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PARAMETRIC TOOLS IN ARCHITECTURE: A COMPARATIVE STUDY

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Parametric tools have recently increased in eminence in architectural practice with several claims made about their potential as a creative design iteration tool to enhance design decision making and problem solving. This paper carried out a survey of two types of architectural practices: one that predominantly uses non-parametric CAD tools and another that primarily employs parametric CAD. The results from the survey were analysed statistically. The findings show that parametric tools did not help conceptual work at the early design stage. Also there was very little difference between both tools regarding their potential in dealing with complex geometry. However parametric tools were found to enhance creative decision making more than non-parametric tools. Their benefits for structural and environmental optimisation, fabrication, articulation of facade patterns and the creation of design variants were also highlighted.

1. INTRODUCTION

Parametric modelling (PM) enables the creation of 3D models of buildings with embedded parameters. (Lee et al. 2006) The data that is fed into these parameters is volatile and changeable, and thus, If a designer changes the values inside the parameters, the form of a geometrical entity changes. The manipulation of building form such as twisting or rotation can be linked to angle parameter; when the angle changes so does the form. These processes make PM packages an ideal tool for the generation of multiple and alternative design solutions or design variants.

There are two types of parametric modelling tools that are popular among architects both in education and practice. The first type includes programmes such as Grasshopper in Rhinoceros (Payne and Issa 2009) and Micro station's Generative Components (GC) (Chadwick 2007) and has an obvious data tree where the association between parameters and components is visually apparent, i.e. wires in Grasshopper. The second type, which includes programmes such as Autodesk's Revit deals with building information modelling (BIM) and has a hidden data tree where the only visible screen is the one which shows the geometry. The first type has also the additional advantage of being able to deal with complex geometry which every so often is associated NURBS (non-uniform rational B-splines) entities.

Recently the popularity of parametric design in architectural practice has risen with many offices opting to create groupings for advanced geometry research and surface annealing. Examples include Arup's Advance Geometry Group (Bosia 2011); Gehry's set of 'dedicated design teams' (Glymph et. al 2004) and the Computational Geometry Group in the architectural practice of Kohn Pedersen Fox Associates (KPF), London. (Dritsas and Becker 2007) Additionally, a link between parametric modelling, pursuit of complex geometry and digital fabrication has been reported in the literature. For example, it has been suggested that 'Parametric modelling has the ability to generate complex forms with intuitively reactive components, allowing designers to express and fabricate structures previously too laborious and geometrically complex to realise'. (Pitts and Datta 2009)

Burry's work (Burry et al. 2001) is a good example on the use of parametric tools to analyse Gaudi's 'ruled surfaces' in the Sagrada Familia and recreate his complex geometry in the reconstruction of building parts that were not finished by Gaudi. Parametric principles were also deployed in a minimalist approach to produce a set of 'ruled surfaces', from a limited number of curves and this approach can conceivably be used to portray building geometry. (Prousalidou and Hanna 2007) Furthermore, Burry (2011) examined the geometrical concept of 'doubly ruled surfaces' and argued that this type of geometry does not only facilitate construction and fabrication in a file-to-factory procedure but it can also be used conceptually to highlight 'a useful distinction between the fundamentals of architecture and the aesthetic priorities of sculpture'. (Burry 2011) He went on to state that doubly ruled surfaces are, 'a subset of ruled surfaces, have at once a geometrical simplicity and a visual sophistication. Their aesthetic ranges from the subtle way they direct light across their surfaces to their ready describability, both in terms of representation and fabrication'. (Burry 2011) However, beauty is not the only attribute of ruled surfaces; they also have great structural strength. If every point on a ruled surface has 2 lines that are completely contained in the surface, then the surface is called 'doubly ruled'.(Iselberg 2009)

One of the reasons for the recent adoption of parametric tools and approaches in design has been identified as being the need for a tool which offers both flexibility and speed. (Salim and Burry 2010) They stated 'the adaptation of parametric modelling has reformed both pedagogy and practice of architectural design.' However, data flow programming which is the norm in parametric tools offers little flexibility in changing the association between parameters and this is considered as a weakness in parametric tools. (Davis, Burry and Burry 2011) The alternative, logic programming, which is claimed to be better but not ideal, is described, 'adept at translating explicit models into parametric models, but lacking continuous flexibility.' (Davis, Burry and Burry 2011)

