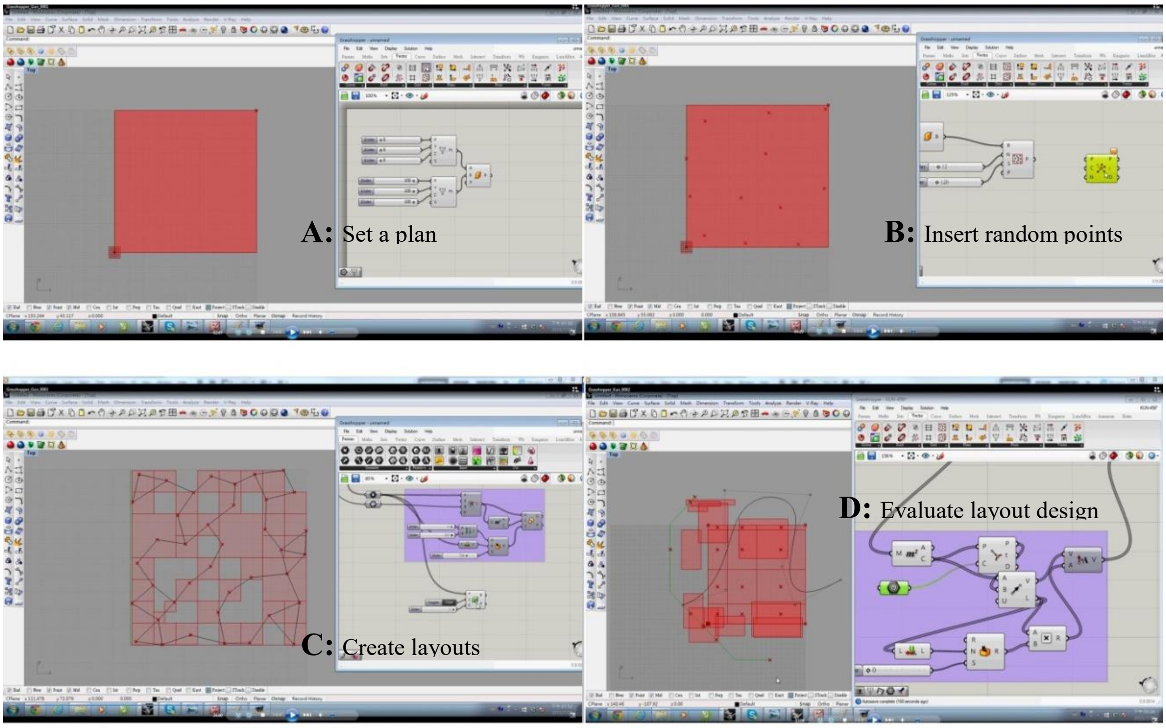
This extended learning process was shown in one algorithmic design definition, the case 04 (Fig.8.12-1), where the architect proposed a centralised design floor plan and extended the design development with the following actions: setting a floor plan range of the site (Fig.8.12-1-A); making a draft layout by inserting random points to establish the orientation of rooms/spatial programs (Fig.8.12-1-B); joining the points into certain room area and scale (Fig.8.12-1-C); and applying different numbers, such as distance, area, and volume for clustering design to adjust the floor plan shape as well as the circulation system (Fig.8.12-1-D).

Fig.8.12 LTM design memory and algorithmic CAD process



Source: Author reproduced/ Grasshopper

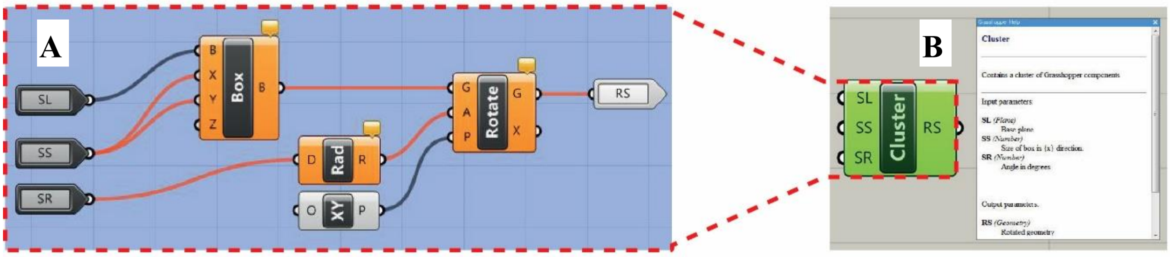
Fig.8.12-1 Extended learning process for the algorithmic design cognition



Source: Architect no.06 produced/ Grasshopper

The algorithmic CAD process was created by adding different algorithms, which in some ways is similar to extending the architect's LTM. These algorithms were then interrelated to present a final algorithmic definition. In the protocol analysis process, this flexible/adaptable memory shows its potential to support design cognition, especially at design problem-solving stages. These algorithms as cognitive memory (Fig.8.12-2-A) can also be constructed into functional components and linked together into a definition-based algorithmic solution (Fig.8.12-2-B). This means the architect can easily locate a specific design problem with this pre-set tool and make modifications according to new design requests or cognitive feedback. As Newell and Simon (1972) highlight, 'there is no measured limit to the amount of information that can be stored in LTM'.

Fig.8.12-2 Constructing design functions into one algorithm



Cluster

Contains a cluster of Grasshopper components

Input parameters

SL (Plane) Base plane

SS (Number) Size of box in (x) direction

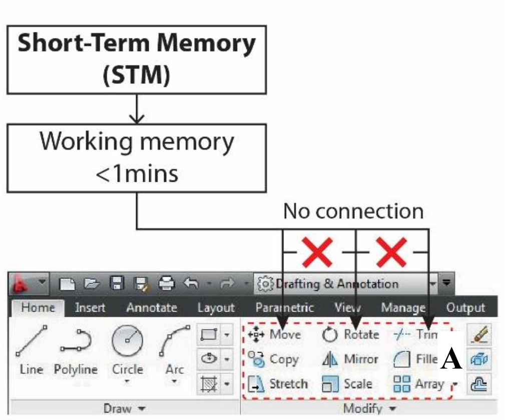
SR (Number) Angle in degrees

Output parameters

RS (Geometry) Rotated geometry

Source: Author reproduced/ Grasshopper

Fig.8.13 STM design memory and AutoCAD



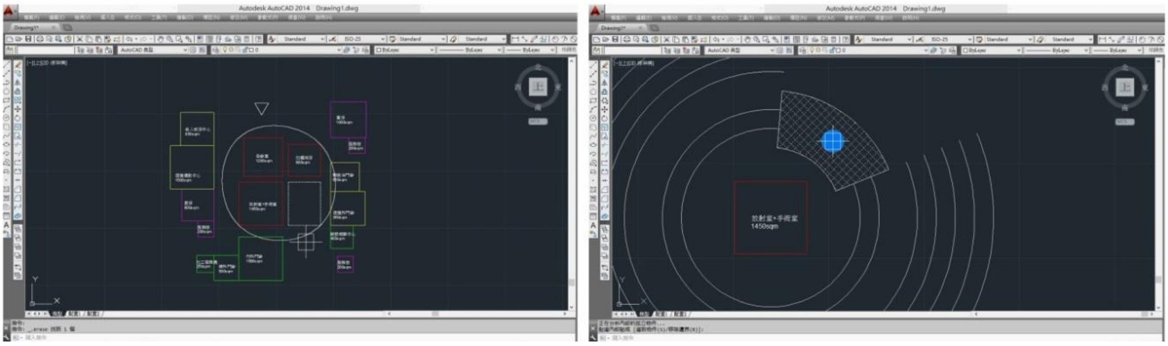
Source: Author reproduced/ AutoCAD

However, a traditional/nonparametric protocol design scheme, such as the Healthcare Building Notes, cannot easily and instantly modify the design feedback to the problem. If the cognitive learning process is not extended and cannot be flexibly integrated into systematic thinking, it sometimes causes mistakes when applying cognitive memory for the design determination. On the other hand, the cognitive memory in nonparametric CAD (AutoCAD) was discovered to be akin to a process associated with 'Short Term Memory – STM' (Lindsay and Norman, 1972; Newell and Simon, 1964) (Fig.8.13). Design functions in AutoCAD are based on limited and non-extendable non-algorithmic design manipulation options (Fig.8.13-A), such as cut, copy, offset, etc.; these are closed processes which are limited in storage capacity. These packaged design tools are menu-driven and can be used in any design geometry because there is no mathematical process involved and there is no structure that influences the interrelation between them. Also, by doing this design method, architects needed to select tools as the cognitive memories according to their past design experience and familiar repeated actions were applied in all design projects.

For example, in case 11 (Fig.8.13-1), the architect sequenced his design by calculating room scales and making them as different 2D boxes, which meant setting the program room (Fig.8.13-1-1-A) and then drawing a pre-set drawing template as a draft layout (Fig.8.13-1-1-B). Unfortunately, these two design actions, the design template and room shape, did not exhibit any cognitive learning taking place between geometrical design and cognitive memories. The square rooms do not geometrically connect a circular template/layout. This meant each section of the design tool only represents a disconnected cognitive memory to or extending from the mind process. Thus, conventional CAD design tools utilising STM only contain a limited amount of design information. If the designer attempts to increase the use of those STMs, the chance of failure in the cognitive process is high and could also be sudden because there is no structure to connect those STMs in the design coordination process. According to Newell and Simon's (1972) work, STM has a significant limitation in the temporal span, which means 'information will erode if not rehearsed after two seconds'. In addition, Lindsay and Norman's (1972) study suggests

‘STM can only hold 2 to 7 units of information at any given time’.

Fig.8.13-1 STM design memory and AutoCAD design cognition

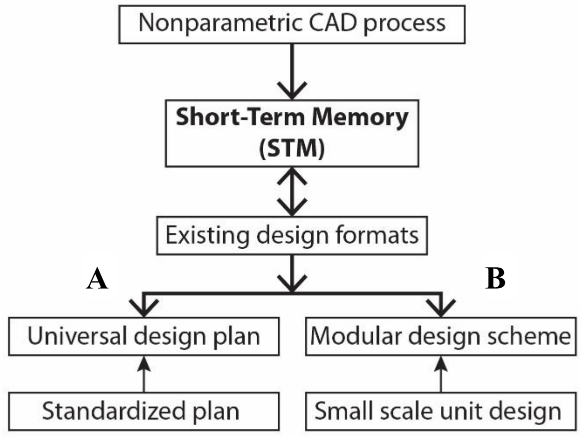


A: Making program box for spatial calculations **B:** Drawing a design template

Source: Architect 11 produced/ AutoCAD

However, the study of nonparametric CAD found the majority of architects used existing design formats to assist their design memory (STM) within a structured mind process to help their cognitive development of the design scheme. This could be because STM has a limited capability to impact on cognitive learning. As a result of this, we can understand how the 70s-80s systematic design hospital method helped with the complex design of hospitals through applying a modular design scheme and contributing those successful building designs such as the Harness and Nucleus design hospital (See the literature review of the Harness and Nucleus hospitals in Section 3.4.2.c, Chapter 3). This effective design method dealt with the weakness of conventional/nonparametric architectural design processes (Fig.8.13-2) but could not provide a valid cognitive learning process using STM; a modular or standardised plan (Fig.8.13-2-A) based on a small-scale unit design (Fig.8.13-2-B) helped in the organising of this design cognition problem.

Fig.8.13-2 STM design memory and design formats

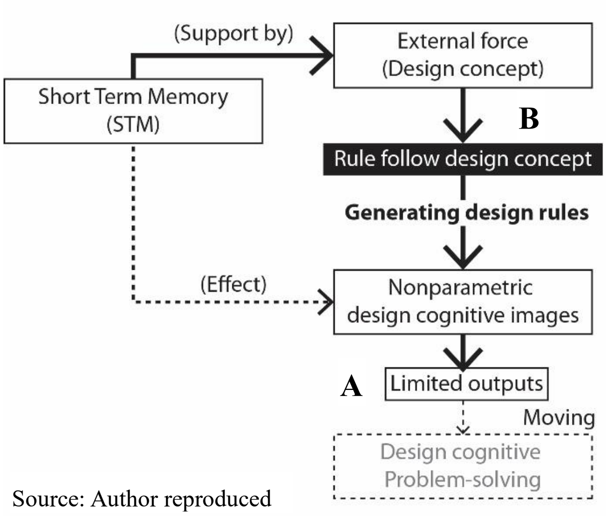


Source: Author reproduced

b) Cognitive imagery

Cognitive imagery is often shown as a cognitive chunk in architectural drawings and it functions to organise hierarchical multi-associated relationships using cognitive memory (Akin, 1986). This means the image representation in the cognition process has a considerable relation to the memory type, STM or LTM. Influenced by STM, it was found in this research that nonparametric CAD users were presenting a large number of images/chunks, but these came after some restriction from a design rule, and the design representation such as image types had very limited variety (Fig.8.14-A).

Fig.8.14 Nonparametric CAD and design imagery



Source: Author reproduced

The reason for this might have been because of the nature of STM, which is linked with a weak cognitive structure. As a result, the architects needed to apply external conceptual inferences (Fig.8.14-B) to support their design cognition and use a structure developing the design drawings as cognitive chunks in their design representations. For example, in case 06, the architect used a circular shape (Fig.8.14-1-A) to present his conceptual plan for layout development. The subsequent design drawings or representations were strictly aligned to this pre-set template. Accordingly, the design results just showed largely repeated imagery such as fractional circular shapes and curve outlines (Fig.8.14-1-B). In another example, case 02, the architect employed a grid system (Fig.8.14-2-A) to support the creation of his design drawings. As a consequence, his final design drawings contain a majority of 'grid-based' clustered spaces (Fig.8.14-2-B) without any innovative design combinations (See the transcription in Appendix 8.5).

Fig.8.14-1 STM design imagery and design template (architect 06)

Circle template and Circular shape

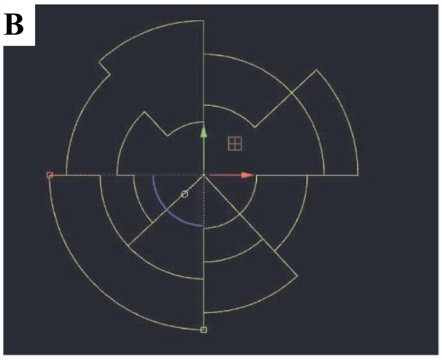
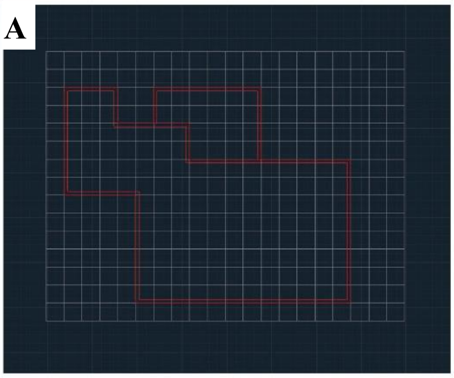
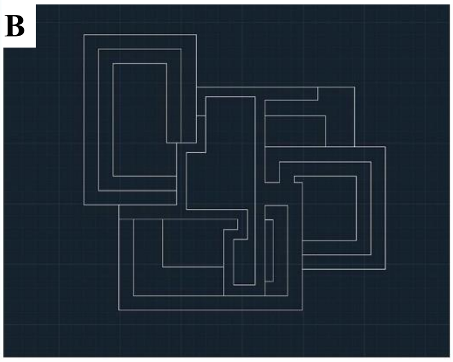


Fig.8.14-2 STM design imagery and design template (architect 02)



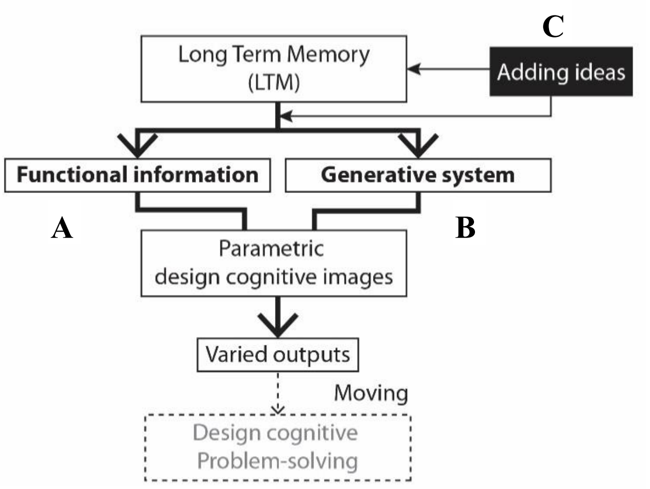
Grid template and Cluster shape



Source: Architect 06 and 02 produced/ AutoCAD

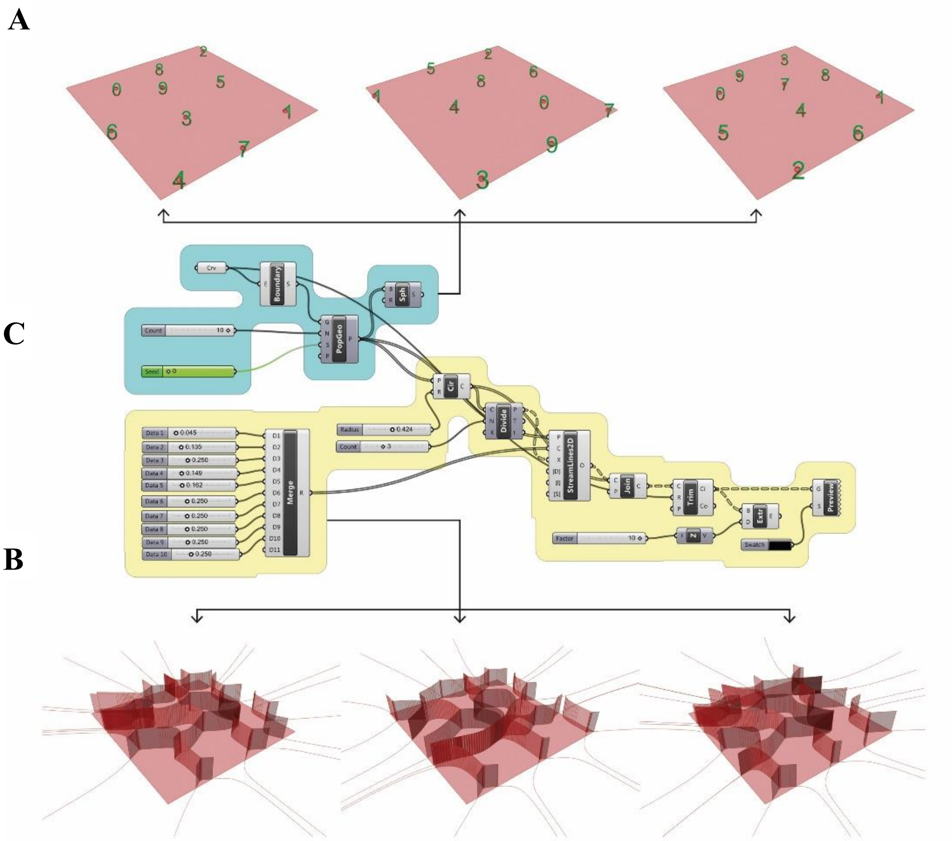
On the other hand, the algorithmic design architects produced their design imagery, like associated chunks, based on LTM (Fig.8.15). LTM, which evolves over a long time span usually involves cognitive image processes containing complex design information (Fig.8.15-A) that was integrated with a generative ‘system’ (Fig.8.15-B) suggesting ideas for the planned design. This meant the design drawing was not restricted to any specific shape or a design statement but could evolve by adding ideas (Fig.8.15-C) to test the design images during the cognitive construction process. For example, architect 01 proposed ‘random numbers’ (Fig.8.15-1-A) for the departmental units’ orientation. This function, random numbers, generated several irregular space arrangements and the architect could pick one of the best results for the next design development. He then added a ‘streamline’ (Fig.8.15-1-B) following the random room positions and created many different types of grouped curve lines as the spatial division. Consequently, the input of these two design functions, ‘randomness’ and ‘streamline’, created a layer-by-layer cognitive imagery replacement and elaborated the design cognition process just from the same given design algorithm (Fig.8.15-1-C). It may also be that the cognitive ‘load’ required by the algorithmic design process is greater than the ‘load’ required by the conventional CAD process (See the transcription in Appendix 8.6).

Fig.8.15 Parametric CAD and design imagery



Source: Author reproduced

Fig.8.15-1 Parametric CAD and design imagery of the architect01



(Random series00+Streamlines type01) (Random series05+Streamlines type02) (Random series10+Streamlines type03)

Source: Architect no.01produced/ Grasshopper

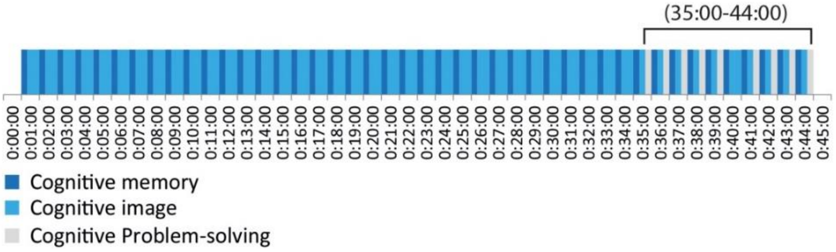
When compared with the nonparametric CAD representations, algorithmic design images contain associated design information which supports a linked strategic decision-making. It is because these design drawings are all generated by the mathematically-based design algorithms, which contain strong logic and a well-defined structure for information processing (See the literature review of the parametric concept in Section 4.3.4.a, Chapter 4). This cognitive approach was discovered by DeGroot (1965) who found that experienced chess players store their strategies as varied cognitive chunks or images and use these to win the game against less-skilled players. Turning to the design process, Chase and Simon (1973) also suggest that better LTM representation upgrades the information (chunks), organising memory and helping to perform skilled problem-solving in the design process. With respect to the infinite learning process in LTMs and the associated cognitive chunks, Hanna (2015) found the length of designer-CAD interaction influenced design cognition.

In hospital design, modular design strategy and standardisation are emphasised to ensure the quality of hospital design. As these standard design outputs are expected to possess high-quality, the use of LTM with associated cognitive design chunks may have supported the algorithmic CAD architects in upgrading modular or standard design proposals into a strategic design process. This information-based design module contains a mathematical logic and can be flexibly modified, reducing the general problems of a traditional modular design system (Harness and Nucleus hospital design) such as rigidity in the use of space, or repetitive forms and a lack of creativity (Smith, 1984).

8.4.2 Cognitive problem-solving in different CAD processes

Akin (1986) suggests 'the success of problem representations relies on their functional appropriateness for state transformation'. If the representation of a cognitive problem-solution transforms well, the consequence will be an efficient solution. In the nonparametric CAD process, the research found that the majority of cognitive

Fig.8.16 Nonparametric CAD of cognitive problem-solving process

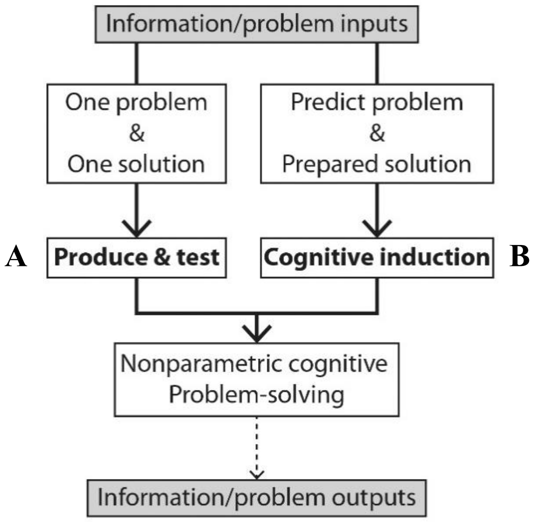


Source: Architect.11/ Excel outputs

problem-solving activities were happening very late in the design stage (Fig.8.16).

For example, the architect 11, his cognitive problem-solving process had only been discovered 22% of overall time spending on the design cognition process ($0.22 = \frac{10\text{mins (cognitive problem−solving)}}{45\text{mins (overall design cognition process)}}$. The architect mainly applied two types of cognitive problem-solving processes; the first was ‘produce and test’ (Fig.8.16-1-A), which is a process taking a particular design problem as a set and producing the relevant responses to each sub-set; and the second was ‘cognitive induction’ (Fig.8.16-1-B), which means to state or predict problems in advance and respond by involving the relevant methods or functions.

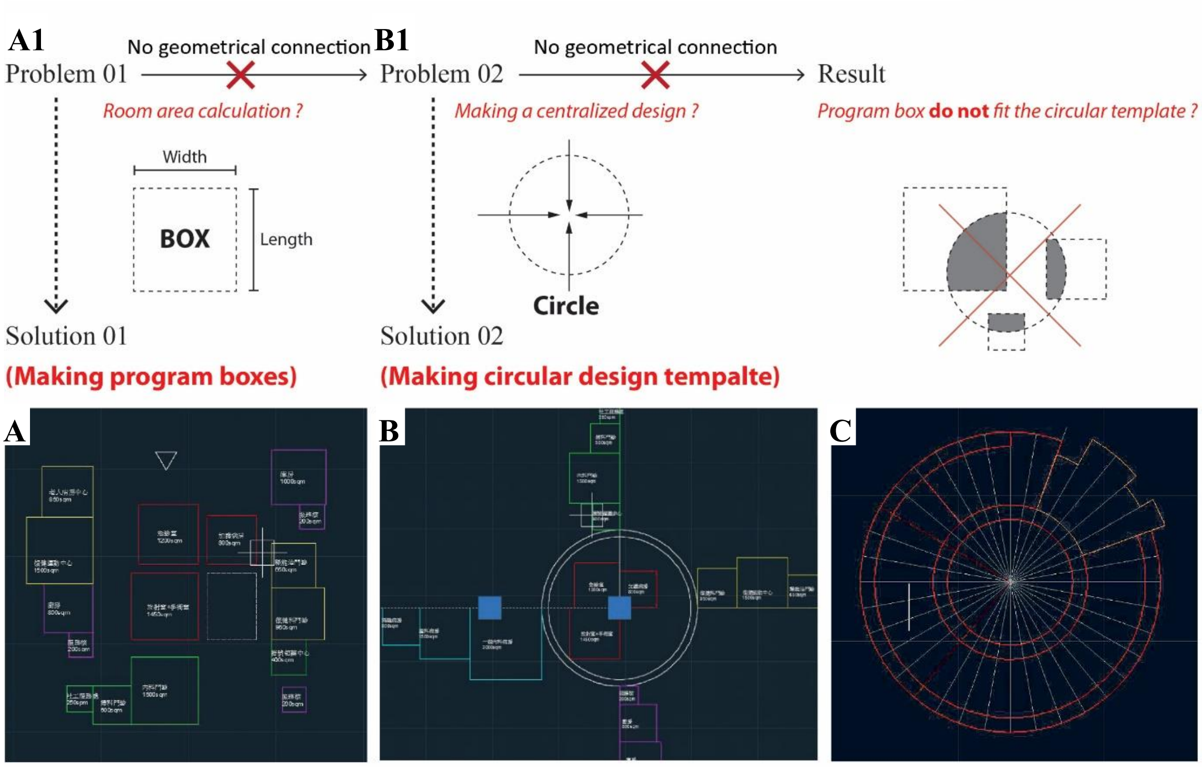
Fig.8.16-1 Nonparametric CAD and cognitive problem-solving methods



Source: Author reproduced

When it came to the protocol analysis, architect 11 chose to rationalise the program’s parameters by making different box sizes (Fig.8.16-2-A1). The reason for selecting a box as the form to solve the design problem, such as the volume calculation by height, was because a square shape is the most straightforward form to address all design parameters by simply using length multiplied by width (Fig.8.16-2-A). Next, he noticed another design issue and produced a centralised design layout for the operating theatre. He moved the pre-generated program boxes and started to use a prepared design template – a circular system, as the solution for this concentrated design plan (Fig.8.16-2-B1) (See the transcription in Appendix 8.5). Again, the selection of a circular shape as the proposed problem solution was because the circle has physical features associated with having a central point (Fig.8.17-2-B). Logically, these two design problem-solving processes had no geometrical relationship and each solution only corresponded to one design problem. Unfortunately, because of the disconnected thinking process, the weak cognitive activities could not support design problem-solving for the final design proposal. Therefore, the architect had to revise the design solution to rationalise the final output (Fig.8.17-2-C). In this case, we can see a difficulty of the nonparametric CAD cognitive process, which is predominately a graphical rather than mathematical way; thus, it is significantly affected by the scale of the design project and the level of geometrical complexity. Such issues are often associated with hospital design. While the presenting design problems, such as varied room sizes or complex circulations, were difficult to solve in one design template, the architect attempted to break down the design issues and to use the above approaches like ‘produce and test’ or use cognitive induction to manage them. However, the induction process cannot make a strong structure for the development of the design cognition. It is actually considered a weak method for cognitive problem-solving. This method is normally established on a hypothesis or assumption rather than being evidence-based. As Newell (1970) argues, if the design problem predictions are based on ‘hypothesis-and-test’, this - puts more pressure on the cognitive process in relation to design thinking.

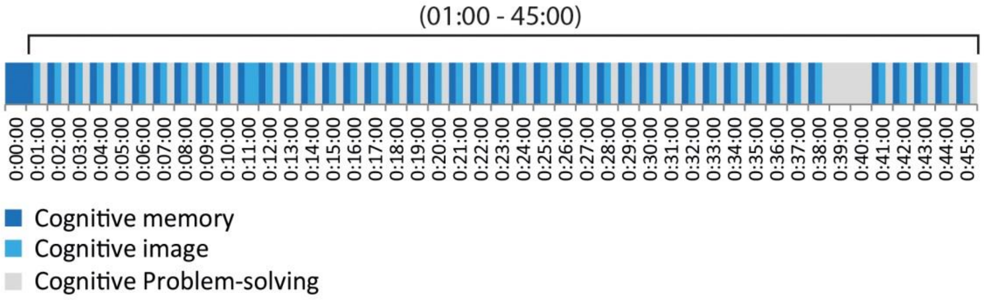
Fig.8.16-2 Nonparametric CAD and cognitive problem-solving process



Source: Architect 11produced/ AutoCAD

On the other hand, parametric/algorithmic CAD presents a continually cognitive problem-solving activity across the entire design process (Fig.8.17). This method is based on heuristic research. For example, architect 01, his cognitive problem-solving process had be discovered 100% of overall time spending on the design cognition process ($1 = \frac{\text{45mins (cognitive problem−solving)}}{\text{45mins (overall design cognition process)}}$.

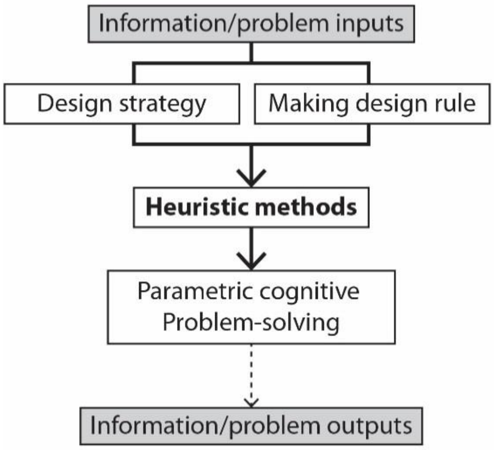
Fig.8.17 Parametric CAD of cognitive problem-solving process



Source: Architect 01/ Excel outputs

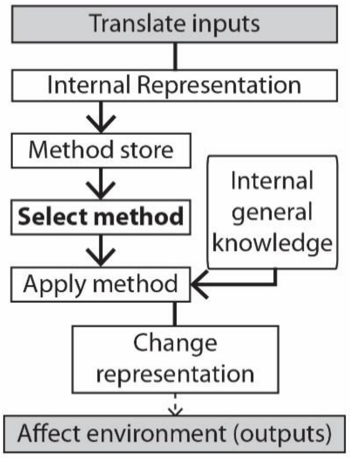
This suggests the process operates as a rule-based system (Fig.8.17-1) rather than a one-to-one problem response, which is closer to Newell's cognitive method (1970) (Fig.8.17-2). In the algorithmic CAD process, there are usually many algorithmic functions or heuristic rules applied in completing an algorithmic definition, like a cognitive process, and they follow regulations of control, confirmation, acquisition, projection, and representation of information.

Fig.8.17-1 Parametric CAD and cognitive problem-solving methods



Source: Author reproduced

Fig.8.17-2 Newell's cognitive problem-solving methods

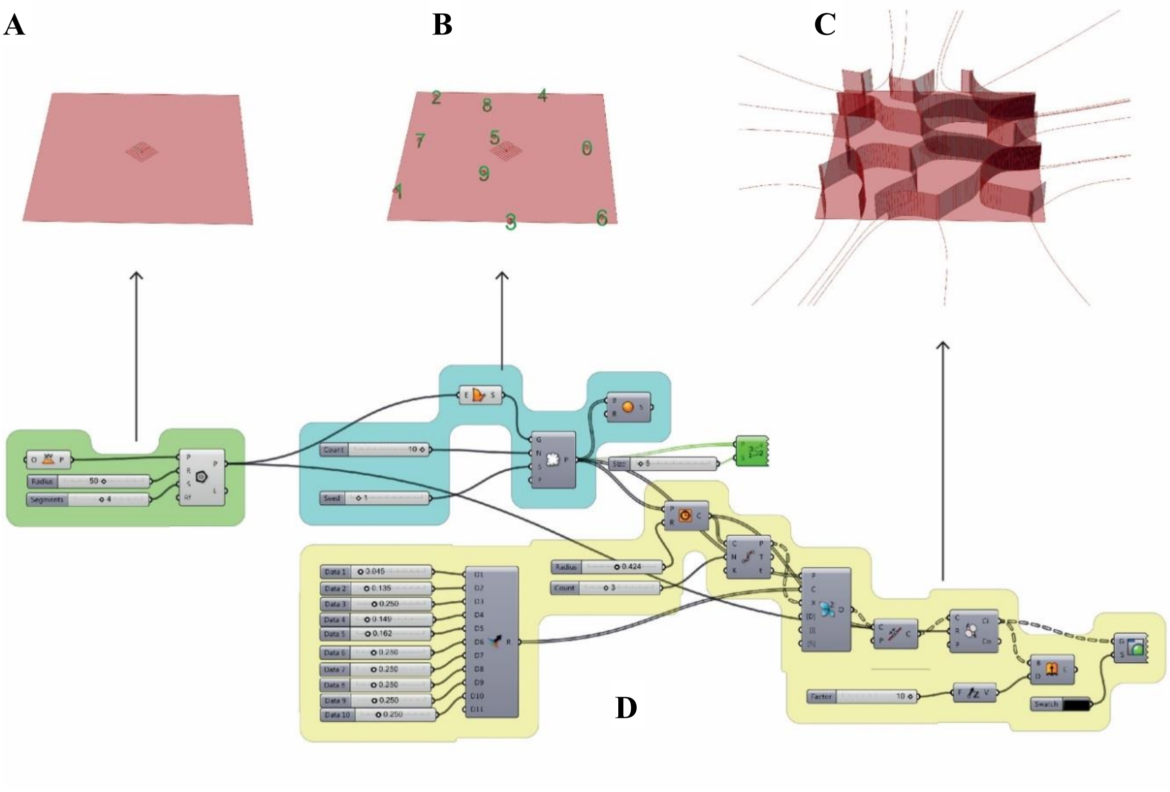


Source: Author reproduced/Newell, 1970

For example, in case 01, the architect proposed a new type of in-depth system plan by applying an algorithmic streamlined diagram, namely, a mathematically defined curve line pattern. While it was being generated, there were some steps that needed to be verified in the algorithmic process, otherwise, it could not be produced successfully. Therefore, he had to define the floor plan area (Fig.8.17-3-A), make the points to draw lines (Fig.8.17-3-B), and finally modify the diagram shape (Fig.8.17-3-C) to become a reasonable proposal. The entire problem-solving activity followed many accumulated and procedural design algorithms, which were affected by different heuristic rules. Each rule represented a function that gradually formed the design algorithmic definition (Fig.8.17-3-D) for this problem-solving process (See the transcription in Appendix 8.6). For the cognitive process, Terzidis (2003) suggests: 'An algorithm is a computational procedure for addressing a problem in a finite number of steps. It involves deduction, induction, abstraction, generalization and structured logic' (See the literature review of the parametric architectural design ideation and expression in Section 4.3.4, Chapter 4).

When it comes to commonly found problems in poor hospital design, Nield (2003) identifies some important factors. The first is failed layouts (lost orientation or inefficient service pattern), the second is a limited design proposal (limited layout types or bad connections to an old building system), and the last is less environmental comfort (lack of lighting, building context, sustainability, and careless design of patient centre services). Those design problems often include poor acoustic or noise control caused by predicting design problem-solutions without sufficient discussion and/or testing and only addressing design problems one at a time. There is a lack of an overall structure or framework that can coordinate various solutions to a multitude of design problems. Therefore, the systematic rules of the heuristic process in the cognition of parametric CAD should be more able to support improvement in hospital design and also could provide an interface for problem-solving discussions.

Fig.8.17-3 Algorithmic CAD and the heuristic cognitive problem-solving method



Radius 50
Segments 4
Count 10
Seed 1
Size 5
Radius 0.424
Count 3
Data 1 0.045
Data 2 0.135
Data 3 0.250
Data 4 0.149
Data 5 0.162
Data 6 0.250
Data 7 0.250
Data 8 0.250
Data 9 0.250
Data 10 0.250
Factor 10
Swatch

Source: Architect 01 produced/ Grasshopper

8.5 The protocol study of CAD form exploration in the hospital design process

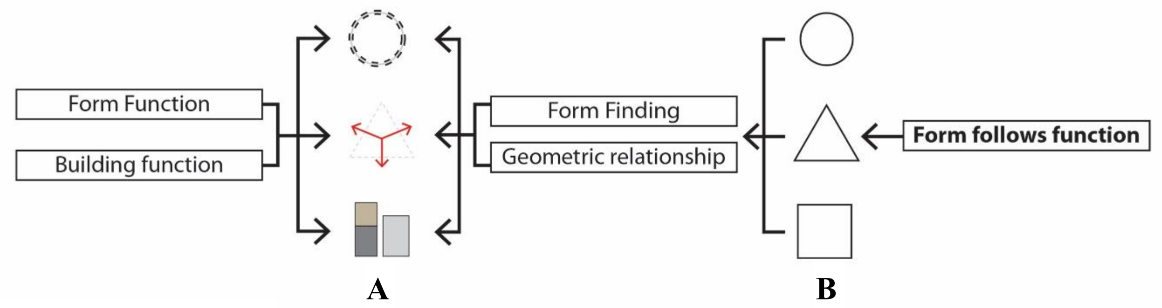
Form exploration may indicate the level of creativity in design outputs such as building shape and floor plans. Both CAD methods contained intense form exploration activity during the design task, but they showed a different interrelation between ***Form Finding*** and the ***Form Function*** link in each CAD process. The following sub-sections examine each CAD type and explain the research findings.

8.5.1 Nonparametric CAD form exploration process

a) Form followed functions

In nonparametric CAD, the protocol analysis showed a form-finding process closely dependent on the relationship of space to functions (Fig.8.18-A) such as circulations or department locations. In other words, the form exploration was based on the idea that 'form follows function' (Sullivan, 1930). In this aspect of the design process, the form exploration was associated with some physical dimensions (Fig.8.18-B) following the arrangement of functions in the building.

Fig.8.18 Form followed functions and nonparametric CAD process



Source: Author reproduced

For example, in the case of architect 02, the adjacency of spaces and spatial orientation (Fig.8.18-1-A) were seen to be linked to the functional parts of the building layout (Fig.8.18-1-B), circulation (Fig.8.18-1-C), and structure (Fig.8.18-1-D). These dimensions directly connected design aesthetics to design functions without much concern about the geometric relationship. In another example, architect 06 used a circular pattern as the basic design shape (Fig.8.18-2-A). This was because the physical aspects of a circle had some benefits for the functional design proposals, such as having the same distance from the edge to the centre (Fig.8.18-2-B) to provide good supervision from nursing stations (Fig.8.18-2-C) (See the transcription in Appendix 8.7). The visual impact and knowledge of geometry were extracted from the selected shape and directly applied to functional programs; however, they were based only on the designer's spatial experience without deeply exploring the shape construction or relations to other geometries.

Fig.8.18-1 Form followed functions and nonparametric CAD process –architect 02

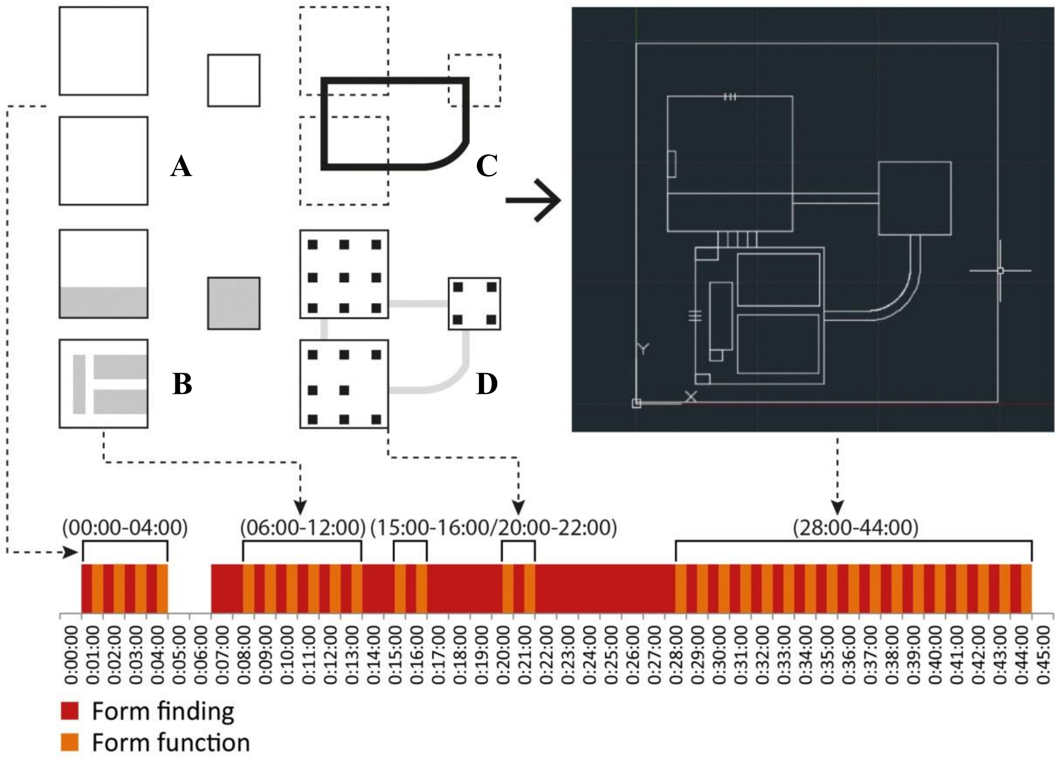
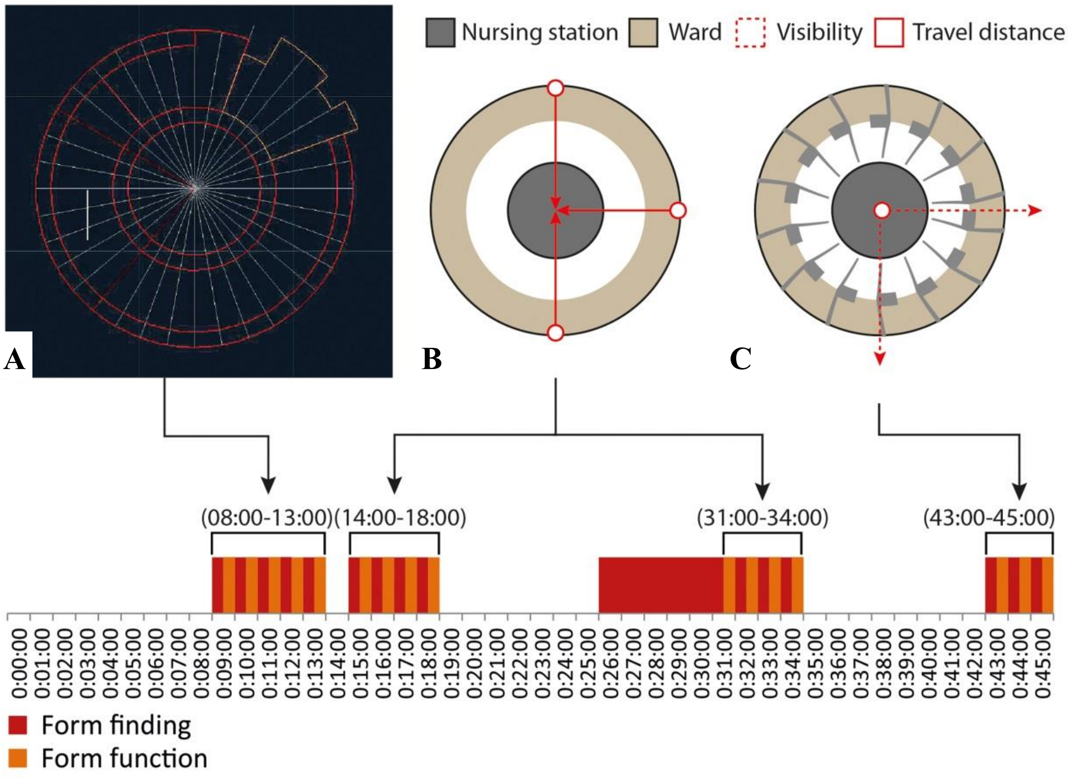


Fig.8.18-2 Form followed functions and nonparametric CAD process – architect 06



Source: Author reproduced/ architect no.02and06

Regarding the aspect of creative form-finding, in the protocol analysis, some of the architects applied a type of geometry and combined or repeated those on a larger scale to formulate a cluster of shapes or an entire hospital design floor plan (1970s-90s) (See the design of layouts in Section 1.5.1.d, Chapter 1). The cluster design was commonly used to reduce the distance between departments, but this typology design had one big disadvantage in that it resulted in many spaces that were difficult to use or not needed. This process was found to be similar to traditional working methods with overlapping sketches producing a new representation of the design outputs (Jones, 1970). The problems caused were that replaced sketches often did not connect to the geometric relationships, although the cluster plan did provide some flexibility in use and created benefits of multiple-use functions in the design proposal. In addition, this protocol observation indicated that the conventional form exploration process did not provide a visible structure for producing design shapes. It is not only that a lack of structure in the form finding process was shown, but it also profoundly influenced the architect's recognition of the necessary geometric type. As Stiny (2006) argues in his publication on shape grammar, 'Design is calculating with forms and rules' and 'understanding shapes is a useful place to start and outline the limits of design'. So, if architects have no sufficient understanding of shapes and geometric information, it means they are unfamiliar and unaware of design limitations. In terms of the hospital design process, conventional/nonparametric form exploration restricted the direction of the architect's thought to focus on only one or a few solutions. For example, using an atrium design (Fig.8.19) of the Evelina children's hospital, London can give more natural lighting and creates an open hall atmosphere; a podium and tower design type of the Leeds teaching hospital NHS Trust (Fig.8.20) can establish a strong image of the hospital for local people; applying a street design type, as in Riks University Hospital (Fig.8.21) helps build extendibility and flexibility.