Schnabel (2007) advocates the use of parametric techniques to create solutions to problems at the early design stage. Schnabel (2007) goes on to suggest that parametric tools 'allow a deeper comprehension of the design objectives and aids designers in their decisions to find solutions'. Aish and Woodbury (2005) summarise their insights into the advantages of using parametric tools in design: 'parameterization can enhance search for designs better adapted to context, can facilitate discovery of new forms and kinds of form-making, can reduce the time and effort required for change and reuse, and can yield better understandings of the conceptual structure of the artefact being designed'. As disadvantages, they list: 'additional effort' and the amplification of 'complexity of local design decisions'. In addition, they cite the difficulty of instant interaction between several screen views as a problem of parametric tools in practice. (Aish and Woodbury 2005)

Holzer et al.(2007) examined the relationship between parametric design and the optimisation of structural design during the early stages of the design process. They made two important conclusions on the limitations of PM at the early design stage. First, it is extremely difficult to construct an overall PM that can cope with the 'disruptive nature' of alterations mandated by the multidisciplinary design team. Second they commented that 'variations of the values of parameters sitting on a high level in the design hierarchy caused dependent child parameters to lose their logical association'.

From observations in practice, Hudson (2008) highlighted a conflict between 'published theory' and visual evidence regarding the deployment of parametric modelling in architectural design. He suggested that while the theoretical literature on PM focuses on their use at the conceptual design stage the evidence from observing practice indicates that their deployment occurred at the design development stage rather than at the conceptual stage. Shepherd (2011), an engineer, examined the parametric approach to engineering design and analysis when he received the architectural parametric model for a stadium from the architect's team. The building form was formulated using relations and parametric rules between objects rather than the conventional way of using CAD to model a building through entities such as lines. He cited two main advantages to this process: a significant improvement in workflow between the architectural and engineering teams which resulted from sharing a single parametric model and the speed of structural design optimisation. Hudson (2009) argues that the 'process of developing a parametric model can begin with incomplete knowledge of the problem'. This suggests that parametric modelling may well be possible and can occur at the early conceptual design stage.

Another area of design where parametrics became a very potent tool is the creation of 'patterns' for decorative facades in buildings. Schumacher (2009) argues that 'articulation is the central core competency of architecture; and designed patterns provide one of the most potent devices for architectural articulation.' He predicts a 'new era of parametric architecture' where the use pattern as a source of innovation will yield a high level of design articulation in building facades. This, according to Schumacher (2009), will lead to the intensification of 'surface difference and correlation', and will ultimately result in 'dynamic, high-performance ornamentation'.

However the intellectual landscape for the use of computers in architectural design was mapped earlier by Jencks (1997). In his treatise 'new science=new architecture' Jencks argues that there is a shift in thought, a departure from the old Newtonian linear science to other forms of science such as that of complexity, fractals and non-linear systems. He calls on architecture as 'a form of cultural expression' to have a similar shift in the framework of thought, citing three 'seminal' buildings of the 1990s to support his thesis of shift. Gehry's Bilbao, Eisenman's Aronoff Centre, Cincinnati and Libeskind's Jewish Museum in Berlin 'are three non-linear buildings and were partly generated by nonlinear methods including computer design', maintains Jencks. Furthermore, Jenks (1997) goes on to question the role of metaphor in the three buildings and concludes that 'new science=new language= new metaphor'. In summary, it is obvious that parametric tools have many advantages over traditional (non-parametric) CAD tools in terms of form finding and dealing with complex geometry through their reactive components. However, the literature review reveals that some of the claims regarding parametric modelling are contradictory and in some cases rely on anecdotal evidence. The contradiction between researchers is clear when PM is discussed in relation to its use at which stage in the design process, for example Schnabel (2007) advocates the use of parametric tools to find solutions at the early design stages, whereas Hudson (2008) and Holzer et al. (2007) concur that they are useful at the developmental and not at the early stages of the design process. Schumacher (2009), on the other hand, views their creative potential as a generative device for façade patterns which can significantly increase 'architectural articulation' of building facades.