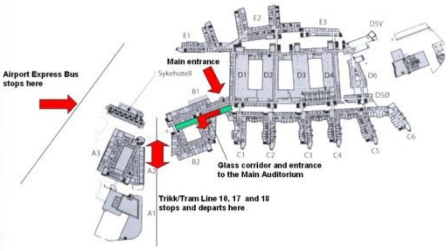
Fig.8.19 Atrium design hospital

Source: Prasad,2008

Fig.8.20 podium tower design hospital

Source: www.juniorreviews.com

Fig.8.21 Street design hospital



Source: www.cmbn.no

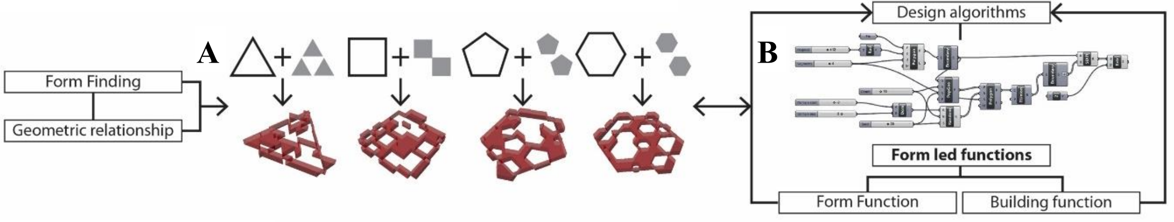
However, without a full understanding of the form's construction process and difficulties, it could create other design problems. For instance, the atrium hospital creates greenhouse effects in summer in the UK and when located in hot countries if architects could not simulate the performance of the building form with the provision of adequate ventilation. As the tower and podium hospital cannot be extended to accommodate further design growth due to the initial design shape of floorplan not having the geometric capability of being extended. The criticism of these problematic designs is about lack of understanding of the impact of both building function and building form. Also, Stavic and Marina (2011) argue that if the design (form) has been exclusively formed into a relevant typological paradigm (design template), this restriction certainly blocks the creativity of morphogenesis.

8.5.2 Parametric CAD form exploration process

a) Form led functions

In parametric CAD, form-finding constituted the major part of the process and only the remaining parts focused on form affected functions. As perceived by the protocol process, the algorithmic CAD method indicated the architects were not concerned about building functions such as layouts or engineering design, but they considered the design concept of the geometric relationships – form construction and morphogenetic testing (Fig.8.22-A) using the design algorithms (Fig.8.22-B). They tried not to make design decisions by selecting a shape and fitting building functions into it because that only represents the lowest level of design information by forcing the ideas to fit into the shape. They thought it was important to embody the design ideas within the form construction and evaluate the potential advantages and disadvantages of this.

Fig.8.22 Form led functions and Parametric CAD process

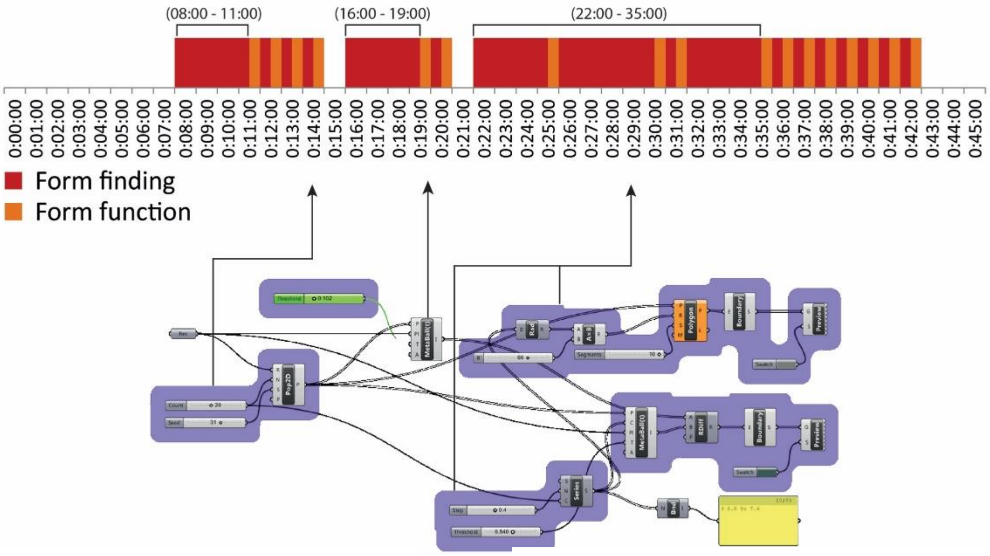


Source: Author reproduced

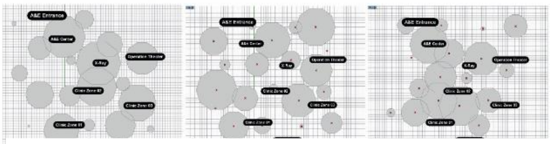
For example, architect 03 applied a mathematical design algorithm called 'Metaball', which defines gaps between objects and makes the closed side merge into a new mesh shape. By using this shape construction method, the algorithmic Metaball had calculated the distance between existing geometries and merged them to become a new mass

(Fig.8.22-1-A). The result showed many different scales of the Metaball (spatial mass) and they also contained the different interrelations (distance ranges) between the generated shapes (Fig.8.22-1-B). Next, the evaluation stage applies another algorithm called 'Galapagos' – computing fitness to further modify the geometric relationships of the group spaces (Fig.8.22-1-C). Galapagos optimised the distances between shapes to make the structures more compact to suit the design plan, optimising working distances for departmental design. This protocol observation did not record any specific building functions involved in the form finding stage. The exploration process only addressed an objective design point – distance, and then the algorithmic program guided the architect to move the design concept step-by-step toward the final proposal. If the design process needed to move on to building functions, the architect could base these on the optimised distance and make more detailed plans for layouts or engineering plans. This method is much more flexible and innovative for the standardisation of the hospital design when compared to the traditional way of literally following building notes and regulations in the planned design.

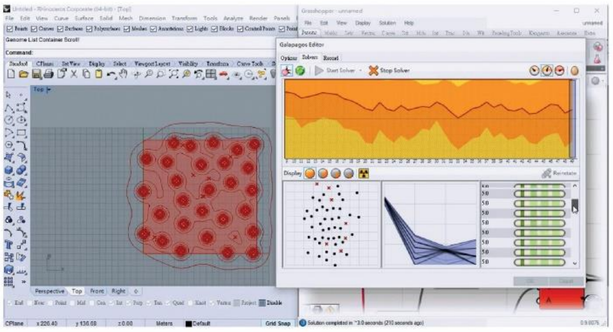
Fig.8.22-1 Form followed functions and nonparametric CAD process –architect 03



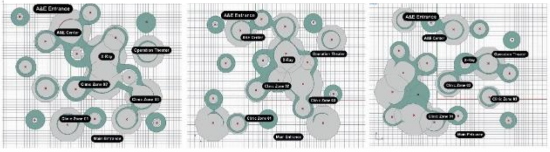
A: Varied types of room design



C: Computing optimization of space syntax



B: Varied types of Metaball mass

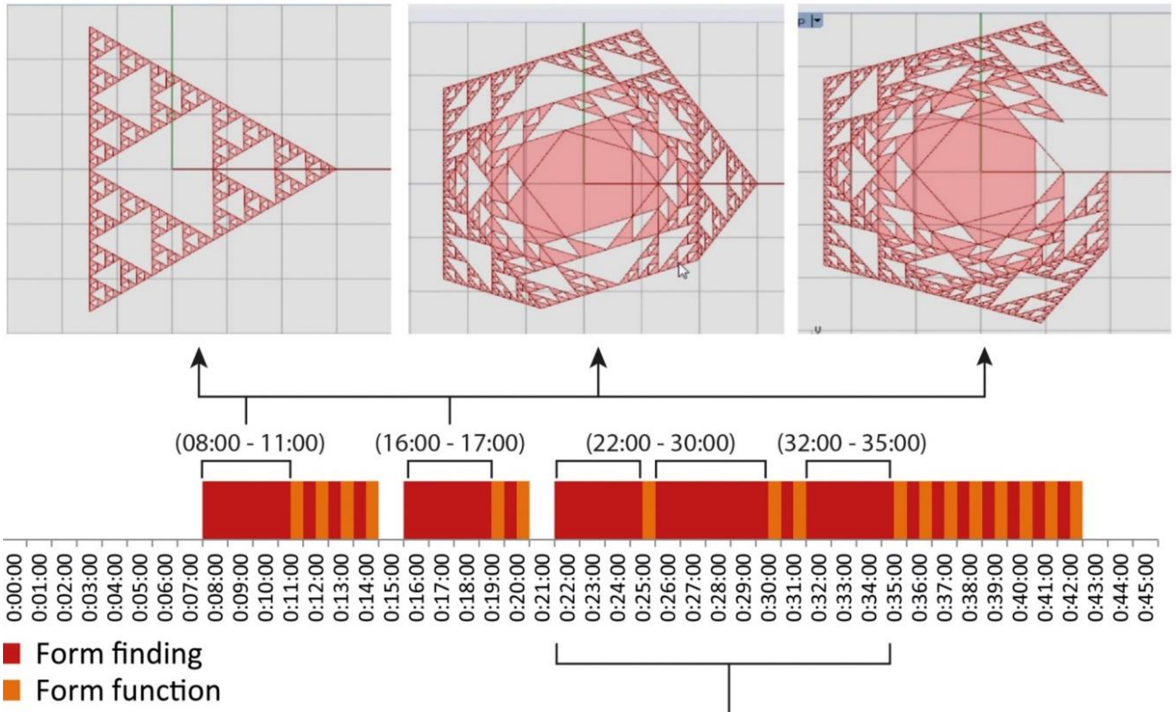


Source: Author reproduced/ architect 03

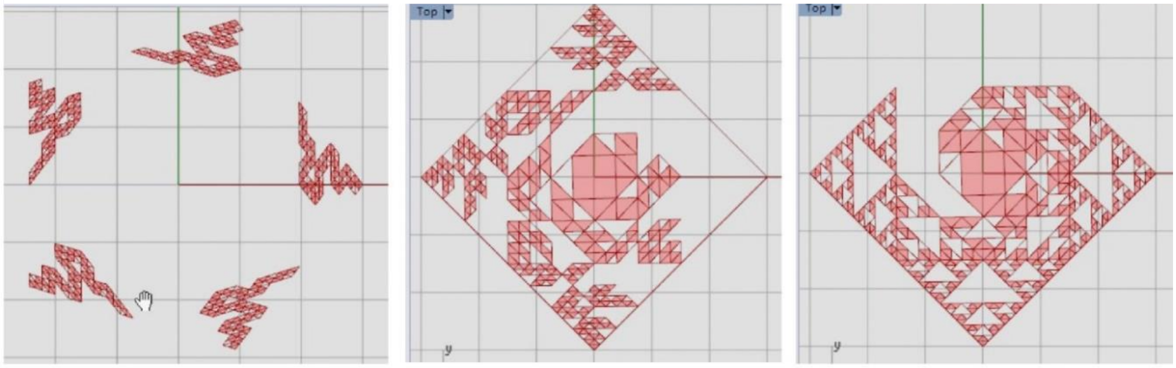
When it comes to creative form finding, there are two factors that could inspire the process of making innovative shapes through the parametric CAD method. The first is an organised design structure; algorithmic CAD can produce clear rules in the form-finding process and helps architects concentrate on the investigation of the geometrical design reasoning. The second is an extendable design process; the algorithmic form exploration is associated with a series of mathematical steps which allow great potential in terms of freely adding or removing geometrical relationships according to a change in the design requirement. For example, the architect in case 01 proposed an algorithmic modular design. He constructed a modular prototype and set the calculation (iteration/recursion) to divide the units into components of an equal size and shape (Fig.8.22-2-A). In this calculation process, he further added another mathematical function called ‘cull pattern’ and ‘random reduction’ to subtract some modular units from the proposed divisions. In addition, for the final design outputs, the algorithmic definition could insert different numbers to create a different range of subdivisions, shapes and scales (Fig.8.22-2-B) (See the transcription in Appendix 8.8). The observation showed that the algorithmic design structure helped the architect process the synthesis and evaluation in the form testing such as calculation, the division of the scale, and shape. Thus, the adaptable algorithms of the mathematical proportion and composition extended the architect’s thinking into the domain of divergent thinking (See the literature review of the population classification in Section 4.3.4.g, Chapter 4).

Fig.8.22-2 Form followed functions and nonparametric CAD process –architect 01

A: Modular types from the algorithmic CAD process



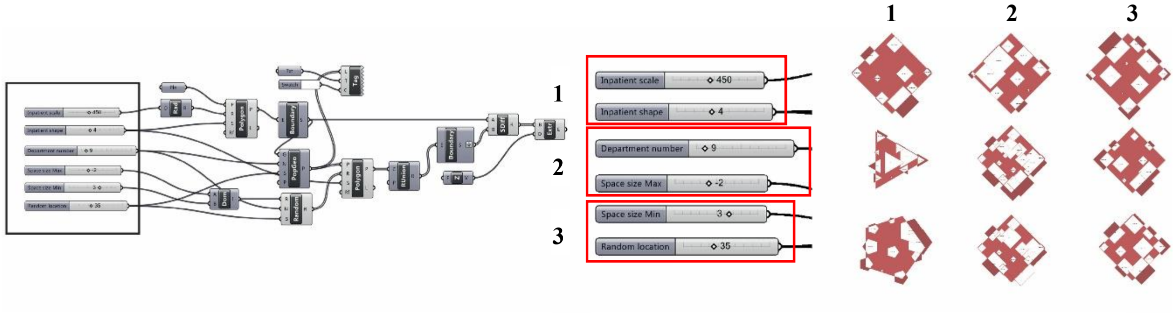
B: Cull patterns from the design units



Source: Author reproduced/ architect no.01

Simply put, the algorithmic CAD method produced the design idea, and this led to the formulation of the form. It is like preparing different schemes (Fig.8.23-A) to respond to a goal but not setting a goal (Fig.8.23-B) and following this with only one plan. Architects could always follow their design intention to find the best form rather than being sucked into a certain type of shape. This generative form design exploration has shifted the conventional idea of 'form followed function to 'form led function'. As Terzidis (2003) states, 'for architects; algorithmic design enables the role of the designer to shift from architectural programming to programming architecture'. Also, it is believed that a parameter aided algorithmic design provides evidence to support the design of the building shape, something that has never been achieved by applying traditional design typology to hospital buildings.

Fig.8.23 Algorithmic CAD definition and scheme for form exploration



A: Algorithmic definition as the design scheme **B:** Design goal and relevant parameters

Source: Author reproduced

8.6 Discussion

This chapter investigated the performance of the design process and the relevant design activities when using two different CAD methodologies in hospital building design. The parametric design method using algorithmic CAD (Grasshopper) produced systematic, well evaluated and strategy-aided design activities across case studies throughout the entire study. The nonparametric design method of traditional CAD (AutoCAD) showed a less logical or identifiable design process for the task. However, the results did not imply or suggest a criticism of particular aspects of the design methodology. The purpose of this study was to observe the process of applying different CAD approaches to hospital design and to highlight how those performances affect architects in the creation of their designs. Regardless of the design logic used in each case, the comparison indicated that design evaluation plays an important role in the design process, especially in complex design projects like hospital buildings. If architects do not have sufficient evaluation of their ideas, they could lack confidence in their decision-making as well as move more slowly in constructing their ideas. This finding makes a new statement on the lack of design evaluation in the systematic hospital design method, which also reinforces the weaknesses of the early systematic method (NHS, 1970s-80s) and further emphasises the notion of how important idea testing is to decision-making, regardless of whether there has been sufficient investigation during the preparation of the design.

In terms of the creativity of these two design processes and problem formulation, although the unstructured ‘black box’ design process, or a primary generator, in nonparametric design can produce good problem-solving scenarios and generate design in line with personalised architects’ styles, the reality of healthcare building design is that it does not require an iconic building style – it needs a rational and organised design process to manage the complex nature of design problems. By contrast, the well-structured, ‘glass box’ design process used by algorithmic CAD shows transparent design procedures. However, it may be doubtful whether a standard process could create flexibility in design thinking, as algorithmic CAD is actually based on mathematical models for design abstraction, not the design subject. There is no specific rule restricting the developer; however, the models, using algorithmic techniques, are all absolutely correct in their mathematical logic (See the literature review of the parametric architectural design ideation and expression in Section 4.3.4, Chapter 4). Moreover, this organised design method provides architects with a better brainstorming process as well as creating divergent thinking in the design solution, which are all important factors in design creativity (Runco and Chand, 1995). The protocol analysis results gave evidence on what is important and necessary in hospital design. There should be a reliable design process with the necessary problem formulation skills that distinguish the more creative algorithmic design thinking process from the conventional design method.

In addition, this study raised a deeper discussion on the psychology of architectural design – examining the cognitive process to further investigate how a systematic and organised algorithmic design process could help cognition in hospital design. The results explained and followed three cognitive stages: memory, imagery and problem-solving. Moreover, the findings considered the difference between LTM (algorithmic CAD design memory) and STM (conventional CAD design memory) in the mental processes relating to hospital design. They showed that LTM increased learning motivation in design problem solving and helped architects to think with diversity; by contrast, STM did not perform well with respect to the learning process involved and sometimes it even created other problems due to the lack of logical thought in the cognitive process. According to contemporary hospital design guidelines, standardised design disciplines ensure better cooperation with other professions and better quality of outputs (Nuffield Trust, 2001). LTM produced the required standardised information and helped the perception of design information. The protocol analysis showed that algorithmic CAD using Grasshopper inspired architects to be flexible, think systematically and use a logical process. It is believed this potentially optimised their design learning using LTM. LTM produced in the algorithmic CAD process also improved the architects' ability to act as a strategic thinker, a feature that has also been observed among the majority of highly-skilled chess players. This characteristic was supported by an organised design structure and the use of cognitive chunks which enabled the production of varied design solutions for each problem type. This variety of thought indicated the potential for the development of creative designs. On the other hand, induction in design cognition was found in the nonparametric CAD process. Without a clear structure applied in design development, this inductive method showed considerable weaknesses in design organisation. Also, the insufficient design evaluation limited the cognitive problem-solving activity so that architects' thinking easily fell into design stereotypes. This meant low levels of creative thinking and a smaller volume of design ideas. This part of the findings on cognition can be used for proposals on future hospital design training for novice architects or students.

In the final section on form exploration, it was argued that hospital design showed a limited design typology without creativity. This might have been because nonparametric CAD design methods could not extend the design into a more varied geometric construction causing the shape to only follow the building's functions and limiting further geometric exploration. On the other hand, the generative algorithmic design process exploring design shapes, following mathematical and geometrical ideas and providing high idea population generation provided design variations with evidence-based shapes, which could potentially create a new horizon for exploration of hospital design. This section tried to emphasise how important the understanding of design geometries is in the design process. The results also demonstrated how common design types (in conventional hospital buildings) showed a lack of innovation and inability in producing an attractive shape. Although there are many complicated issues affecting hospital shape design, this study has provided a direction for future design thinking using algorithmic CAD. It also highlighted the need to explore architects' design perceptions where a lack of knowledge of their design shapes can be avoided. As Stiny (2006) maintains, 'understanding shapes is a useful place to start and outline the limits of design'.

Part III/ Chapter 9 – Research Findings 4

Case Study 2-2: A correlation study of parametric/algorithmic and nonparametric design behaviour in the hospital design process.

9.1 Introduction

Chapter 8 observed the design activities in the different CAD methodologies for the hospital design process. Although identifying the different CAD activities found in the individual design performance, the protocol analysis did not explore the interrelationship between these activities and the potential influences on the exhibited creativity. This section performs the required analysis using the Statistical Package for the Social Sciences (SPSS) and re-analysis of design protocols of Chapter 8 to further investigate the statistical correlation, variance, and significance of design behaviour on design creativity. The contents of the chapter are divided into two parts:

The first part of section 9.2 analyses the number of ideas produced in both the parametric/algorithmic and nonparametric CAD processes and then investigates how these different numbers were influenced by each CAD method.

The second part – sections 9.3-9.5 tests the correlation between the design behaviour across the two different CAD methods and provides a relevant discussion on the influences of design ideation process.

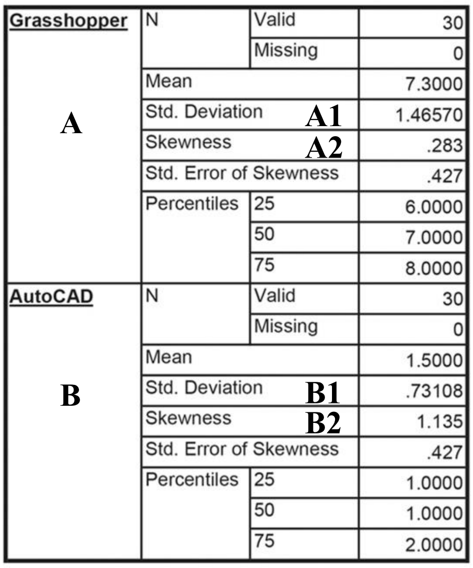
9.2 Creativity in the CAD methods of the hospital design process

This section investigates the correlation between idea numbers and design behaviours in order to find the potential design creativity and the distinct performances across the two different CAD approaches. The creativity indicator makes a reference to the generation of ‘idea numbers’ (Torrance, 1971; Guilford, 1950) (See the literature review of creativity measurement in Section 3.6.2, Chapter 3). The idea numbers produced in the design process use the definition of design intention, a single design idea, which follows Goldschmidt’s (1991) definition: ‘an act of reasoning which presents a coherent proposition pertaining to an entity that is being designed as a segment’.

9.2.1 Idea numbers in the different CAD processes

The first part of the results exhibits the descriptive statistics used for idea production associated with the performance of CAD in each group. The study summarises the results in Table 9.1 and concludes that there was a statistical mean of 7 ideas generated in the algorithmic/parametric CAD process (Table 9.1-A), compared to a mean of 1.5 to 2 ideas created by the nonparametric CAD activities. Table 9.1 percentiles also indicate that over 50% of participants using Grasshopper developed at least 6 or 7 ideas in general (Table 9.1-A1). On the other hand, of the participant's designing with AutoCAD of the nonparametric CAD, over 50% could only generate 1 idea for the design task (Table 9.1-B1). Moreover, if we check the value of the standard deviation (SD), we can measure the extent of dispersion of idea production in each of the design methods. The parametric design method (Grasshopper) shows a 1.47 SD (Table 9.1-A2) and the SD for the nonparametric design using AutoCAD is 0.73 (Table 9.1-B2). This result confirms that AutoCAD/nonparametric CAD was involved in idea generation but only where the data distribution is located within a very small range; 1 to 2 (idea numbers). Although the SD value for algorithmic CAD was higher than for nonparametric CAD, the result is explained by the algorithmic CAD approach producing a wide range of idea numbers with a potential impact on design creativity which, by implication, will yield a large value (more dispersion of data).

Table9.1 Idea numbers and CAD

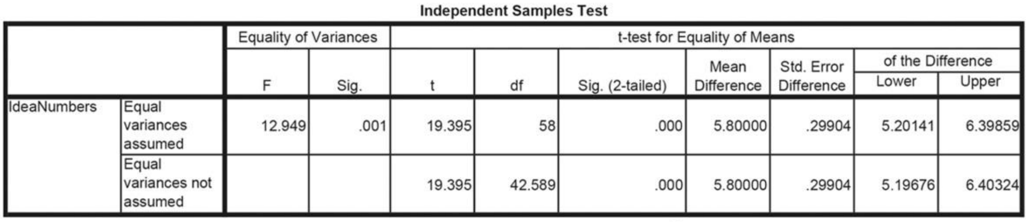


Grasshopper	N	Valid	30
		Missing	0
	Mean		7.3000
A	Std. Deviation	A1	1.46570
	Skewness	A2	.283
	Std. Error of Skewness		.427
	Percentiles	25	6.0000
		50	7.0000
		75	8.0000
AutoCAD	N	Valid	30
		Missing	0
	Mean		1.5000
B	Std. Deviation	B1	.73108
	Skewness	B2	1.135
	Std. Error of Skewness		.427
	Percentiles	25	1.0000
		50	1.0000
		75	2.0000

Source: Author reproduced/ SPSS outputs

The second part displays the relationships between these variables (Table 9.2). The results of the independent samples test – T-Test, demonstrate there was a statistically significant difference ($P<0.05$) between the different CAD methods and idea production. The Eta squared, $red = \frac{t}{t^2+(N1+N2-2)}$, measure additionally shows that the effect size of these groups equalled 0.9, which strongly supports a large effect. This means if the architects switched design methods from nonparametric CAD (AutoCAD) to parametric/algorithmic CAD (Grasshopper), this could have an obvious and positive impact on their ability to produce a greater volume of ideas (shown by a large effect size – 0.9).

Table9.2 T-Test for idea numbers and CAD methods



Independent Samples Test

		Equality of Variances		t-test for Equality of Means					of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
IdeaNumbers	Equal variances assumed	12.949	.001	19.395	58	.000	5.80000	.29904	5.20141	6.39859
	Equal variances not assumed			19.395	42.589	.000	5.80000	.29904	5.19676	6.40324

$$\text{Eta squared} = \frac{t}{t^2 + (N1+N2-2)}$$

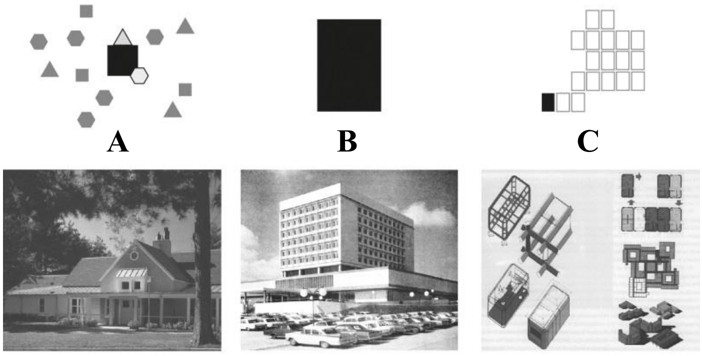
$$0.9 = \frac{19.4^2}{19.4^2+(30+30-2)}$$

.01= Small effect
.06= Moderare effect
.14=Large effect

Source: Author reproduced/ SPSS outputs

From the above results, the ideas generated in architectural design are normally considered to be an important part of the problem-solving process. The design idea helps to establish the design direction, especially in providing a model of design constraints for structuring design problems. When it came to comparing the observation of computer-based protocol tasks between the two CAD groups (See the protocol analysis study in Chapter 8), the majority of the AutoCAD architects only proposed 1 or 2 ideas, which guided the entire design process. The idea was identified as a design framework at a very early stage of the design task and then it influenced relevant design issues such as going for a compact layout type or a podium building style. The design ideas produced by AutoCAD architects were normally expressed as a strong design statement or a model of symbolic constraints, such as introducing the idea of 'commodity building' (Fig.9.1-A), 'symbolic building' (Fig.9.1-B) or 'modular space' (Fig.9.1-C), which were similar to the design concepts in the NHS healthcare building design, 1984 (See the literature review of late twentieth century modern hospital design in Section 2.4.3, Chapter 2).

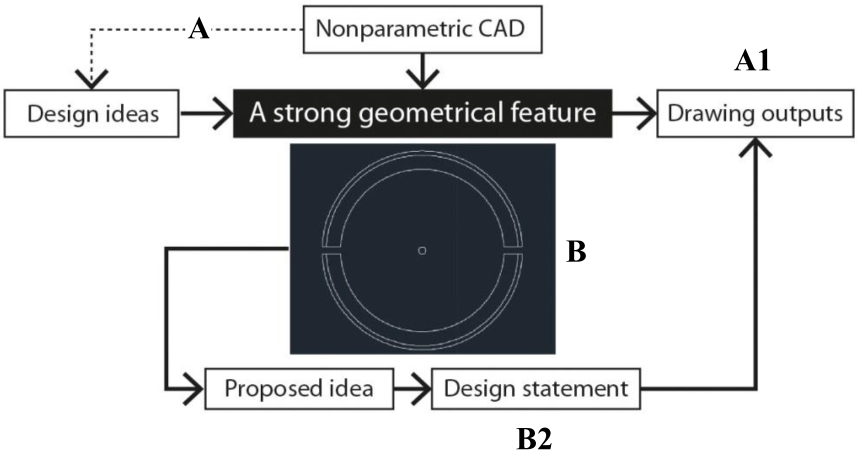
Fig.9.1 Strong design model of symbolic building



Source: Author reproduced/ Verderber and Fine,2000/ Prasad, 2008

Although it is important to design hospital buildings with function as a foremost consideration, these rigid statements or ideas, one could argue, restrict the flexibility of the design development. We can assume that these design ideas were aimed at targeting some specific goal and associated problems and this then obliged the entire design strategy/cognitive process to follow the proposed framework to solve the problems. This is understandable, as design with AutoCAD has no obvious substructure for a geometrical relationship between the proposed ideas (Fig.9.2-A) and drawing outputs (Fig.9.2-A1); architects have to find a strong geometrical feature (Fig.9.2-B) representing the main design idea (Fig.9.2-B1) and create the statement of problem constraints (Fig.9.2-B2) to drive them. This design limitation has been found in many modern hospital designs, particularly during the 1970s-90s, the era of the international style designed hospitals, such as the Hill-Burton and the 'Racetrack Plan' in the USA, and the Brutalism hospitals in the UK (Verderber and Fine, 2000) (See the literature review of the Hill-Burton or the racetrack plan in Section 2.4.2.a-1, Chapter 2). As Lawson (1990) argues, a symbolic idea is just a subjective outcome depending on the initial design vision; there is no real philosophical design thinking behind the idea. It puts the design idea at risk of criticism and it is not possible to understand the thinking behind the concept. In other words, this symbolic idea generation could not only restrict the architect's ideation to limited directions (characteristics) but also restrict creativity.

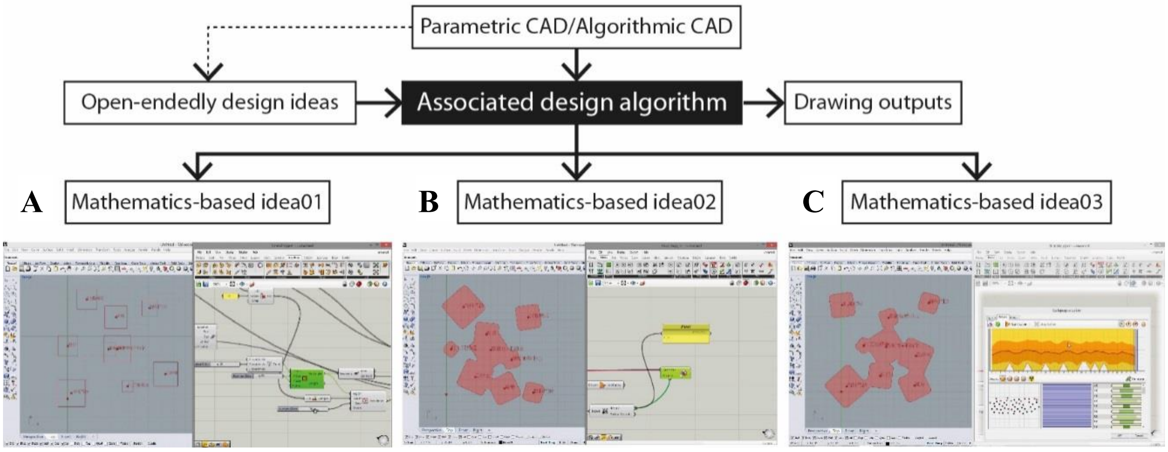
Fig.9.2 Nonparametric CAD and design ideas



Source: Author reproduced

On the other hand, in the same observation, parametric design using the algorithmic method created a flexible ideation process. Each design idea was generated with an associated algorithm or a group of algorithmic procedures and could be open-endedly connected to other ideas. For example, architect 06 suggested a concept of cluster floorplan design for departmental layouts. Unlike the conventional way to apply clustering shape construction, the architect applied some design algorithms to construct his concept. First he used a random orientation as the idea 01(Fig.9.3-A) for arranging the clinic waiting area; second, he added a rotation function to change the clinic direction (idea 02) (Fig.9.3-B) to gain different layout patterns for interiors and he additionally employed a computer simulation to verify the shortest distance of idea 03 (Fig.9.3-C) between rooms. The above three ideas,1. Random, 2. Rotation and 3. Shortest distance, enriched the ideation process and achieved the design requirements. Such a mathematically-based and associated algorithmic design ideas can be easily added to or modified using an absolutely correct mathematical process with objective parameters such as scale, distance, angle, length and width. They increase the complexity and elaborateness of the design definition step by step and can complete the design problem-solving process with an appropriate solution (See the literature review of the parametric concept in Section 4.3.4.a, Chapter 4).

Fig.9.3 Parametric CAD/Algorithmic CAD and design ideas

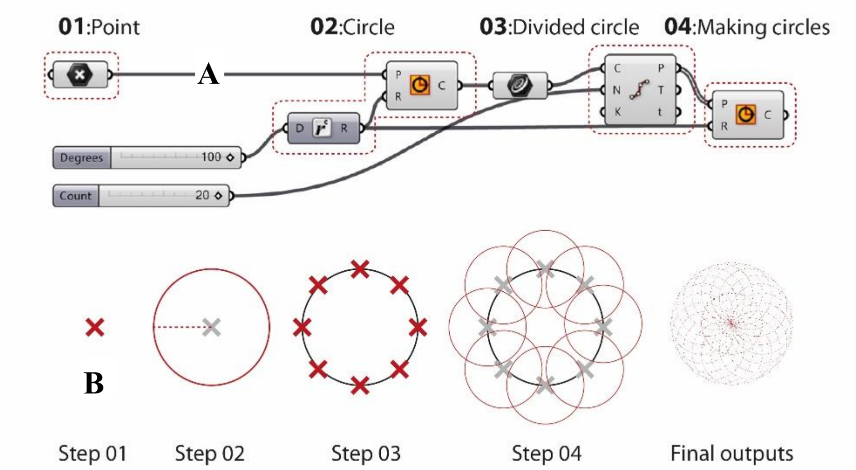


Source: Author reproduced/architect no.6

The way in which the algorithmic definition by the Grasshopper supports the ideation process can be explained in two ways: the first is a node-diagram (Fig.9.4-A) providing a visual design, a data structure which is connected to the geometric reasoning and the architectural proposal. Tedeschi (2014) suggests that a visually-based design process using Grasshopper certainly helps architects to target complex design problems; the node-diagram, also called a ‘flow chart’, visualises the design dependencies with instant effects on the design drawing. The second advantage of design ideation using an algorithmic approach is that ‘An algorithm is a procedure for addressing a problem in a finite number of steps using logical if-then-else operations’ (Terzidis, 2006) (Fig.9.4-B). This indicates that algorithmic CAD defines every design action as a functional component;

these components can be linked in a finite diagram, which means the architect never loses sight of the design process.

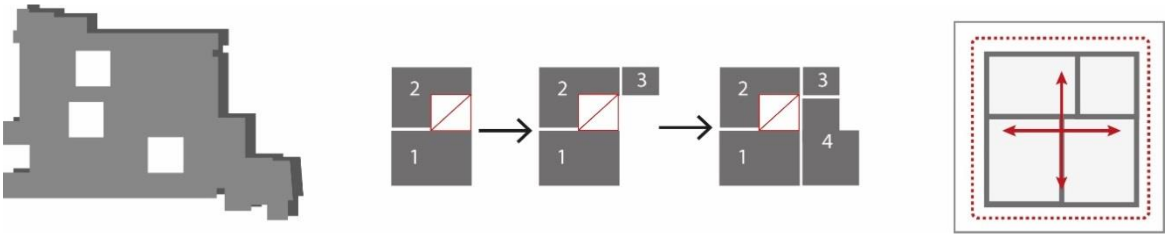
Fig.9.4 Algorithmic CAD and ideation process



Source: Author reproduced/Grasshopper

In hospital design, the most important aspect is to understand the correlation between the spatial arrangements and make them correspond to the needs of the necessary medical services. However, traditionally designed (nonparametric CAD) hospitals normally only identify one main design concept and follow this through for the rest of the detailed planning process, such as floor plan layouts, facility design, or construction planning. For example, the design idea for the Greenwich Hospital (1970s) was proposed with a mega-sized ‘Monoblock’ style (Fig.9.5-A) in order to emphasise the concentrated service system. Therefore, subsequent phasing design (Fig.9.5-B) and building circulation (Fig.9.5-C) were strictly developed following this conceptual framework. The main disadvantage of such a strong design conceptual statement when using conventional (nonparametric) design methods was that it could not help architects to deal flexibly with changing design requirements arising from unexpected problems or future design developments. On the other hand, by using algorithmic CAD, architects can take advantage of its process to organise their ideas structurally at the earlier conceptual design stages.

Fig.9.5 The Greenwich Hospital design and idea developments



A: Monoblock style **B:** Centralized phasing design **C:** Circulation

Source: Author reproduced

9.2.2 Correlation of idea numbers and different CAD behaviour

Besides focusing on the number of ideas, this section aims to extend the study of the ideation process into a pattern works of design behaviours across the two types of CAD method. The study provides a test of statistical correlation between design activities and idea numbers as well as providing a mathematical regression equation for calculating the present and future performance of the time spent on the design interactions and its influences on the production of design ideas.

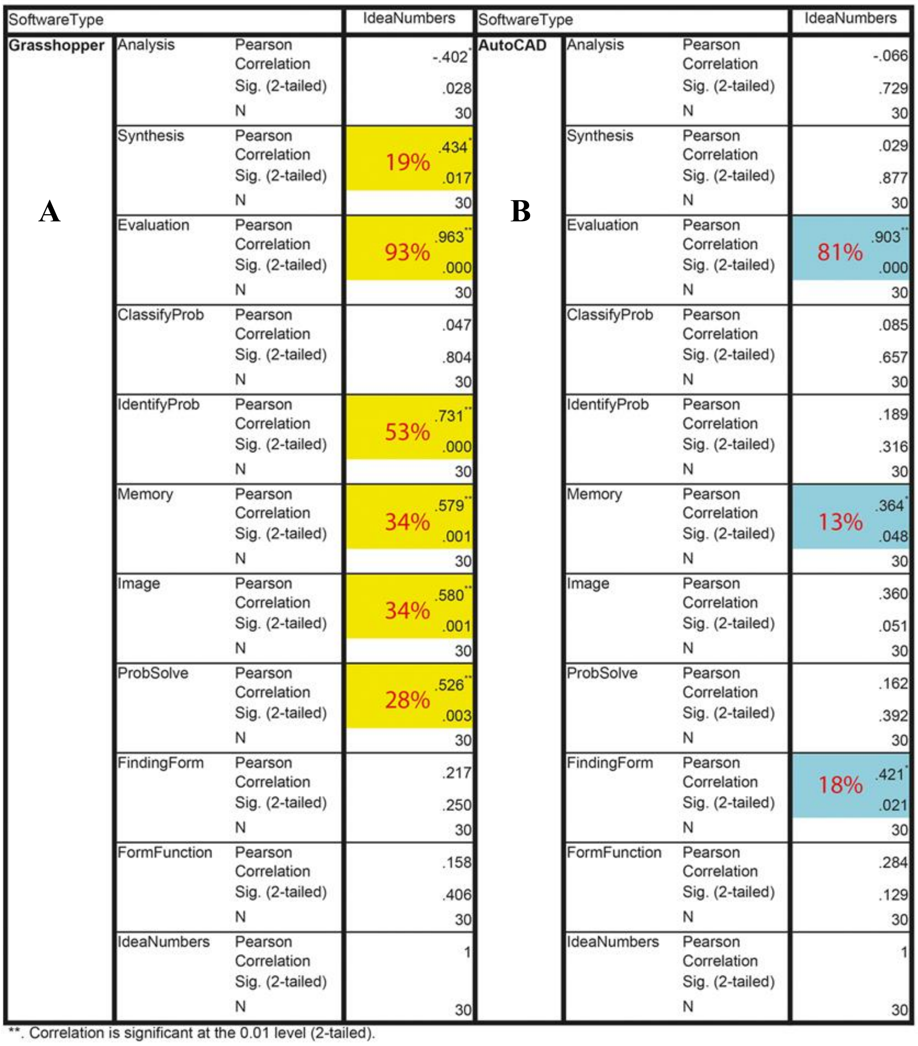
a) The parametric/algorithmic design method using Grasshopper

Using the Pearson correlation test (Table 9.3-A), three aspects were reported in the results. First, the synthesis (r=0.43, p<0.01, 19% of variance) and evaluation (r=0.96, p<0.00, 93% of variance) of the algorithmic CAD process showed a significant correlation with the production of idea numbers. In particular, the 93% $(r^2 * 100 = y\%)$ of variance between design evaluation and idea numbers indicated there was a significant relation between idea testing and idea production. This confirmed that the majority of the algorithmic design ideas had been supported by the design evaluation activity. Nigel (2011) suggests that an intensive engagement with idea testing is often found in innovative designers' processes.

Second, a strong correlation was also shown between problem identification (r=0.73, p<0.00, 53% of variance) and idea numbers meaning the mathematically-based design algorithms not only helped the architects in their design problem-solving processes but also improved the production of idea numbers. Jones (1970) highlights that mathematics is good not only for defining the design problem but also for optimising the design solutions.

Last, a close relationship between the design cognition process (cognitive memory: r=0.58, image: r=0.58 and problem-solving: r=0.53; p<0.00) and idea numbers indicated that algorithmic design cognition may well have supported the design ideation process. Along with the earlier discussion of long-term memory (LTM) in algorithmic design cognition (See the research finding of cognitive memory in Section8.4.1.a, Chapter 8), this statistical analysis confirmed the importance of strategic design thinking among the algorithmic assisted CAD architects in the making of a large number of design ideas.