Some of the researches describe the use of parametric workflow from the perspective of using it in a single building and make generalisations from that. Therefore, it seems there is a need for a consensus on some aspects of parametric modelling use in architectural practice. More importantly we should aim to ascertain whether parametric tools do help or hinder the creative decision making of problem solving in design.

2. CASE STUDY

In order to find a consensus about the use of PM using parametric tools in architectural practice, we conducted a survey of two types of offices: non parametric and parametric. Furthermore, the research also aimed to test the null hypothesis (H0) that *'there is no significant difference between traditional CAD practices (non-parametric) and parametric practices regarding their use of CAD in the design process.'* The word 'significant' implies a statistical significance or a P value which has to be <0.05 for the difference to be accepted as sufficient to reject the null hypothesis.(Bryman and Cramer 2011) If the null hypothesis is to be rejected, then the target hypothesis (H+), which is the opposite and sometimes is called the research hypothesis, will be confirmed. The research design which is diagrammatically represented in Appendix 1, is based on Popper's hypothetico deductive method of 'deduction-hypothesis formulation-hypothesis testing.' (Popper 2002)

Questionnaires were e mailed to over 60 architectural offices form UK and Europe and returns were received from only 18 traditional (non-parametric CAD) and 14 parametric CAD practices. Traditional practices are those which use CAD tools primarily for drawing automation and three dimensional modelling and visualisation. There were two types of questions, closed and open ended, which were intended to gather knowledge and data on the use of CAD parametrically and non-parametrically in the design process. There were also few questions concerning the impact of CAD tools, both parametric and non-parametric, on 'creativity' in design problem solving. The questionnaire used Torrance's seminal work as a framework to define creativity; offices were asked to answer the questions on creativity using this framework. Torrance (1966) identified four main parameters for creativity: fluency (generating a volume of ideas); flexibility (to do with the variety of ideas); originality (uncommonness of ideas); elaboration (advancing an idea). This ensured that there was no misunderstanding on what the dimensions of creativity are. The relationship between Torrance's 4 dimensions of creativity and the research design of this paper is displayed in Appendix 2. For a detailed review of creativity and its measurements, see (Hanna and Barber 2001). The returns were statistically analysed using the Statistical Package for the Social Sciences (SPSS). A summary of the findings from this survey are presented below.

3. FINDINGS

3.1 Descriptive Statistics

The bar chart in Figure 1 shows some differences in attitudes toward the use of CAD by both office types. In the chart, the Y-axis represents the percentage of offices who answered yes to the questions on the nature of CAD usage within the design process. The chart indicates that every office in each category (100% of the sample) uses CAD for drawing automation, 3D modelling and visualisation. On façade design around 30% of non-parametric offices use traditional CAD whereas around 85% of parametric practices use parametric CAD in façade design. Parametric practices suggested that they use parametric CAD to morph any shape, a series of shapes or articulated patterns to any building surface and create well- articulated building facades. One of the strengths of parametric tools is that the basic geometrical entity for a facade pattern while maintaining its basic shape, changes in proportion to follow the curvature of the surface. Parametric CAD scored higher than non-parametric CAD in areas of design variants, fabrication, work flow and optimisation (structural and environmental). Surprisingly, non-parametric CAD was more effective as a tool than parametric CAD at the early (conceptual) design stage. Five parametric practices commented that parametric CAD is very rigid as a design tool at the early stages. Among the negative feedback received in the questionnaire returns were statements such as: 'creation of 3D entities is laborious'; 'it is all data structure between parameters, components and wires'; 'you need to have a concept and a 3D conception of a form before you start, otherwise this thing is useless'; 'no device like a mouse and no graphical screen, how can this be useful at concept formulation?'; 'you need to move between two screens, one for data structure and another for graphics, it is not easy to keep moving between the two and have a design concept in your head'. (**See figure 1**)

On the design issue of exploring complex geometry parametric CAD was used by 90% of parametric practices whereas non parametric CAD was used by 70% of non-parametric offices. Among the 70% were architects who hinted that the 'creation of surfaces based on elliptical curves