Table9.3 Correlations of the idea numbers and the different CAD behaviours



SoftwareType			IdeaNumbers	SoftwareType			IdeaNumbers
Grasshopper	Analysis	Pearson Correlation	-.402*	**AutoCAD**	Analysis	Pearson Correlation	-.066
		Sig. (2-tailed)	.028			Sig. (2-tailed)	.729
		N	30			N	30
	Synthesis	Pearson Correlation	19% .434*		Synthesis	Pearson Correlation	.029
		Sig. (2-tailed)	.017			Sig. (2-tailed)	.877
A		N	30	**B**		N	30
	Evaluation	Pearson Correlation	93% .963**		Evaluation	Pearson Correlation	81% .903**
		Sig. (2-tailed)	.000			Sig. (2-tailed)	.000
		N	30			N	30
	ClassifyProb	Pearson Correlation	.047		ClassifyProb	Pearson Correlation	.085
		Sig. (2-tailed)	.804			Sig. (2-tailed)	.657
		N	30			N	30
	IdentifyProb	Pearson Correlation	53% .731**		IdentifyProb	Pearson Correlation	.189
		Sig. (2-tailed)	.000			Sig. (2-tailed)	.316
		N	30			N	30
	Memory	Pearson Correlation	34% .579**		Memory	Pearson Correlation	13% .364*
		Sig. (2-tailed)	.001			Sig. (2-tailed)	.048
		N	30			N	30
	Image	Pearson Correlation	34% .580**		Image	Pearson Correlation	.360
		Sig. (2-tailed)	.001			Sig. (2-tailed)	.051
		N	30			N	30
	ProbSolve	Pearson Correlation	28% .526**		ProbSolve	Pearson Correlation	.162
		Sig. (2-tailed)	.003			Sig. (2-tailed)	.392
		N	30			N	30
	FindingForm	Pearson Correlation	.217		FindingForm	Pearson Correlation	18% .421*
		Sig. (2-tailed)	.250			Sig. (2-tailed)	.021
		N	30			N	30
	FormFunction	Pearson Correlation	.158		FormFunction	Pearson Correlation	.284
		Sig. (2-tailed)	.406			Sig. (2-tailed)	.129
		N	30			N	30
	IdeaNumbers	Pearson Correlation	1		IdeaNumbers	Pearson Correlation	1
		Sig. (2-tailed)				Sig. (2-tailed)	
		N	30			N	30

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Coefficient of determination

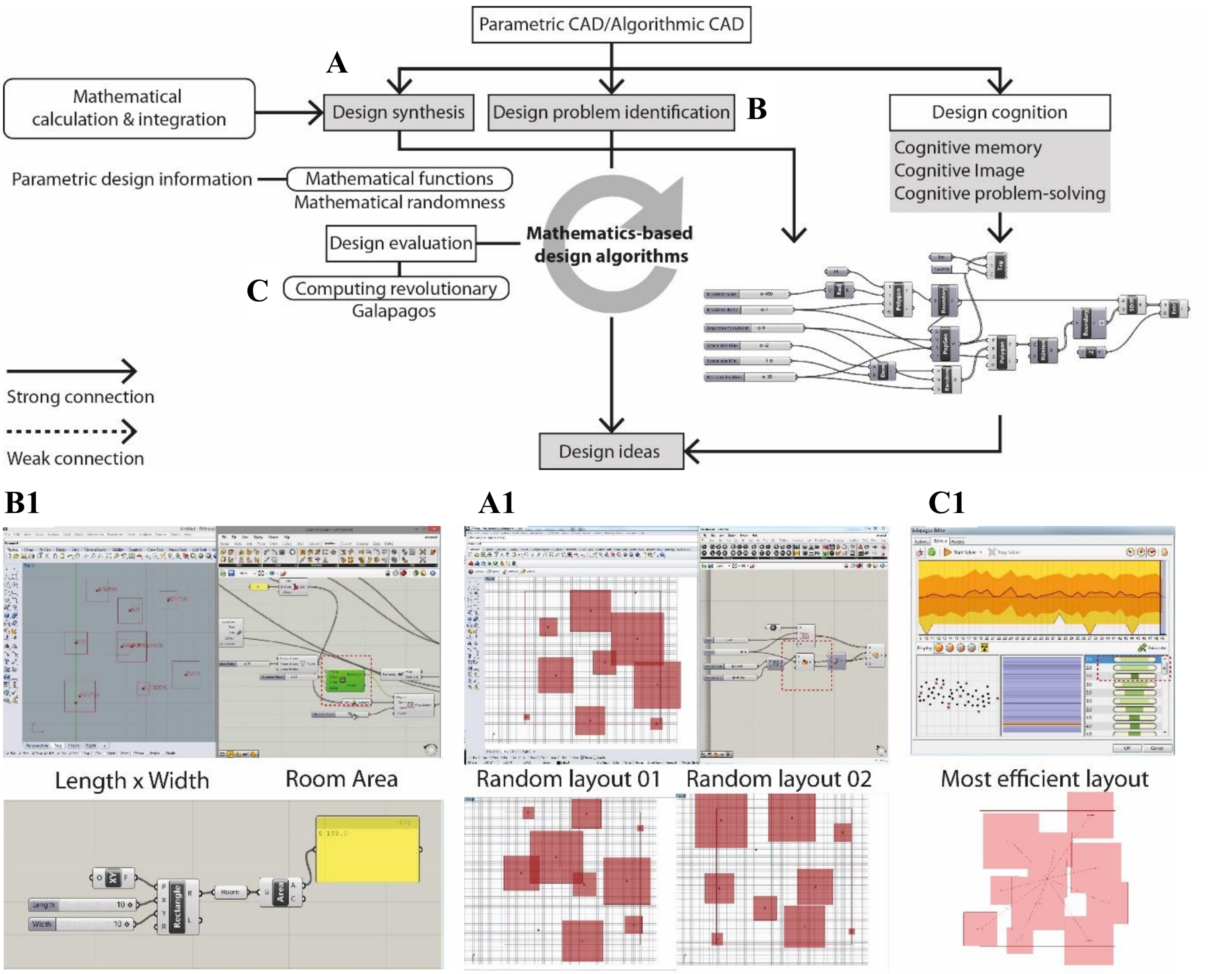
$r^2 \times 100 = y\ \%$

Small	r=.10 to .29
Medium	r=.30 to .49
Large	r=.50 to 1.0

Source: Author reproduced/ SPSS outputs

In the observation of the protocol analysis, the design activities were found to be utilising an elaborate design interaction in the algorithmic ideation process (Fig.9.6). For instance, architect 06 introduced his first step by making mathematical calculations to rationalise different clinic rooms using relevant size, volume and data. These calculations gave a design synthesise process (Fig.9.6-A) and established an algorithmic design relationship by transferring spatial requirements to the associated parameter design activity (See the 'parametric concept' of algorithmic thinking process in Section 4.2.4.1, Chapter 4). This algorithmic design process helped the problem identification process (Fig.9.6-B) by converting design information into a mathematical function (Fig.9.6-B1) (See the literature review of taxonomy of parameters in Section 4.3.4.b, Chapter 4) rather than just manually classifying the spatial design through basic conditions, like shape or functional design, which is used frequently in the conventional/nonparametric CAD process. Next, he moved to the space integration process. The architect input random numbers for the program rooms in a free-standing orientation in order to avoid any typical style at the start of the design layout process. Randomness is a mathematically-based technique (Fig.9.6-A1) of locating the spaces without a man-made design pattern. Although the randomness algorithm could produce unlimited design outcomes, the random type was controlled by a man-made range of parameters, namely, the information integration of spatial design synthesis that is under an adaptable mathematical algorithm process. After the construction of the draft layouts, the architect decided to verify (Fig.9.6-C) his proposed plan design with a practical design requirement – an efficient circulation test, which means shortening the distance between these random rooms. Computing techniques with a visual simulation tool called 'Galapagos' (Fig.9.6-C1) were used to test this particular design issue with pre-set parameters with a range of distances.

Fig.9.6 Algorithmic CAD and the ideation process



Source: Author reproduced/ architect 06

From the aspect of design cognition, we can ensure that the algorithmic ideation contains an organised design strategy especially focused on the exploration of certain design problems and solutions rather than quickly targeting one specific answer to the design proposal. The mathematical thinking also extends the architect’s mental process through a series of mathematical problem-solving activities; for instance, the problem of travel efficiency needs to be identified as a mathematical process of distance calculation Also, this design method is flexible in process and can be tested and upgraded through the construction of a specific design algorithm, which exhibits a cognitive design learning activity. As Nigel (2011) states, idea creativity means that ‘the clear, generative concept is not simply found in the problem as given, but is largely created by the designer; it is not a matter of recognizing a pre-existing pattern in the data, but of creating a pattern that re-formulates the problem and suggests directions toward a solution’.

Unlike the conventional/nonparametric CAD process, the algorithmic CAD is able to create a complex design idea and establish an effective responsive design solution from visible and generative algorithmic diagrams (See the literature review of the population classification in Section 4.3.4.g, Chapter 4). Moreover, the evidence-based design algorithm creates a potential for explaining design concepts across different groups such as medical staff, engineers and architects. Phiri (2015) argues the evidence-based design process and real-time visual modelling system can also offer a better discussion environment for hospital design planning at an early stage, which is simply not possible in nonparametric design.

Design efficiency measures the time spent on individual design activities in relation to the number of ideas generated. The first of the scatter diagrams and relevant regression equation (Appendix 9.1-A) provide further evidence of the relationship. For example, if the architects individually spent 10 minutes *(600 Sec.)* on design synthesis $(6=4.48+1.7*0.001*600)$, evaluation $(4=1.56+4.25*0.001*600)$, and identifying problems $(4=2.55+2.86*0.001*600)$, they were able to get around 4 to 6 relevant idea numbers. Although it is difficult to separate the parts of design behaviour of time spent on each, the results provide a regression analysis between the relationship of creativity and design activities, indicating that these actions did produce a given number of design ideas.

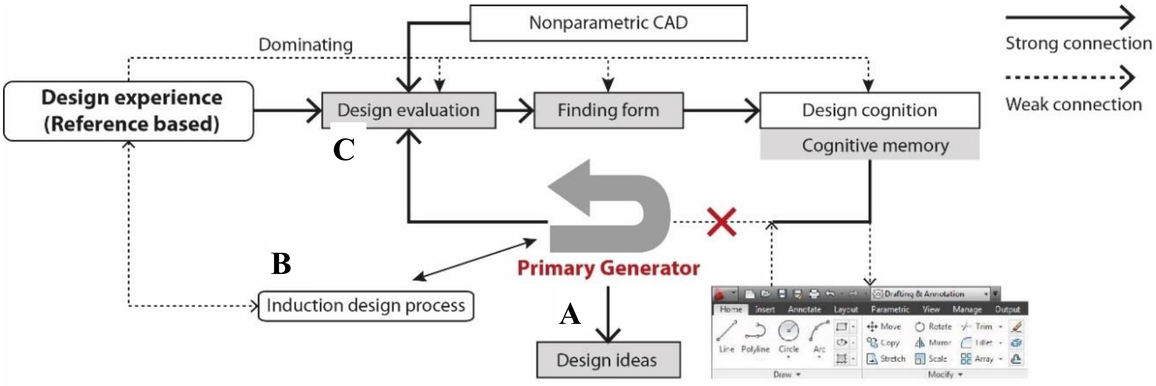
The second regression test (Appendix 9.2-A) further provided predictive calculations of the design performance between activities and ideas for future expectations. The prediction equation *Z (idea numbers) = a(X) proposed design behaviour + C (constant value)* confirms that if the architects were to engage in design synthesis $(10.5=0.002*3000+4.478)$, evaluation process $(10=0.004*3000 - 1.563)$, and problem identification $(11.5=0.003*3000+2.546)$ for 50 minutes *(3000 Sec.)*, the predicted idea numbers could be approximately 10 to 12, which means these design activities could support very productive ideation. The above equations based on the hospital design process show a link between idea production and specific design stages and offer the possibility of predicting future idea numbers.

This has not been identified in any research to date in the field of hospital design. These findings not only measure the efficiency of design activities but also confirm the significance of the relationship between idea generation and the algorithmic design processes of synthesis, evaluation and problem identification.

b) The nonparametric design method using AutoCAD

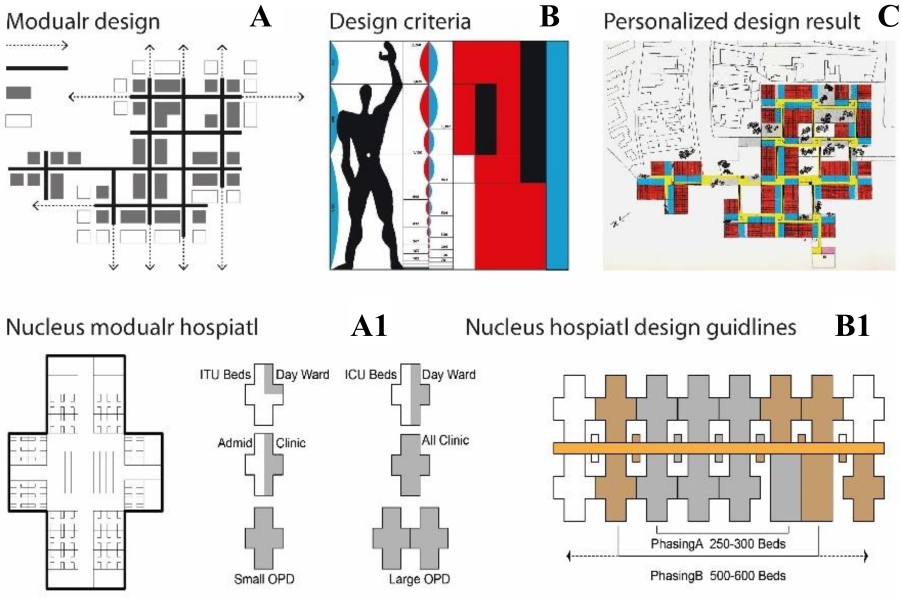
When it came to the nonparametric design process, the Pearson correlation (Table 9.3-B) found that idea numbers had a considerable relationship to design evaluation in 82% of the variance, $r = 0.9$ (large effects), $p < 0.00$. Medium effects between ideas and cognitive memory were also formed (13% variance, $r = 0.4$, $p < 0.048$) as well as finding form (18% variance, $r = 0.4$, $p < 0.02$). Surprisingly, the idea generation of the nonparametric CAD process was not closely associated with the design 'synthesis' or the 'problem exploration'. It meant the nonparametric CAD architects presented their idea assessment through their design experience rather than identifying their design process. Additionally, 'cognitive memory' (tool functions) and 'finding form' were connected to idea production, which indicates the architects could have had some design prototypes in mind and directly presented them while they were engaging in the design project. That is to say, these AutoCAD/nonparametric CAD architects certainly employed a 'primary generator' as their design method which is a conventional design ideation process representing design ideas arising from a pre-defined design concept (Darke, 1978) (See the literature review of systematic thinking of design behaviour in Section 3.5.1, Chapter 3). This design method has to be aligned with a pre-defined evaluation process, as Agabani (1980) argues in their proposal that evolutionary and revolutionary modification are essential processes in the early design stage of the primary generator. However, the primary generator design method (Fig.9.7-A) is similar to an induction design process (Fig.9.7-B), which creates a subjective design idea and forces the design process, including evaluation (Fig.9.7-C), to follow and support the main concept. In other words, there is no objective idea testing as in Le Corbusier's modular design proposal for his Viennese hospital in 1964-65 (See the literature review of Le-Corbusier, urban design aided hospital in Section 2.4.2.b-1, Chapter 2). The Corbusier modular design (Fig.9.7-1-A) is a method that establishes subjective interpretations which are then used as criteria (Fig.9.7-1-B) in the following testing process based on the principle of personalised design interpretation (Fig.9.7-1-C). The design results were impressive in that the 'modular system' worked in controlling the development of the design; however, this 'nonparametric system-based' design process often creates one design type only, making it difficult to update the design situation. In other words, this design method could easily be out of date in the studying of a new design project. In another example, systematic design hospitals, such as the Harness Hospital or the Nucleus Hospital (Fig.9.7-1-A1) (DHSS, 1970-80s), contained several design guidelines (Fig.9.7-1-B1) for ensuring the quality of the building design development (See the literature review of Harness and Nucleus hospitals in Section 3.4.2.b, Chapter 3). However, in the end, these design principles could not improve design variation; there was some negative feedback caused by the pre-defined design systems such as limited options in the departmental design or the site plan being limited to only a few shapes (King's Fund Centre, 1980). The problem is that this method and the related design considerations can block idea generation due to its subjective design testing and the repeated utilisation of experience and memory of some typical form and layout prototypes, all of which may hinder design creativity.

Fig.9.7 Nonparametric CAD and the ideation process



Source: Author reproduced/Grasshopper

Fig.9.7-1 Primary generator and modular design process



Source: Author reproduced/ Allard, Hyde, Sarkis and LeCorbusier, 2001

However, the scatter diagram and the related regression equation (Appendix 9.1-B) shows that when the AutoCAD architects spent 10 minutes *(600 Sec.)* on design evaluation, they could produce 4 ideas *(4=1.14+4.78*0.001*600)*. In addition, the regression test (Appendix 9.2-B) confirmed that if the architects were to engage in design evaluation for around 50 minutes *(3000 Sec.)*, the prediction of idea numbers could be approximately 16 *(16.4=0.005+3000*+1.142)*. These outcomes indicate how the evaluation of the design supported idea generation in the nonparametric CAD design process. Although the results for design evaluation show a very productive impact on idea numbers, in reality, the percentile Table 09 shows 25% of architects had spent less than 2 minutes *(around 70 Sec.)* on design evaluation. The reason for this is simply that nonparametric design using AutoCAD cannot provide a valid objective design evaluation platform; the CAD program does not have any tools for the simulation of geometrical functional and environmental performance of design ideas and functions. In addition, without the mathematics-based design ideation process, it is also difficult to engage in concept evaluation except for other extra forces such as technical assistance and engineering study.

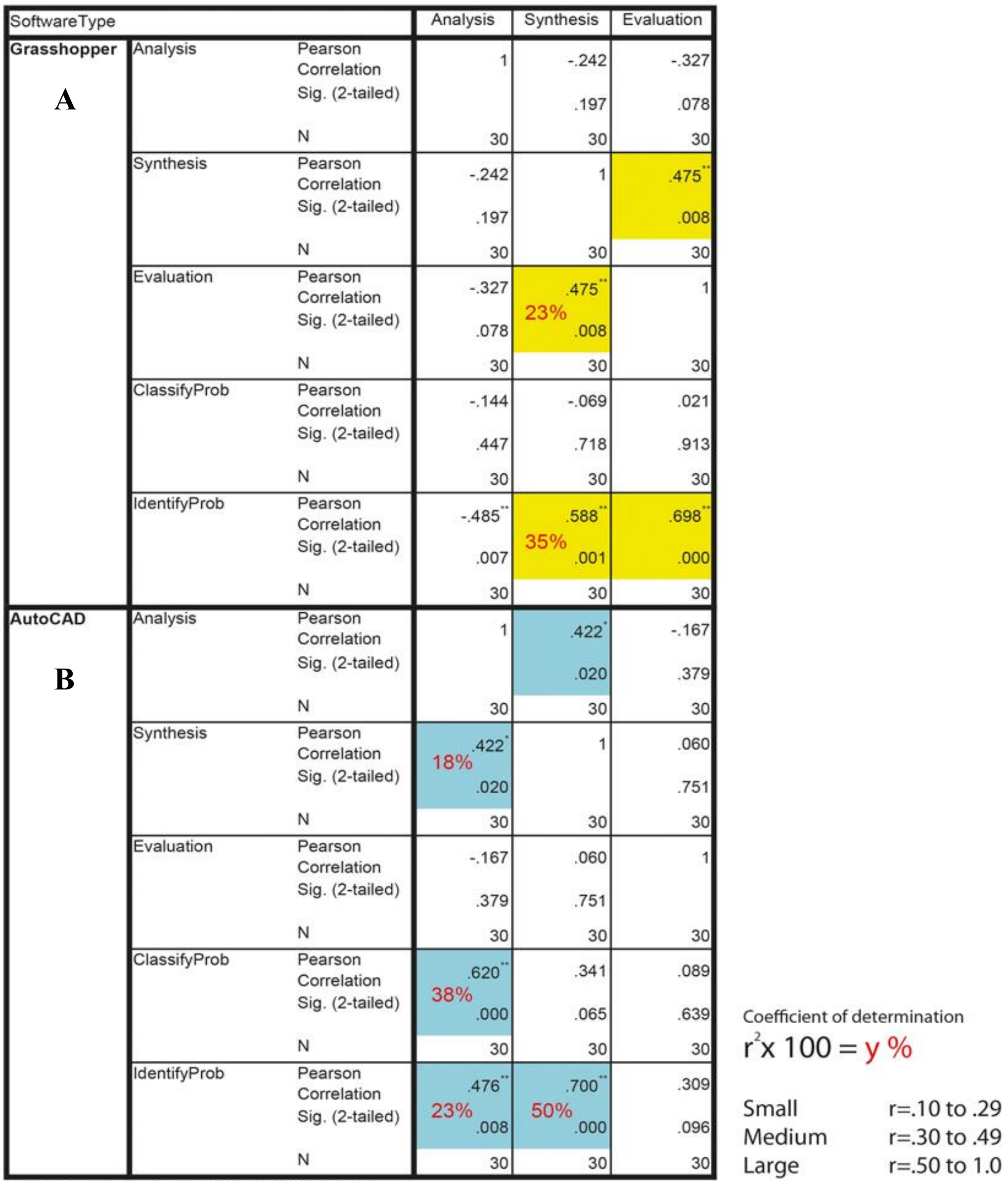
9.3 Correlation study of the different CAD process for hospital design

Archer (1965) defines design as ‘a goal-directed problem-solving activity’. This means the design process has a close connection to the design problem formulation process. This section explores the statistical testing of the relationship between the design process and problem formulation activities while the architects were applying CAD methodology during design protocol observations. The first activity examines the three stages of the design process: *analysis, synthesis,* and *evaluation*; the second stage considers the two design problem formulation steps: *design problem classification* and *identification process*.

9.3.1 The parametric CAD process and problem formulation

When applying the Pearson correlation test (Table 9.4-A) to datasets of the algorithmic CAD process and the associated problem formulation, the results indicated that there were two significant relationships between these variables. The first correlation was found between design synthesis and evaluation. The coefficient indicated a medium to large effect connected with these two factors r=.48, p<.008 with a 23% variance. This means that the design synthesis had a medium to strong effect on the design evaluation during the CAD process. As explained in the last section 9.2.2.1, the algorithmic CAD method carried mathematically-based design algorithms, so architects can simply integrate the design problems under mathematical definitions and test their design ideas.

Table9.4 Correlations of the CAD process and problem formulation



SoftwareType			Analysis	Synthesis	Evaluation
Grasshopper **A**	Analysis	Pearson Correlation	1	-.242	-.327
		Sig. (2-tailed)		.197	.078
		N	30	30	30
	Synthesis	Pearson Correlation	-.242	1	.475**
		Sig. (2-tailed)	.197		.008
		N	30	30	30
	Evaluation	Pearson Correlation	-.327	.475** 23%	1
		Sig. (2-tailed)	.078	.008	
		N	30	30	30
	ClassifyProb	Pearson Correlation	-.144	-.069	.021
		Sig. (2-tailed)	.447	.718	.913
		N	30	30	30
	IdentifyProb	Pearson Correlation	-.485**	.588** 35%	.698**
		Sig. (2-tailed)	.007	.001	.000
		N	30	30	30
AutoCAD **B**	Analysis	Pearson Correlation	1	.422*	-.167
		Sig. (2-tailed)		.020	.379
		N	30	30	30
	Synthesis	Pearson Correlation	.422* 18%	1	.060
		Sig. (2-tailed)	.020		.751
		N	30	30	30
	Evaluation	Pearson Correlation	-.167	.060	1
		Sig. (2-tailed)	.379	.751	
		N	30	30	30
	ClassifyProb	Pearson Correlation	.620** 38%	.341	.089
		Sig. (2-tailed)	.000	.065	.639
		N	30	30	30
	IdentifyProb	Pearson Correlation	.476** 23%	.700** 50%	.309
		Sig. (2-tailed)	.008	.000	.096
		N	30	30	30

Coefficient of determination

$r^2 x\ 100 = y\ \%$

Small	r=.10 to .29
Medium	r=.30 to .49
Large	r=.50 to 1.0

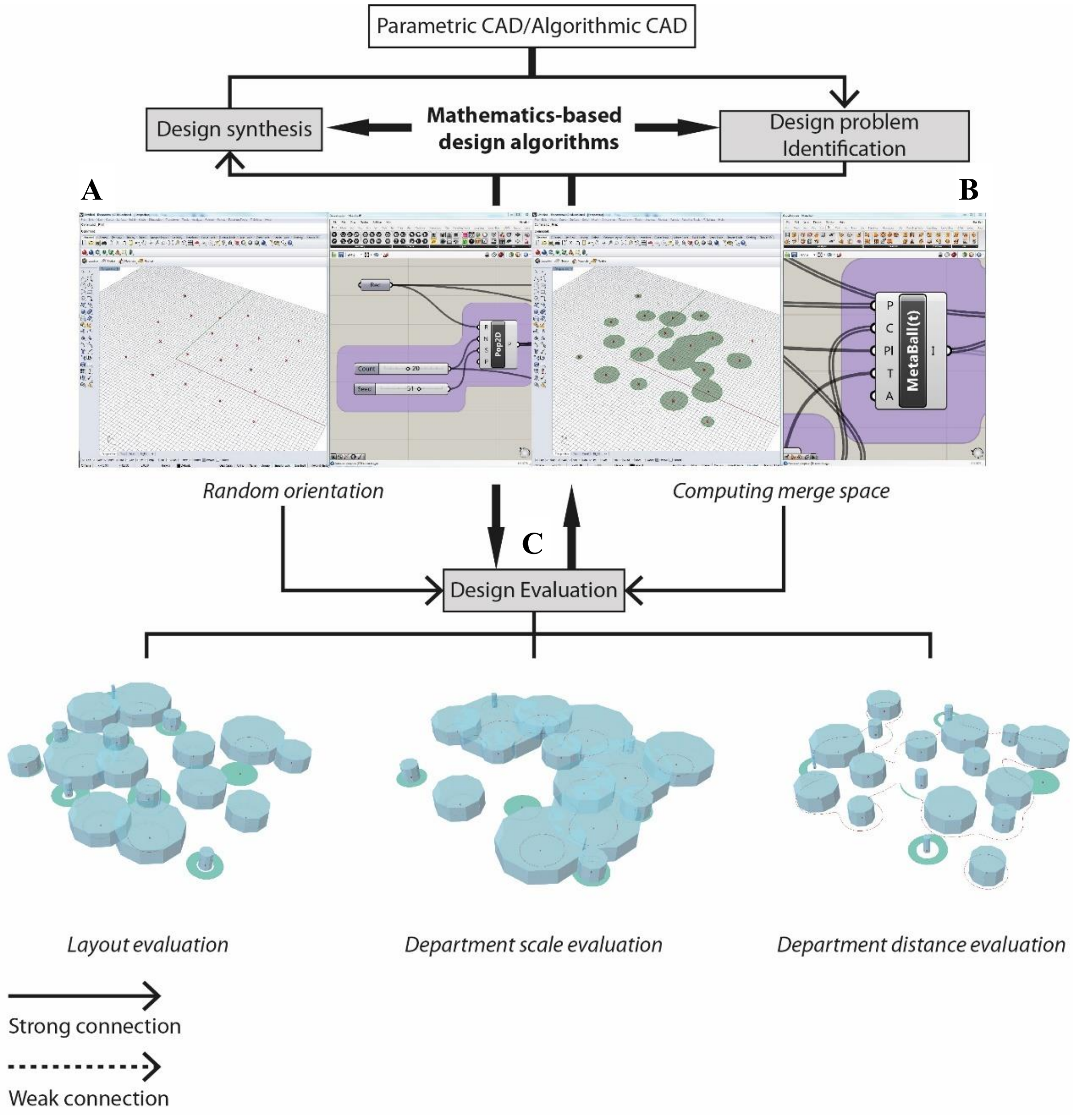
**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Source: Author reproduced/ SPSS outputs

The second relation observed how the design synthesis and evaluation were associated with the identification of design problems, r=0.59, p<0.001 with 35% variance and r=0.69, p<0.00 with 49% variance, respectively. According to the Cambridge dictionary, identification means ‘the act of recognizing and naming something’; so, we can state that algorithmic design functions helped architects to recognise design problems through the application of mathematical knowledge and logic. For example, during the protocol observations, architect 25 (Fig.9.8) attempted to explore the idea of an efficient circulation design floor plan through the testing of various computing layout systems. He applied two algorithmic functions; the first was based on ‘random points’ (Fig.9.8-A), which was intended to produce an automatically-computed, point based, spatial orientation without resorting to the aid of any manually-produced design layout; the second used another function called Metaball (Fig.9.8-B), which could integrate the closest distance factor into a new organic and computed shape. Conducting these two functional algorithms, the architect became involved in a mathematically-based spatial synthesis and evaluation (Fig.9.8-C). Because these design algorithms had inserted parameters necessary for processing and operating the mathematical functions in creating design outputs, this meant the architect had to consider the relationship between the parameters selected and the algorithms produced (See the literature review of taxonomy of parameters in Section 4.3.4.b, Chapter 4). This series of algorithmic processes helped the architect to think mathematically in identifying problems in the design. For instance, non-manually-produced layouts utilised a mathematics-based design function of ‘computed randomness’ because humans cannot efficiently produce random numbers (Figurska, Stańczyk and Kulesza, 2008). In another example, ‘efficient circulation’ was mathematically calculated by a ‘shorten distance’ function applied to distances between clinic rooms.

Fig.9.8 Algorithmic CAD and problem formulation process



Source: Author reproduced/ architect 25

Given the above reasons, the design problems of the algorithmic CAD process were rationalised into a series of ‘systematic’ algorithms and parametric processes rather than just being merely a conceptual process. Regarding this process, Jones (1963) suggests a systematic design process will especially focus on the operational design activities of synthesis and evaluation rather than design analysis in order to fully understand design problems as well as to avoid misconceptions leading to inaccurate or inappropriate solutions. However, this ‘systematic’ CAD method of the parametric/algorithmic CAD is not to be confused with the nonparametric/conventional systematic design method such as that used in the 1970-80s and called the systematic design of hospitals. The parameter-based design system using algorithmic CAD presents logical and identified design steps, unlike a traditional/nonparametric hospital design method that only provides design guidelines and has limited design options. In addition, the algorithmic CAD method contains powerful computing evaluation tools for complex modelling process such as Kangaroos of physics simulation and Weaverbird of topological mesh editor, which allows architects to create generative design explorations rather than just being limited to any design guidelines. Terzidis (2003) states, 'Algorithms are understood as abstract and universal mathematical operations that can be applied to almost any kind or any quantity of elements (design problems)'.

When it came to testing how the efficiency of each design stage can be measured from the findings, the scatter diagram and the regression equation (Appendix 9.3-A) predict certain design interactions based on a timed performance. For example, when the architect spent 10 minutes *(600 Sec.)* on algorithmic design synthesis, it predicted the time used in the evaluation process to be about 04 minutes 12 seconds *(252=1.38*0.001+0.42*600)*. Also, when the algorithmic architects spent 10 minutes on both design synthesis and evaluation, the results show less time was spent on problem identification, 05 minutes 54 seconds *(354=6.84*0.01+0.59*600)* and 08 minutes 13 seconds *(493=19.35+0.79*600)*, respectively. This means the process of algorithmic design synthesis and evaluation was useful in establishing the connection between the testing of design ideas and also assisted architects to structure design problems, so they could easily target the generation of the solution. In addition, the linear regression study (Appendix 9.4-A) provided a further mechanism for the prediction of future design performance. It predicts that if the architect spent 50 minutes *(3000 Sec.)* with an algorithmic CAD process on design synthesis, he/she would also engage in design evaluation for 44 minutes 10 seconds *(2650=0.422*3000+1384.025)*. This closed design interaction between design synthesis and design evaluation has been found as a typical design activity happening in the systematic design procedure (See the literature review of systematic design methodology in Section 3.4.1, Chapter 3).

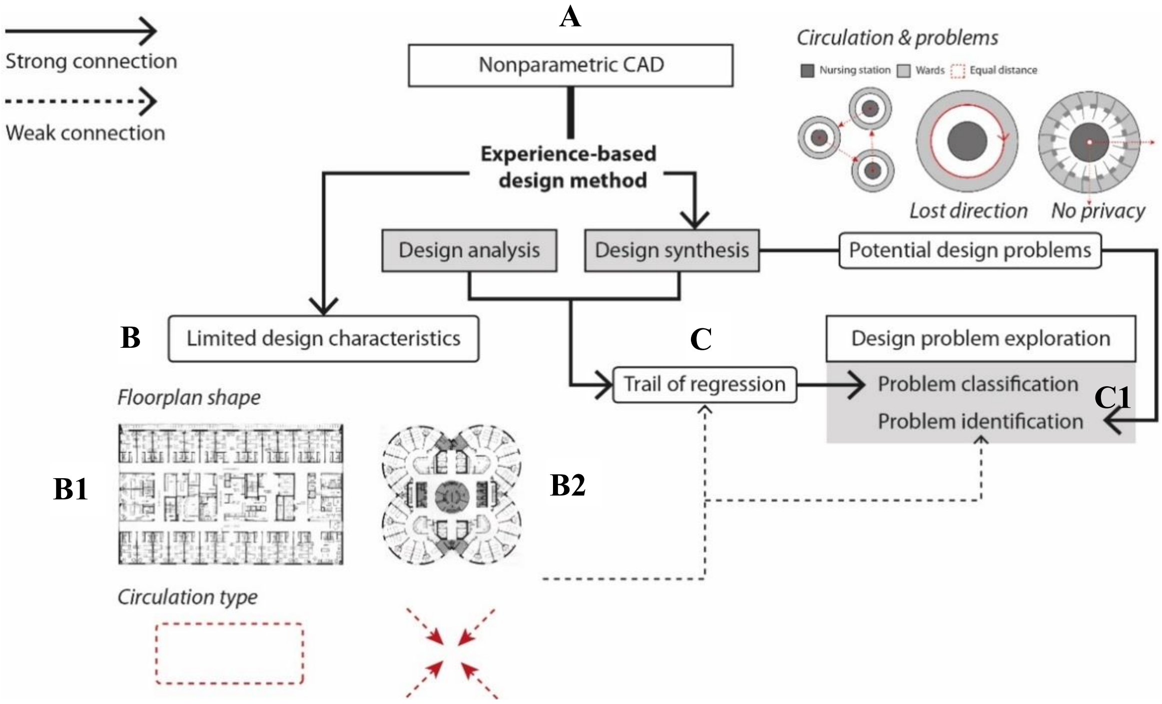
In terms of problem formulation, if the architect spent a greater length of time on design synthesis and evaluation, this activity, in turn, supported the problem identification process. More specifically, when the time spent on algorithmic design evaluation was 50 minutes, the time spent on problem identification was significantly reduced to only 39 minutes 40 seconds *(2380=0.787*3000+19.355)*. This provides further evidence that in algorithmic design, the evaluation process has a positive effect on organising complex design problems. Moreover, the completed problem identification along with the relevant design evaluation guarantees the quality of the problem-solving process. Especially for a design project like hospital building, the Nuffield Trust (2001) suggests a rigorous and reliable design evaluation should be applied to the quality of future hospital design (See the future healthcare architecture design and expectations in Section 1.6, Chapter 1). Algorithmic evaluation and optimisation tools, such as Smart Space Analyser (SSA) in the spatial performance evaluation, Kangaroo in the Live physical simulation or Ladybug in the lighting simulation, should provide a trustworthy scientific evaluation process and evidence-based response to any critical hospital design problems regarding evaluation.

9.3.2 The nonparametric CAD process and problem formulation

On the other hand, the correlation test (Table 9.4-B) pointed out that the main nonparametric design relationship was between design analysis and synthesis and the problem formulation process. Design analysis showed a strong correlation with the synthesis process $r=0.42$, $P<0.02$, with an 18% variance and a medium-sized effect relationship. That is a problem of the traditional CAD method could not coordinate design information as in a mathematically-based system like the parametric design. The designers needed to intensively process design analysis, which helped them discover design problems and then construct the contents. For instance, in the protocol observation of the AutoCAD design process, all architects spent the majority of their time on distinguishing the space information of the hospital's departmental functions and sizes to define the spatial relationship and avoid a wrong circulation arrangement. Very often, previous design experience or old concepts become an important resource to support their decision-making for this analysis stage. However, this experience-based design analysis and synthesis only provided a rough picture of design direction (Fig.9.9-A). In addition, it did not show any evidence to support the reasoning behind the decision-making. The problem that can be recognised is that without producing a strategy to connect these design activities, there was less possibility that the design intuition can be correctly followed. As a result, the nonparametric design activities were an imitation of previous design thinking, producing limited new design ideas (Fig.9.9-B). If the architect introduced their design idea with a certain shape, they could lose objectivity and synthesis by only focusing on the representation of old ideas, for example, making a design proposal using a rectangular floor plan design (Fig.9.9-B1) connected to a ring-road like circulation, which was proposed by the Hill-Burton or Racetrack plan, USA (1941-1946). Another common design type of presenting a radiator style plan (Fig.9.9-B2) means a centralised service design was firstly proposed in 1975 for the Prentiss Hospital for Women and Psychiatric Institute, USA. (See the literature review of international style hospitals in Section 2.4.2, Chapter 2).

In terms of problem formulation and design activity, the design analysis registered a strong correlation between the classification of the design problem ($r=0.62$, $P<0.00$, 38% variance) and problem identification ($r=0.47$, $P<0.01$, 23% variance), as both showed a strong effective relationship. This means that design analysis had certainly influenced the problem formulation process in the nonparametric CAD method. In the protocol analysis investigation, it was found that the AutoCAD architects prefer to classify the design situation before finding the certain solution. The process is like cutting design ideas into different parts and considering them step-by-step. This method is called ‘trail of regression’ (Fig.9.9-C) and is used to discover design problems (Fig.9.9-C1) (Eberhard, 1970). This procedure applies a single logical solution with analysis coming before synthesis and data collection preceding analysis. But using this design approach makes it very difficult to fully examine what information could be relevant to design problems until the solution is attempted (Jones, 1992). This means it may not be possible to effectively manage the design problem formulation process, leading to a more complicated design situation.

Fig.9.9 Nonparametric CAD and problem formulation process



Source: Author reproduced/ architect 25

Returning to the scatter diagram (Appendix 9.3-B), the equation/model shows that when an architect spent 10 minutes on design analysis, he/she was predicted to have spent only 06 minutes 12 seconds on classifying problems *(372=7.91*0.01+0.62*600)*. This evidence clearly means that when AutoCAD architects spent a greater length of time on design investigation, this might have resulted in less time being used for problem classification. By contrast, the linear regression analysis predicted what would happen if the architect spends a long time on specific design activities. The table in Appendix 9.4-B shows that if the architect used 50 minutes *(3000 Sec.)* on design analysis, it certainly did not provide a lot of support to problem classification (44min 23sec) *(2663 =0.624*3000+791.197)*. Therefore, we can understand that the problem of the early systematic design method used for hospitals in the 1970s and 80s, which greatly emphasised design analysis and data investigation over other things. But the long design analysis process cannot help in the early problem classification activities. Especially once the project requires a longer time period, the results shown from regression/prediction testing indicate that the design analysis had less support architects in an efficient way to even classify design problems.

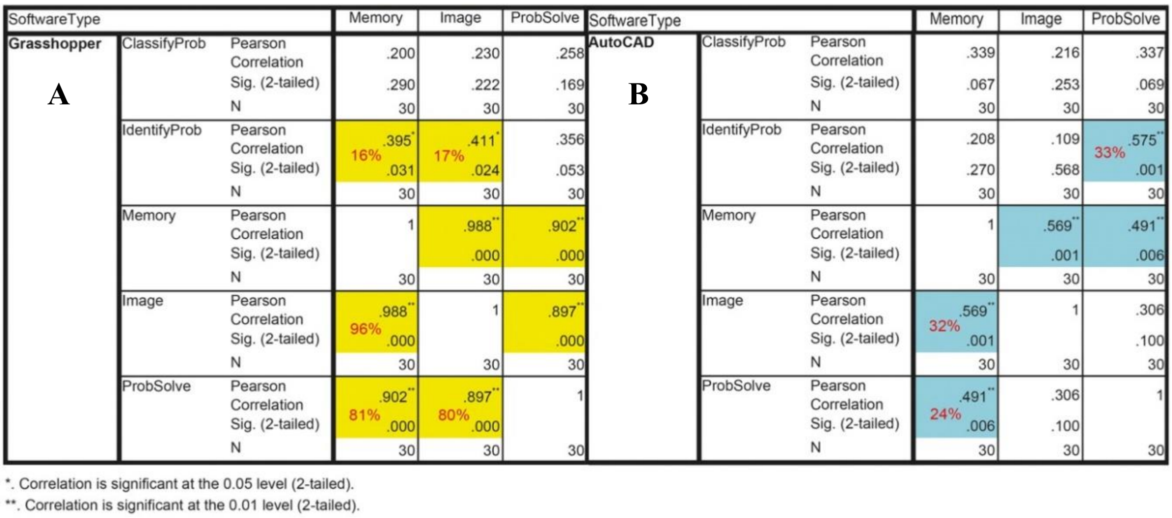
9.4 Correlation study of different CAD cognition for hospital design

This section discusses the relationship between design cognition and problem formulation. The study of the cognitive process with related design problem formulation could assist us to understand the design impacts of both parametric and nonparametric design methods on the development of design cognition.

9.4.1 The parametric CAD cognition and problem formulation processes

As to the parametric design process, the results (Table 9.5-A) show two aspects of the correlation between design cognition and problem formulation. First, cognitive memory had a significant correlation with both cognitive image (r=0.98, p<0.00) and cognitive problem-solving (r=0.90, p<0.00). Also, the coefficient calculation showed around an 80% variance between these three cognitive interactions. Furthermore, identifying design problems had a strong relationship with cognitive memory (r=0.4, p<0.03) and imagery (r=0.4, p<0.02) and displayed 16% and 17% variance, respectively.

Table9.5 Correlations of the CAD cognition and problem formulation



SoftwareType			Memory	Image	ProbSolve
Grasshopper A	ClassifyProb	Pearson Correlation	.200	.230	.258
		Sig. (2-tailed)	.290	.222	.169
		N	30	30	30
	IdentifyProb	Pearson Correlation	.395* 16%	.411* 17%	.356
		Sig. (2-tailed)	.031	.024	.053
		N	30	30	30
	Memory	Pearson Correlation	1	.988**	.902**
		Sig. (2-tailed)		.000	.000
		N	30	30	30
	Image	Pearson Correlation	.988** 96%	1	.897**
		Sig. (2-tailed)	.000		.000
		N	30	30	30
	ProbSolve	Pearson Correlation	.902** 81%	.897** 80%	1
		Sig. (2-tailed)	.000	.000	
		N	30	30	30

SoftwareType			Memory	Image	ProbSolve
AutoCAD B	ClassifyProb	Pearson Correlation	.339	.216	.337
		Sig. (2-tailed)	.067	.253	.069
		N	30	30	30
	IdentifyProb	Pearson Correlation	.208	.109	.575** 33%
		Sig. (2-tailed)	.270	.568	.001
		N	30	30	30
	Memory	Pearson Correlation	1	.569**	.491**
		Sig. (2-tailed)		.001	.006
		N	30	30	30
	Image	Pearson Correlation	.569** 32%	1	.306
		Sig. (2-tailed)	.001		.100
		N	30	30	30
	ProbSolve	Pearson Correlation	.491** 24%	.306	1
		Sig. (2-tailed)	.006	.100	
		N	30	30	30

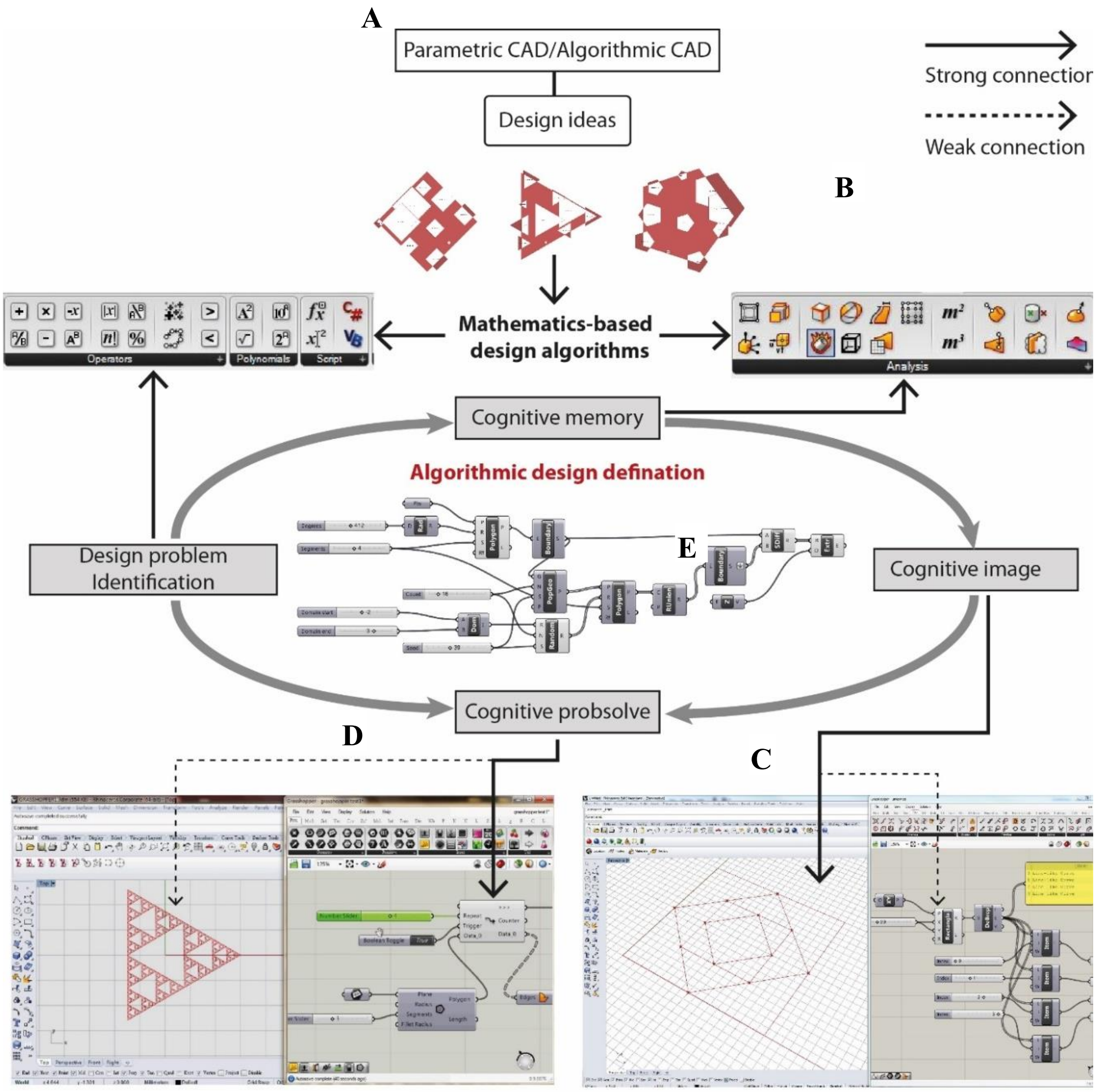
*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Source: Author reproduced/ SPSS outputs

In the protocol design task, architect 28 proposed an idea of modular design layout and showed the design cognition activity with (Fig.9.10-A) an algorithmic process. He went through the function menu (Fig.9.10-B) presenting a searching of cognitive design memories for curve construction and then he tested different curve shapes and evaluated the modular unit. Afterwards, he worked on different mathematical calculations in order to ensure the algorithm can present different proportions of the sub-divided geometries (Fig.9.10-C). In the final stage, he employed a computing loop system to automatically and constantly sub-divide (Fig.9.10-D) the input geometry with different sizes and numbers for the modular design template. We can see that the algorithmic design architect made sure that every design action went through a full design cognition process: finding algorithm as cognitive memory, generating geometries as cognitive imagery, and testing modular pattern as the cognitive problem-solving. The entire design process was actually constructed from a series of algorithmic inputs and created definitions (Fig.9.10-E) until the design moved forward to the completion stage. We kept finding these design activities worked as a design strategy, illustrating how this busy mental activity was controlled by the digital process. In addition, because the cognitive process was based on mathematical definitions such as length, width or proportion, it helped architects to easily identify the design problem as well as progress and move forward to evaluate their cognitive problem-solving process.

Fig.9.10 Algorithmic CAD cognition and problem formulation process



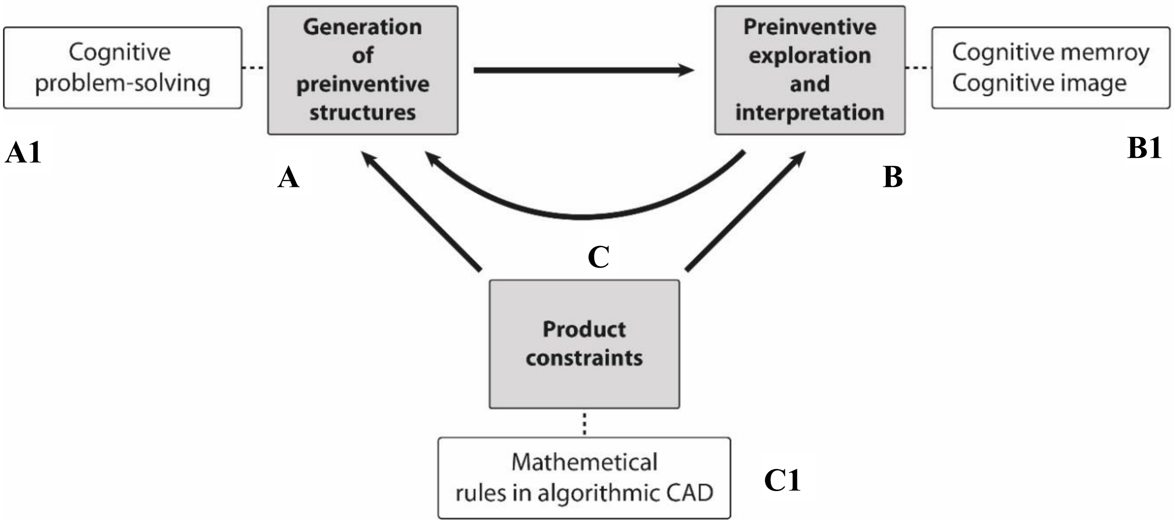
Source: Author reproduced/ architect 28

Apart from the observation of statistical significance in the design interaction, the scatter diagram (Appendix 9.5-A) calculated the time-based design relationships between design cognition and problem formulation. If the architect was to spend 10 minutes (*600 Sec.)* on the cognitive memory and imagery stages the scatter illustrates that he would spend less than half the amount of time on the design problem identification process.

Moreover, if he continually worked with algorithmic design, the study also applied a linear regression test (Appendix 9.6-A) to predict how significantly algorithmic design cognition will support helps in problem recognition. The calculation estimated that if 50 minutes *(3000 Sec.)* was spent on improving cognitive memory *(2001=0.481*3000+558.391)* and cognitive imagery *(2026=0.507*3000+505.174)*, the problem identification process could be reduced down to about 33 minutes.

The above result confirms that design cognition based on an algorithmic process optimises the mental processes and produces a theme of systematic thought rather than an unplanned design strategy. This design procedure is similar to a method of a mental process called 'Geneplore model' (Finke, 1992) (Fig.9.11) – a creative functioning proposing that an organised cognitive process could help the creativity of design. The model contains two stages with one further evaluation stage: a generation process (Fig.9.11-A), an exploratory process (Fig.9.11-B), and the use of product constraints (Fig.9.11-C). The generation process represents a process of retrieving design functions, namely, the analyses and selection of the design functions (memory and image) (Fig.9.11-A1). The exploratory process means integrating and discovering the next mental process (problem-solving) (Fig.9.11-B1). Finally, in order to manage these two mental processes (generation and exploratory), there cannot be unlimited development. Like mathematical rules of the design algorithm, product constraints provide objective relevant constraints on this cognitive process (Fig.9.11-C1).

Fig.9.11 Algorithmic CAD cognition and Geneplore model



Source: Author reproduced/ Finke,1992

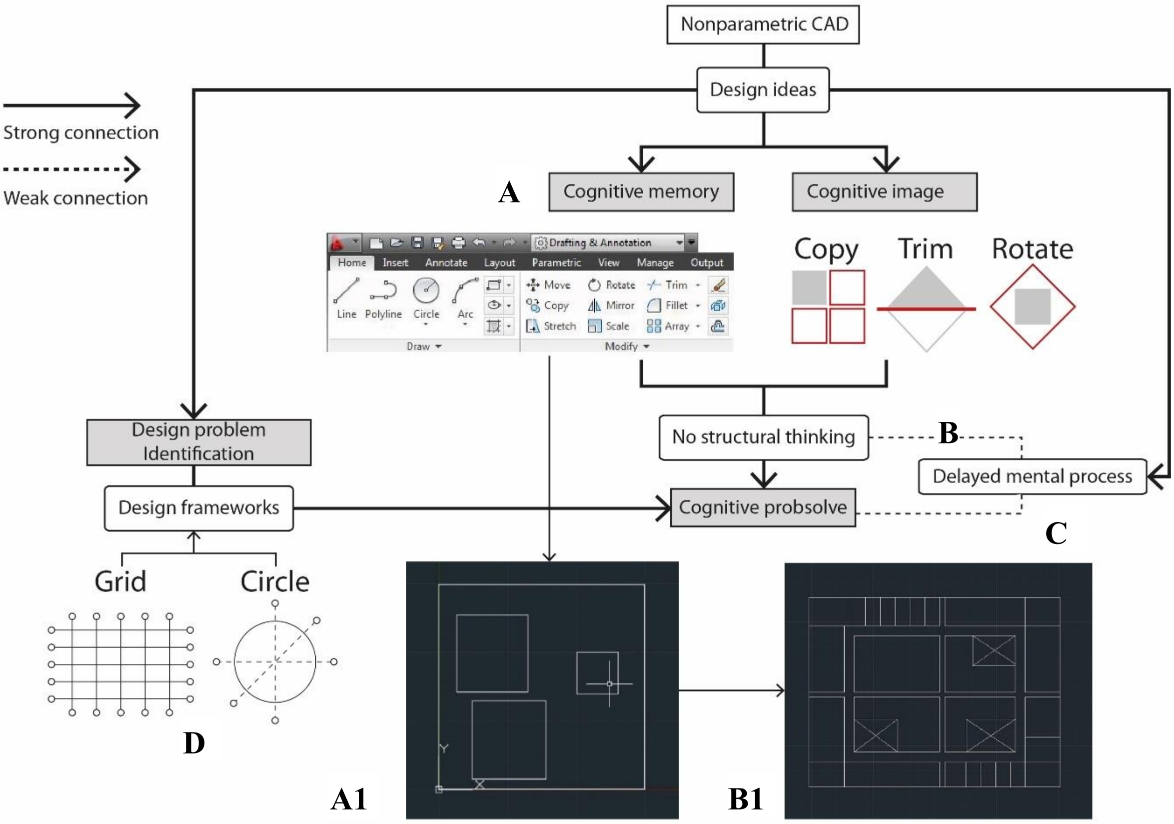
In the part of hospital design, the existing research has tried to examine hospital design through an evidence-supported approach. However, these evidence-based design guidelines are designed for the latter hospital design stages and the evaluation of a building in use rather than the conceptual stage of hospital designs. It could be because as the early design ideation is not based on parametric design processes and mathematically-based ideas, the evaluation cannot be easily applied as an objective test of those idea proposals. Besides that, there is very little design research focused on how to establish this evidence-based design process for the early concept proposal as well as exploring, from a cognitive aspect, how the design structure could be optimised by algorithmic CAD and its related mathematical logic.

9.4.2 The nonparametric CAD cognition and problem formulation process

Regarding the nonparametric design process, the correlation analysis (Table 9.5-B) also revealed two types of relationships between design cognition and problem formulation. First, cognitive memory had a significant correlation with cognitive image ($r=0.56$, $p<0.00$) and problem-solving ($r=0.49$, $p<0.01$). Second, the identification of design problems was shown to have a strong correlation with cognitive problem-solving ($r=0.57$, $p<0.00$). Although both design methods of the parametric and nonparametric CAD showed similar correlation values with design cognition, the 'variance' had a lower value for nonparametric design cognition than for parametric. Cognitive memory, cognitive image and problem-solving were lower by about 32% and 24% when compared with around 80% and 81% for those same aspects in algorithmic design. AutoCAD design cognition indicated a small variance in the interaction between cognitive memory and problem-solving, which implies that the selection of design drawing tools could support the cognitive problem-solving process in the CAD approach.

If we check the case studies, in the cognitive design memory stage, the AutoCAD architects all chose similar design functions such as drawing polylines, circles, trim, copy, paste, etc. These design functions (Fig.9.12-A) only presented a single drawing step which cannot be mentally attempted in the cognitive problem-solving stage. This tells us that the design cognitions structurally could not coordinate design information and could not have mental connections (Fig.9.12-B) between design memory and the problem-solving process. Repeated design actions seem to be a necessary process in AutoCAD design cognition because the designers could be familiar with the tool functions and drawing outputs, although these cycling design activities did not efficiently help the mental process, especially in the discovery of solutions to problems. For example, in his design, architect 25 planned the clinic rooms to be located in a pre-cast squared area (Fig.9.12-A1). Next, he had a series of repeated design actions, such as trimming space, copying space and offsetting lines, in the layout for this squared-based design plan. But later, he found there was not enough space in this pre-set plan; therefore, he had to erase the shape and re-draw a rectangular space big enough to solve this design problem (Fig.9.12-B1). This case points out that this is a problematic design process of the nonparametric/AutoCAD. The design cognition could not immediately respond to cognitive design problem-solving because there was no instead design feedback system to response design inputs and outputs. Therefore, there were delays in the mental process (Fig.9.12-C) followed by a series of functional testing. This problem has also been discovered as the 'uncertain verbal data' during the nonparametric design process (See the research finding of the nonparametric CAD design process in Section 8.2.2, Chapter 8).

Fig.9.12 Nonparametric CAD cognition and problem formulation process



Source: Author reproduced/ architect 25

With the design problem aspect, the correlation between 'identifying a design problem' and 'cognitive problem solving' indicated that the AutoCAD design process had a weak association with the cognitive generation process and directly moved to a particular solution according to pre-defined frameworks of design problems (Fig.9.12-D). In the case studies, many AutoCAD architects allowed old design ideas to dominate their design thinking and, in turn, their proposal. By doing this, these non-parametric processes blocked design cognition, preventing careful exploration in the design thinking, although some architects stated that existing case studies helped them to economically control design problems. For instance, the examples/old ideas functioned like a design precedent, which, in turn, provided the first step in processing their design ideation. For instance, the 1960s hospitals took the idea of the international style (Fig.9.12-1-A) from other public buildings; the 80s and 1990s atrium hospitals (Fig.9.12-1-B) referenced the design of a hotel lobby; and the 60s and 1970s residential hospital design (Fig.9.12-1-C) was affected by the design of residential buildings (See the literature review of new Residentialism and regionalism hospital in Section 2.4.3.b-3, Chapter 2). Ward and Sifonis (1997) found human brains usually applied existing knowledge, such as the type of features in familiar categories, to structure imaginative innovations for new categories they are not familiar with. This means the nonparametric CAD architects frequently followed their design intuition or copied concepts but did not go through their design cognition supported by the CAD method. Moreover, Guilford (1950) argues that a repetition of ideas or design actions leads to only a slim possibility of creative design ideations.

As to testing how cognitive memory in the nonparametric process could influence the performance of problem-solving processes, the following results were found. Through time relationships, the scatter diagram (Appendix 9.5-B) technique indicated that cognitive memory and the cognitive problem-solving process did not directly influence each other; 10 minutes *(600 Sec.)* was spent on cognitive memory processes but the problem-solving process needed an even longer time spent on it, about 12 minutes 54 seconds *(774 =-1.56*0.001+1.29*600).* Interestingly, the linear regression analysis (Appendix 9.6-B) predicted that once the time involved in the cognitive image process increased, for example to 50 minutes *(3000 Sec.)*, the problem-solving process could be reduced to around 38 minutes 26 seconds *(2305 =1.289*3000-1561.483).*

A possible interpretation could be that because the hospital design process is complex, there are so many program functions and spatial correlations that need to be considered at the very start. If cognitive memory is not supported by a structured system or by applying a trained long-term memory in the design process, novice architects would find it hard to manage their design cognition and, in particular, deal efficiently with complex sets of design data and easily progress through the problem-solving stage. As the regression testing suggested, it was important that AutoCAD architects be involved with this design method for a sufficient length of time to be able to understand hospital design. In particular, they should be familiar with the use of design functions such as drawing tools or X-reference to make a design plan, or they might not able to progress their design effectively.

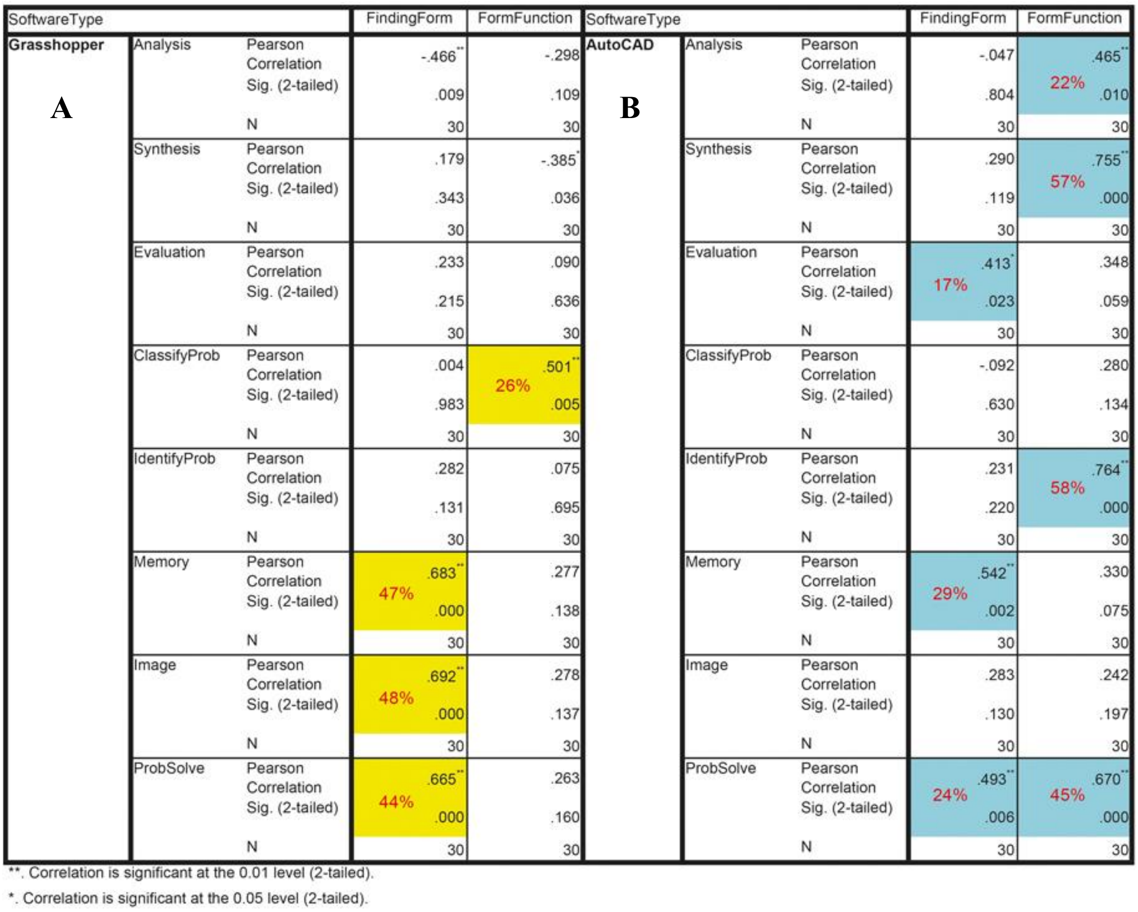
9.5 Correlation study of different CAD form exploration process for hospital design

Form exploration has always played an important part in building design as an architectural design principle. Architectural slogans such as Sullivan's (1930) 'form follows function' must have affected the design of buildings, including hospital building design, where different building shapes can significantly influence building circulations as well as treatment deliveries (Prasas, 2008). So, contemporary hospital design usually mixes one or more building types in order to accommodate the complicate functional requirements and their integration with services. Therefore, this section primarily investigates the interaction between form exploration process and other design behaviours, for example, design process, problem formulation, and design cognition in order to ascertain differences between parametric and nonparametric design methods.

9.5.1 The parametric form exploration process

In the parametric design process, (Table 9.6-A) the correlation analysis showed that the 'form-finding' process had a significant connection to three cognitive aspects; cognitive memory ($r=0.7$, $p<0.00$), cognitive image ($r=0.7$, $p<0.00$), and cognitive problem-solving ($r=0.7$, $p<0.00$) with an average variance found to be about 45%. These results suggest the parametric design process using the algorithmic method mainly focuses on form-finding activity with the aid of intensive reasoning from various design cognition processes.

Table9.6 Correlations of the CAD process and form exploration



A

SoftwareType			FindingForm	FormFunction
Grasshopper	Analysis	Pearson Correlation	-.466**	-.298
		Sig. (2-tailed)	.009	.109
		N	30	30
	Synthesis	Pearson Correlation	.179	-.385*
		Sig. (2-tailed)	.343	.036
		N	30	30
	Evaluation	Pearson Correlation	.233	.090
		Sig. (2-tailed)	.215	.636
		N	30	30
	ClassifyProb	Pearson Correlation	.004	26% .501**
		Sig. (2-tailed)	.983	.005
		N	30	30
	IdentifyProb	Pearson Correlation	.282	.075
		Sig. (2-tailed)	.131	.695
		N	30	30
	Memory	Pearson Correlation	47% .683**	.277
		Sig. (2-tailed)	.000	.138
		N	30	30
	Image	Pearson Correlation	48% .692**	.278
		Sig. (2-tailed)	.000	.137
		N	30	30
	ProbSolve	Pearson Correlation	44% .665**	.263
		Sig. (2-tailed)	.000	.160
		N	30	30

B

SoftwareType			FindingForm	FormFunction
AutoCAD	Analysis	Pearson Correlation	-.047	22% .465**
		Sig. (2-tailed)	.804	.010
		N	30	30
	Synthesis	Pearson Correlation	.290	57% .755**
		Sig. (2-tailed)	.119	.000
		N	30	30
	Evaluation	Pearson Correlation	17% .413*	.348
		Sig. (2-tailed)	.023	.059
		N	30	30
	ClassifyProb	Pearson Correlation	-.092	.280
		Sig. (2-tailed)	.630	.134
		N	30	30
	IdentifyProb	Pearson Correlation	.231	58% .764**
		Sig. (2-tailed)	.220	.000
		N	30	30
	Memory	Pearson Correlation	29% .542**	.330
		Sig. (2-tailed)	.002	.075
		N	30	30
	Image	Pearson Correlation	.283	.242
		Sig. (2-tailed)	.130	.197
		N	30	30
	ProbSolve	Pearson Correlation	24% .493**	45% .670**
		Sig. (2-tailed)	.006	.000
		N	30	30

**. Correlation is significant at the 0.01 level (2-tailed).

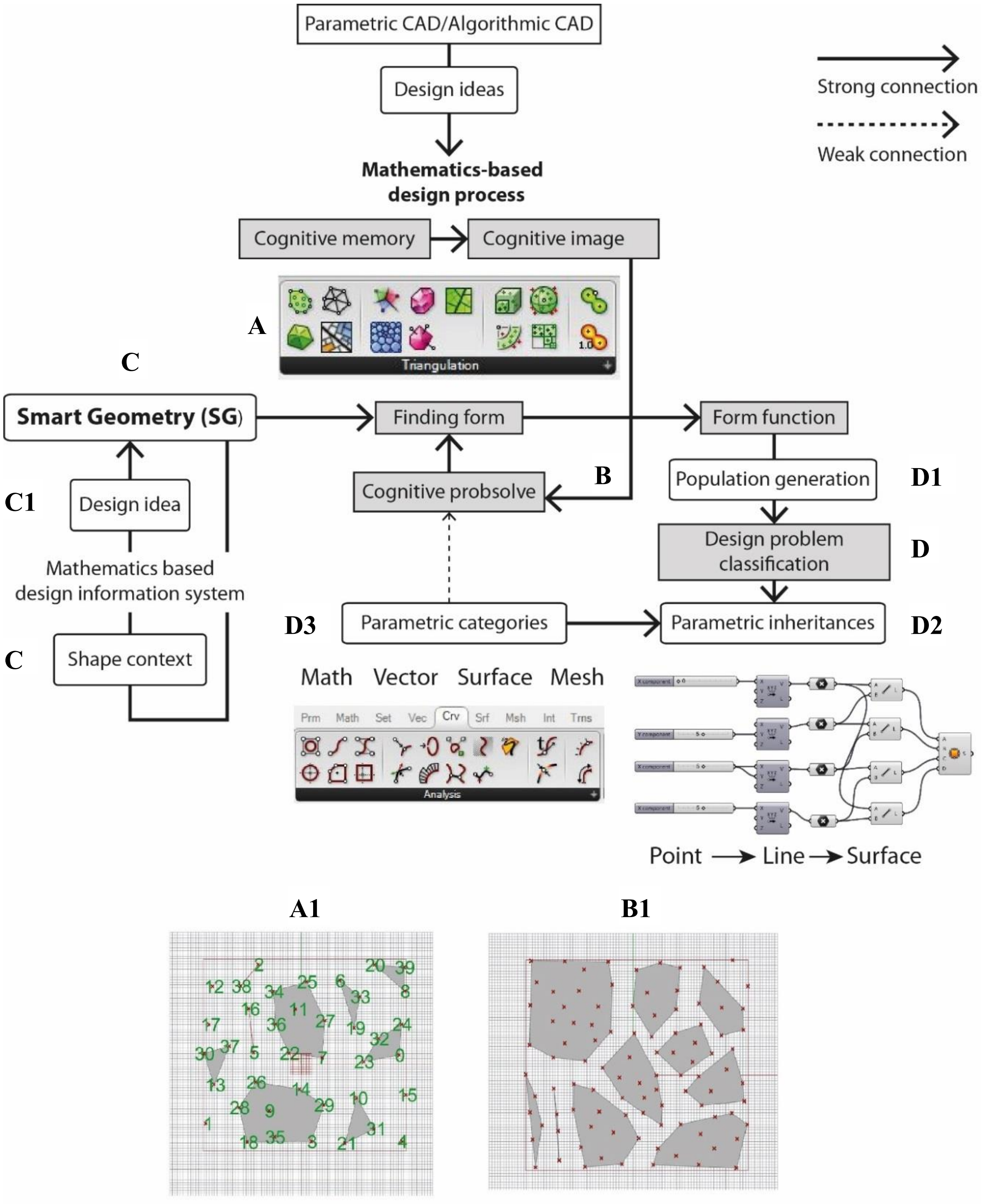
*. Correlation is significant at the 0.05 level (2-tailed).

Source: Author reproduced/ SPSS outputs

In the protocol studies, the majority of the architects favoured exploring design ideas and relevant geometrical construction within an algorithmic system rather than roughly giving a function to the space. From choosing design tools from the algorithmic design manual (Fig.9.13-A) the architect were following the mathematically designed rules and then generating varied design forms. This was a careful step by step process, systematically and logically constructed by their cognitive problem-solving process (Fig.9.13-B). For example, architect 22 proposed a computed layout design based on random numbers and convex hull algorithms (Fig.9.13-A1). The convex hull lets architects calculate the smallest spatial boundary for the most economical use of the outpatient department. Through increasing the random points, if there is more space required, the convex hull can automatically search for department shapes and sets them to a pre-set or minimised scale (Fig.9.13-B1). Moreover, because computing randomness can produce unlimited compositions, this means the convex hull, the department unit, can be formed in countless design genres. In this design process, every design geometry must contain a range of design information called the ‘algorithmic definition’. This process is generally described as a ‘smart geometry (SG)’ design (Fig.9.13-C), which means an information-based design geometry. It focuses on design intent in the process of the form construction and builds a geometrical relation between the design idea (Fig.9.13-C1) and the shape context (Fig.9.13-C2). Jabi (2013) highlights that parametric CAD using algorithmic thinking can produce varied and iterative design outputs; it is a powerful method for minimising the time spent on achieving that optimisation. Jabi also states, ‘the process of the parametric CAD is like the field of calculus, continuous differentiation alludes to a feature of versioned, iterative and mass-customized parametric work that allows for differences to occur within a continuous field or rhythm’. In other words, this generative form-finding process helps architects to distinguish the minor differences between design geometries, which have great potential for creating innovative views of the design of new hospital buildings.

Moreover, the statistical correlation showed a significant relationship between problem classification and the form-function process, r=0.5, p<0.00 with a large effect size (Fig.9.13-D). This is interesting in that it means the algorithmic design architects tend to ‘classify’ design form and function with the relevant problem but do not ‘identify’ a particular form and function with an individual problem. This is because the algorithmic design process is based on a ‘population generation’ (Fig.9.13-D1); one design algorithm normally can have a range of design outputs (See the literature review of the population classification in Section 4.3.4.g, Chapter 4). Parametric thinking can associate the design object and its function with a series of conceptual families and inheritances (Fig.9.13-D2). For example, a parametric designed building using BIM design contains a wall family, a window family, a door family, a structure family, etc. In algorithmic CAD, the design function can also be divided into several categories like parameter, math, vector, mesh, etc. (Fig.9.13-D3). Therefore, architects can easily classify design problems with associated functional algorithms, which give multiple choices of design possibility during the form exploration process. In addition, Mayr (1963) argued that population thinking increases the morphogenetic process; this natural view of design ideation evolved from biological processes and gave a flexible structure to the optimisation of conceptual evolution. In other words, it has a significant potential for design creativity.

Fig.9.13 Algorithmic CAD and form exploration process



Source: Author reproduced/ architect 22

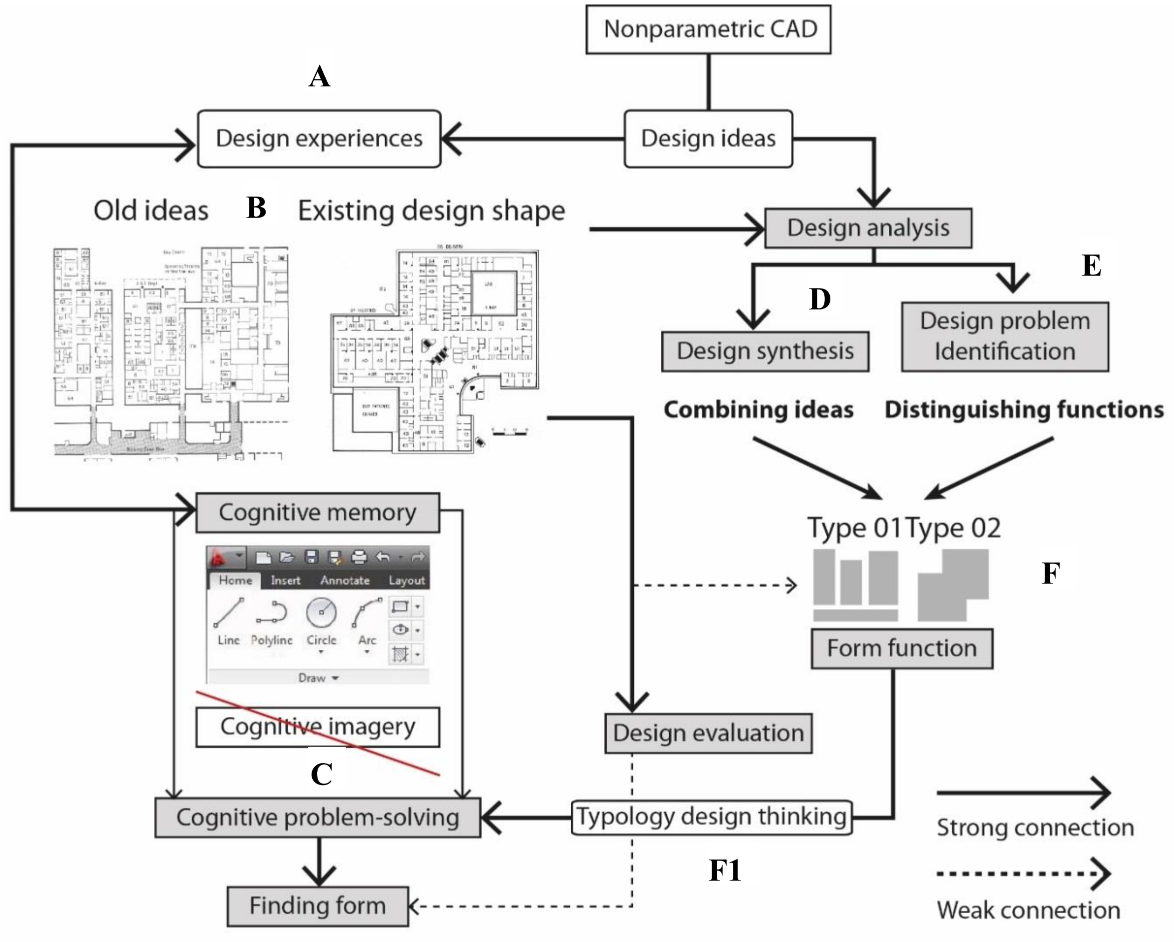
On time-based analysis of correlation, the scatter diagram (Appendix 9.7-A) shows that when problem classification took 10 minutes *(600 Sec.)* in the design process, the time consequently spent on the arrangement of the building functions was reduced to only 03 minutes 12 seconds *(192 =4.97*0.01+0.32*600)*. The linear regression test (Appendix 9.8) also predicted that if the classification problem took over 50 minutes *(3000 Sec.)*, it would optimise the functional design in the form exploration process, completing this in only 36 minutes 12 seconds *(2172 =0.003*3000+2162.582)*. As a result, we can confirm that the algorithmic design method has found a way to improve functional arrangements by involving a mathematically-based form or a shape-based design process. Also, it is believed that the concept of classifying design problems, rather than quickly identifying the design problem, is evolutionary in nature where this population thinking could make the design more flexible and could possibly stimulate architects to generate new design ideas. As Terzidis (2003) argues, ‘algorithmic form is not about perception or interpretation but rather about the process of exploration, codification, and extension of the human mind’.

9.5.2 The nonparametric form exploration process

In contrast, nonparametric design using the AutoCAD method demonstrates a two-part relationship between form exploration and other design activities (Table 9.6-B). In the first part, finding form had a significant connection to design evaluation (r=0.41, p<0.02) as well as cognitive memory (r=0.54, p<0.00) and the problem-solving process (r=0.49, p<0.00). The r value suggests that the relationships had a medium effect size with 17% to 30% variance. These results show that the nonparametric CAD form-finding process depended on the design evaluation activity (Fig.9.14-A), but the protocol analysis exhibited that the majority of the nonparametric CAD architects judged their design ideas via ‘past design experiences’. Again, this means the form-finding activity frequently relied on old ideas and shapes (Fig.9.14-B). Besides that, the cognitive imagery process did not display a correlation with the nonparametric form-finding activity, indicating that the nonparametric design form or shape was not arrived at through an organised design cognition (Fig.9.14-C). In other words, the architects did not explore structured thinking in their design cognition process and had skipped the stage of cognitive imagery when developing their design solutions/ideas.

In the second part, the form-function association was discovered to have a significant relationship with design analysis (r=0.46, p<0.01), synthesis (r=0.75, p<0.00), problem identification (r=0.76, p<0.00), and cognitive problem solving (r=0.67, p<0.00). In particular, design synthesis (57%) and identifying problems (58%) showed a large variance, which means a close relationship with regard to the form-function process. Design synthesis (Fig.9.14-D) means ‘combining’ different design issues or problems into ‘a whole’ and identifying problems (Fig.9.14-E) means ‘establishing’ or ‘distinguishing’ the design problem. When it came to the connection with the form-function process, this meant the nonparametric architects tended to apply a particular shape or form (Fig.9.14-F) to combine or distinguish the design problems or functions. This implies typological design thought (Fig.9.14-F1) that gives functional definitions for the existing form and uses these in the design process (See the literature review of typology design in Section 4.3.2.c, Chapter 4). According to Quincy’s theory of architectural typology (Lavin, 1992), the form (geometry) is classified and represented by the relevant functions in the design aid.

Fig.9.14 Nonparametric CAD and form exploration process

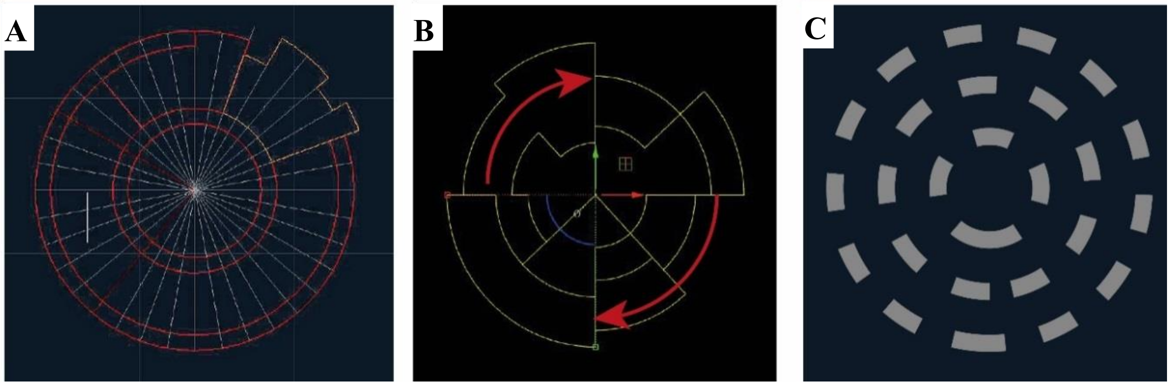


Source: Author reproduced

For example, architect 24 proposed a big circle as a design form; he defined the criteria for this geometrically physical function, such as equal distances to the centre of the circle, to fit all design functions into this pre-set shape. Therefore, the function-form process determined that the circle is chosen as the only shape to dominate all design issues including circulation (Fig.9.14-1-A), layout system (Fig.9.14-1-B) and structure plan

(Fig.9.14-1-C). This typological design thinking has been found in many AutoCAD architects' proposals. However, the pre-set shape did not consider a geometrical construction process but rather took the outcome of the geometrical shapes provided by the CAD tools. These functional considerations, followed by the specific typology of forms, were all based on the architect's geometrical knowledge and their understanding of the design background. The experience-based design learning is like an apprenticeship and it is difficult to share an idea or join a discussion with others (Jones,1970). The risk in typology thinking is that the form only represents a geometrical profile without strong design reasoning behind it, which means a very subjective design process. The main criticism of design typology is that it is considered to turn the type into a stereotype (Gϋney, 2007).

Fig.9.14-1 Nonparametric CAD functions were decided by the form



Source: Architect 24

Furthermore, the time-based correlation presented some interesting results on form formulation and its associated design behaviour. The scatter diagram (Appendix 9.7-B) confirms that the architects spent 20 minutes (*1200 Sec.)* on the form-finding process but only 22 seconds on the design evaluation process *(22 =-86.1+0.09*1200)*. This means that the nonparametric CAD form-finding process did not have enough time spent on design evaluation. In other words, the form-finding process could be roughly decided by architects' design experience or existing cases of precedence. On the other hand, with respect to nonparametric CAD form-function, activity and design analysis helped in the production of a functional design with 10 minutes (*600 Sec.)* spent on the analysis and only 06 minutes 12 seconds used for the functional designs *(372 =4.24*0.001+0.62*600).*

The above discussion reveals that some negative points may arise from using a conventional nonparametric CAD process in hospital design. Due to the fact that conventional CAD does not provide design tools or functions to guide geometric construction, this means it will leave the architect lacking information on how to evaluate their form-finding results. In turn, this causes them to only concentrate on the building functions or other facility designs to make up the shape. This is because the function-form process only needs to be concerned with fitting a particular shape whereas cognitive problem solving is more abstract as it deals with establishing an overall structure for receiving, editing and manipulating design information, which is a combination of 2D and 3D information. That is to say, without fully understanding the process of generating design shape or form, users of nonparametric CAD might not be able to manage the relationship between function and proposed geometries, and that is why many design problems arise leading to the wrong choice of shape design to match the necessary functions of a hospital building, which is caused by a weak consideration of the shape/form selection in the earlier design stage. For example, the 1970s centralised hospital design style created many problems due to a lack of understanding of the proposed building shapes, for example, the design of huge building blocks usually lacked natural light, leading to one easily losing their direction inside hospitals (See the literature review of international style hospitals in Section 2.4.2, Chapter 2).

9.6 Discussion

Hospital design is complex; the difficulty of the project is not only in creating space for medical services but also in providing an evidence-based design process (Phiri, 2015). The design process can be associated with many different issues, but the most important issue is how to define these, namely, finding the correlation between the design actions and identifying and discussing how they fit into the design process. This chapter extended the findings in the last chapter on protocol analysis and applied statistical techniques to add more rigour to the investigation in order to find similarities or differences between different CAD applications and their potential impact on the creativity of design.

First, the impact on idea numbers and the related design behaviour showed that parametric design produced impressive idea numbers, which is an important indicator according to Torrance's (1950) creativity identification system (See the literature review of creativity measurement in Section 3.6.2, Chapter 3). These ideas, in fact, improved the design process particularly in the making of different design decisions in both CAD processes. For instance, the variety of ideas in parametric design upgraded the level and intensity of cognitive thought. The node-based diagrammatic design process and the visualisation of design steps and problems, which are both attributes of parametric design, seem to have helped architects to find more options for design problem-solving. Furthermore, the statistical results based on protocol studies introduced an original mathematical equation that can calculate and predict idea generation. The calculation predicted that the longer the experience with using algorithmic CAD, the better architects were able to produce more design ideas. This shows the same result as the questionnaire survey (See the research findings of idea numbers and user experiences in Section 6.3.1.b, Chapter 6). On the other hand, the study registered a close relationship between form-finding and idea numbers, which indicates that nonparametric design operated with ‘a central idea’ design method – the primary generator (Darke, 1978). This meant the architect pre-defined the structure for problem-solving based on a single concept in order to master the design challenges (problems) and reduce the time lost on chasing ‘wicked design problems’ (See the literature review of unpredictable design problems and design process in Section 3.6.2, Chapter 3). Although the regression analysis suggested that if architects could apply a valid process for design evaluation, they could get more impressive design idea numbers, nonparametric CAD systems do not provide valid design evaluation systems, especially on the aspect of geometric testing in idea production. The findings also suggested it is important to develop an objective testing process for hospital design ideas in the early stage of the design process. Furthermore, this could not only improve the design creativity, but a lack of systems for design evaluation could limit design options for architects.

Second, the correlation test between the design process and design behaviour demonstrated that parametric/algorithmic CAD was well-organised with a systematic thought process and was focused on decision-making strategies through the activity of design synthesis and evaluation as well as the problem identification. This strategic thinking is akin to a scientist’s thought processes, namely, being problem focused; it obliged architects to understand the design problem structurally and improved recognition of design problems through a process of algorithmic design definitions. By contrast, nonparametric design appeared to show disconnected design thinking when targeting particular design problems and an inability to think about all cognitive factors together. In addition, the time calculations on design performance using scatter diagram and linear regression analysis techniques suggested that nonparametric design analysis took too long and affected the problem formulation process in terms of both problem classification and problem identification. This was because the weaker design structure could not support the design synthesis process, which made the design context more complicated; consequently, architects needed to spend more time on both the making of the design structure and the problem-solving process.

Third, regarding the cognitive process involved, parametric design followed a mathematically-based and systematic cognitive process with an associated cognitive structural model in three parts: generation processes, exploratory processes, and the product constraints (Finke, 1992). However, the nonparametric design cognitive process did not show particularly obvious and structured mental processes but applied a method called 'extending concepts' as the main cognitive process in problem-solving. In addition, the length of time architects had been involved with AutoCAD design was found to positively support the problem formulation process. By contrast, the Grasshopper design (algorithmic CAD) group displayed a steady and improving performance on the cognitive process and problem investigation.

Lastly, form exploration in parametric design exhibited that the form-finding process had involved a generative design process, creating a dialogue between architects' proposed idea and the design shapes or forms. This meant the form-finding process of algorithmic CAD offered design learning activities with geometrical constructions that could potentially inspire alternative design decision-making. This learning activity could be found in LTM (long-term memory of design cognition) and can help the optimisation of the design methods (See the research finding of cognitive memory in Section8.4.1.a, Chapter 8).

Conversely, the nonparametric design process did not exhibit many connections with the form-finding process. However, many design relationships were discovered between the function-form process and other design behaviours such as design synthesis, problem identification and the cognitive problem-solving process. Because nonparametric CAD (AutoCAD) does not possess the option of systematically based geometrical construction, the architects could only rely on a visually-based form selection process which reflected subjective experience and depended less on geometric logic. In addition, the statistical tests found that AutoCAD architects did not concern themselves with design evaluation in their form-finding process and directly introduced some existing design shapes, as in the case of a modular-based design plan. This meant that producing a form was lacking in typological thinking, which could lead to failure in flexible design thinking and create problems during further design modification.

Choosing the wrong building design form, especially in hospital design, could cause significant problems for the medical services. These problems are normally caused by the lack of design functions to evaluate the spatial scales and relevant design issues. For example, in the case of Greenwich General Hospital, because of an oversized building shape, it was reported that the complex circulation design made visitors lose direction and some staff offices did not have sufficient natural lighting (Stone, 1980).

Hospital design is complex because it is multi-disciplinary in nature with many professions involved. Moreover, medicine, technology, and policy are constantly changing and for architects, the challenge of how to manage design complexity and optimise the quality of design are persistent issues faced in this area. So, the study of design relationships within different CAD methodologies may help us understand the impacts and the performance issues when using different CAD tools. Furthermore, it can aid our understanding of the advantages of applying different CAD methods to the design problem-solving process as well as increasing the potential and opportunities for creative design. Additionally, to explore a systematic design process, this research carried out an in-depth investigation into multiple aspects of cognition: design process, problem formulation, design cognition and form exploration. The study results may suggest a way of managing complex design projects like hospital buildings as well as improving one specific design concept, that of design quality, and shorten the time involved in a desi.0gn, i.e. increase design efficiency. A positive change in all these design parameters may lead to the future development of innovative concepts in hospital design.

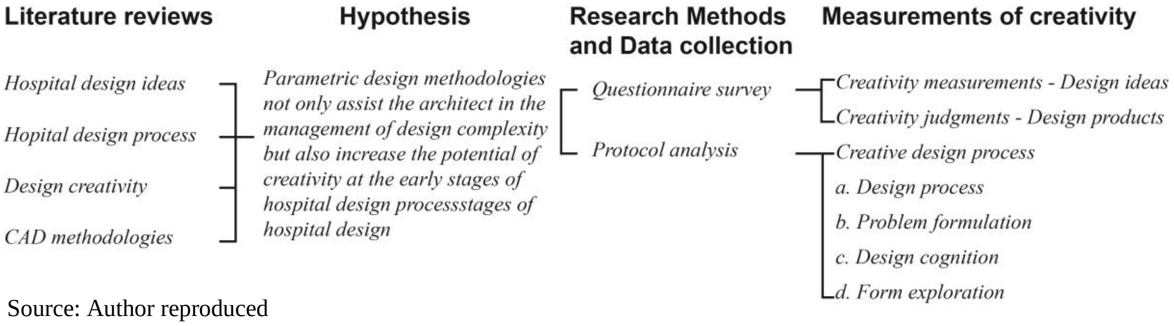
Chapter10 – Conclusion

10.1 Research direction

‘Hospitals are perhaps the most interesting and certainly the most complex of building types’ (Stone, 1980). This complexity might affect their architectural design in different ways such as the spatial scale, functional facility and engineering equipment. However, if architects can evaluate a hospital design idea from the earlier stage, this can provide a clear direction to develop their proposed designs. So, this PhD research has aimed to discuss the hospital design ideation process using two different CAD methods, parametric and nonparametric CAD, and to explore their impact with particular emphasis on the creativity of design.

The hypothesis of this research argues *’Parametric design methodologies not only assist the architect in the management of design complexity but also increase the potential of creativity at the early stages of hospital design process’.* To argue the case for the hypothesis and seek responses to the relevant research questions, the researcher employed a combination of research techniques including an exhaustive literature review, survey questionnaires, and a computer-based protocol investigation. The study then processed this collected data further with the aid of statistical analysis techniques to add rigour to the data analysis process and increase the validity of the research findings. The following diagram (Fig.10.1) displays this PhD research plan.