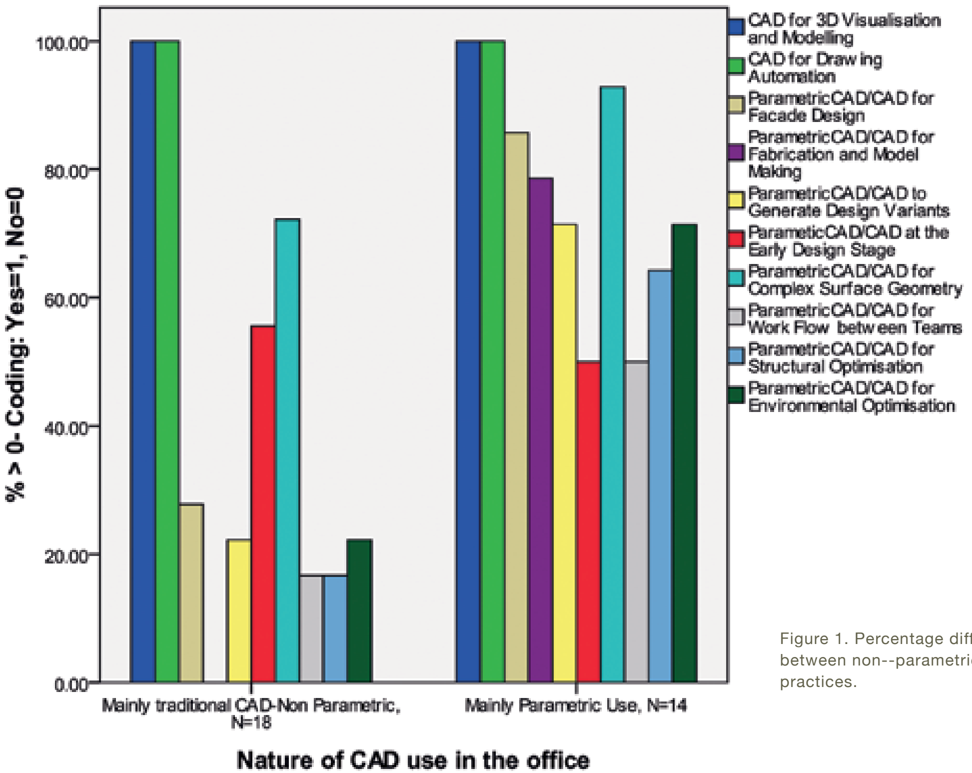

Figure 1. Percentage difference between non--parametric and parametric CAD practices.

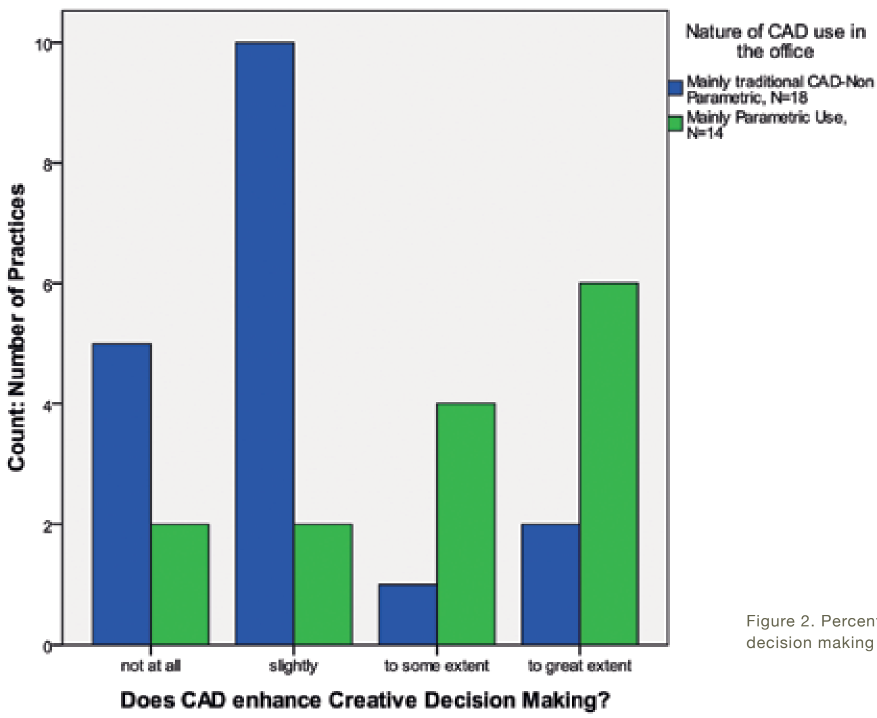

Figure 2. Percentage difference on the creativity of decision making by office type.

is really easy with the Rhinoceros software' and that the use of 3D digitising arm makes this process easier. One practice said that 'we move all the time between CAD and physical models using 3D digitisation'.