Fig.10.1 The PhD research plan



Source: Author reproduced

From the review of the literature, the material indicates that design ideas at the early stage of hospital design could influence the later schematic and structural development of hospital buildings, especially as the design concept is often connected to the provision of medical/functional services. In addition, future expectations of healthcare architectural design, as published in The Nuffield Trust (2001) guidebook, emphasises that the main goal of the next generation of healthcare architecture should focus on design quality improvement. Put another way, improving design quality means more innovation in design ideas.

10.1.1 Design creativity and measurement

As the research hypothesis states on the creative potential for the hospital design process, the empirical study was applied to measure the performance of CAD methods. The literature review examined the certain studies of design creativity and identified two major domains, the ‘process’ creativity and ‘product’ creativity, as the concept to this study (See the literature review of the creativity study in Section 3.6.2, Chapter 3). Besides, these two areas of creativity studies in the hospital design process were extend to develop deeper investigation on the study of design cognition with the design practice; for instance, the observations of design behaviour, divergent thinking and problem-solving ability.

10.1.2 Computer Aided Design CAD typologies

The use of CAD tools has improved hospital design ideation toward a more elaborate and carefully considered development (See the literature review of new age (21st century) hospital design and CAD in Section 2.5, Chapter 2). As part of the new trend of using parametric CAD for architectural design, the British government has stated that by the end of 2016, all public buildings should be submitted through BIM design formats (one parametric design system) (Barnes and Davies, 2015). It is imperative, therefore, that this research investigates different CAD methods, parametric and nonparametric, and comparative factors exploring their interrelation with the hospital design process as well as their impact on design creativity. However, some practices predominantly (mostly and largely) exploit CAD for 2D drafting and 3D modelling, others predominately use BIM/Revit for speed and efficiency because it automates the building of 3D entities, allows better workflow and integration between architects and other building industry professionals such as engineers and quantity surveyors. A third type of office tends to use parametric/algorithmic CAD to arrive at novel and statistically infrequent solutions to design problems. Therefore, this thesis examines and analyses software packages and how one software package is embedded into or overlaps with another [i.e. Grasshopper algorithm software inside Rhinoceros (2D/3D CAD software) and Dynamo as a plug-in for Revit (BIM)]. Considering the nature of its use in practice and how the software industry packages CAD, CAD can then be interpreted as an overlapping contemporary process.

Furthermore, in the two case studies of this PhD, the main issue of software was mainly related to the predominant (or frequent) use of a particular type of CAD package, which was the criteria used to classify CAD into the three norms/modes: conventional, BIM, and parametric/algorithmic. The question was: which type of CAD application does the practice use most frequently?

10.2 Research method

This PhD thesis focuses on the hospital design process employing different CAD methodologies and extends this into a discussion of design cognition and creativity of design. This study plan is two dimensional and more challenging than just providing a single case study. Therefore, an empirical research method was needed to provide objective judgments and arguments for the relevant in-depth investigations. As the research question highlights; *how is empirical research into the measurement of design performance related to creativity?* The study results have responded through investigation and measurement of the design impacts of applying two distinct CAD methodologies. Also, the review of user experiences was a vital factor in the design of this research.

There were two kinds of methods deployed for the purposes of the research. The first was a retrospective approach which could be evaluated through a survey questionnaire of practising architects as to their opinions of their hospital design projects. The second was a concurrent study method which involved some architects' taking part in a small design task and applying a think-aloud (verbal discussion) technique called protocol analysis to express their design ideas. These two research methods were profoundly connected to each other and this, in turn, has enhanced the depth of the investigation. For example, the questionnaire demonstrated that algorithmic CAD architects had a more productive ideation process than the non-algorithmic architects and were good at updating design ideas. Next, the protocol analysis further identified that this was because the algorithmic design user tended to spend more time on design synthesis and evaluation, a practice which provided them with sophisticated skills in the formulation of design problems at an early design stage. Moreover, the varied design shapes produced when utilising algorithmic CAD showed the interrelationship between the use of algorithmic design and form exploration; the architects went deeply into understanding the design geometry, so they were able to produce more varied geometric representations (See the research design of dual research methodologies in Section 5.4, Chapter 5).

Therefore, the design of this research was intended to add value to existing research when it was connected to a variety of research findings. Although this comprehensive study is based on the hospital building design process, its findings and suggestions, it is believed, could be applied to other architectural areas, to other design professions, to research on design creativity or CAD research as well as encouraging the use of parametric CAD methods in complex building design.

10.3 Measurement of design creativity for the CAD process of hospitals

This section aims to review the research findings of the design creativity according to the parametric and nonparametric CAD users' hospital design experiences and then extend to relevant discussions with the parametric design optimisation. As the main research question in this thesis was stated as, '*To what extent do the different CAD methodologies influence the performance of the hospital's design ideation process?'*, the measurement of creativity was applied to understanding long-term impact of different CAD methods on design creativity in this study. Therefore, Torrance's (1971) creativity test was referenced to identify the creativity in the ideation process; *1. Idea fluency (numbers), 2. Idea flexibility (types) 3. Idea originality (uniqueness)*.

10.3.1 A summary of the statistical analysis of the design creativity from the CAD groups

a) The idea fluency in the hospital design process

In the first of these, the number of ideas generated indicates 'idea fluency' during the architects' engagement with the hospital design proposal. The survey questionnaire results (Fig.10.2-A) show the majority of traditional CAD users (62.67%) thought the CAD method had helped them to generate 3 ideas during the design process, and 16% of users were able to produce 5 ideas by using the same tool. Although only 51.35% of BIM users thought they had produced 3 ideas in the design, 21.62% of users had produced over 5 ideas (around 6% higher than with traditional CAD). Remarkably, 60% of algorithmic CAD users claimed an impressive number of 10 design ideas during the design process.

When calculating the statistical mean of the data distribution, the results (Fig.10.2-B) show there were about 3-4 ideas generated using traditional CAD, 4 ideas for BIM and 8-9 ideas for algorithmic CAD. Clearly, architects who deployed algorithmic CAD generated almost twice as many ideas as the others (See the research finding of idea fluency as a parameter of creativity in Section 6.3.1, Chapter 6). In addition, given that the variance test compared data (idea numbers) across the three CAD groups (traditional CAD, BIM and algorithmic CAD), the results (Table 10.1) indicated that the algorithmic design architect group had the highest F score, implying the strongest significant relation between the use of the CAD method and idea production with F (2,139) =171.06; P =0.00 <0.05 (F ratio indicates the variability between the groups; P value presents the significance value).

Fig.10.2 CAD methods and idea fluency

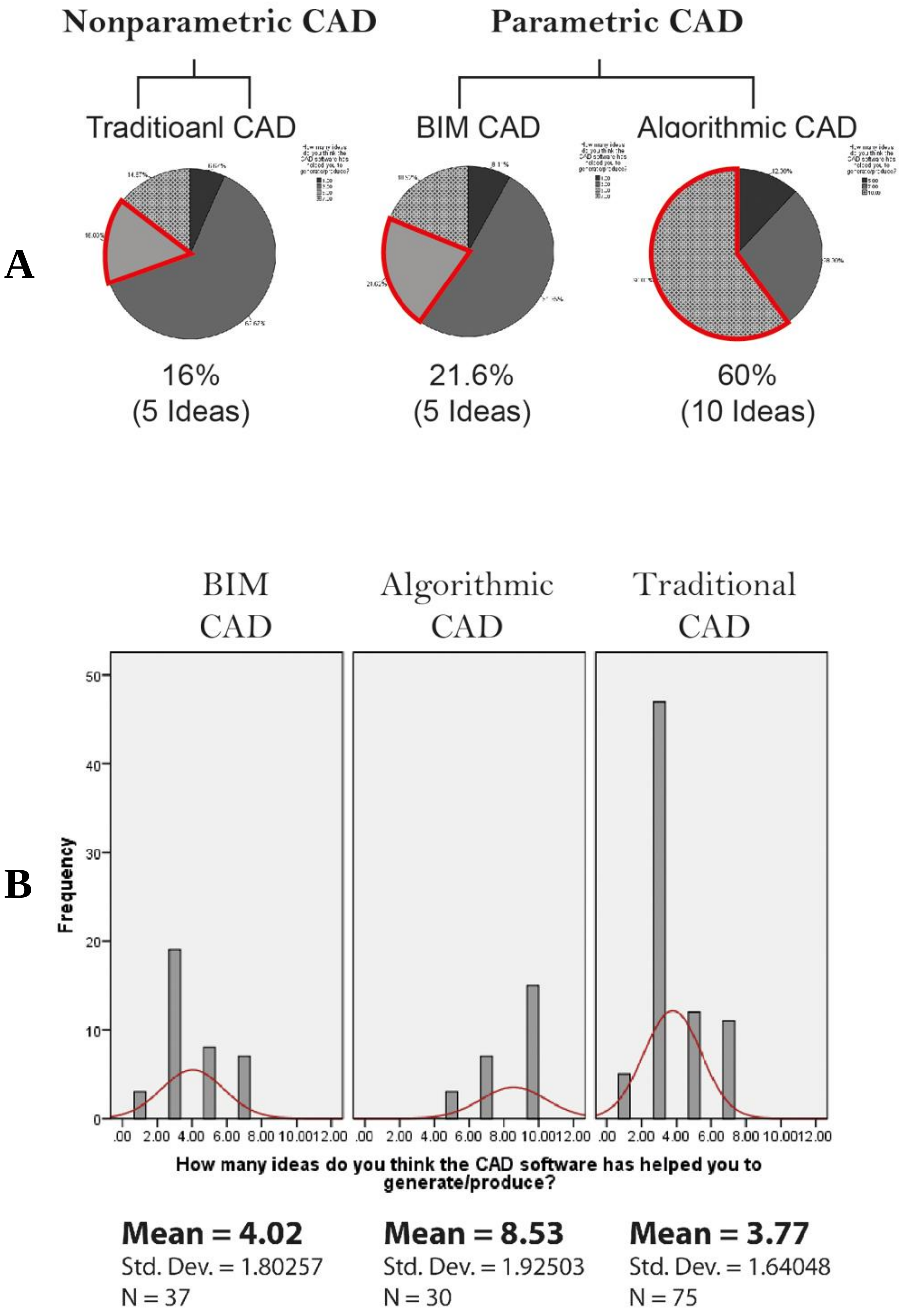
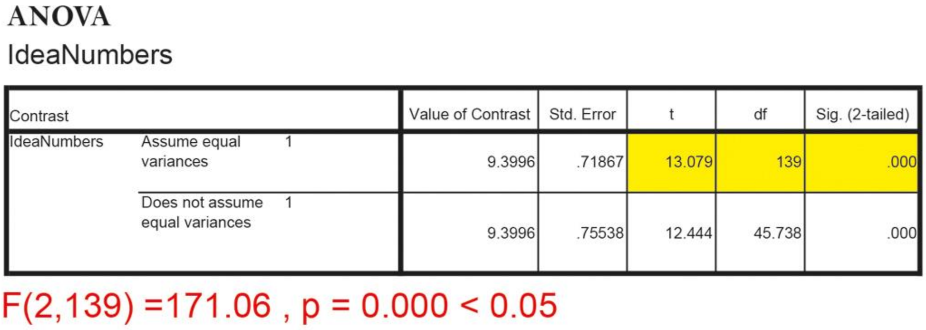


Table10.1 Correlation between CAD methods and idea fluency



ANOVA

IdeaNumbers

Contrast			Value of Contrast	Std. Error	t	df	Sig. (2-tailed)
IdeaNumbers	Assume equal variances	1	9.3996	.71867	13.079	139	.000
	Does not assume equal variances	1	9.3996	.75538	12.444	45.738	.000

F(2,139) =171.06 , p = 0.000 < 0.05

Source: Author reproduced/ SPSS

Source: Author reproduced/ SPSS

b) The idea fixability to the hospital design process

In the second case, idea flexibility means producing varied idea types for a design process. The concept's variety could present an indicator of detailed consideration at the design ideation stage. Summarising the data produced (Fig.10.3-A), the majority (73.33%) of nonparametric CAD (traditional CAD) users thought the tool had helped them to generate up to 2 different idea types and only 26.67% of users were able to produce 3 idea types during the design process. In the parametric CAD category, for the algorithmic CAD users, over 60% agreed that the CAD tool encouraged them to produce 7-10 types of ideas. Although over 60% of BIM users thought they had only produced 2 idea types for the design, over 20% of users had actually produced 3 to 4. These outcomes from the parametric CAD tools were generally better than for traditional CAD users (See the research finding of idea flexibility as a parameter of creativity in Section 6.3.2, Chapter 6). Also, the Standard Deviation (SD) and curve shape (Fig.10.3-B) further explained the different relationship between idea types generated and the CAD type used. Algorithmic CAD provided a large SD (2.61) with the mean 7.17; the SD is 3 times that of traditional CAD (SD=0.77) with the mean 1.95. The SD value indicates the level of dispersion in the data distribution. A small value means a close clustering of the data set values and a smaller distance (difference) between values and the mean value; a large SD means the opposite. The data implied that conventional CAD confined users' performance on the variety of ideas generated to only 2 types and there were only limited exceptions. By contrast, the higher SD value (2.6) for the algorithmic CAD method is related to the fact that with this method, designers produced a large range of idea types, with 3 to 10 types. Regarding the impact of applying different CAD method to typological design, the variance test (ANOVA) (Table 10.2) confirmed that algorithmic CAD had a considerable influence on the production of design types when compared with the other two CAD methods (the traditional CAD and the BIM); $F =(2,139)=310.6$, $P = 0.00 <0.05$.

Fig.10.3 CAD methods and idea flexibility

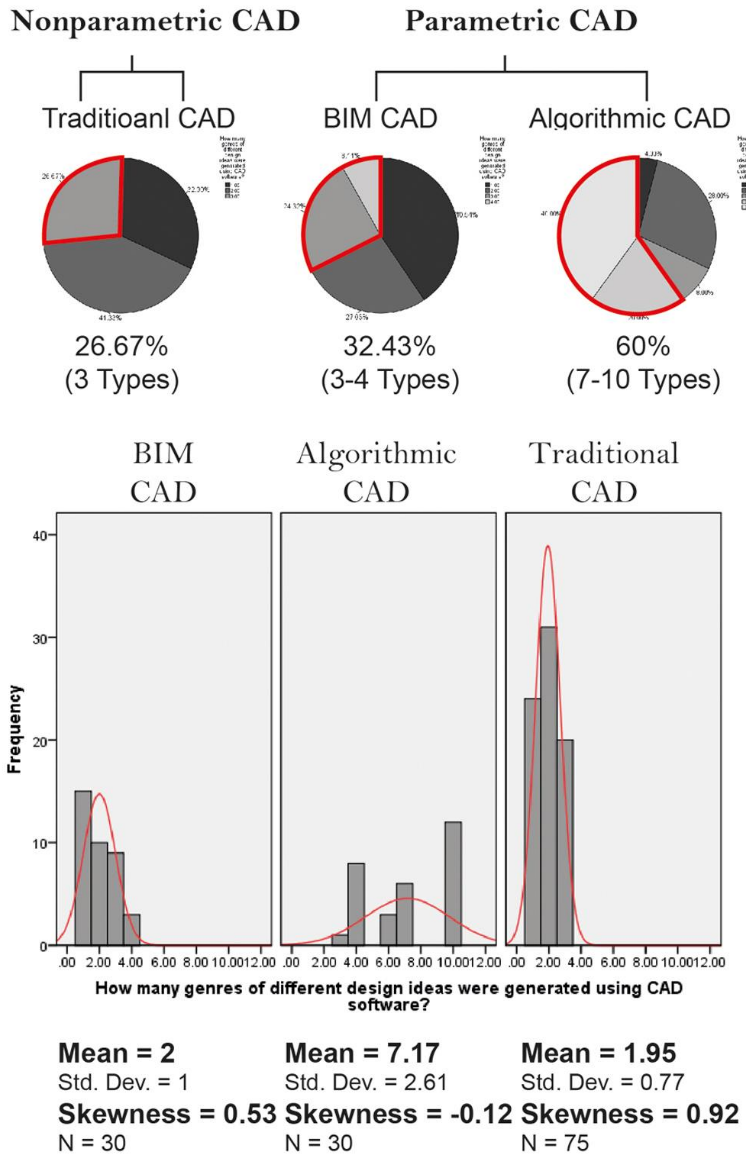
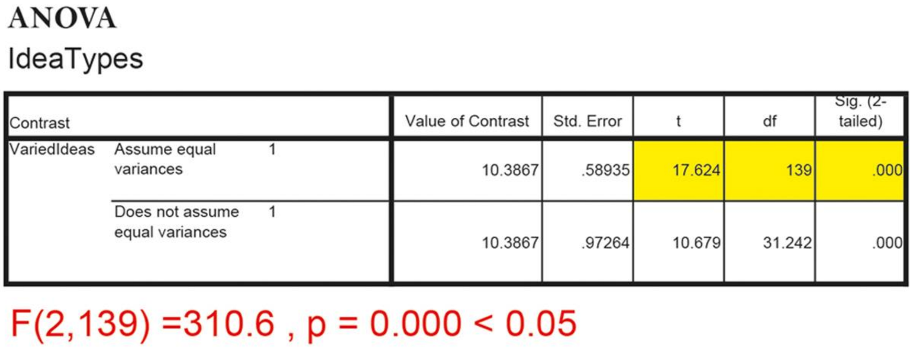


Table10.2 Correlation between CAD methods and idea flexibility



ANOVA

IdeaTypes

Contrast			Value of Contrast	Std. Error	t	df	Sig. (2-tailed)
VariedIdeas	Assume equal variances	1	10.3867	.58935	17.624	139	.000
	Does not assume equal variances	1	10.3867	.97264	10.679	31.242	.000

F(2,139) =310.6 , p = 0.000 < 0.05

Source: Author reproduced/ SPSS

c) The Idea originality to the hospital design process

The last identification of creativity measured users' opinions about the originality of their design ideas and types. Originality is fundamental to realising creativity and attitudes toward an important aspect of the designed products (architecture).

The data collected (Fig.10.4) showed that 70% of the nonparametric CAD users described the originality of their design ideas in terms of originality as very common and only 8% of users thought the originality of design was uncommon or 'unique' in terms of originality. By contrast, 56% of parametric CAD users described originality of their design ideas as very common and common; only 19% of them registered uncommon and rare results. The statistical average for these, the mode, showed the highest frequency (response) in the case of each CAD tool: level 1 (very common) for BIM, level 5 (rare) for algorithmic CAD and level 2 (common) for traditional CAD (See the research finding of idea originality as a parameter of creativity in Section 6.3.3, Chapter 6). When it came to the connection between idea originality and CAD method, the U-test (Table 10.3-A) confirmed there was a significant difference regarding idea originality between the algorithmic CAD group and the traditional CAD group; $U = 621.5$, $Z = -3.699$, $P = 0.00 < 0.05$. In addition, the effect on idea originality ($r=0.4$) for algorithmic CAD and traditional CAD was above average (medium) and close to a large effect (Cohen's criteria, 1988). For the algorithmic CAD and the BIM groups, the test (Table 10.3-B) also suggested a similar significant difference with $U = 294.5$, $Z = -3.83$, $P = 0.00 < 0.05$; and the effect size ($r=0.3$) also showed a medium effect.

Fig.10.4 CAD methods and idea originality

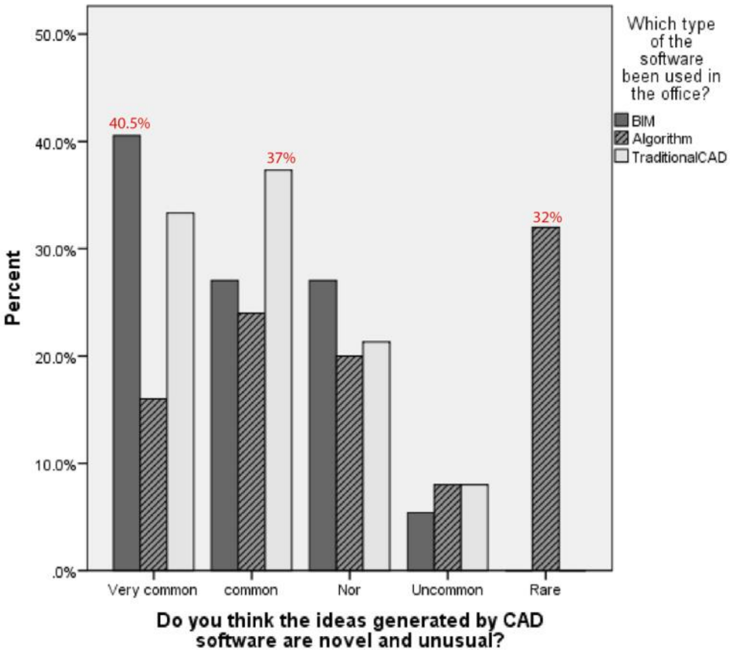
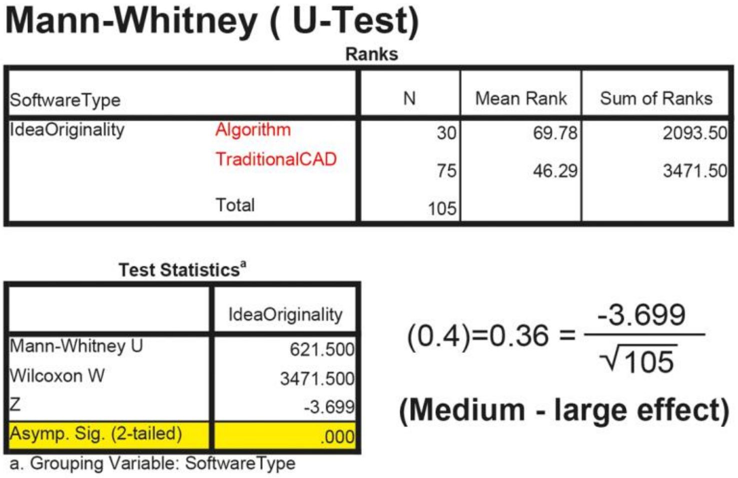


Table10.3 U-Test between CAD methods and idea originality



Mann-Whitney (U-Test)

Ranks

SoftwareType		N	Mean Rank	Sum of Ranks
IdeaOriginality	Algorithm	30	69.78	2093.50
	TraditionalCAD	75	46.29	3471.50
	Total	105		

A

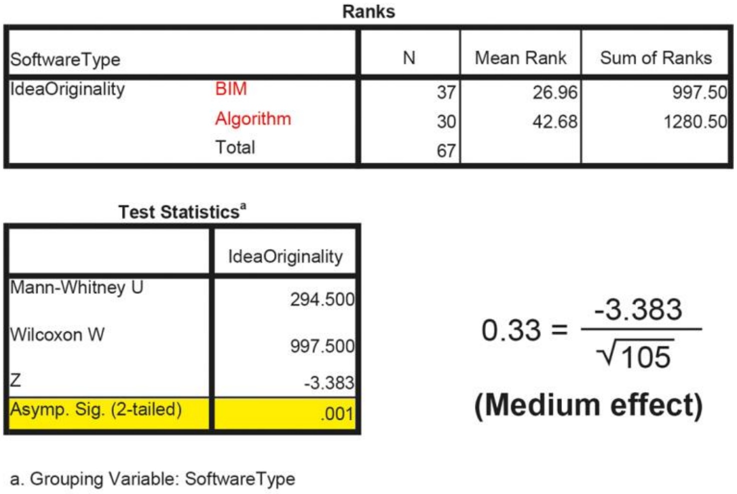
Test Statistics[a]

	IdeaOriginality
Mann-Whitney U	621.500
Wilcoxon W	3471.500
Z	-3.699
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: SoftwareType

$$(0.4)=0.36 = \frac{-3.699}{\sqrt{105}}$$

(Medium - large effect)



Ranks

SoftwareType		N	Mean Rank	Sum of Ranks
IdeaOriginality	BIM	37	26.96	997.50
	Algorithm	30	42.68	1280.50
	Total	67		

B

Test Statistics[a]

	IdeaOriginality
Mann-Whitney U	294.500
Wilcoxon W	997.500
Z	-3.383
Asymp. Sig. (2-tailed)	.001

$$0.33 = \frac{-3.383}{\sqrt{105}}$$

(Medium effect)

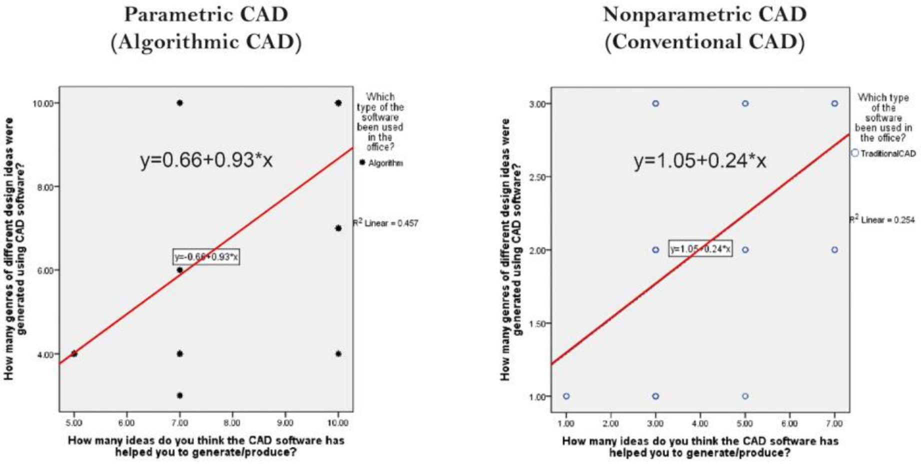
a. Grouping Variable: SoftwareType

Source: Author reproduced/ SPSS

10.3.2 Discussion of the design creativity and the CAD ideation process

As the section of 10.3.1 summaries, the CAD groups present different variables of idea production. This part further checks the statistical relationship between the two variables; the idea number and idea type. A correlation test using a scatter diagram (Fig.10.5) showed the interrelation between the idea numbers and genres and the calculation sequence. The results from the regression equation exhibited that for algorithmic CAD users, they possibly had generated around 5 ideas and 5 types, according to the equation: 5.31((Y)idea type) = 0.66+0.93*5((X)idea number). At the same time, traditional CAD users could only generate 5 ideas with 2 to 3 genres as predicted with the regression equation: 2.25(Y) = 1.05+0.24*5(X). Using the same regression principle, the BIM users presented almost 2 genres; 1.88(Y) = 2.48-0.12*5(X), using the same number of ideas (5).

Fig.10.5 Correlation of idea number and idea type



Parametric CAD
(Algorithmic CAD)

Nonparametric CAD
(Conventional CAD)

Source: Author reproduced/ SPSS

The high scores of idea types and numbers presenting from the algorithmic CAD group indicate the design method provides a potential influence to optimise the design solution from these two variables of design concept generation. In the hospital design process, one design problem presents a systematic problem. It means the solution/design idea should able to respond to varied design aspects. For example, the façade design contains not only the building's aesthetics but also the lighting/thermal issue to the ward design. If architects can apply the algorithmic CAD for their concept proposal, they should gain more confidence to respond to this design complexity. Caladas and Norford (1999) explore the design optimisation of the thermal and lighting design of a building by using a method of algorithmic design, the Genetic Algorithm search (GAs). They state the algorithmic CAD process can generate a great number of possible solutions and increase the solutions depending on the level of problem complexity as the user's requirements. For instance, the complex design between buildings and climates cannot be satisfied in a traditional way, such as a scenario-by-scenario based design method because the scale of the project or site location is involved to accumulate the design complication. However, an algorithmic design method can possibly be carried out as the search procedure and produce varied solutions. The great production of ideas/solutions from the use of generative algorithms can provide highly satisfactory and confidence for the design process and extend to a wide range of thoughts that no conventional method could offer.

10.4 Discussion of the CAD optimisation for hospital buildings

Besides idea measurement, there are other design parameters which can be used for the evaluation of the creativity of hospital building design. As the research question states '*To what extent do the different CAD methodologies for a complex design project such as hospital improve the assessment of the design, in terms of its materials, shape and concept?'*; for answering these questions, the creative judgements of products according to Amabile (1982) were divided into three clusters to help identify the different creative aspects of hospital building design. The first was the *Creativity cluster* (*Novel use of material, Novel idea, Variation in shapes, Details and idea Complexity),* the second the *Technical cluster (Organisation, Neatness, Planning, Symmetry and Expression of meaning)* and the last was the *Aesthetic judgment cluster (Liking and worth displaying)*. Responses were graded on a 1 to 5 scale according to architects' views of the support provided by the CAD method, with rankings of 1. None, 2. Slightly, 3. Moderately, 4. Above average, and 5. Immensely/Greatly.

The next 2 sections summarise the research findings based on a highest score of some judgements with the particular CAD utilised for the hospital building design. Each content also concludes the findings of statistical charts and relevant case studies relating to design optimisation according to the creativity judgments. In addition, further discussion of the CAD design impacts, such as the potential influences on the design innovation, are individually mentioned in the section.

10.4.1 Design optimisation of algorithmic CAD for the hospital buildings

Regarding the judgements on creativity in the final designed product (hospital building) based on creative ideas and elaborate design concepts, the algorithmic CAD group presented impressive results regarding shape variation, innovative design ideas and elaborate design concept. For example, the algorithmic CAD users (Fig.10.6-A) showed in

64% of cases (n=30) that the tool was of 'good' and 'great help' in creating novel hospital design ideas; the algorithmic CAD users showed 'good’ and 'great' performance from the tool in 100% of cases in the elaboration of the hospital design concept (Fig.10.6-B). In terms of the impact on these creativity design sections, the statistical analysis (Table 10.4) indicated that algorithmic CAD largely supported these particular parts of hospital building design ($r>0.4$ = Medium to Large effect; Cohen’s criteria, 1988) and the case studies used also provided innovative hospital design plans within the creative design process (See the research finding of novel design ideas in Section 6.4.1.c and elaboration of design ideas in Section 6.4.1.e, Chapter 6).

Regarding judgments of creativity with respect to building design project, the review of the complex building design provided a further discussion as to how CAD helped the project development. For instance (Fig.10.7-A), the national Taichung opera house (2016) designed by Toyo Ito and Associates, proposed a continuous mathematically-designed surface which was able to formulate and integrate sub-spaces within a bounding box. This connected surface design was based on the idea of parabolic shape design which breaks away from conventional spatial design (columns, beams and floor plans) and shows continuous and infinite space experiences including better visual extension and structural efficiency. Without a parametric CAD process, nonparametric CAD methods cannot easily manipulate such complex mathematical design ideas. Regarding complex design idea generation (Fig.10.7-B), the UN studio has a specialised parametric design group applying the latest algorithmic CAD method – The Smart Parametric Platform (SPP). SPP is not just a conventional modelling system; it contains many complex algorithmic programs/disciplines and processes which uses non-geometric parameters such as social, economic, political, materials, etc. Through the integration of design information, the parametric synthesis system has increased the elaboration of the design idea and improved the quality of the design proposal (See the research finding of novel design ideas in Section 7.3.1 and elaboration of design ideas in Section 7.3.2, Chapter 7).

For the hospital design proposals, if architects apply the use of the algorithmic CAD method, they can possibly improve their design idea through constructing the mathematics/algorithm-based design plan rather than adhering to any specific/existing design model. In addition, the advantage of the algorithmic design is that the CAD function can integrate complex design parameters to make a disciplined system, like spatial volume, scale, orientation, etc. More design information is input; the algorithmic definition becomes complete and can check design development in a multi-design process.

Abdelsalam (2009) reported the algorithmic CAD could be a powerful method to manage design information and upgrade them to the rich and innovative ideas. He stated that ‘integrating these algorithms in the parametric software led to variations in building design concepts increasing alternatives and decreasing the repetitive work previously need in conventional/nonparametric CAD software’. Additionally, he suggests that ‘using simple or complex mathematical equations help to explore a new series of shape and solid. Each designer can add his own new feature which create designs that are more innovative expressing his own character.’

Fig.10.6-A Algorithmic CAD and innovative idea

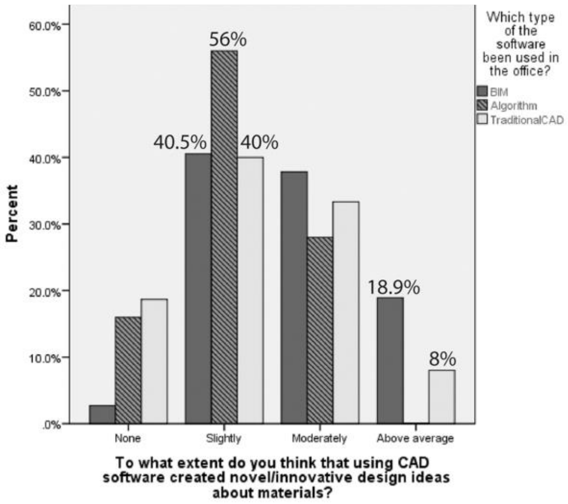


Fig.10.6-B Algorithmic CAD and elaborate design

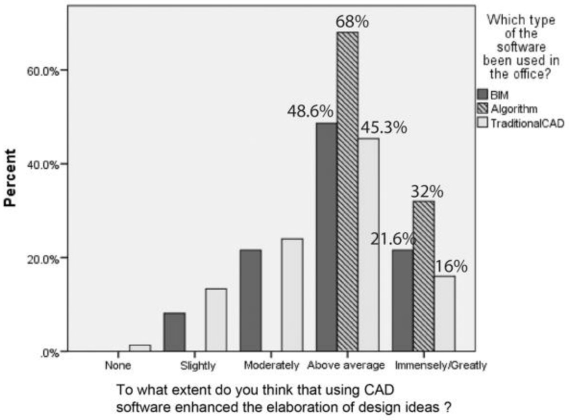
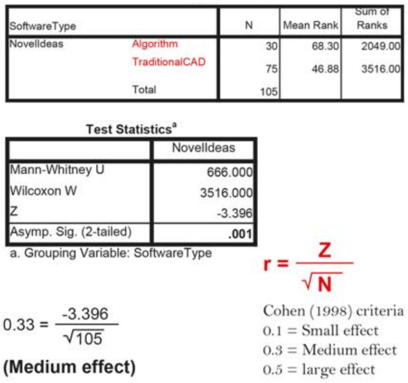


Table10.4-A KW Test between algorithmic CAD and innovative idea



SoftwareType		N	Mean Rank	Sum of Ranks
NovelIdeas	Algorithm	30	68.30	2049.00
	TraditionalCAD	75	46.88	3516.00
	Total	105		

Test Statistics[a]

	NovelIdeas
Mann-Whitney U	666.000
Wilcoxon W	3516.000
Z	-3.396
Asymp. Sig. (2-tailed)	.001

a. Grouping Variable: SoftwareType

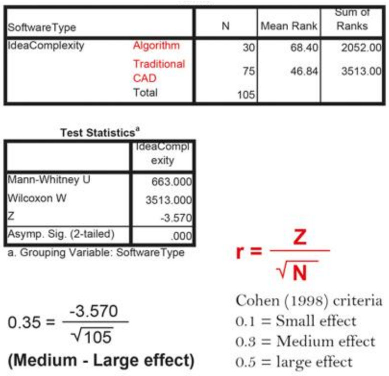
$$r = \frac{Z}{\sqrt{N}}$$

$$0.33 = \frac{-3.396}{\sqrt{105}}$$

(Medium effect)

Cohen (1998) criteria
0.1 = Small effect
0.3 = Medium effect
0.5 = large effect

Table10.4-B KW Test between algorithmic CAD and innovative idea



SoftwareType		N	Mean Rank	Sum of Ranks
IdeaComplexity	Algorithm	30	68.40	2052.00
	Traditional CAD	75	46.84	3513.00
	Total	105		

Test Statistics[a]

	IdeaComplexity
Mann-Whitney U	663.000
Wilcoxon W	3513.000
Z	-3.570
Asymp. Sig. (2-tailed)	.000

a. Grouping Variable: SoftwareType

$$r = \frac{Z}{\sqrt{N}}$$

$$0.35 = \frac{-3.570}{\sqrt{105}}$$

(Medium - Large effect)

Cohen (1998) criteria
0.1 = Small effect
0.3 = Medium effect
0.5 = large effect

Fig.10.7-A Innovative design ideas in Taichung opera house

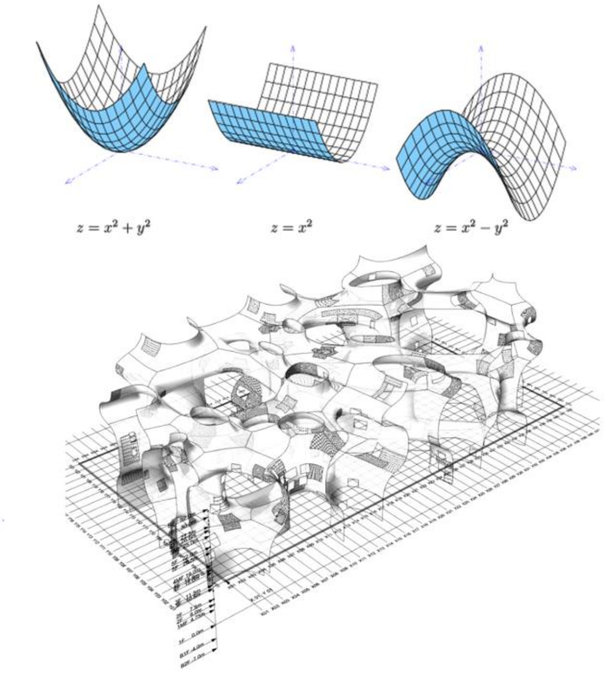
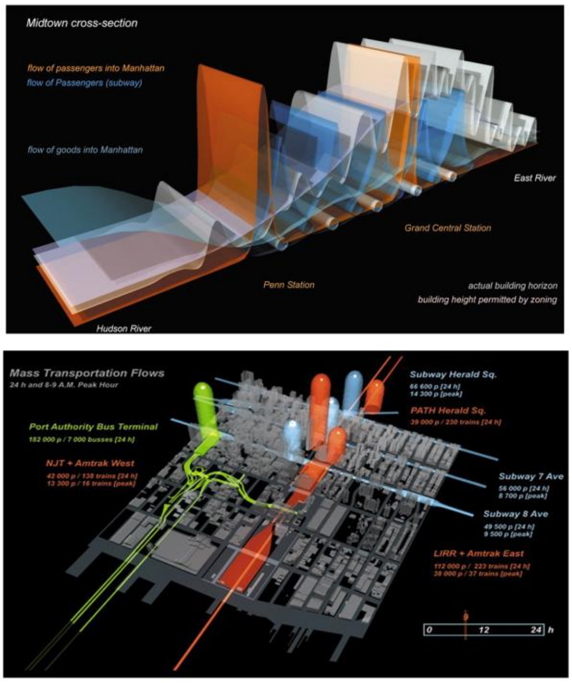


Fig.10.7-B Complex design idea with the algorithmic CAD (UN studio)



Source: Author reproduced/ SPSS/Toyo Ito architect; UN studio

10.4.2 Design optimisation of BIM design to the hospital buildings

With respect to the creativity technical cluster, the BIM design group presented noticeable results on the aspects of design and functional organisation and expression of the design message. For instance, regarding design neatness, in over 70% (n=37) of cases, the BIM users showed that they thought the impact of CAD method was 'good' or 'excellent' for the design management (Fig.10.8-A). In addition, there were over 78% (n=37) of the BIM users also showed that the software provided 'good' or 'immense' help in the hospital design idea’s expression (Fig.10.8-B). In terms of the technical aspects of the creative impact, the statistical analysis (Table 10.5) indicated that BIM design could largely support ($r>0.4$ = Medium to Large effect; Cohen’s criteria, 1988) two specific aspects of building design such as the organisation of functional programs and expression of the design message (See the research finding of organisation and neatness of the functional programs in Section 6.4.2.a and expression of the design message in Section 6.4.2.d, Chapter 6).

In the case study examples, the GRO architects, Jackson Green Housing (Fig.10.9-A), Jersey City, New Jersey, 2012-14 proposed 22 units of residential housing in a design project with a modular design assembly system. The BIM system was parametrically employed to organise different parts, such as design simulation, modular design variation, modular fabrication and budgetary control. These design sections were formed into a parameter-based simulation process and optimised to fit the design concept – the modular design. Unlike the early modular design hospitals, such as the Harness and Nucleus hospitals, these modular hospitals largely relied on conventional CAD methods, which could not easily create such a flexible system, especially when sharing the same design layout across different building professions like module prefabricators. Expensive design cost and limited types of modular design are discovered in this more traditional design process. Regarding design message expression, the Shanghai Tower (Fig.10.9-B), Shanghai, China, 2008-14 designed by Gensler, employed the BIM design system and through a parameter-based design simulation (Computational Fluid Dynamic - CFD), successfully interpolated a twisted form of skyscraper design following local climate variations. This parametric design method improved on the idea expression available in traditional (nonparametric) building design, which can only give a symbolic image of building types; this parametric design approach was based on scientific parameters and directly applied these to the building shape design (See the research finding of organisation and neatness of the functional program in Section 7.3.3 and expression of the design message in Section 7.3.4, Chapter 7).

If the BIM workflow can be applied to modular hospital design, it may then be possible to improve the quality and efficiency of the design planning process and give potentially better design optimisation to customise the quality of design as well as address the criteria of better healthcare design standards. Moreover, BIM design supports a parameter-based design framework, which gives ideas exchange at the early conceptual stage and successfully transfers feedback into a digital process. By doing so, the design communication can certainly be improved, and the quality of the design can also be enhanced. Fernando, Burden and Drogemuller (2012) state BIM design provides information-rich objects allowing multiple design disciplines to be individually examined during the early design process. This process not only helps the design objects being ‘immaterial’, it demands processing but can also be integrated with other design disciplines. This object-oriented modelling design builds a bridge and connects the conceptual and development stage, which is believed can improve the initial design explorations. In terms of the development of a hospital’s design standard, a parametric design framework provided by the BIM design could help to synthesis complicated design information as a modular design process and achieve better design solutions. Succar (2009) cites ‘The BIM design framework is an integrated framework incorporating different approaches to information within a consistent whole. It might incorporate not only the information model but also the reference process model and dictionaries’.

Fig.10.8-A BIM design and design organization

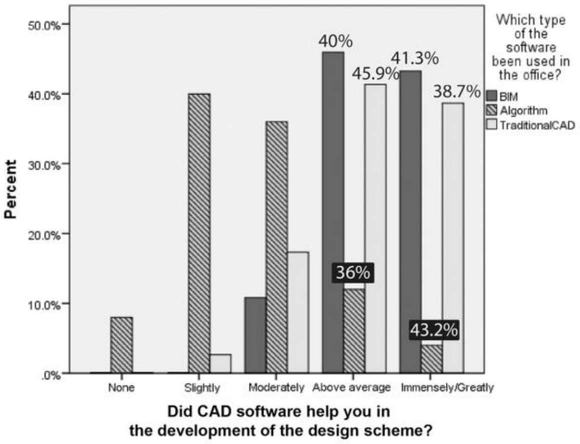
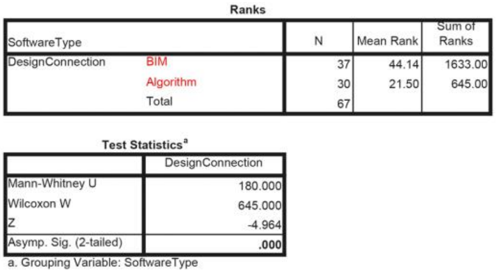


Table10.5-A KW Test between BIM design and design organization



Ranks

SoftwareType		N	Mean Rank	Sum of Ranks
DesignConnection	BIM	37	44.14	1633.00
	Algorithm	30	21.50	645.00
	Total	67		

Test Statistics[a]

	DesignConnection
Mann-Whitney U	180.000
Wilcoxon W	645.000
Z	-4.964
Asymp. Sig. (2-tailed)	**.000**

a. Grouping Variable: SoftwareType

$$0.6 = \frac{-4.964}{\sqrt{67}}$$

(Large effect)

Fig.10.8-A BIM design organization in Jackson housing design process

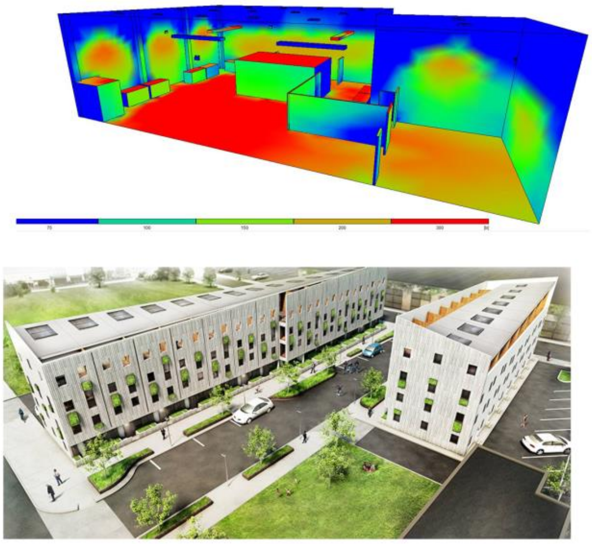


Fig.10.8-B BIM design and idea expression

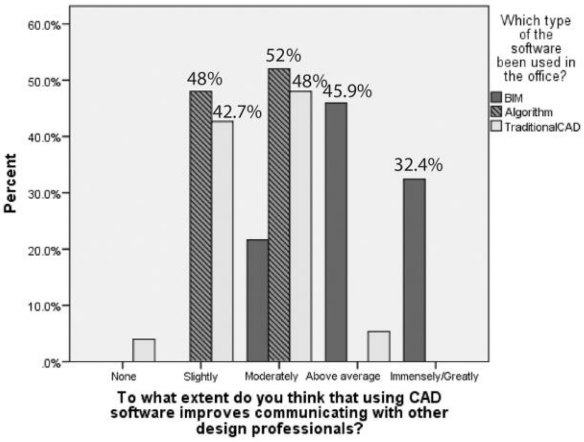
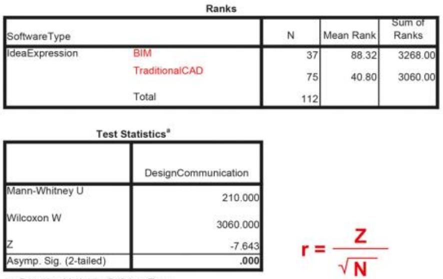


Table10.5-B KW Test between BIM design and idea expression



Ranks

SoftwareType		N	Mean Rank	Sum of Ranks
IdeaExpression	BIM	37	88.32	3268.00
	TraditionalCAD	75	40.80	3060.00
	Total	112		

Test Statistics[a]

	DesignCommunication
Mann-Whitney U	210.000
Wilcoxon W	3060.000
Z	-7.643
Asymp. Sig. (2-tailed)	**.000**

a. Grouping Variable: SoftwareType

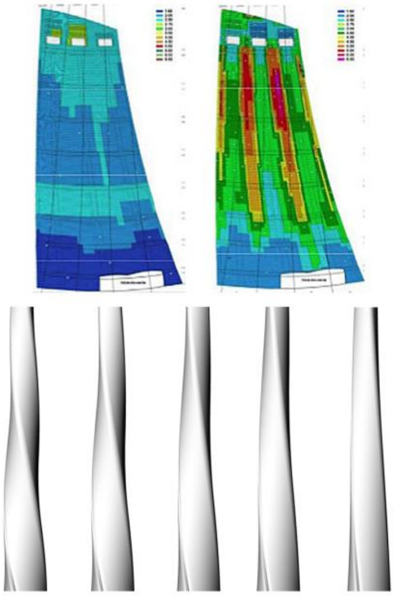
$$0.7 = \frac{-7.643}{\sqrt{112}}$$

(Large effect)

$$r = \frac{Z}{\sqrt{N}}$$

Cohen (1998) criteria
0.1 = Small effect
0.3 = Medium effect
0.5 = large effect

Fig.10.8-B BIM design for idea expression for Shanghai tower



Source: Author reproduced/ SPSS/GRO architect; Gensler architect

10.5 Discussion of the CAD behaviours regarding the design creativity of the hospital design process

A computer-based protocol analysis was applied to observe the on-going design behaviour when using different CAD methodologies, parametric design by algorithmic CAD – Grasshopper and nonparametric/conventional CAD - AutoCAD) for a pre-selected design task to tackle design problems for a hospital outpatient centre. The two following research questions were applied to the observation direction and as the means to develop the findings:

1. *What is the correlation between the design activities and each of the two different CAD methods and does this design behaviour promote more logical/systematic design thinking and is it able to generate varied design ideas?*
2. *In the design process, how can cognitive design be influenced through the employment of different CAD methods and how do these different design cognitions enhance the problem-solving process as well as promote divergent thinking in the design project?*

In responses to these two questions, the study is divided into two parts; the first part calculated the generation of idea numbers and discovered the relationship between design ideas and different CAD design behaviour. The second section further explored the interrelationships between different design activities which were categorised into four aspects: *1. Design process, 2. Problem formulation, 3. Design cognition and 4. Form exploration* (See the research design of coding list in Section 5.8.1c-2, Chapter 5).

10.5.1 The CAD process and idea generations

a) The parametric/algorithmic CAD activity and idea explorations

According to the study of the computer-based protocol analysis, the parametric design method using algorithmic CAD (Grasshopper) exhibited systematic, well evaluated and strategy-aided design activities across case studies throughout the entire study. This well-structured, ‘glass box’ design process used by algorithmic CAD shows an intensive design interaction between the design synthesis and design evaluation; the design evaluation part especially occupied most of the algorithmic CAD process. For example, architects 01 and 03 both had over 30 minutes time spending on the design evaluation process for their idea construction (Fig.10.9). This frequently uses design evaluation, as the main design activity created a series of design actions which helped them to gain the optimum design solutions. Such a pattern of design activities was identified in Ahmed's (2003) research into experienced designers' design process (Fig.10.9-A). The experience designers tend to primarily run over a design draft and then provide cycling design evaluation to explore the design solution, thus, avoided staying in the design analysis stage. (See the research finding of parametric CAD in design process in Section 8.2.3, Chapter 8)

Fig.10.9 Algorithmic CAD design process

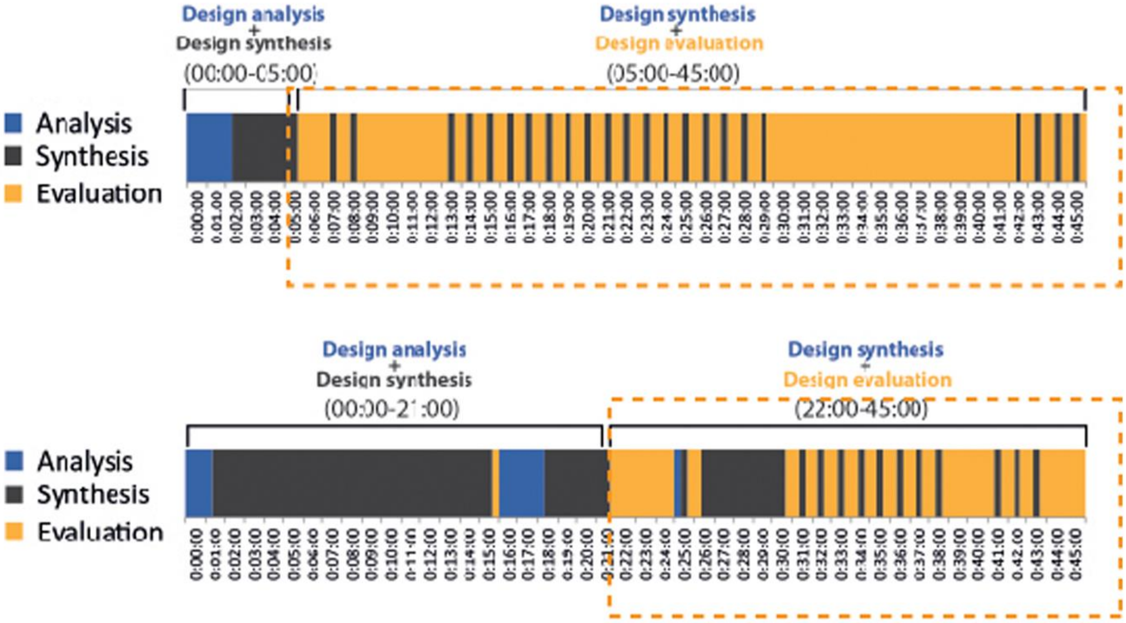
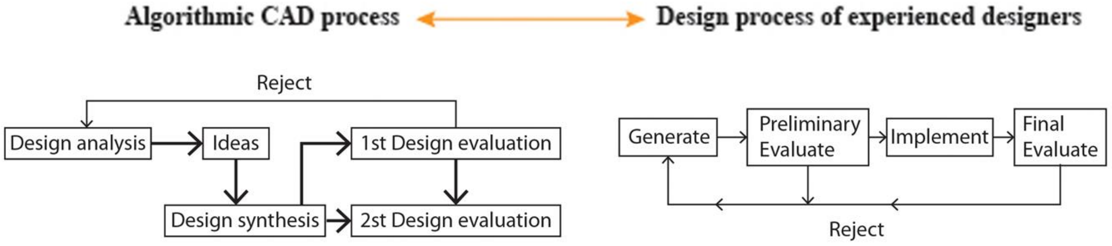


Fig.10.9-A Algorithmic CAD and design process of experienced designers



Source: Author reproduced/ Ahmend (2003) design process of experienced designers

Further exploring what other design activities could be associated with the idea generation of the CAD approach, the research applied the statistical correlation test (Table 10.6-A) and showed that ideas generated in the algorithmic design process (Grasshopper) had significant connections to the time spent on design synthesis ($r=0.43$, $p<0.01$, 19% of variance), design evaluation ($r=0.96$, $p<0.00$, 93% of variance), design problem identification ($r=0.73$, $p<0.00$, 53% of variance) and the completed design cognition process (memory, imagery and problem-solution with 34%, 34% and 28% variance, respectively; $r=0.5$, $p<0.00$). These design relationships (synthesis, evaluation, problem identification and the completed design cognition) indicated that the parametric design process using algorithmic tools created an architects' ideation process and a context very close to brainstorming or generative thinking. In particular, 93% of the variance between design evaluation and idea numbers indicated a significant relationship between idea testing and production. In addition, a strong correlation shown between idea number and problem identification ($r=0.73$) meant algorithmic design ideation is a problem-focused thought process and this kept the activities in an organised cognitive loop (cognitive memory, image and problem-solving $p<0.00$) to support the brainstorming process (See the research finding of creativity in the CAD methods of hospital design process in Section 9.2, Chapter 9).

In his research of computers and creativity, Sarasani (2011) mentions that the use of computer functions, such as algorithmic programs, can perform a very good result in a well-structured problem-solving activity. Also, computing algorithms are good at integrating information and retrieving them, as they can handle much more information than a human brain and quickly give task responses according to the programmer's requirements. The algorithm of the computer could explore all possible states of the system and effectively manipulate it. If the architect applied the algorithmic CAD for their design tasks, powerful functions such as information integration, problem-solving and instantly feedback supported their design cognition in the complex design project, like the hospital design process.

b) The nonparametric CAD method and idea explorations

On the other hand, the study found the nonparametric architects spent a lot of time between design analysis and design synthesis. No design evaluations were discovered for idea testing. For example, the architect 10 nearly spent 45 minutes on design analysis and 40 minutes of design synthesis (Fig.10.10). This lengthy design analysis and synthesis in the design process was because the architects tended to use an induction technique to reach their design decisions. In addition, the study found that the nonparametric CAD architects frequently presented uncertain verbal data as a temporary summary of the design intention such as ‘I think here could be….’, ‘this circular form might help…’ or, ‘there might be enough space…’. This delay in idea expression or less confidence in the presentation shows that the architects could not gain enough information to support their design process moving to the design evaluation stage. Regarding the aspect of architects’ performance during the design process, although the participants all had 3 to 5 years’ experience in hospital design, their design thoughts/behavioural patterns were identified as having similar problems to those of novice designers (Fig.10.10-A), such as less confidence in the design development or being focused on certain design details and ignoring the design planning (Novice designers’ approach to a design task) (Ahmed, Wallace and Blessing, 2003). (See the research finding of nonparametric CAD in design process in Section 8.2.2, Chapter 8)

Fig.10.10 Nonparametric CAD design process

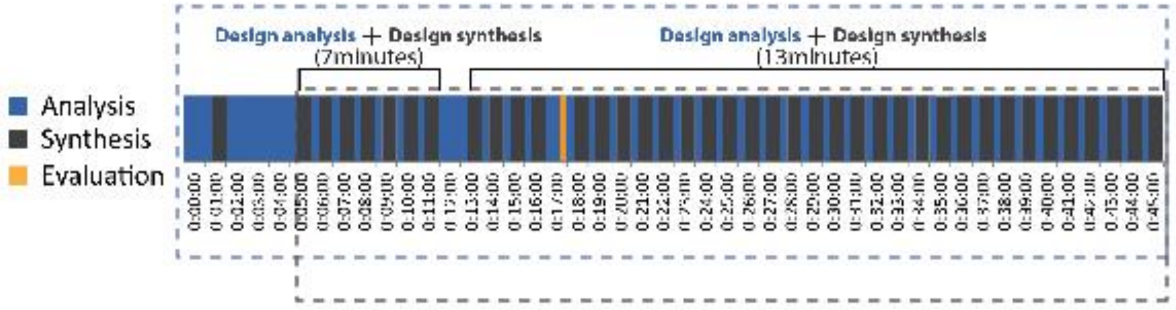
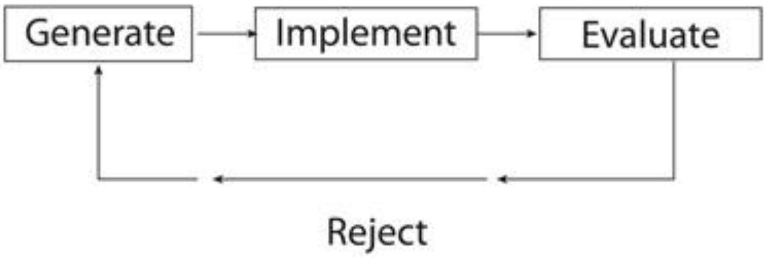


Fig.10.10-A Nonparametric CAD and design process of novice designers

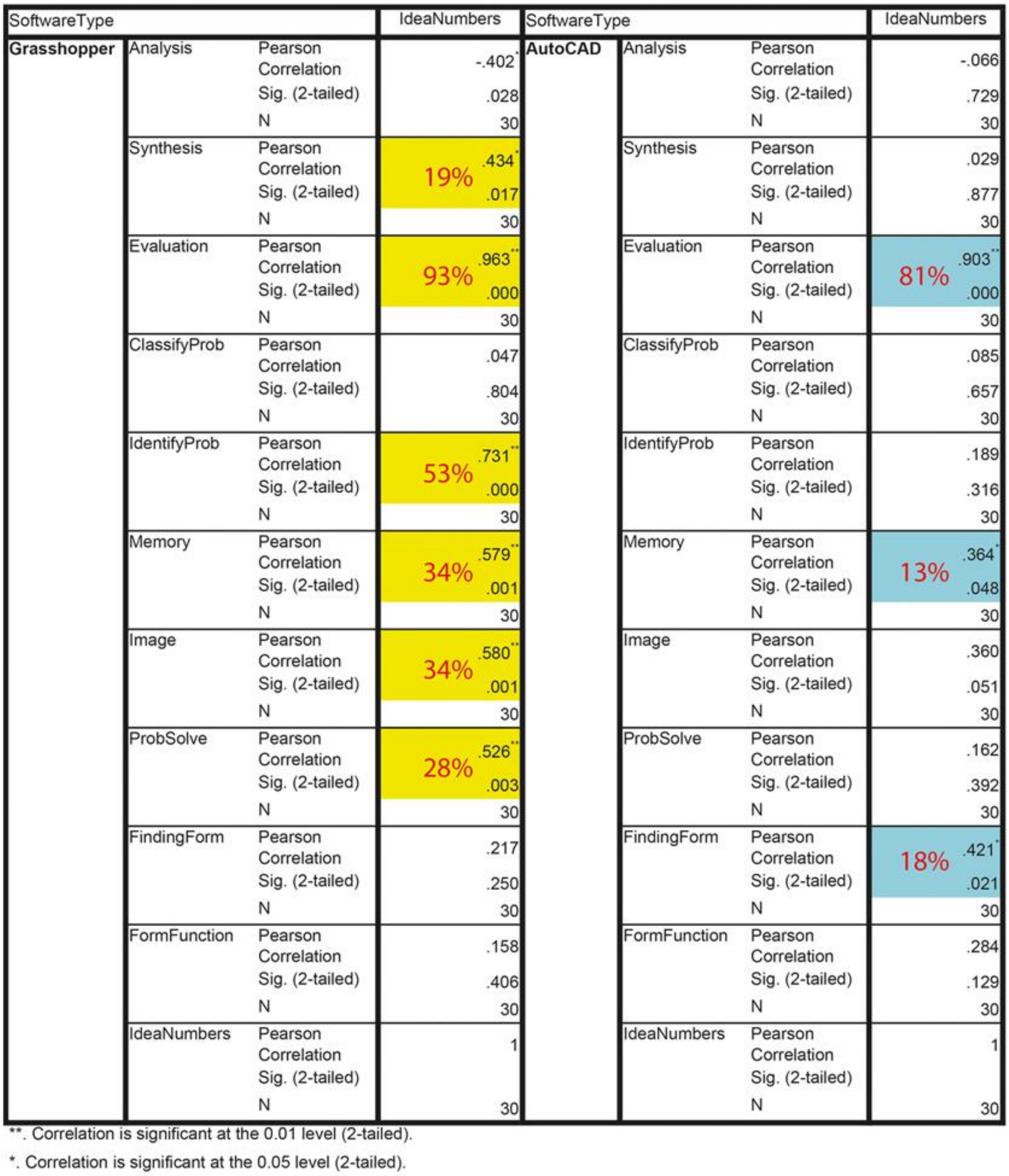


Source: Author reproduced/ Ahmend (2003) design process of novice designers

When it comes to discovering the interrelationship of the nonparametric CAD process and idea production, the correlation test (Table 10.6-B) found that idea numbers had a considerable relation to the design evaluation with 82% variance, r =0.9 (large effects), p<0.00. Medium effects between ideas and cognitive memory were also discovered (13% variance, r =0.4, p<0.048) as well as with finding form (18% variance, r =0.4, p<0.02). Although there were very limited actions of design evaluation found during the CAD process, the finding-form activity could be an important part to support the nonparametric idea presentation. We can deduce that the delays in the nonparametric CAD design process were because the architects attempted to find a predominant design use for their design inductions (See the research finding of creativity in the CAD methods of hospital design process in Section 9.2, Chapter 9).

Suwa and Tversky (1997) argue ‘exploring psychological aspects of visual forms should help architects understand the interplay between form and function’. They also suggest practising or experienced architects know how to balance their design thoughts and the proposed visual features; therefore, they prefer to rapidly move through the design actions of attributing depicted elements such as shape, size and orientation and avoid focusing on a new thought. This means the parametric/conventional CAD architect is less concerned with developing or testing new ideas but tend to follow their experience for design completion. Unfortunately, hospital design changes frequently; architects have to continuously testing their idea for future hospital building designs. If the architects only repeated their design idea, it shows no creativity for the type of building design.

Table10.6 Pearson correlation of idea exploration and CAD process



SoftwareType			IdeaNumbers	SoftwareType			IdeaNumbers
Grasshopper	Analysis	Pearson Correlation	-.402*	**AutoCAD**	Analysis	Pearson Correlation	-.066
		Sig. (2-tailed)	.028			Sig. (2-tailed)	.729
		N	30			N	30
	Synthesis	Pearson Correlation	19% .434*		Synthesis	Pearson Correlation	.029
		Sig. (2-tailed)	.017			Sig. (2-tailed)	.877
		N	30			N	30
	Evaluation	Pearson Correlation	93% .963**		Evaluation	Pearson Correlation	81% .903**
		Sig. (2-tailed)	.000			Sig. (2-tailed)	.000
		N	30			N	30
	ClassifyProb	Pearson Correlation	.047		ClassifyProb	Pearson Correlation	.085
		Sig. (2-tailed)	.804			Sig. (2-tailed)	.657
		N	30			N	30
	IdentifyProb	Pearson Correlation	53% .731**		IdentifyProb	Pearson Correlation	.189
		Sig. (2-tailed)	.000			Sig. (2-tailed)	.316
		N	30			N	30
	Memory	Pearson Correlation	34% .579**		Memory	Pearson Correlation	13% .364*
		Sig. (2-tailed)	.001			Sig. (2-tailed)	.048
		N	30			N	30
	Image	Pearson Correlation	34% .580**		Image	Pearson Correlation	.360
		Sig. (2-tailed)	.001			Sig. (2-tailed)	.051
		N	30			N	30
	ProbSolve	Pearson Correlation	28% .526**		ProbSolve	Pearson Correlation	.162
		Sig. (2-tailed)	.003			Sig. (2-tailed)	.392
		N	30			N	30
	FindingForm	Pearson Correlation	.217		FindingForm	Pearson Correlation	18% .421*
		Sig. (2-tailed)	.250			Sig. (2-tailed)	.021
		N	30			N	30
	FormFunction	Pearson Correlation	.158		FormFunction	Pearson Correlation	.284
		Sig. (2-tailed)	.406			Sig. (2-tailed)	.129
		N	30			N	30
	IdeaNumbers	Pearson Correlation	1		IdeaNumbers	Pearson Correlation	1
		Sig. (2-tailed)				Sig. (2-tailed)	
		N	30			N	30

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

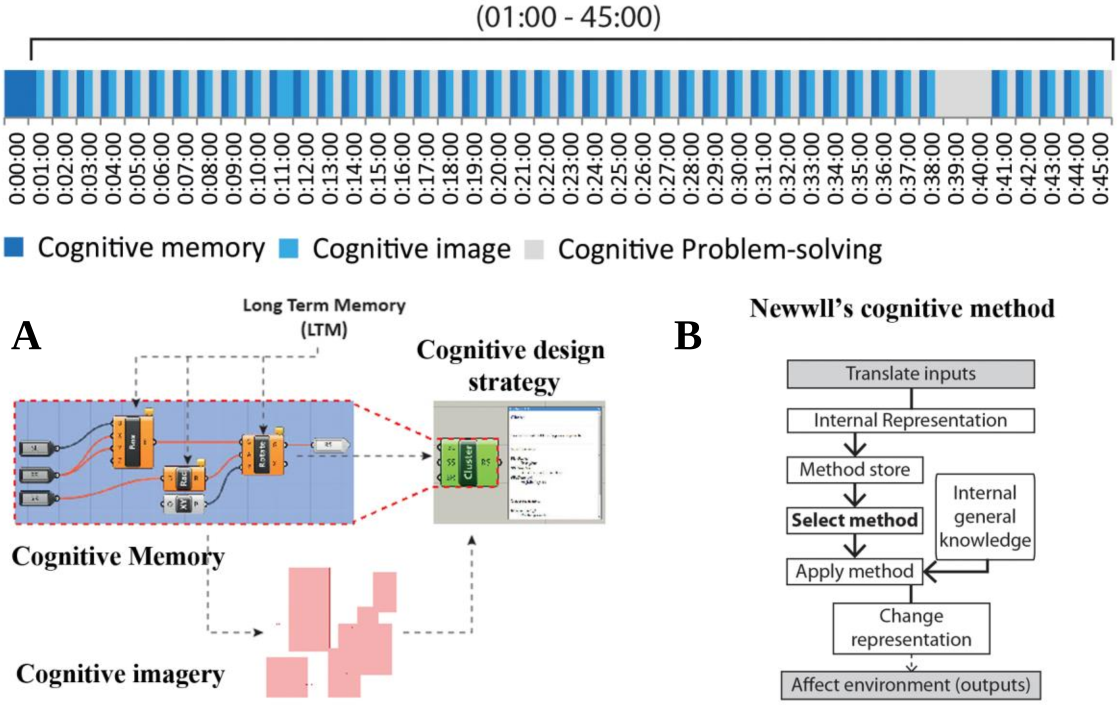
Source: Author reproduced/ SPSS

10.5.2 The CAD process and design cognitions

a) The parametric/algorithmic CAD and the design cognition development

The study of design cognition in algorithmic CAD (Grasshopper), has been found to be linked to Long-Term Memory – LTM (Newell and Simon, 1972; Posner, 1973). This memory type correlated with algorithmic design functions and parameters, which created an unlimited learning process (Fig.10.11). This is an associated and extendable learning mind process supporting the design cognition from cognitive memory to images and the problem-solving activity. It is an information-based pattern, or design strategy, which helps architects present their design thinking as making a design plan rather than completing a random design action (Fig.10.11-A). This process operated as a system or rule, which was close to Newell's cognitive method (1970) (See the research finding of the protocol study of the CAD cognition in the hospital design process in Section 8.4, Chapter 8). There are usually many heuristic rules applied to the algorithm definitions when completing a cognitive process, and they follow regulation of control, confirmation, acquisition, projection, and representation of information (Fig.10.11-B).

Fig.10.11 Algorithmic CAD design cognition



Source: Author reproduced/ Newwell's (1970) design cognition

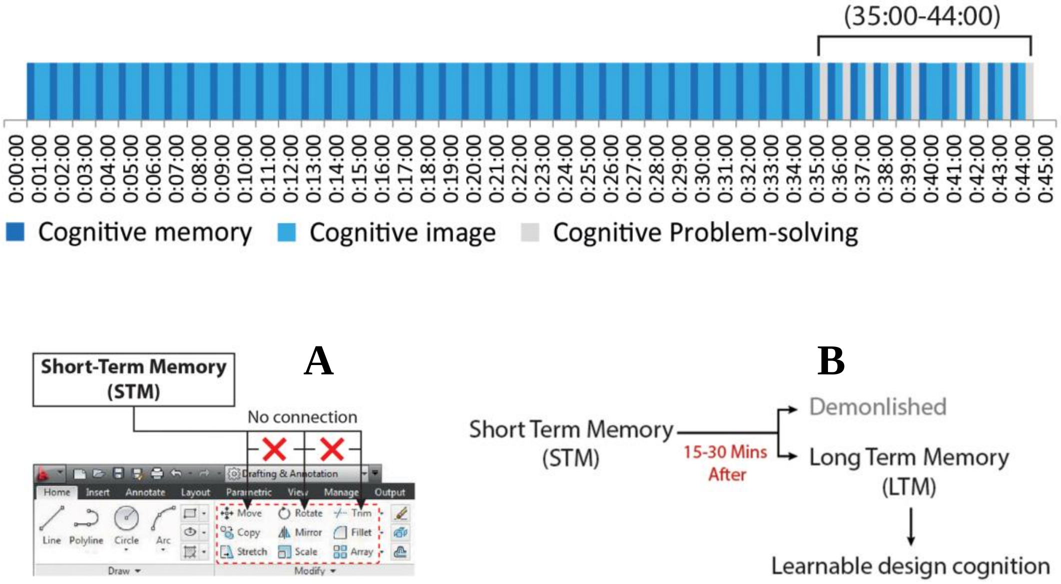
In order to understand how the mind process of design cognition could affect the design problem formulations, the statistical analysis was applied to explore the interrelationship of these design activities. The statistical correlation test (Table 10.7-A) based on the subject of design cognition showed two aspects of the study. First, cognitive memory had a significant correlation with both cognitive image ($r=0.98$, $p<0.00$) and cognitive problem-solving ($r=0.90$, $p<0.00$). It confirmed that LTM helped or supported the cognitive process, keeping it running in three steps (memory, imagery and problem-solution). Dorst and Cross (2001) discovered experienced industrial designers avoid only focusing on individual design subject and tend to connect varied design aspects/subjects to evaluate their design problem and then produce the creative ideas. The LTM-based design activity of the algorithmic CAD can provide an associated design activity which is like the experienced designer, and the design algorithms also supported architects to produce many creative design ideas. Second, identifying design problems had a strong relationship with cognitive memory ($r=0.4$, $p<0.03$) and imagery ($r=0.4$, $p<0.02$) and showed 16% and 17% variance, respectively. It meant the design function selection and the generated images were all connected with the problem identification that could support the problem-solution process at the later stages. (See the research finding of correlation study of the different CAD cognition for hospital design in Section 9.2, Chapter 9). In the study of 'creativity in design', Christiaans (1992) reported the more time a subject spent in identifying and understanding the problem, the better designers were able to achieve an innovative outcome.

b) The nonparametric CAD and the design cognition development

The study of design cognition in nonparametric CAD (AutoCAD) architects found they applied a memory type called 'short-term memory – STM' (Lindsay and Norman, 1972; Newell and Simon, 1964) for their design process (Fig.10.12). The STM cannot store much design information, so it cannot build a valid learning activity in the design process. The design functions in AutoCAD are based on limited and non-extendable design and object editing menus, such as cut, copy, offset, etc (Fig.10.12-A).

These tools are independent and cannot be checked or modified with new design algorithms, which means the cognitive process in design memory and images lack design information and cannot build a learning process for the cognitive problem-solving activity. Therefore, in the problem-solution stage, the nonparametric CAD architects had to apply a strong design statement established on a hypothesis or assumption and presented design instructions for supporting this disconnected type of design cognition (See the research finding of the protocol study of the CAD cognition in the hospital design process in Section 8.4, Chapter 8).

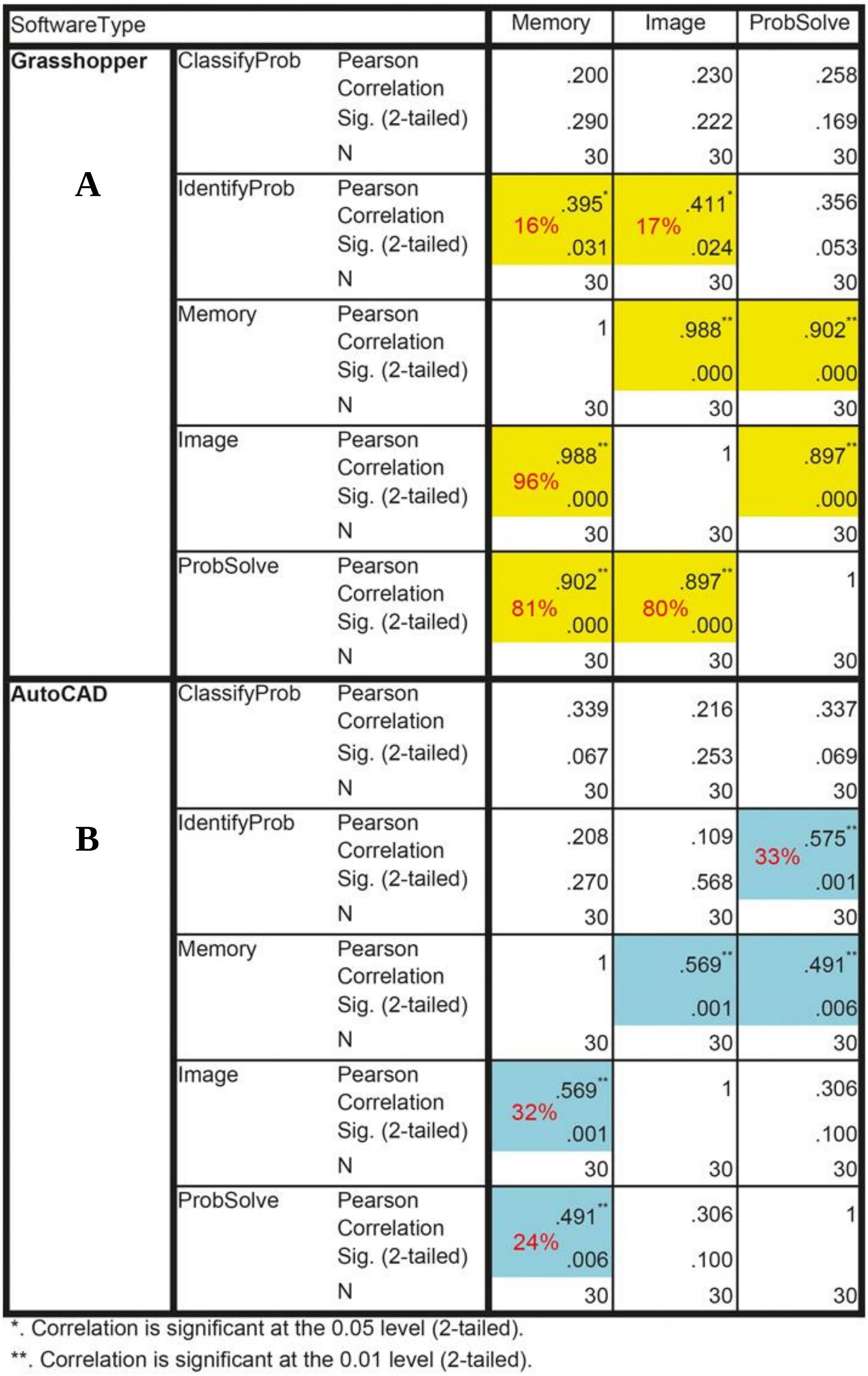
Fig.10.12 Algorithmic CAD design cognition



Source: Author reproduced/ Lindsy and Norman, 1972/ Newell and Simon, 1964, STM

In the correlation analysis, the results (Table 10.7-B) also showed two types of relationships between design cognition and problem formulation in conventional CAD cognition. First, cognitive memory had a significant correlation with cognitive image (r=0.56, p<0.00) and problem-solving (r=0.49, p<0.01). Second, the identification of design problems was shown to have a positive strong correlation to cognitive problem-solving (r=0.57, p<0.00). Although both design methods (parametric and nonparametric) showed similar correlation structures in design cognition, the variance had a lower value for nonparametric design cognition than for the parametric one. Cognitive memory, image and problem-solving were lower than 35% when compared with around 80% for those same aspects in algorithmic design. AutoCAD design cognition indicated a small variance in the interaction between memories and problem-solving, meaning the selection of design functions supported the cognitive problem-solving process to a lesser extent with only a 24% difference (See discussion of ‘the nonparametric CAD cognition and problem formulation processes’ in Section 9.4.1, Chapter 09). As Newell and Simon (1972) explain, STM can only hold information about 15 and 30 minutes, after that, the information could commit to LTM or be demolished. It means the attempted delay or repeat of using STM in the nonparametric CAD process could possibly upgrade the memory type to be LTM and able to construct a learnable design cognition (Fig.10.12-B). Unfortunately, this transferring of cognitive memory is hard to predict and cannot be examined or contribute to extending the learning of the design subject. (See the research finding of correlation study of the different CAD cognition for hospital design in Section 9.2, Chapter 9)

Table10.7 Pearson correlation of design cognition and CAD process



SoftwareType			Memory	Image	ProbSolve
Grasshopper	ClassifyProb	Pearson Correlation	.200	.230	.258
		Sig. (2-tailed)	.290	.222	.169
		N	30	30	30
A	IdentifyProb	Pearson Correlation	16% .395*	17% .411*	.356
		Sig. (2-tailed)	.031	.024	.053
		N	30	30	30
	Memory	Pearson Correlation	1	.988**	.902**
		Sig. (2-tailed)		.000	.000
		N	30	30	30
	Image	Pearson Correlation	96% .988**	1	.897**
		Sig. (2-tailed)	.000		.000
		N	30	30	30
	ProbSolve	Pearson Correlation	81% .902**	80% .897**	1
		Sig. (2-tailed)	.000	.000	
		N	30	30	30
AutoCAD	ClassifyProb	Pearson Correlation	.339	.216	.337
		Sig. (2-tailed)	.067	.253	.069
		N	30	30	30
B	IdentifyProb	Pearson Correlation	.208	.109	33% .575**
		Sig. (2-tailed)	.270	.568	.001
		N	30	30	30
	Memory	Pearson Correlation	1	.569**	.491**
		Sig. (2-tailed)		.001	.006
		N	30	30	30
	Image	Pearson Correlation	32% .569**	1	.306
		Sig. (2-tailed)	.001		.100
		N	30	30	30
	ProbSolve	Pearson Correlation	24% .491**	.306	1
		Sig. (2-tailed)	.006	.100	
		N	30	30	30

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

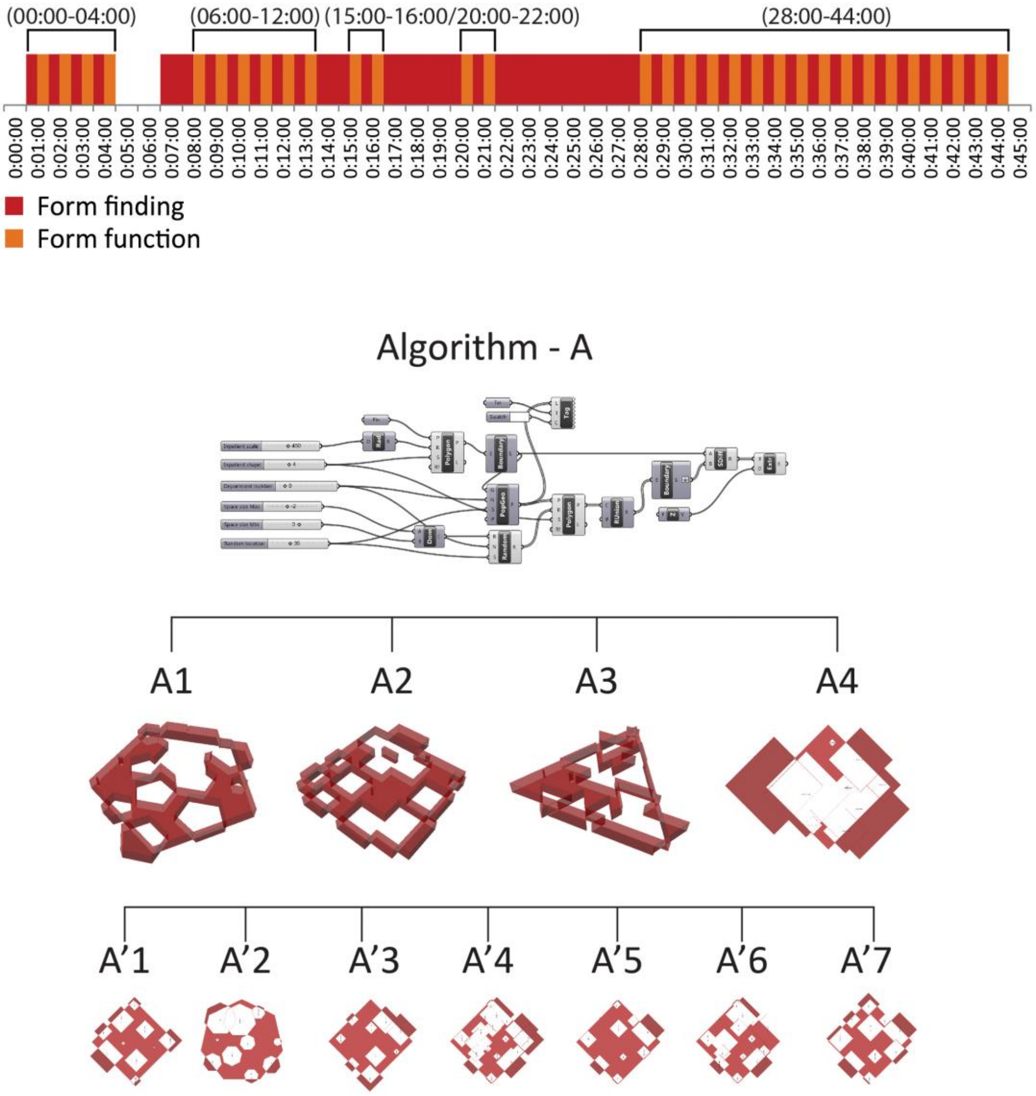
Source: Author reproduced/ SPSS

10.5.3 The CAD process and form explorations

a) The parametric/algorithmic CAD and the form discovering process

In the algorithmic design process, form-finding constituted the major part of the process and the remaining parts only focused on giving functions to the design form (Fig.10.13). As perceived by the protocol process, the algorithmic CAD method did not show the architects to be primarily concerned with building functions such as departmental layouts or engineering facilities, but they only considered and emphasised the geometric relationships – form construction and morphogenetic testing of their design concepts. Simply put, the algorithmic CAD method produced generative design ideas, and this led to the genesis of the form. It was like preparing different schemes to respond to a goal but without setting a goal and following it with only one plan (Fig.10.13-A). This potential form design method by design variation and generative algorithm have shifted the conventional idea of ‘forms following functions’ to ‘form led functions’ (See the research finding of parametric CAD form exploration process in Section 8.5.2, Chapter 8).

Fig.10.13 Algorithmic CAD and form exploration process



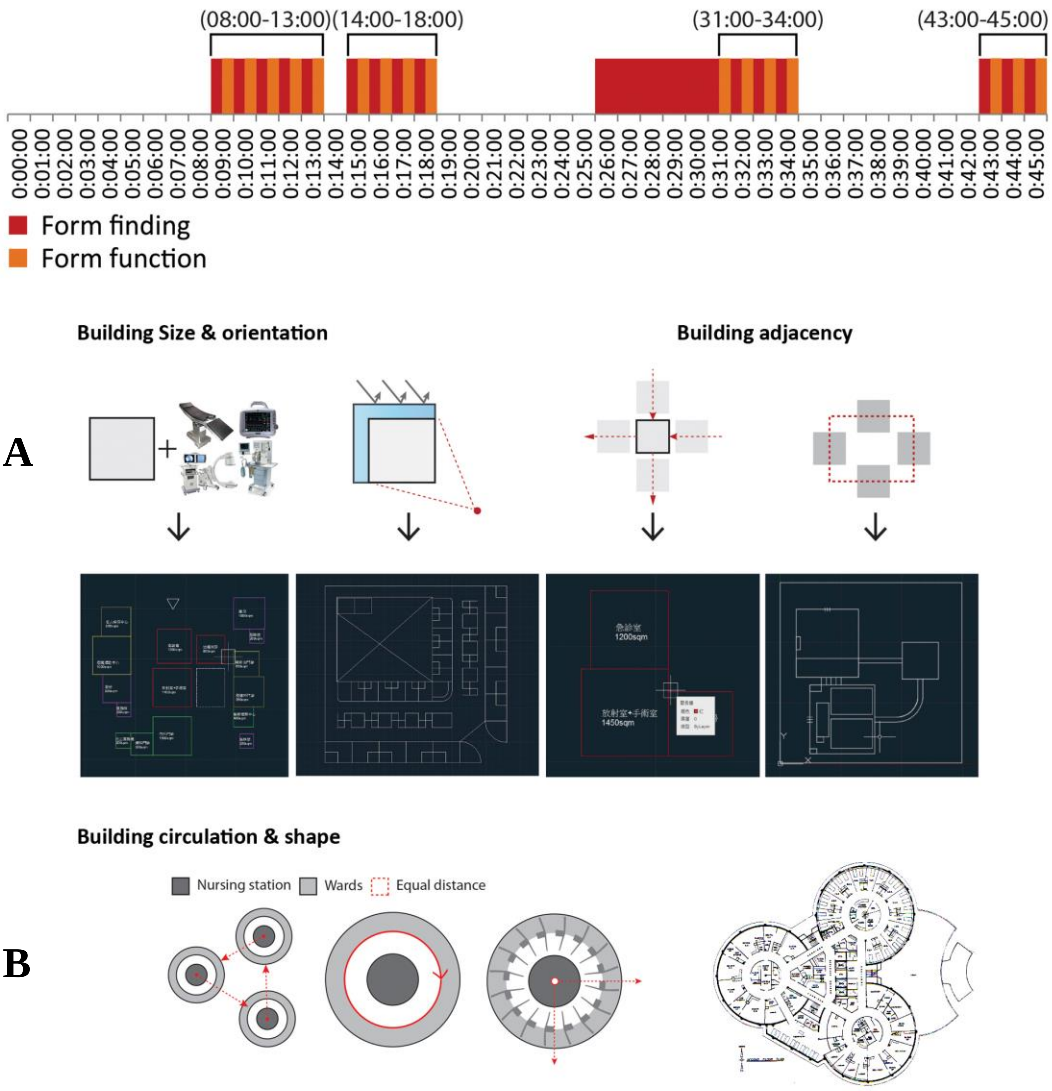
Source: Author reproduced

Some people might argue that the computational form-finding process does not involve human determination; it could cause design failure due to the unspecified building shape from designer's thoughts. The statistical analysis (Table 10.8-A) showed the form finding process of Grasshopper had a significant connection to three cognitive activities; cognitive memory (r=0.7, p<0.00), cognitive image (r=0.7, p<0.00) and cognitive problem-solving (r=0.7, p<0.00, 45% variance) (See the research finding of correlation study of the different CAD form exploration for hospital design in Section 9.5, Chapter 9). These results confirmed the algorithmic design process using the algorithmic methods had associated form finding with intensive design cognition involvement and were determined through a cognitive problem-solving process. In addition, Abdelsalam (1999) stated the algorithmic CAD process allows each designer to insert their own design character using simple or complex mathematical equations to discover a new series of form. Especially in the design of hospital buildings, an optional form proposal means we can better adapt different requirements for departmental layouts and provide for the possibility of future building growth.

b) The nonparametric CAD and the form discovering process

In nonparametric CAD, the protocol analysis showed a form-finding process highly dependent on the relationship of space to functions such as program arrangements or department locations (Fig.10.14). In other words, the form exploration was based on the idea that ‘form follows functions’ (Sullivan, 1930) (See the research finding of nonparametric CAD form exploration process in Section 8.5.1, Chapter 8). In this aspect of the hospital design process, the form exploration was associated with some physical dimensions following the arrangement of functions in the building; for example, building adjacency, spatial shape and departmental orientation (Fig.10.14-A) linked the functional services to the building layout, hospital circulation and building structure (Fig.10.14-B). These dimensions directly connected pre-conceived imagery to design functions (the past design experience) without much concern for a geometric relationship. This means the form-finding activity was based on subjective design determination rather than objective thinking during shape/form explorations. However, this nonparametric form exploration process did not provide a structure for producing design shapes, which created some problems in the design layout process. Also, in this method, it was not just a lack of structure in the form finding process that was shown to have profoundly influenced the architect’s recognition of the necessary geometric type. In terms of the hospital building design section, understanding of the building shape meant avoiding unnecessary design space, which could lead to an increased building budget and slow down the efficiency of medical services (James and Tatton-Brown, 1986). Also, in his publication on shape grammar, Stiny (2006) argues ‘Design is calculating with forms and rules,' and ‘understanding shapes is a useful place to start and outline the limits of design'. So, if architects have a sufficient understanding of shapes and geometric information; it means they would be familiar with design limitations.

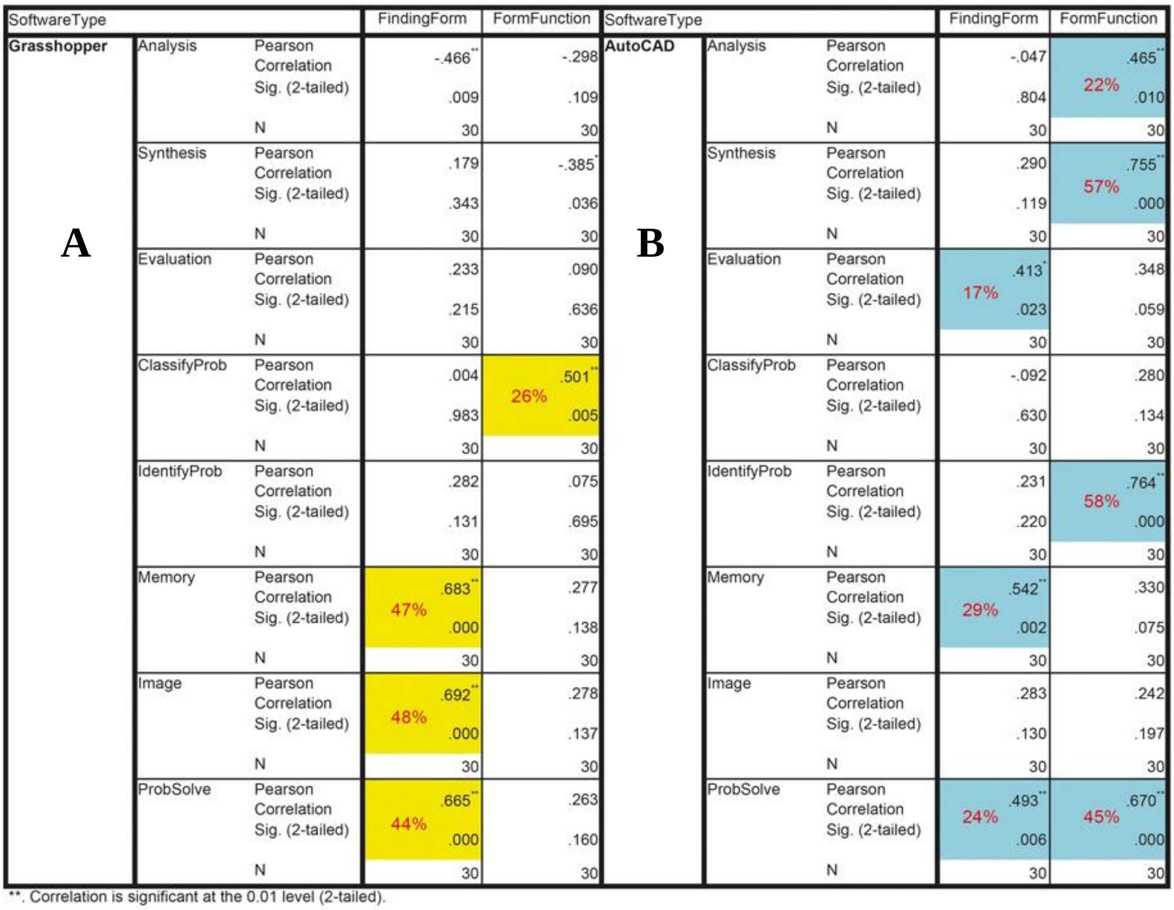
Fig.10.14 Nonparametric CAD and form exploration process



Source: Author reproduced

Turning to the statistical analysis (Table 10.8-B) of the form making process and design behaviour, the AutoCAD method demonstrated a two-part relationship between form exploration and other design activities. In the first, form finding had a significant connection to design evaluation (r=0.41, p<0.02) as well as cognitive memory (r=0.54, p<0.00) and the problem-solving process (r=0.49, p<0.00). The r value suggests the relationships had a medium effect size with 17% to 30% variance. In the second, form function was discovered to have a considerable relationship with design analysis (r=0.46, p<0.01), synthesis (r=0.75, p<0.00), problem identification (r=0.76, p<0.00) and cognitive problem solving (r=0.67, p<0.00). Besides the design analysis, the form function (form dominated by function) presented a big variance from the other three design behaviours: synthesis (57%), identifying problems (58%) and cognitive problem-solving (45%). These results denoted that non-parametric CAD (AutoCAD) design relied on the making of building functions for the design (See the research finding of correlation study of the different CAD form exploration for hospital design in Section 9.5, Chapter 9). In other words, this was typological design thinking that gave functional definitions to the existing form and used these in the design process. According to the theory of typology (Quincy 1755-1849), the geometry (form/shape) is classified and represented by the relevant functions as a design aid. Each type of form contains the meaning of the utilities, so the form finding process does not focus on the development process but chooses an existing functional evaluation to reach a solution for ‘form’ at the cognitive problem-solving stage (See the literature review of typology design in Section 4.3.2.c, Chapter 4). But the risk in typological thinking is that the form only presents a pre-conceived profile without any information relating to design information. Normally, designers/architects define the shape with the proposed function according to their own experience and this is a very subjective process. The main criticism of typology design is that it is considered to turn the type into a stereotype (Gϋney, 2007).

Table10.8 Pearson correlation of form exploration and CAD process



SoftwareType			FindingForm	FormFunction	SoftwareType			FindingForm	FormFunction
Grasshopper	Analysis	Pearson Correlation	-.466**	-.298	**AutoCAD**	Analysis	Pearson Correlation	-.047	22% .465**
		Sig. (2-tailed)	.009	.109			Sig. (2-tailed)	.804	.010
		N	30	30			N	30	30
	Synthesis	Pearson Correlation	.179	-.385*		Synthesis	Pearson Correlation	.290	57% .755**
		Sig. (2-tailed)	.343	.036			Sig. (2-tailed)	.119	.000
A		N	30	30	**B**		N	30	30
	Evaluation	Pearson Correlation	.233	.090		Evaluation	Pearson Correlation	17% .413*	.348
		Sig. (2-tailed)	.215	.636			Sig. (2-tailed)	.023	.059
		N	30	30			N	30	30
	ClassifyProb	Pearson Correlation	.004	26% .501**		ClassifyProb	Pearson Correlation	-.092	.280
		Sig. (2-tailed)	.983	.005			Sig. (2-tailed)	.630	.134
		N	30	30			N	30	30
	IdentifyProb	Pearson Correlation	.282	.075		IdentifyProb	Pearson Correlation	.231	58% .764**
		Sig. (2-tailed)	.131	.695			Sig. (2-tailed)	.220	.000
		N	30	30			N	30	30
	Memory	Pearson Correlation	47% .683**	.277		Memory	Pearson Correlation	29% .542**	.330
		Sig. (2-tailed)	.000	.138			Sig. (2-tailed)	.002	.075
		N	30	30			N	30	30
	Image	Pearson Correlation	48% .692**	.278		Image	Pearson Correlation	.283	.242
		Sig. (2-tailed)	.000	.137			Sig. (2-tailed)	.130	.197
		N	30	30			N	30	30
	ProbSolve	Pearson Correlation	44% .665**	.263		ProbSolve	Pearson Correlation	24% .493**	45% .670**
		Sig. (2-tailed)	.000	.160			Sig. (2-tailed)	.006	.000
		N	30	30			N	30	30

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Source: Author reproduced/ SPSS

10.6 Limitations

The research was carefully designed and executed, but it was limited by some factors in two aspects of the research plan.

In the first, the survey questionnaire was presented to hospital design architects using different CAD types aimed to discover feedback on the long-term design impact of the associated computer design tool. However, the limitation of this retrospective method (survey questionnaire) is that correct data might not always be correctly presented by the participants. For example, a wrong memory might lead to incorrect or misleading answers to questions. In addition, the initial survey sample was opened to different nationalities to have more varied opinions in developing the research but some of the population of different nationalities might not achieve the reliability requirement for the statistical analysis. So, finally, the sample background was selected for the largest collection of nationalities and for a country with an excellent healthcare system - Taiwan/Asia; this restriction has a small impact in that the study results cannot be extended to different user backgrounds where there is also a good level of creativity (Hennessey and Amabile, 2009). However, the sample selection and analysis through the statistical process were objective so the data suggestions can also provide positive results to support further research.

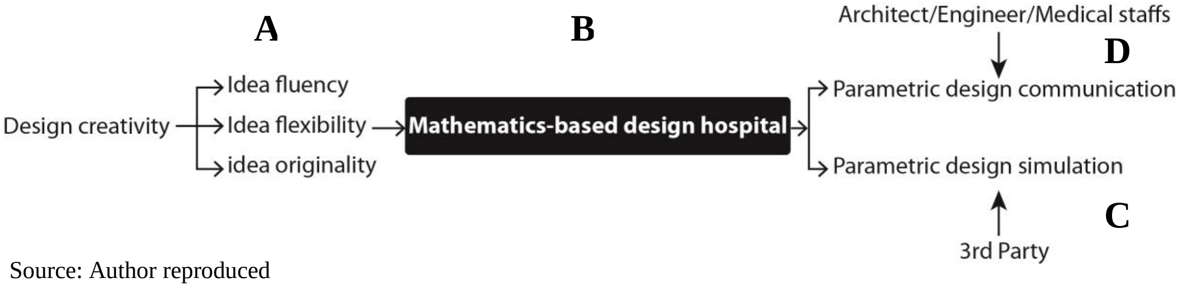
In the second, the computer-based protocol analysis was limited by the time of performance and the code list. A longer recording of the protocol process could allow participants to present more ideas and adapt more to the recording activity. Although the design project was only for an outpatient centre with specific functions, the spatial organisation and requirements were still complicated. So, these challenges were affected by the time restriction. However, protocol analysis is a time-consuming process; the longer the test involved, the greater the data generated. This might increase the study complexity and decrease the research efficiency. Furthermore, the code list was clearly defined but the transfer process was done by the author, so this might lead to the inclusion of subjective views. Especially in this the part of design process, it is sometimes difficult to separate issues clearly or the design cognition could be subjectively identified during the recording process.

10.7 Recommendations

Hospital design is complex; the difficulty of the project is not only in creating space for medical services but also in approaching the problem from an evidence-based design process. The design process could be associated with many different issues but more importantly is how to define them, to find the correlation between the CAD approaches and to identify and discuss how they aid the design process. However, this PhD research did not aim to promote any design application or criticise specific CAD methods. It expected to present a comprehensive overview of how to improve design creativity in new hospital design and sought to suggest scientific research activities, which formed a better theory of design methodology and CAD utilisation for future planning in the healthcare architectural learning environment. So, there are four parts of these research recommendations; the suggestions are also exhibited as a diagram with further explanations.

Firstly, based on an in-depth creative performance comparison between parametric and nonparametric CAD methodologies, results indicate that if the architects aim to improve their design innovation through a greater number of ideas and more variety in idea types and originality (Fig.10.15-A), then using a logical ideation process which is mathematically-based (Fig.10.15-B) could positively support their design ideation. Also, parametric thinking on the content of the design is necessary. The parametric process transfers the physical design observations such as site context or building volume into numeric information; these design elements are coded and forwarded in the exchange, interaction and interpretation between architects and the CAD interface (software). The result of such a process is an absolute and mathematically correct design, which can always be examined by a third party (Fig.10.15-C). In other words, the process of design ideation is no longer vague and abstract but transparent and understandable. This ideation-based design activity may also improve the conventional hospital design practice of making concepts which are largely based on existing design examples. These current hospital design concepts are mainly tested and confirmed by user experience, but they do require a long-term evaluation process to be able to conduct long-term measurements of the design performance. This may mean low efficiency of design assessment and a high possibility of design failure. This might be because the initial design concept could not be tested or evaluated through an objective process. Also, there is not an obvious interaction between design parameters and functional requirements. Therefore, a lack of information exchange (Fig.10.15-D) at the early design stage of hospital planning can cause problematic design development in terms of design, building construction or utilisation of space. More importantly, it may also restrict the creative design development for new hospital design ideas.

Fig.10.15 Design creativity and mathematical design thinking for hospitals

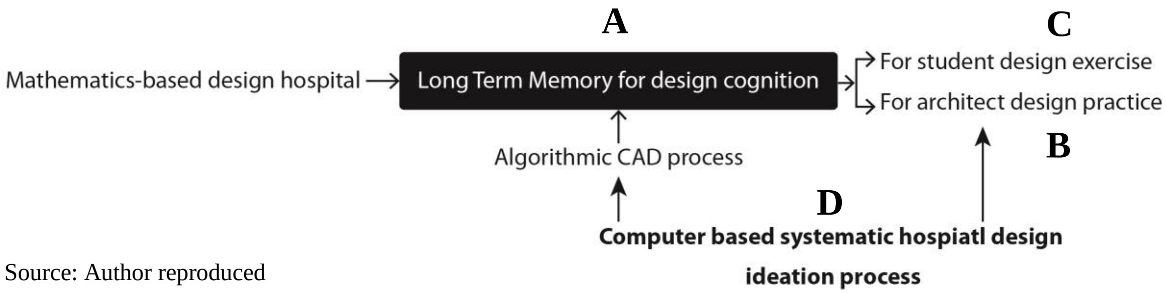


Source: Author reproduced

Secondly, the specific parametric design project for a complex building which was used provided a practical design example and suggested particular design methodology insights that could improve innovation in new hospital design ideas. Those case studies demonstrated that while the design went well using a parametric process, it not only could benefit design integration but could also help in the prediction of conceptual problems. In hospital design, as part of a complex building typology, design errors could have a significant effect on medical services and cause critical damage to patient health or lives. Conventional hospital design methods rely on a complicated documentation process to examine design plans and control design development. This may also block innovative thinking at the early design stage. On the other hand, the parametric design method which supports an instant design evaluation system may, in fact, provide an efficient and objective process. Moreover, the parameter-based design library could follow the latest medical updates on spatial requirements, so it can address the changing nature of design problems arising from advances in medicine. Through the parametric principle, different professions together can contribute their knowledge and build a communication platform to promote better design quality for future healthcare architecture.

Thirdly, the findings of the parametric/algorithmic design process show the importance of having structured design thinking to the creativity of design, and how the structured design system helps architects in the design testing process as well as development in design cognition. In particular, the algorithmic design method creates an effective cognitive learning process established on LTM (Fig.10.16-A). LTM plays a vital role in design cognition and supports architects in applying strategic thinking in the production of their design ideas. The impact of LTM/strategic thinking on the cognitive process could profoundly increase architects' (Fig.10.16-B) and students' (Fig.10.16-C) ability to build their own experience of design planning, which gives a pointer for investment in hospital design education. Traditional architectural education or training has very little space committed to healthcare design in design studios. This might be because healthcare buildings such as hospitals are a specialist typology of buildings that require knowledge from an array of disciplines or professions and is of such a scale that makes it a complex and difficult design undertaking. Parametric design using the algorithmic method (Fig.10.16-D) could address this partly by breaking down the design process into finite steps and exhibit how ideas could be generated and translated into varied shapes. For example, the efficiency of service circulation could be related to the distance calculated between design geometries.

Fig.10.16 LTM, design learning and systematic thinking for hospital design ideation



Source: Author reproduced

Finally, the dual research methodologies established for this thesis only targeted a specific group and size. If the sample size and background were to be extended, it would mean the analysis and evaluation, especially the statistical investigation, could generate more varied findings with a stronger support from a larger sample. Also, the research was exclusively focused on design creativity; this means the design ideas and reviews were based on a flexible early design stage. The design of hospitals in practice contains many more complex issues and building considerations, meaning the experimental design ideas used cannot fully represent the real hospital building issues. However, if architects can learn lessons from applying the suggested design methods and adopt a generative design process for their ideas, then their performance may directly support innovative hospital development and increase the potential for producing creative new hospital designs in the near future.

10.8 Further areas of research

This PhD thesis discovered creativity measurement and design psychology studies for the hospital design ideation process using CAD methods. This section is going to extend the psychology discussion of design thinking processes, namely, design cognition, and further explore the differences between Long Term Memory (LTM) – found in the algorithmic CAD design process, and Short Term Memory (STM) – found in the conventional CAD design process, in mental processes relating to CAD hospital design processes and effects. The first part identifies the distinguishing features of LTM and STM in terms of the capacity of mental processes and the ability to affect the design cognition process. The second part further explores how those two types of cognitive memory relate to thinking approaches for cognitive problem-solving processes.

10.8.1 Cognitive memory of LTM and STM

According to the protocol analysis in chapter 8 and 9, the result demonstrated that LTM found in the algorithmic CAD users' thinking process increased learning motivation in design problem solving and helped them to think with diversity. In terms of the memory capability, Newell and Simon (1972) highlight, 'there is no measured limit to the amount of information that can be stored in LTM'. It means the LTM is able to construct design information through the algorithmic script, increasing the complexity/elaboration to the design output. From the protocol analysis reports, this flexible memory type shows its potential to support design cognition, especially at design problem-solving stages. The design algorithm produced by the CAD software package is like cognitive LTM; each algorithm can be connected with others into one functional component and operated as a definition-based algorithmic solution for design proposals (See the research finding of the protocol study of CAD cognition in the hospital design process in Section 8.4, Chapter 8).

By contrast, the STM found in conventional/nonparametric CAD thinking activity did not perform well with respect to the learning process involved and sometimes it even created other problems due to the lack of logical thought in the cognitive process. According to Newell and Simon's (1972) work, STM has a significant limitation in the temporal span, which means 'information will erode if not rehearsed after two seconds'. In addition, Lindsay and Norman's (1972) study suggests 'STM can only hold 2 to 7 units of information at any given time'. Thus, conventional CAD design tools utilising STM only contain a limited amount of design information. If the designer attempts to increase the use of those STMs, the chance of failure in the cognitive process is high and could also be sudden because there is no structure to connect those STMs in the design coordination process (See the research finding of the protocol study of CAD cognition in the hospital design process in Section 8.4, Chapter 8).

10.8.1.1 Cognitive memories and effects to the CAD activity

Due to the disconnected cognitive memory type of STM, the weak cognitive activities could not support design problem-solving activity for the ideation proposal. For example, Design functions in AutoCAD are based on limited and non-extendable non-algorithmic design manipulation options, such as cut, copy, offset, etc. These packaged design tools are menu-driven and can be used in any design geometry but there is no mathematical process involved and there is no structure that influences the interrelation between them. Therefore, architects tend to repeat their design plan in order to avoid unpredictable problems during the idea construction stage. Most of the time they have been found attempting to revise the predominated solution/idea to rationalise their thinking process. Thus, it is significantly affected by the flexibility of the design ideation stage and the elaboration of design problem-solving process. This situation, namely the predominated design thinking, is normally described as a mental thinking method of hypothesis or assumption rather than being evidence-based. But Newell (1970) argues, if the design problem predictions are based on 'hypothesis-and-test', this puts more pressure on the cognitive process in relation to design thinking.

On the other hand, the cognitive memory type of LTM presents a continually cognitive problem-solving activity across the entire algorithmic CAD process. Each design algorithm could be connected and created into a cluster showing the process of final outputs such as design ideas. The algorithmic CAD ideation is like exploration or adventure for the solution finding process because the morphological generating power of the algorithmic CAD offers architects an unlimited discovering process (See the parametric architectural design ideation and expression in Section 4.3.4, Chapter 4). It gives support to the construction of LTM and creates the elaborated cognitive problem-solving activity. This activity is based on heuristic research which was introduced by Newell's (1970) cognitive method; the heuristic rules operate as the regulations of control, confirmation, acquisition, projection, and representation of information. During the design cognition process, the entire problem-solving activity followed many accumulated and procedural design algorithms, which were affected by different heuristic rules. Each rule represented a function that gradually formed the design algorithmic definition for this problem-solving process.

10.8.2 Cognitive memory type and further researches

The study of cognitive psychology based on Long Term memory (LTM) could raise another independent research domain of how hospital design issues could be improved by an understanding of the CAD cognitive memory. According to the research findings, the LTM can improve CAD activity with strategy thinking and adapt complex design concept as mathematical logic (See the research finding of the protocol study of CAD cognition in the hospital design process in Section 8.4, Chapter 8). To extend these studies further, the findings of design cognition are referenced. The following contents are divided into three proposed topics.

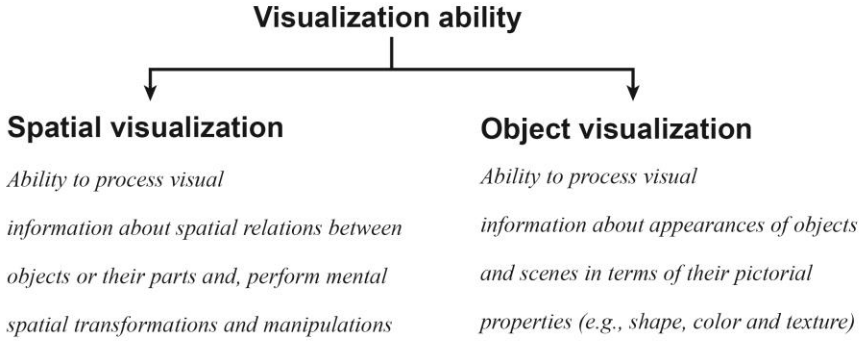
10.8.2.1 Generative algorithms, cognitive memory and human errors

The first concerns the generative design process in algorithmic parametric CAD, which provides flexible, reliable and varied design evaluations. This could suggest a new research topic, namely, that of an investigation into how the generative design process can minimise design errors in the hospital building design process. The generative algorithmic design activity would mean an assessment of design ideas that determine the problematic issues appearing or likely to appear during the hospital design ideation stage. For example, if the architect wants to build a well-designed floorplan layout without a lack of natural lighting, the generative design algorithm could provide varied design models and test these in lighting simulations. Consequently, this process can evaluate the potential impact of lighting design errors and the generative floorplan design. The main reason for establishing this next design extension is based on the research findings on the relationship between LTM and the algorithmic CAD process. It is believed that LTM helps to specify the cognitive operations and reduce the errors appearing during the design process. As Reason, Wagenaar and Hudson (1990) argue in the research into cognitive under-specification and error forms, ‘When cognitive operations are underspecified (flexible), they tend to default to conjecturally appropriate, high-frequency responses’. In other words, this flexible CAD method of giving varied design options cannot only reduce the number of errors but can also improve the quality of the design proposals.

10.8.2.2 Cognitive memory, visual thinking, and creative potential

According to the research examining the relationship between creativity, visualization ability, and visual cognitive style’ Kozhevnikov, Kozhevnikov, Yu and Blazhenkova, (2013) found that imagery has a significant influence on cognitive style and is associated with two creativity types: artistic creativity and scientific creativity. The architectural design process generally concerns two visualisation abilities: object and spatial ability (Fig.10.17) (Kozhevnikov et al., 2015), supporting architects to verify the different building design aspects. For instance, the object visual skill helps the architect to deal with materials and the detail design process; the spatial visual skill supports the optimization of floorplan layout and circulation design. The impact of the imagery cognition should have a connection with the cognitive memory type. For example, the LTM produced by the algorithmic CAD process can provide instant and varied imagery to respond to the design cognition activity (see the research finding of the protocol study of CAD cognition in the hospital design process in Section 8.4, Chapter 8). If new research can extend this domain and develop a discussion based on the impact level from cognitive LTM on the creative dimension of the architect's visual design thinking (ability), it could help us to understand creativity in architectural design from the perspective of architectural drawing and, in turn, increase the creative potential of the design problem solving process.

Fig.10.17 Visualization ability



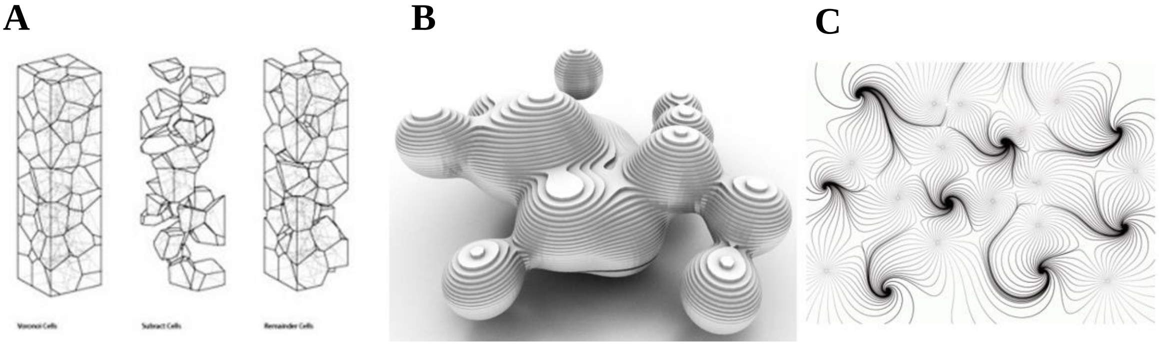
Cited: http://www.nmr.mgh.harvard.edu/mkozhevnlab/?tag=visualization-abilities

10.8.2.3 Design aesthetics and cognitive appraisal

The last aspect concerns judgments of aesthetics in the creativity study which were not mentioned the part of cognitive appraisal in this thesis. As some hospital designs are described as lacking in aesthetics, as being less visually attractive, and lacking comfort in the medical environment (Prasad, 2008), the aesthetic aspect of hospital design could be the next valuable topic in research. Although aesthetics is difficult to be objective on cognitive judgments, criticism is believed to add value and help to understand to art or design work. Thus, by going through a process of criticism, people can improve the organisation of the design profile and its beauty (Stiny and Gips, 1978). For example, from the investigation of the algorithmic CAD process, we can see that the architects presented their design ideas based on mathematical functions such as Voronnoi (Fig.10.18-A), Metaball (Fig.10.18-B), and Streamlines (Fig.10.18-C). These design patterns present the beauty of mathematics and could be evaluated through changing parameters as well as increasing other algorithmic functions for aesthetic interpretation. This algorithmic design interaction is an explicit activity of design cognition, which gives a meaning to geometric composition and also creates a dialogue between the architects' mental matching process and their designed outputs.

In other words, the algorithmic CAD process is able to establish a mathematically-based design reasoning and influences the mental and visual processes of design thinking. The CAD activity can produce a unique aesthetic message and progress the designer's ideation process. It can also improve the transparency of looking through current problems associated with design ideas. For instance, LTM affected by the CAD process shows the design algorithms so, each design output contains its unique set of geometric relationship, which is interpolated as the meaning for design aesthetics (see the research finding of the protocol study of CAD cognition in the hospital design process in Section 8.4, Chapter 8).

Fig.10.18 Aesthetics of algorithmic CAD and products



Cited: matsysdesign.com/ food4rhino.com/ Grasshopper3d.com

Therefore, the cognitive judgement on algorithmic aesthetics could be extended into a new discipline within CAD. In addition, a visual vocabulary can be developed to serve as a framework or a referencing system for a criteria driven appraisal of algorithmic aesthetics and investigate its impact on the hospital design experience.

There are still several possibilities for the extension of research into hospital design and creativity. This PhD thesis provides a novel overview of CAD methods in relation to creative design. It is hoped the present study will contribute to current knowledge and future hospital design research and may also help to develop a better environment for healthcare design in practice as well as in education.

Hospital glossary key

The dreamer hall was a space that is simply an open chamber, sometimes separated into two parts for the different genders. The general intention was to provide a place for sleeping and recovery while people were experiencing illness or discomfort.

The military hospital (Roman empire) was of a uniform layout in building design with efficient service provision that was located to provide easy access from other army barracks so that the wounded could be sent directly to the hospital.

The convent building was an open hall space next to the church that provided services for sick pilgrims.

The monastery hospital and infirmary were a mid-medieval Christian monastery of two building categories, the church and the monastic hospital or infirmary for sick pilgrims.

The open ward was an empty hall that was converted to ward functions. Patients were able to see and hear the sounds from the altar while they stayed in bed.

The cross wards were two open halls in a rectangular shape that intersected with a raised centre part as a chapel.

Symmetrical or panoptical institutions were used for supervision and management; the early asylum hospital was proposed to follow the rule of symmetrical or circular floor plans.

The Nightingale wards were the first scientific knowledge-based ward designed by Florence Nightingale. To provide sufficient natural ventilation, the floorplan design principle was based on the dimensions for air flow – 33 feet wide and 128 feet long. Open courtyards were located between the wards and helped to exchange fresh air.

International style hospitals featured flat roofs, monolithic building blocks, reduced façade decoration, connected by large glasses, and a single-colour or white-only coating. The building was constructed with precast concrete and a steel structure.

The Hill-Burton Act is the standard hospital floorplan construction method published by the US Public Health Service (1941–1946). It included room layouts, bedding numbers, and the reduction of unnecessary procedures for diagnosis and clinics.

The racetrack plan followed the Hill-Burton design standard, where the ward plan was designed as a circular delivery service operating between nursing stations and units, which improved the service efficiency and provided better supervision.

Brutalism hospitals followed the hospital design scheme of the National Health Service (NHS).

UK hospitals were analogous with village and town development, providing healthcare services in small community buildings.

Mothership hospitals were designed as a medical mothership combining many high-tech facilities run with efficient services.

High-tech romanticism hospital design was based on a modular or capsule-like building with high technological facilities and an adaptable construction system.

The **atrium hospital** was designed as a hotel lobby with a shopping mall appearance and a big transparent atrium.

The **new regionalism hospital** was designed like a residence with brick façades, canopy entrance, gable roofs, and homestyle interiors with patterned carpets.

The **sustainable design hospital** aimed to reduce and minimise the adverse environmental effects that might result from architectural operations. This design includes sustainability measurement factors including saving energy, the use of recycled materials, and cultural redevelopment.

A **therapeutic hospital** was designed to help particular patients suffering from specific diseases or conditions to help relieve their symptoms during the recovery stage.

The Greenwich District Hospital (GDH): During the 1960s and 1970s, the GDH was a The Department of Health and Social Security (DHSS) research project to replace an existing old district hospital, St Alfege's. The project was started in 1960, went through three phases in 16 years, and was finally finished in 1976.

The Best Buy Hospital (BBH) was established in 1967 at St Edmunds, UK, and was another research project of the DHSS. It aimed to provide an economic hospital design to replace certain expensive district hospitals such as the GDH.

The Harness and Nucleus Hospitals (HH & NH) were modular design types for new DHSS research projects in the 1970s and 1980s in the UK. In the design briefing, it was found that the most efficient building layouts are based on T, H, and cruciform shape design as this matched standard healthcare requirements.

Design process/method glossary key

Wicked problems: Rittel and Webber (1973) suggest that during the architectural design process, the problem has many unpredictable factors and structures. It is not possible to easily identify individual issues.

Tame problems: Rittel and Webber (1973) suggest engineering design problems follow initial proposals and develop in a clear content, so the type of problem is logical and easy to identify.

Ill-structured problems: Simon (1973) says that architectural design problems were identified as ill-structured problems that do not have clear targets, solution directions, or predictable answers.

Well-structured problems: Simon (1973) says other design problems, such as engineer design, were identified as well-structured problems that have specific goals, a defined solution direction, or accepted answers.

The primary generator: Darke (1979) suggests that many designers apply an ideation process with a primary generator to produce early design concepts with limited objectives.

The **black box method** is a design process that can only be viewed in terms of its inputs and outputs, without any knowledge of its internal working.

The **glass box method**, as opposed to the black box method, analyses design based on its structure, process, and decision-making. The process is constructed as a sequence of events, which includes identification, analysis, synthesis, and evaluation.

Design cognition glossary key

The heuristic method is a mental practice that allows people to solve problems and make judgements. The process contains rules-of-thumb strategies to shorten decision-making time to function without constantly stopping to think about the coming course of action.

Cognitive psychology is a disciplined approach to answering how the human brain processes information and reacts during the design process in the real world.

Adaptive control of thought (ACT) was proposed by Anderson in 1983; he states that there are two kinds of long-term memory associated with the cognitive process, one is called declarative memory and the other is production memory.

General problem solver (GPS) is based on a means-to-an-end process to construct plans with plans for the problem-solving activity.

State, operator, and result (SOAR) is an open-ended and dynamic mind model with a cyclical system based on cognitive construction.

The **artificial neural network (ANN)** is a computing systems approximately designed according the biological neural networks that account for animal brains. The neural network itself is not an algorithm. But it can be the reference as a framework for many different machine learning algorithms to work together and process complex data analysis.

The self-organised map (SOM) is a two-layer type cognitive process that can maximise various feature maps during its operation; designers can use any mapping process to self-organise information and get rich solutions.

Creativity glossary key

Big C: Eminent creativity, a relatively rare display of creativity that has a major impact on others.

Little c: Everyday creativity, daily problem-solving, and the ability to adapt to change.

Creativity force: The creativity is identifies as different force levels. Like a concentric circles, from the centre to the utter, each force/level follows the hierarchy which demonstrates neurological, affect/cognition/training, individual/personality, groups, social environment, culture/society, and systems approach.

Scientific creativity: Creativity apparent in scientific discovery, for example, a comprehensive study of science and scientific discovery requires a sufficiently rich set of ideas for a detailed and logical investigation.

Artistic creativity: Creativity that exhibits an artistic innovation process including skills and talent to create fine works of art such as painting, drawing, sculpting, or musical composition. Artistic creativity is about the sense or talent to use the imagination to create and problem-solve without any scientific techniques.

Object visualisation is a term used to describe one visual thinking type. This type of visual process is based on an object's colour, texture, pictorial detail, shape, and size.

Spatial visualisation is a term used to describe the other visual thinking type that is based on a spatial location, movement, spatial transformations, and relations.

The **Torrance test of creative thinking (TTCT)** was created by Torrance (1971) to evaluate the creativity of the design process according to three specific criteria: idea fluency (idea numbers), idea flexibility (idea types), and idea originality (uniqueness).

Consensual Assessment Technique (CAT): Amabile (1982) suggests a product-centred definition as an empirical research methodology for defining creativity. The test consists of three parts: a creativity cluster (novel use of material, novel idea, variation in shapes, details, and complexity), a technical cluster (organisation, neatness, planning, symmetry, and expression of meaning), and aesthetic judgement (liking, aesthetic appeal, and worthy displaying).

Computer glossary key

NVivo08 is a qualitative data analysis computer software package produced by QSR International. It was designed for qualitative researchers working with very rich text-based and/or multimedia information, where deep levels of analysis on small or large volumes of data are required.

Computer-Aided Design (CAD) is software used by architects, engineers, drafters, artists, and other professionals to produce design illustrations and technical drawings. CAD software can be applied to generate 2D drawings or 3D digital models.

Non-Uniform Rational Basis Spline (NURBS) is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces.

Rhinoceros3D is a commercial 3D computer graphics and CAD application software developed by Robert McNeel and Associates, founded in 1980. The software's geometry is based on the NURBS mathematical modelling system, which focuses on producing a mathematically precise representation of curves and freeform surfaces in computer graphics.

Nonparametric architectural design methods are tools that include a pencil, T-square, scales, drawing board, and conventional CAD products such as the electric sketchpad or AutoCAD, and representations like hand sketching, physical modelling, and traditional CAD digital drawing.

Typology design is a traditional design methodology using systematic thinking, which was inspired by comparative physical building environments.

Parametric architectural design methods offer variable features with mathematic or geometric algorithms. The parametric model is created by values for parameters, variables, and equations to establish the correlations between the objects or geometries. Conceptual parametric design means creating new computing objects (geometries) and operating them by using parametric values, a norm used in programs such as Grasshopper (a plug-in for Rhinoceros). On the other hand, constructive parametric design assembles the design elements by using a pre-set parametric system and integrates the relationships for building construction, such as a procedure found in software packages like Revit and ArchiCAD.

Algorithmic CAD glossary key

Grasshopper is a visual programming language and environment, developed by David Rutten at Robert McNeel and Associates, that runs within the Rhinoceros 3D. Design functions are made by dragging components onto a canvas. The outputs to these components are then connected to the inputs of subsequent components. Grasshopper is primarily used to build generative algorithms and its program may also contain many types of algorithms including numeric, audio-visual, texture, and haptic tools.

Metaball is a function of generating computer graphics, organic-looking n-dimensional geometries, which was invented by Jim Blinn in the early 1980s. Each metaball is defined as a function in n-dimensions. Once a threshold value is chosen to research the number of solid volumes, the geometry transforms and creates a new output.

Isovist is a visual measurement plug-in for Grasshopper; the function is the set of all points visible from a given vantage point in space and with respect to an environment. The shape and size of an isovist are liable to change with position.

Galapagos is a computing algorithm based in Grasshopper that provides a generic platform for the application of evolutionary algorithms to be used on a wide variety of problems. The applications apply evolutionary logic and are either focused on solving specific problems or they are generic libraries that allow programmers to piggyback along.

Streamline is a plug-in to visualise a vector field that is generated through positive and negative point charges. The path lines (streamlines) are calculated with the ‘Runge-Kutta 4th Order Method’ (short form ‘RK4’), developed by the German mathematicians C. Runge and M.W. Kutta around 1900.

Voronoi: in mathematics, a Voronoi diagram is a partitioning of a plane into regions/units based on the distance to points in a specific subset of the plane. The points are specified beforehand, and for each unit, there is a corresponding region consisting of all points closer to that seed than to any other.

Building information modelling (BIM) is a design and documentation system that supports the design, drawing, and scheduling required for a building project. BIM delivers information about project design, scope, quantities, and phases when you need it. The current operating software packages include Revit and ArchiCAD.

Algorithmic CAD process: Berlinski (2000) defined an algorithm ‘as a finite procedure, written in a fixed symbolic vocabulary, governed by precise instructions, moving in discrete steps, 1, 2, 3…, whose execution requires no insight, cleverness, intuition, intelligence or perspicuity, and that, sooner or later, come to an end.’ The algorithmic CAD process is understood as programs or programming languages for parametric design methods.

Population thinking is the idea that goes against typology thinking and is also recognised as the proper explanation for parametric design methods. Population thinking indicates objects by their characteristic process. It is a morphogenetic process that provides an understanding of those communications rather than focusing on a single geometry.

A **generative algorithm** is an iterative design process based on algorithms. Design algorithms involve a program that will generate a certain number of design results that can meet certain constraints. The designer is able to manipulate design algorithms by changing the minimal and maximal parameters in order to explore or reduce the number of outputs from which to choose.

Emergent algorithms can exhibit/imitate emergent behaviour from some particular systems. For example, to study and define a rule to the design algorithm that can generate a biometric form product, like structure design of bird net or tree branch.

Statistics glossary key

Statistical Package for the Social Sciences (SPSS) is a widely used program for statistical analysis in social science. It has been used for different research, such as market research, health research, surveys, and by groups such as government, education researchers, marketing organisations, data miners, and others.

Nominal variable: This variable type has two or more categories without having any kind of natural order, they are variables with no numeric value, such as occupation or political party affiliation.

Ordinal variable: This variable type contains a categoric variable for which the possible values are ordered. Ordinal variables can be identified as in-between, categorical, and quantitative variables, for example, scores might be categorised as 1, 1.5, or 2.

Mean: The mean value shows the central tendency of the data, or the average, in typical statistical observations.

Standard Deviation (SD): the value indicates a variation in the data distribution; a small value means close proximity between the variables and more coherence in the data and a large value means a great range of variety and data dispersion.

Histogram: exhibits a frequency-based data distribution with the selected variable.

Skewness: The skewed shape (bell shape) and the mean indicate the general tendency of the variable. On the other hand, the skewness and the skew’s side on the histogram identifies the tendency of the variable.

Scatter: The scatter diagram explores the regression correlation between two variables.

The Pearson correlation can compute the strength and direction of the linear relationship between two variables.

The partial correlation is a statistical function that provides a measure of the strength and direction of a linear relationship between two continuous variables while controlling for the effect of one or more other continuous variables.

One-way ANOVA is used to determine whether there are any statistically significant differences between the mean of three or more independent groups/variables.

Percentiles are a measure used in statistics indicating the value below which a given percentage of observations in a group of observations falls.

The T Test is a type of inferential statistic that is used to determine if there is a significant difference between the mean of two groups that may be related in certain features.

The KW-Test is a rank-based nonparametric test that can be applied to determine if there are statistically significant differences between two or more groups of an independent variable or an ordinal dependent variable.

The U Test, also called the Mann–Whitney U test, is a nonparametric test of the null hypothesis where it is equally likely that a randomly selected value from one sample will be less than or greater than a randomly selected value from a second sample.

The factor analysis is a statistical function employed to describe variability among observed correlated variables in terms of a potentially lower number of unobserved variables called factors.

Protocol analysis is a psychological research approach that draws out verbal reports from research proposals. Protocol analysis is applied to study thinking in cognitive psychology, behaviour analysis, and cognitive science.

Eta squared is a statistical measure of effect size used in t tests as well as univariate and multivariate analyses of variance.

Regression test: In statistics, linear regression is a linear approach to modelling the relationship between a scalar response and one or more explanatory variables.

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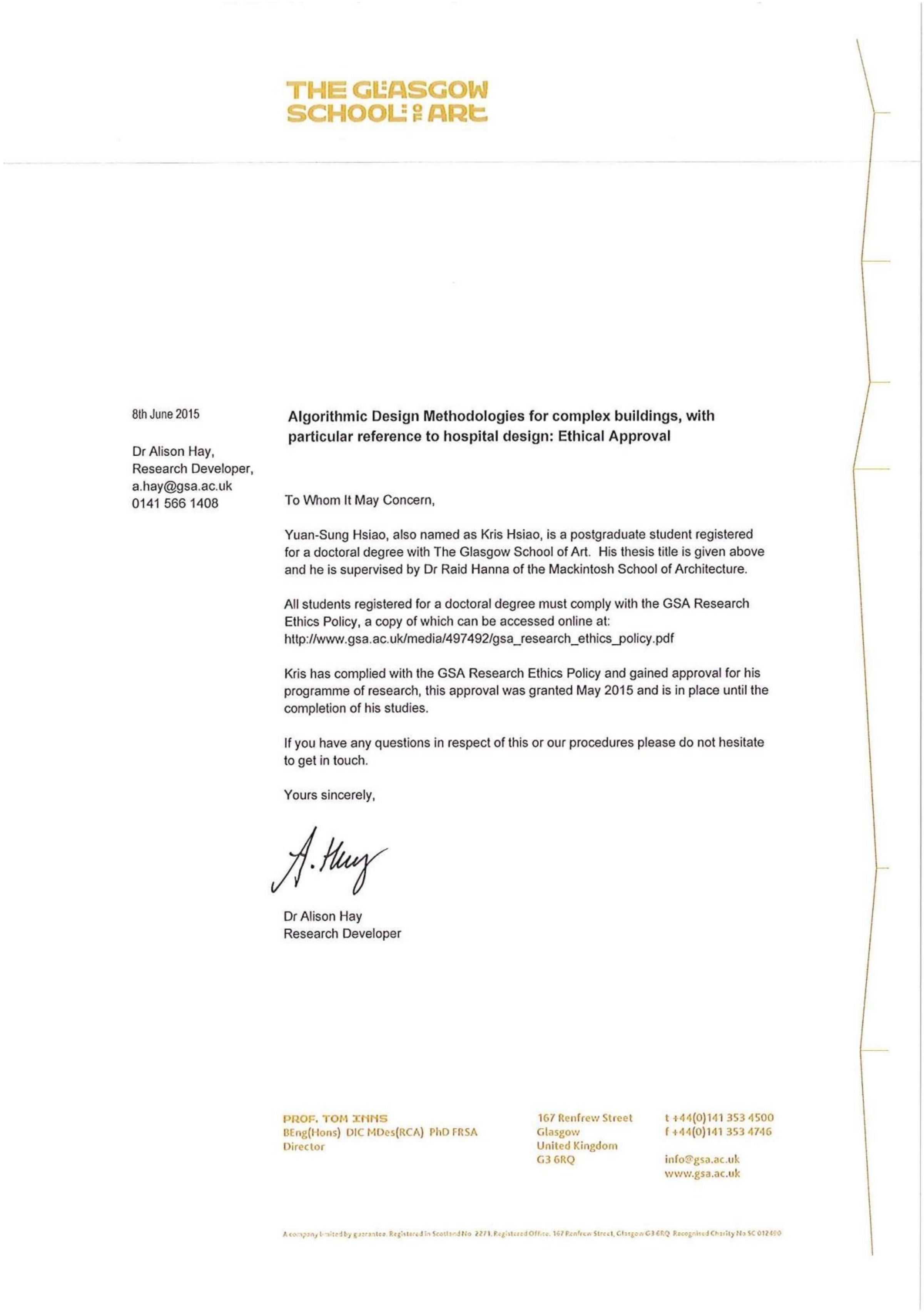
Appendix

Appendix 1



THE GLASGOW
SCHOOL OF ART

8th June 2015

Dr Alison Hay,
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Algorithmic Design Methodologies for complex buildings, with particular reference to hospital design: Ethical Approval

To Whom It May Concern,

Yuan-Sung Hsiao, also named as Kris Hsiao, is a postgraduate student registered for a doctoral degree with The Glasgow School of Art. His thesis title is given above and he is supervised by Dr Raid Hanna of the Mackintosh School of Architecture.

All students registered for a doctoral degree must comply with the GSA Research Ethics Policy, a copy of which can be accessed online at:
http://www.gsa.ac.uk/media/497492/gsa_research_ethics_policy.pdf

Kris has complied with the GSA Research Ethics Policy and gained approval for his programme of research, this approval was granted May 2015 and is in place until the completion of his studies.

If you have any questions in respect of this or our procedures please do not hesitate to get in touch.

Yours sincerely,

A. Hay

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Appendix 8.1

Nonparametric CAD process

Architect 10

00:00 From my experience, the complexity of hospital design depends on functional programs like departments and circulations; so service efficiency is the most vital point for departmental layouts.

00:56 Therefore, I would like to start with a centralized design proposal. **(Design Analysis)**

01:00 As the task requests that the A&E center and Operating Theater are connected together.
It is core that they are also in the same zone. **(Design Synthesis)**

02:03 When it comes to the functional design for other spatial programs, such as a day ward, it may have pregnant woman nearby therefore the ward area needs to be moved forward. **(Design Analysis)**
04:23 Hence, the Outpatient Clinic Dept. and sickroom can be connected. In conclusion, from sectional relationships, it is fine to locate the ward area on the ground floor… **(Design Analysis)**

05:30 Un… there is a problem; seems the floorplan shape cannot allow me to shorten the distance from the separate entrance to the A&E center. **(Design Analysis)** **(Design Synthesis)**

11:09 (Silent and thinking…) **(Design Synthesis)**

20:25However the distance between A&E and entrance is significantly important that could affect the rescue time in some kinds of busy period; **(Design Analysis)** there is trouble if A&E is located too far from the entrance. **(Design Synthesis)** I should have realized this problem; unfortunately the AutoCAD did not have a function to allow me to check for spatial distance while making my design drawing… **(Design Synthesis)**

35:52 OK I will try another layout type, and this time I would start with A&E center designed with the entrance together in the beginning… **(Design Analysis)** **(Design Synthesis)** Or maybe I can start to work on moving those sub-rooms and try to get enough space for making the shortest distance for A&E center. **(Design Synthesis)**

Architect 5

00:00
We’re going to use AutoCAD to conduct the hospital design process
02:53
Firstly, the initial concept is to determine the basic size of a unit by analysing the character of the program, we set 50sqm as a basic unit and try to fit into the grid system **(Design Analysis)**
06:27
We will first setup a basic rectangular grid system, and fill up the grid by putting in the unit. **(Design Analysis)**
07:30
From the size of each program, we know the smallest size of unit is 50sqm. Now we going to build up the grid with the minimum size of 5x10 meters, and then we start arranging the space. **(Design Analysis)**
11:04
The next setting is to fill up the grid with each of the specific space programs

11:23
Like a magic cube, bringing them into the system **(Design Analysis)**

12:27
We place the operation room at the center of the layout; we make it as an anchor for space arrangement. **(Design Synthesis)**
So ,we need to occupy 29 units for 1450 sqm space volume **(Design Analysis)** **(Design Synthesis)**
14:00
I roughly draw out the size of a space **(Design Synthesis)**
14:45
The first space volume will roughly occupy this amount of area, then we place the following spaces which are the senior citizen ward, maternity ward, and emergency ward **(Design Analysis)** **(Design Synthesis)**
19:22
After determining all the space volumes, the operation room and X-ray center are illustrated with blue solid hatch, next is to differentiate their volume in 3d. **(Design Analysis)** **(Design Synthesis)**
20:00
So far, when the space is becoming 3D, there will be an accuracy problem in calculation, the current phase is to roughly know the required space volume, then we can further develop according to the layout. **(Design Analysis)** **(Design Synthesis)**
22:00
Let’s assume that the spaces with similar characteristics are bound in the same region **(Design Analysis)** **(Design Synthesis)**
23:46
We turn off the grid so that it doesn’t interfere with the alteration on the second layout **(Design Analysis)** **(Design Synthesis)**
24:13
Now we need to think about the morphing process **(Design Analysis)** **(Design Synthesis)**
25:30
Let’s first define a circulation route, at the beginning part; 2 circulation routes may direct and dictate the layout into a different direction. **(Design Synthesis)**

Architect 4

01:42 Here are some requirement of design area. I’ll just write it down. **(Design Analysis)**
06:42 **(Design Analysis)** **(Design Synthesis)**

Operating theater	1450 sqm
Geriatrics Dept.	850 sqm
Gynecology Dept.	900 sqm
Kitchen	600 sqm
Rehabilitation Dept.	950 sqm
Rehabilitation Outpatient Dept.	950 sqm
Occupational Therapy Dept.	650 sqm
Psychiatry Dept.	800 sqm
Emergency Room	1200 sqm
Social Work Services	400 sqm
Outpatient Clinic Dept.	2000 sqm
Ward Area	3000 sqm

12:11 Most of these (spaces) are in square meters (units). The smallest space is the Social Service Dept., and the biggest one is the operating theater. **(Design Analysis)**

16:35 Because all of the units are in square meters and the numbers are in integer number such as 1450 so we can have a modular design while we operate in CAD. **(Design Analysis)**

17:01 Firstly, I create a 10*10 model. It seems too small so change to 500*500
Usually, there are rectangular spaces while we are designing with AutoCAD. So, when I want to try a fancy design, I will arrange the program first, and then transform the elevation outline…
(Design Analysis) **(Design Synthesis)**

21:45 This is our first layer. We start to put function design to the departments
Here, we draw a 100*100 grid here, then move this design template (the grid) to the space we needed. **(Design Analysis)**
24:01 So, we put the drawing order of the grid system to the back. **(Design Synthesis)**
It seems not clear enough, but the object is over the grid in this viewpoint.

31:33 We better move the square to another place to make it more obvious. **(Design Synthesis)**

36:55 It means that in the following step, I will use the white frame as the standard module. **(Design Analysis)**

41:22 Functional programming will be the prior consideration while designing in CAD. So we list down the tasks over here. **(Design Synthesis)**

We create a grid system and change the grid line into color 250.
We will have our design beyond this grid system..

43:00 We start to sort out the spaces which might be on the ground floor. **(Design Synthesis)**
The task has categorized the same properties of the spaces. **(Design Synthesis)**
Social Services Dept. and Outpatient Clinic Department have the same special properties,

44:01 So, these two spaces should be on the ground floor. **(Design Synthesis)**
And then, the emergency room, kitchen, Gynecology Dept., Geriatrics Dept. and radiation center would are of the same type. **(Design Synthesis)**
And the next category is the rehabilitation Dept., occupational therapy Dept., psychiatry Dept.
Processing in the CAD environment is not freely available, this brings some trouble, like we will separate the space into tranquil or crowded, open or restricted area. Maybe we can have a basic program. **(Design Synthesis)**
We can list out the ground floor program, and just mark a cross for the rest…

Appendix 8.2

Parametric CAD process

Architect 1

00:32 For the inpatient centre, I think the deep-plan system plays an important part in the layout design. **(Design Analysis)**

01:02 However, the traditional way of designing a deep-plan system is based on clustering space design and then moving to the corridor system, then making the circulation design which I think is less interesting for this design task. So I would like to try and make a line-graph design partner rather than making geometric arrangement for this deep-plan proposal. **(Design Analysis)**

01:55 Here the functional algorithm is called: streamline. It is a mathematics based line graph which presents an instantaneous, tangent curve based on the vector presenting the velocity of the flow. However, in the design aspect, I assume this smooth line system could offer better circulation design such as for bed transporting or nurse movement. **(Design Analysis)**

03:21 We should start from giving proposed points as the functional room like clinic or day wards. Then the algorithmic function (grasshopper component) is asking to give value of the points. **(Design Synthesis)** It could be the service ranking or type of the department; for example, the value of A&E centre could be more than reception. **(Design Synthesis)** Following the instructions, here we are giving the rest of the parameters to feed the design algorithm…**(Design Synthesis)**

12:16 OK so in order to understand if this streamline gives an optimized result, I will apply a computing evaluation, the CUBRA, to calculate the most simple line-graph generated by the streamline. **(Design Evaluation)** The CUBRA will follow my pre-set parameters, for example, the shortest distance between lines **(Design Evaluation)**, or longest line length **(Design Evaluation)**, to merge my line pattern and give it an optimized result. **(Design Evaluation)** This gives varied options if I wish to create the different departmental layouts with the deep plan system… **(Design Evaluation)**

27:11 This type is not my ideal pattern because the lines are too close to each other that mean there is no space between departments **(Design Evaluation)**; however, I will change the input numbers so we can try again the different pattern. **(Design Evaluation)**

Architect 3

00:36 From my experience, the traditional hospital inpatient centre is always designed as a clustered layout system within a bounding box. This could be good option because departments are close to each other. **(Design Analysis)**

But that result, the clustered design type, I personally believe, is caused by the CAD tool and its limitations. It means if we are using a different CAD tool and design method there might be some different results which could be presented.

01:00 For example, in Grasshopper, there is a function called ‘ Metaball’ ; it is a very good function to solve the clustered space with multi-circular shapes. It is also a bit like a ‘cell division’ process which I personally like and for me it feels more interesting when doing the design layouts.

However, in Grasshopper this Metaball is based on a mathematical calculation between multiple geometries, so I would say it is logical process of making a new shape of design layout rather than just an another typological design like earlier modernist architectural design ..haha **(Design Analysis)**

02:56 Next we can start to give our space numbers, scale and the proposed location. **(Design Synthesis)**

04:22 Here for the proposed location I applied another algorithm called 'random numbers', this gives computed random numbers to change the location of my points and also affects the layout compositions… **(Design Synthesis)**

13:59 I think we should have more space for each room so I would say 20-50 in this parameter slider …. **(Design Synthesis)** **(Design Evaluation)**

30:01 Here there is a merge value which indicates the distance I wish to give between departments. Because this is the inpatient centre design, I might just set a range distance between 1-5 meters… **(Design Synthesis)** **(Design Evaluation)**

19:00 So far we have constructed the Metaball algorithm so I can generate unlimited options based on this type of design plan. However, I still not sure what is the best solution for my design, because I hope I can figure out which one has the shortest distance between departments, or say these Metaball units. **(Design Synthesis)** **(Design Evaluation)** So I will use an algorithmic computing function – Galapagos can help me to calculate the result depending on the optimized factor I gave such as distance between departments. **(Design Evaluation)**

31:00 According to the calculation, the minimum distance of 2-3meters is the shortest distance and based on one type of layout which I think is good for this design proposal… **(Design Evaluation)**

35:21 Or we can try to test by putting in the 'maximum distance' for the calculation, it will be around 10 meters. Un… it could present if I want some particular department to have a quieter quality like a geriatric department… **(Design Evaluation)**

Architect 6

00:51 We have read the task is to provide these essential program spaces, so I will start with building program boxes and combining them in a clustered type of design layout. **(Design Analysis)**

02:12 Anyway, in algorithmic CAD there is no rapid way to make a program box. I need to find an geometric construction function called (Centre Box) and give width and length so I can apply 'area' to calculate the right scale for this specific space… **(Design Synthesis)** and use intersection to unify two or three spaces into a clustered block… **(Design Synthesis)**

16:12 This process might look boring but in fact I feel I have more understandings of each space and the relation between other relevant functional rooms. **(Design Analysis)** **(Design Synthesis)**

19:43 For example, I can see the width and length of these clinic spaces; if I wish to think about the combination of them, I also need to consider whether the final layout would involve too long distances for service circulation or any other trouble… **(Design Synthesis)** **(Design Evaluation)**

35:21 This mathematical design process allows me to think of space mathematically but, of course, my previous experience also helps to determine some points. However, I would say the parameter based design process helps me to identify the space through numbers, scales and that physical information rather than just finding a template to cover all my ideas… **(Design Synthesis)** **(Design Evaluation)**

Appendix 8.3

Nonparametric CAD_ Problem formulation

Architect 7

02:25 For the inpatient design, there are some problems which need to be classified before we process the layout design. **(Problem classification)**

03:01 First, the room size and facilities, like maternity wards, operation day wards and intensive care wards. From my experience I would prefer to make program boxes as the calculation and to help my design decision. **(Problem classification)**

08:12 Here I will put a larger size for those rooms according to my program box calculation, it should be around 2*5 meter… **(Problem identification)**

07:22 Second, the location of a department could be affected by environmental conditions such as sufficient lighting for waiting area. **(Problem classification)**

21:55 This very critical part of design issues, without sufficient design experience we will not able to determine where these spaces should be arranged within a location… **(Problem classification)**

27:06 I will arrange the clinic department just next to the reception; one reason is that it is good for outpatients who could easily be served by the reception; the other reason is there should be better natural views and lighting from the main entrance… **(Problem identification)**

28:55 Third the circulation design is important to service efficiency, especially for the clinic departments. I would like to start with the X-ray centre design, according to my previous project design, the X-ray room played a centralized service for the majority of treatments arranged by clinic departments. **(Problem classification)**

39:46 Also the ring road circulation can efficiently sort the medical service system such as equipment delivery, transfer services and supplementary supplies… **(Problem classification)** **(Problem identification)**

Appendix 8.4

Parametric CAD_ Problem formulation

Architect 6

00:23 In the Grasshopper design interface, I normally think of design problems and search for the relevant design algorithms to support my problem formulation. **(Problem classification)**

02:25 We have read the task is to provide these essential program spaces, so I will start with building program boxes and combining them in a clustered type of design layout. **(Problem identification)**

05:50 Anyway, in algorithmic CAD there is no rapid way to make a program box. I need to find an geometric construction function called (Centre Box) and give width and length so I can apply ‘area’ to calculate the right scale for this specific space… and use intersection to unify two or three spaces into a clustered block… **(Problem identification)**

25:23 This process might look boring but in fact I feel I have more understandings of each space and the relation between other relevant functional rooms. **(Problem identification)**

32:15 For example, I can see the width and length of these clinic spaces; if I wish to think about the combination of them, I also need to consider whether the final layout would involve too long distances for service circulation or any other trouble… **(Problem identification)**

39:02 This mathematical design process allows me to think of space mathematically but, of course, my previous experience also helps to determine some points. **(Problem identification)**

40:12 However, I would say the parameter based design process helps me to identify the space through numbers, scales and that physical information rather than just finding a template to cover all my ideas… **(Problem identification)**

Appendix 8.5

Nonparametric CAD cognition

Imagery -Architect 11

00:05 The first step I would like to start with, is to confirm the unit status, check the dimensions, then we back to Autocad, choose a rectangle and draw out the exact dimensions.

01:12 From the size of each program, we know the smallest size of unit is 50sqm. Now we going to build up the program boxes with the minimum size of 5x10 meters, and then we start arranging the space.

03:30 The first box will be the radiation center and OR, 1450sqm, we do it with 50 by unit, so it's an area consisting of a total 50x29m rectangle. We identify its relative angle, and then assign dimension length 50 and width 29, this is the first radiation center and OR, and we leave it as it is

05:15 Because we need a centralized design floorplan, I would like to choose a circular shape as the design template. We can see from the circumference to the center, each point can be connected by the same distance. It means the travel distance will be equal under this design plan.

15:52 The next step is to fill up a circular shape with those program spaces, like a magic cube, bringing them into this pre-set design shape…

20:25 The operating room is at the center of the layout; we make it as an anchor for space arrangement…

35:20 It is not very easy to manipulate those program-box into the circular shape, it is because I cannot convert the two different shapes into a template; also it is not possible to calculate if I have used a correct scale while I am transferring these program boxes into the partial circle…

Problem-solving -Architect 11

00:12 The first step I would like to start with, is to confirm the unit status, check the dimensions, then we oback to Autocad, choose a rectangle and draw out the exact dimensions.

01:23 From the size of each program, we know the smallest size of unit is 50sqm. Now we going to build up the program boxes with the minimum size of 5x10 meters, and then we start arranging the space.

03:52 The first box will be the radiation center and OR, 1450sqm, we do it with 50 by unit, so it's an area consisting of a total 50x29m rectangle. We identify its relative angle, and then assign dimension length 50 and width 29, this is the first radiation center and OR, and we leave it as it is

20:22 Because we need a centralized design floorplan, I would like to choose a circular shape as the design template. We can see from the circumference to the center, each point can be connected by the same distance. It means the travel distance will be equal under this design plan.

35:10 The next step is to fill up a circular shape with those program spaces, like a magic cube, bringing them into this pre-set design shape… **(Cognitive problem-solving)**

40:01 The operating room is at the center of the layout; we make it as an anchor for space arrangement…

43:11 It is not very easy to manipulate those program-box into the circular shape, it is because I cannot convert the two different shapes into a template; also it is not possible to calculate if I have used a correct scale while I am transferring these program boxes into the partial circle… **(Cognitive problem-solving)**

Appendix 8.6

Parametric CAD cognition

Imagery – Architect 4

00:23 In the beginning, I will set plan for a total volume of requirements.

03:20 I formulate proper area, a BOX, by definition of two points.

03:45 Firstly, we design in 2D plane.

05:56 As there are 12 spaces in the task, then I just create 12points.We can discuss later about the space form of every point.

08:53 I use random number components to generate 12 random points on a 2D plane and set the value of randomness (500) to determine 12 spaces in 500 permutations. This cluster can be input into 3D space or any geometric modeling.

16:21 Then I would like to try the Voronoi design diagram as the initial proposal, each Voronnoi cell with a scale tool and additional random effects to accomplish variation of space. Hence, it breaks out into different corridor space which is similar to the Deep Plan system which is often used in hospital design.

29:22 The widths of passages change with adjustment of random values, so I can find a suitable one from all of these results.

30:18 When we input the random value to the radius component, concentric circle figures appear which are not the figures I expect. According to my judgement, the generator points and Voronoi Diagram value cannot operate independently hence it cannot reach the results that I expect.

42:15 In simple words, components of a Vononoi Diagram cannot generate the random region by individual generator points. Entire points must expand their radius together to generate a Voronoi Diagram therefore to generate a Voronoi cell from an individual point might go against the Voronoi principle. In that case, I move back the steps and adjust the domain of random values of circle radius to 0-20.

Problem-solving Architect 1

00:15 For the inpatient centre, I think the deep-plan system plays an important part in the layout design.

01:20 However, the traditional method of the deep-plan system is based on clustered space design and then switches to the corridor system, then makes the circulation design which I think is less interesting for this design task.

06:30 So I would like to try and make a line-graph design pattern rather than making geometric arrangements for this deep-plan proposal. Here the functional algorithm is called ‘streamline’. It is a mathematically- based line graph which presents an instantaneous, tangent curve based on the vector presenting the velocity of the flow. **(Cognitive problem-solving)**

08:01 However, from the design aspect, I assume this smooth line system could offer better circulation design such as for bed transport or nurse movement. **(Cognitive problem-solving)**

15:33 We should start by giving proposed points for functional rooms such as clinics or day wards. **(Cognitive problem-solving)**

20:32 Then the algorithmic function (grasshopper component) asks us to give values for the points. It could be the service ranking or type of the department; for example, the value of A&E centre could be more than reception. Following the instructions, here we provide the rest of the parameters to feed the design algorithm… **(Cognitive problem-solving)**

36:12 OK, so in order to understand if this streamline gives an optimized result, I will apply a computing evaluation, CUBRA, to calculated the most simple line-graph generated by the streamline. **(Cognitive problem-solving)**

40:23 CUBRA will follow my pre-set parameters, for example, the shortest distance between lines, or longest line length, to merge my line pattern and give it an optimized result. This gives varied options if I wish to create different departmental layouts with the deep plan system… **(Cognitive problem-solving)**

42:01 This type is not my ideal pattern because the lines are too close to each other that mean there is no space between departments; however, I will change the input numbers so we can try again with different patterns. **(Cognitive problem-solving)**

Appendix 8.7

Nonparametric CAD form exploration

Architect 2

00:56 In order to make a smooth connection between the outpatient department and the supply department **(Form Function)**,

01:25 I create two closed blocks adjacent to each other. **(Form Finding)** This design shape not only benefits circulation but also makes a compact space arrangement for integrating multiple functional spaces… **(Form Function)**

06:21 A long corridor design **(Form Finding)** for a clinic department might not be ideal for functional utilization **(Form Function)**

13:06 So I would like to apply the shape **(Form Finding)** to be a more square design rather than a rectangular one…. **(Form Finding)**

26:12 I am going to divide this space, a big square **(Form Finding)**, into four small squares **(Form Finding)**; because it means I can use equal sub-spaces for the room arrangement… **(Form Function)**

Architect 6

08:00 Because we need to locate a centralized design floorplan **(Form Function)** so I would like to choice a circular shape as the design template. **(Form Finding)**

15:12 We can see from the circumference to the center **(Form Function)**

18:00 Each point can connect by the same distance. **(Form Function)**

34:01 It means the travel distance will be equally under this design plan. **(Form Function)**

Appendix 8.8

Parametric CAD form exploration

Architect 3

01:23 From my experience, the traditional hospital inpatient centre is always designed as a clustered layout system within a bounding box. This could be good option because departments are close to each other.

05:12 But that result, the clustered design type, I personally believe, is caused by the CAD tool and its limitations. It means if we are using a different CAD tool and design method there might be some different results which could be presented.

08:12 For example, in Grasshopper, there is a function called ‘ Metaball’ ; it is a very good function to solve the clustered space with multi-circular shapes. **(Form Finding)** It is also a bit like a ‘cell division’ process which I personally like and for me it feels more interesting when doing the design layouts.

11:21 However, in Grasshopper this Metaball is based on a mathematical calculation between multiple geometries, so I would say it is logical process of making a new shape of design layout rather than just an another typological design like earlier modernist architectural design ..haha **(Form Finding)**

17:25 Next we can start to give our space numbers, scale and the proposed location. Here for the proposed location I applied another algorithm called ‘random numbers’, this gives computed random numbers to change the location of my points and also affects the layout compositions… **(Form Finding)**

22:21 I think we should have more space for each room so I would say 20-50 in this parameter slider …. **(Form Finding)**

25:02 Here there is a merge value which indicates the distance I wish to give between departments. Because this is the inpatient centre design, I might just set a range distance between 1-5 meters… **(Form Finding)**

30:25 So far we have constructed the Metaball algorithm so I can generate unlimited options based on this type of design plan. **(Form Finding)**

32:02 However, I still not sure what is the best solution for my design, because I hope I can figure out which one has the shortest distance between departments, or say these Metaball units. **(Form Finding)**

36:01 So I will use an algorithmic computing function – Galapagos can help me to calculate the result depending on the optimized factor I gave such as distance between departments. **(Form Finding)**

38:22 According to the calculation, the minimum distance of 2-3meters is the shortest distance and based on one type of layout which I think is good for this design proposal… **(Form Function)**

40:12 Or we can try to test by putting in the ‘maximum distance’ for the calculation, it will be around 10 meters. **(Form Function)**

41:23 Un… it could present if I want some particular department to have a quieter quality like a geriatric department… **(Form Function)**

Architect 1

00:45 I want to make a modular design as my design proposal by using computing loops which means the computer can calculate the subdivision of my presented geometry into many sub-units with the same shape.

08:21 Let’s start with a ‘polygon’ design algorithm; this algorithm is flexible in creating different geometrical shapes. **(Form Finding)**

16:23 For example, if I insert parameter 3, 4 and 5 the algorithm could generate triangular, square, and pentagonal shapes… **(Form Finding)**

25:25 However, because I am going to subdivide this geometry into many sub units, I have to measure the length of each side and decide how many segments I would like to divide it into …. **(Form Finding)**

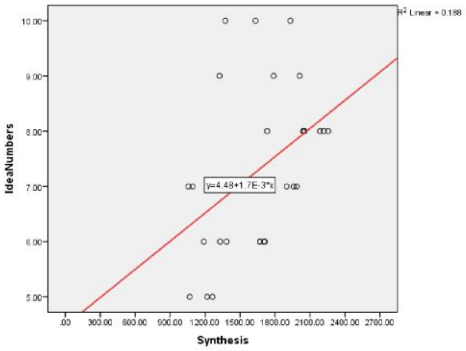
36:01 After the sub-division algorithm is done, we can run the looping function, and here we can see if I introduce more frequent looping, the subdivision creating bigger numbers of smaller units… **(Form Finding)**

37:25 Besides that, we can introduce ‘cull pattern’ or ‘random reduce’. These two functions allow me to subtract some units as void space such as courtyards for the interior layouts… **(Form Function)**

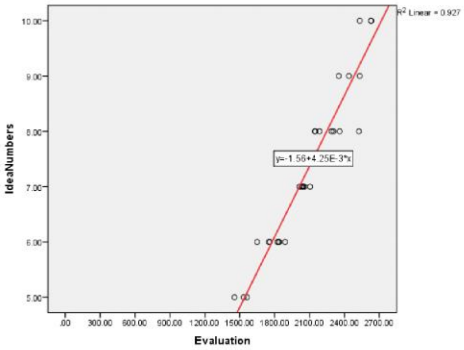
39:11 As a result, I just need to see what types of medical service are suited **(Form Function)** to the geometric type so I can automatically generate a modular space and even control void space… **(Form Finding)**

Appendix 9.1-A

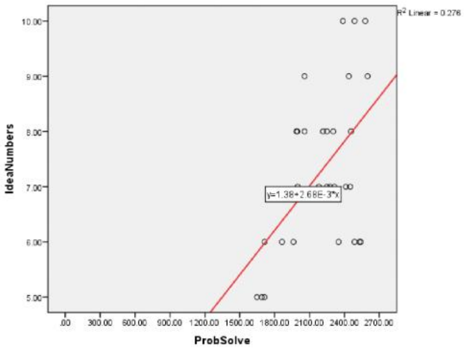
Parametric CAD process - Algorithmic CAD Grasshopper



6=4.48+1.7*0.001*600
(Idea numbers & Design synthesis)



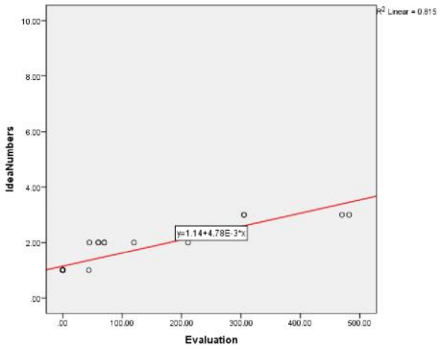
4=1.56+4.25*0.001*600
(Idea numbers & Design evaluation)



4=2.55+2.86*0.001*600
(Idea numbers & Cognitive problem-solution)

Appendix 9.1-B

Nonparametric CAD process - AutoCAD



4=1.14+4.78*0.001*600
(Idea numbers & Design evaluation)

Appendix 9.2-A

Parametric CAD process - Algorithmic CAD - Grasshopper

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.434[a]	.188	.159	1.34400

a. Predictors: (Constant), Synthesis

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	11.722	1	11.722	6.489	.017[b]
	Residual	50.578	28	1.806		
	Total	62.300	29			

a. Dependent Variable: IdeaNumbers

b. Predictors: (Constant), Synthesis

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	4.478	1.135		3.947	.000
	Synthesis	.002	.001	.434	2.547	.017

a. Dependent Variable: IdeaNumbers

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.963[a]	.927	.924	.40288

a. Predictors: (Constant), Evaluation

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	57.755	1	57.755	355.830	.000[b]
	Residual	4.545	28	.162		
	Total	62.300	29			

a. Dependent Variable: IdeaNumbers

b. Predictors: (Constant), Evaluation

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1.563	.476		-3.286	.003
	Evaluation	.004	.000	.963	18.863	.000

a. Dependent Variable: IdeaNumbers

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.526[a]	.276	.250	1.26892

a. Predictors: (Constant), ProbSolve

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	17.216	1	17.216	10.692	.003[b]
	Residual	45.084	28	1.610		
	Total	62.300	29			

a. Dependent Variable: IdeaNumbers

b. Predictors: (Constant), ProbSolve

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1.382	1.825		.757	.455
	ProbSolve	.003	.001	.526	3.270	.003

a. Dependent Variable: IdeaNumbers

Z = a(X) + C

(Dependent Value) (In dependent Value) (Constant Value)

If spend 3000 Sec. = 50 Mins at X

Idea numbers & Sythesis	10.5 = 0.002*3000+4.478
Idea numbers & Evaluation	10 = 0.004*3000-1.563
Idea numbers & Identify Prob	11.5 = 0.003*3000+2.546

Appendix 9.2-B

Nonparametric CAD process - AutoCAD

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.903[a]	.815	.808	.32040

a. Predictors: (Constant), Evaluation

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	12.626	1	12.626	122.987	.000[b]
	Residual	2.874	28	.103		
	Total	15.500	29			

a. Dependent Variable: IdeaNumbers

b. Predictors: (Constant), Evaluation

Coefficients[a]

Model		Coefficients		ed	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1.142	.067		17.104	.000
	Evaluation	.005	.000	.903	11.090	.000

a. Dependent Variable: IdeaNumbers

Statistics

		Analysis	Synthesis	Evaluation
N	Valid	30	30	30
	Missing	0	0	0
Percentiles	25	1864.7500	1443.0000	0.0000
	50	2029.0000	1844.0000	0.0000
	75	2437.7500	1961.2500	70.0000

Z = a(X) + C

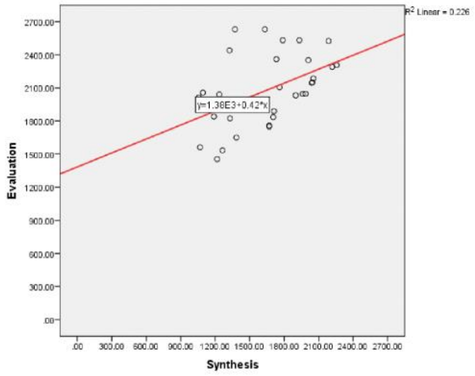
(Dependent Value) (In dependent Value) (Constant Value)

If spend 3000 Sec. = 50 Mins at X

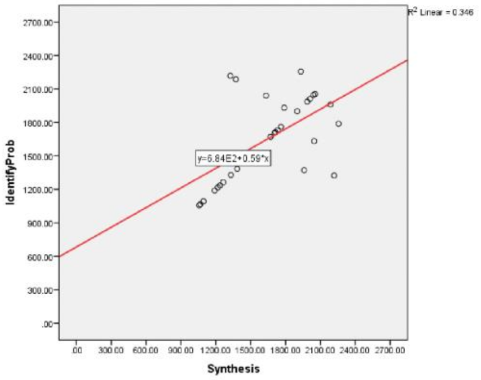
Idea numbers & Evaluation	16.4= 0.005*3000+1.142

Appendix 9.3-A

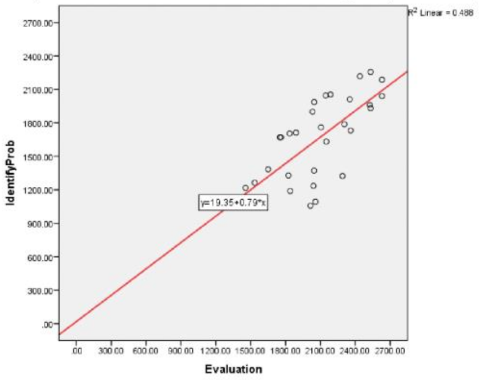
Parametric CAD process - Algorithmic CAD Grasshopper



252=1.38*0.001+0.42*600
(Design evaluation & Design synthesis)



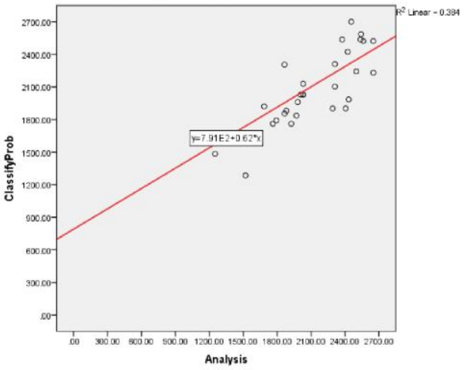
354=6.84*0.01+0.59*600
(Problem identification & Design synthesis)



493=19.35+0.79*600
(Probblem identification & Design evaluation)

Appendix 9.3-B

Nonparametric CAD process - AutoCAD



372=7.91*0.01+0.62*600
(Classifying problems & Design analysis)

Appendix 9.4-A

Parametric CAD process - Algorithmic CAD - Grasshopper

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.475[a]	.226	.198	297.12674

a. Predictors: (Constant), Synthesis

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	721058.382	1	721058.382	8.167	.008[b]
	Residual	2471960.318	28	88284.297		
	Total	3193018.700	29			

a. Dependent Variable: Evaluation

b. Predictors: (Constant), Synthesis

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1384.025	250.830		5.518	.000
	Synthesis	.422	.148	.475	2.858	.008

a. Dependent Variable: Evaluation

Model Summary

Model	R	R Square	Square	the Estimate
1	.698[a]	.488	.470	272.30706

a. Predictors: (Constant), Evaluation

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1978097.517	1	1978097.517	26.677	.000[b]
	Residual	2076231.850	28	74151.137		
	Total	4054329.367	29			

a. Dependent Variable: IdentifyProb

b. Predictors: (Constant), Evaluation

Coefficients[a]

Model		Unstandardized Coefficients		Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	19.355	321.435		.060	.952
	Evaluation	.787	.152	.698	5.165	.000

a. Dependent Variable: IdentifyProb

Z = a(X) + C

(Dependent Value) (In dependent Value) (Constant Value)

If spend 3000 Sec. = 50 Mins at X

Evaluation & Synthesis	(44:10)	2650 = 0.422*3000+1384.025
IdentifyProb & Evaluation	(39:40)	2380 = 0.787*3000+19.355

Appendix 9.4-B

Nonparametric CAD process - AutoCAD

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.620[a]	.384	.362	293.18525

a. Predictors: (Constant), Analysis

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1501124.879	1	1501124.879	17.464	.000[b]
	Residual	2406812.487	28	85957.589		
	Total	3907937.367	29			

a. Dependent Variable: ClassifyProb

b. Predictors: (Constant), Analysis

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	791.197	321.451		2.461	.020
	Analysis	.624	.149	.620	4.179	.000

a. Dependent Variable: ClassifyProb

Z = a(X) + C

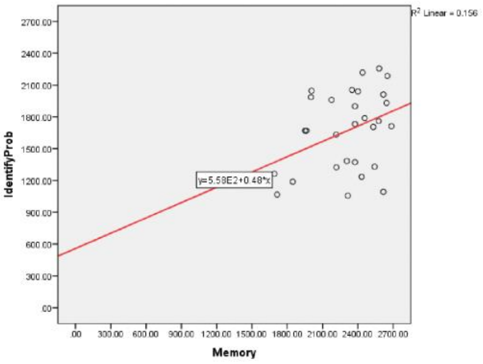
(Dependent Value) (In dependent Value) (Constant Value)

If spend 3000 Sec. = 50 Mins at X

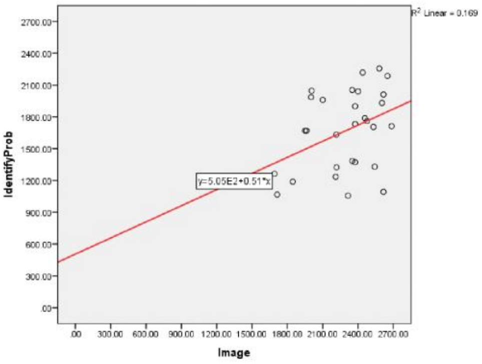
ClassifyProb & Analysis	(44:23)	2663 = 0.624*3000+791.197

Appendix 9.5-A

Parametric CAD process - Algorithmic CAD Grasshopper



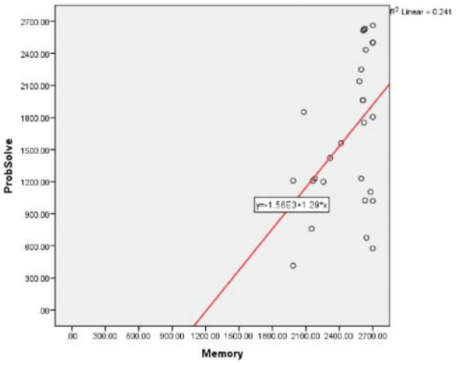
288 =5.58*0.01+0.48*600
(Problem identification & Cognitive memory)



306 =5.05*0.01+0.51*600
(Problem identification & Cognitive image)

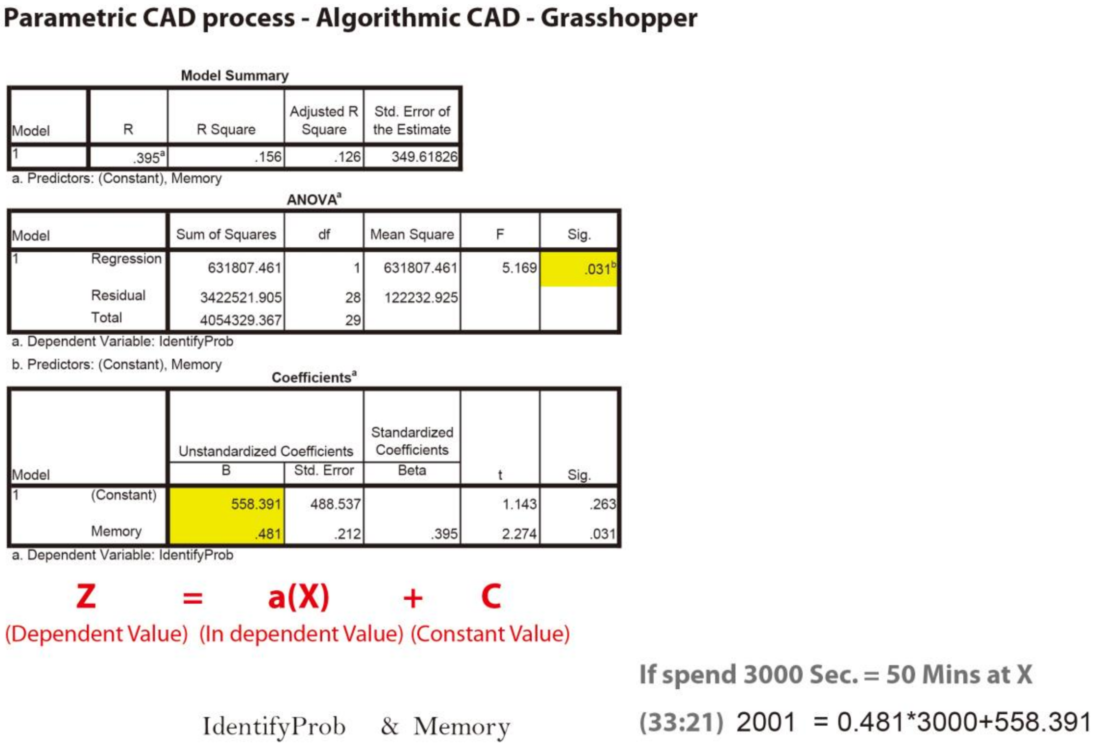
Appendix 9.5-B

Nonparametric CAD process - AutoCAD



774 =-1.56*0.001+1.29*600
(Cognitive problem-solution & Cognitive memory)

Appendix 9.6-A



Parametric CAD process - Algorithmic CAD - Grasshopper

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.395[a]	.156	.126	349.61826

a. Predictors: (Constant), Memory

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	631807.461	1	631807.461	5.169	.031[b]
	Residual	3422521.905	28	122232.925		
	Total	4054329.367	29			

a. Dependent Variable: IdentifyProb

b. Predictors: (Constant), Memory

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	558.391	488.537		1.143	.263
	Memory	.481	.212	.395	2.274	.031

a. Dependent Variable: IdentifyProb

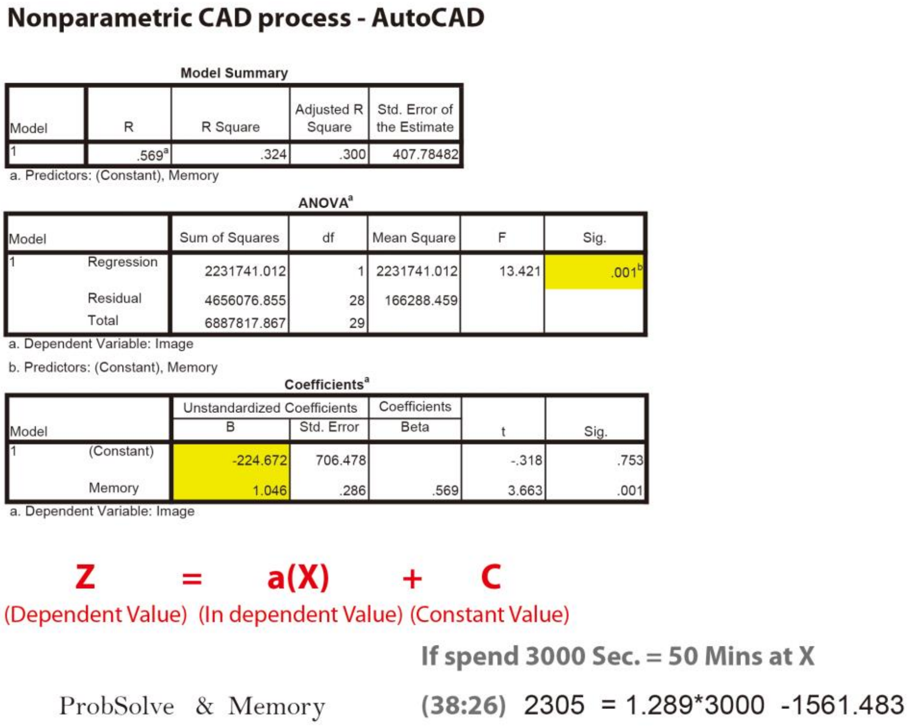
Z = a(X) + C

(Dependent Value) (In dependent Value) (Constant Value)

If spend 3000 Sec. = 50 Mins at X

IdentifyProb & Memory (33:21) 2001 = 0.481*3000+558.391

Appendix 9.6-B



Nonparametric CAD process - AutoCAD

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.569[a]	.324	.300	407.78482

a. Predictors: (Constant), Memory

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2231741.012	1	2231741.012	13.421	.001[b]
	Residual	4656076.855	28	166288.459		
	Total	6887817.867	29			

a. Dependent Variable: Image

b. Predictors: (Constant), Memory

Coefficients[a]

Model		Unstandardized Coefficients		Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-224.672	706.478		-.318	.753
	Memory	1.046	.286	.569	3.663	.001

a. Dependent Variable: Image

Z = a(X) + C

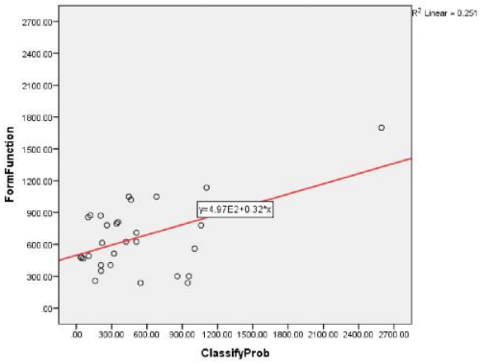
(Dependent Value) (In dependent Value) (Constant Value)

If spend 3000 Sec. = 50 Mins at X

ProbSolve & Memory (38:26) 2305 = 1.289*3000 -1561.483

Appendix 9.7-A

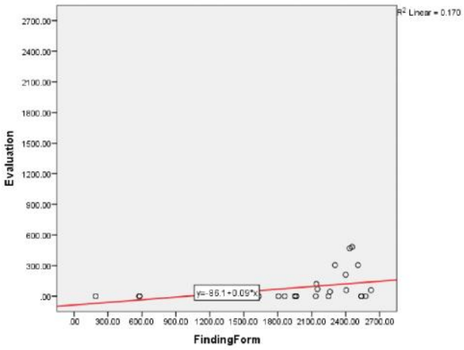
Parametric CAD process - Algorithmic CAD Grasshopper



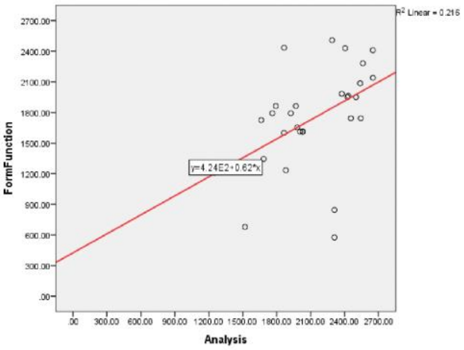
192 =4.97*0.01+0.32*600
(Form Function & Problem classification)

Appendix 9.7-B

Nonparametric CAD process - AutoCAD



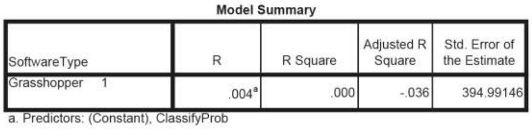
22 =-86.1+0.09*1200
(Design evaluation & Finding form)



372 =4.24*0.001+0.62*600
(Form function & Design analysis)

Appendix 9.8-A

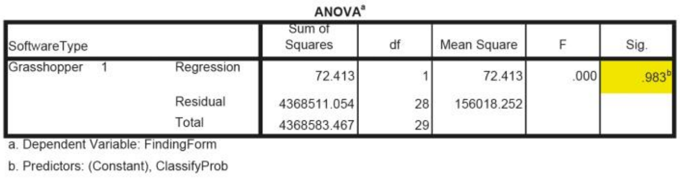
Parametric CAD process - Algorithmic CAD - Grasshopper



Model Summary

SoftwareType		R	R Square	Adjusted R Square	Std. Error of the Estimate
Grasshopper	1	.004[a]	.000	-.036	394.99146

a. Predictors: (Constant), ClassifyProb

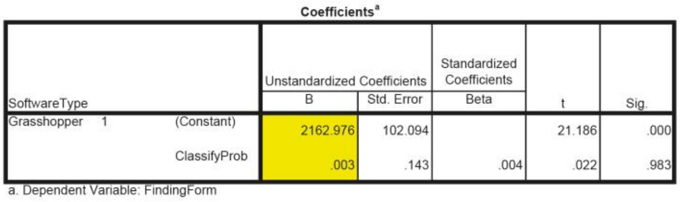


ANOVA[a]

SoftwareType			Sum of Squares	df	Mean Square	F	Sig.
Grasshopper	1	Regression	72.413	1	72.413	.000	.983[b]
		Residual	4368511.054	28	156018.252		
		Total	4368583.467	29			

a. Dependent Variable: FindingForm

b. Predictors: (Constant), ClassifyProb



Coefficients[a]

SoftwareType			Unstandardized Coefficients		Standardized Coefficients	t	Sig.
			B	Std. Error	Beta		
Grasshopper	1	(Constant)	2162.976	102.094		21.186	.000
		ClassifyProb	.003	.143	.004	.022	.983

a. Dependent Variable: FindingForm

Z = a(X) + C

(Dependent Value) (In dependent Value) (Constant Value)

If spend 3000 Sec. = 50 Mins at X

FindingForm & ClassifyProb

(36:12) 2172 = 0.003*3000+2162.582