On the difference between practices regarding the creativity of problem solving in the design process, Figure 2 displays the findings on this variable.

A quick glance at Figure 2 reveals that parametric CAD was seen by its users as more enhancing to the creative decision making process than non-parametric CAD. Ten practices out of a total of 14 intimated that parametric CAD helped their creative decision making 'to some extent' and 'to great extent'. This implies that although parametric CAD performed less than non-parametric CAD in terms of its effectiveness as a design tool at the conceptual stage, parametric users must have felt that there is more to creative decision making than just the conceptual stage. Designers must have considered such issues as performance optimisation, generation of design variants, fabrication and façade design, all to be very significant elements of creative decision making, i.e. creativity of design process.

3.2 Inferential Statistics

The above figures clearly confirm that there is a difference between parametric and non-parametric practices in terms of attitudes toward CAD in the design process. However, there is nothing to suggest whether or not the computed difference is statistically significant. The paper used the Analysis of Variance (ANOVA) test in SPSS to compute the variance between both groups which is represented in Table 1 by: Mean Square; F statistics; Significance. The two variables that did not show a significant difference between parametric and non-parametric practices (P>0.05) were: the use of CAD at the early design stage and its value as a tool for exploring complex surface geometry. The finding on the latter variable, of no significant difference between parametric and non-parametric CAD on potential for exploring complex geometry is surprising as it is in disagreement with current established beliefs on this issue. For example Chadwick (2007) maintains that parametric design tools use 'the power of symbolic math – through graphical and scripting tools - in order to generate complex geometry with component relationships.' Also, what makes these tools very powerful in experimenting with complex geometry is their ability to logically link 2D and 3D geometry in a rule-based situation; a modification of one component will automatically force a change in other components in conformity with 'the applied rules'.(Chadwick 2007)

Table 1. ANOVA results by office type. P (significance) <0.05 means that the difference is statistically significant and not due to chance

ANOVA Table

			Sum of Squares	df	Mean Square	F	Sig.
ParametricCAD/CAD for Facade Design * Nature of CAD use in the office	Between Groups	(Combined)	2.643	1	2.643	14.891	.001
	Within Groups		5.325	30	.178		
	Total		7.969	31			
ParametricCAD/CAD for Fabrication and Model Making * Nature of CAD use in the office	Between Groups	(Combined)	4.862	1	4.862	61.875	.000
	Within Groups		2.357	30	.079		
	Total		7.219	31			
ParametricCAD/CAD to Generate Design Variants * Nature of CAD use in the office	Between Groups	(Combined)	1.907	1	1.907	9.584	.004
	Within Groups		5.968	30	.199		
	Total		7.875	31			
ParameticCAD/CAD at the Early Design Stage * Nature of CAD use in the office	Between Groups	(Combined)	.024	1	.024	.092	.764
	Within Groups		7.944	30	.265		
	Total		7.969	31			
ParametricCAD/CAD for Complex Surface Geometry * Nature of CAD use in the office	Between Groups	(Combined)	.335	1	.335	2.216	.147
	Within Groups		4.540	30	.151		
	Total		4.875	31			
ParametricCAD/CAD for Work Flow between Teams * Nature of CAD use in the office	Between Groups	(Combined)	.875	1	.875	4.375	.045
	Within Groups		6.000	30	.200		
	Total		6.875	31			
ParametricCAD/CAD for Structural Optimisation * Nature of CAD use in the office	Between Groups	(Combined)	1.786	1	1.786	9.375	.005
	Within Groups		5.714	30	.190		
	Total		7.500	31			
ParametricCAD/CAD for Environmental Optimisation * Nature of CAD use in the office	Between Groups	(Combined)	1.907	1	1.907	9.584	.004
	Within Groups		5.968	30	.199		
	Total		7.875	31			

On whether or not parametric and non-parametric CAD tools do enhance creative decision making, the ANOVA test also calculated differences between the two groups, which were found to be statistically significant (Table 2: P=0.009, <0.05); designers using parametric tools gave the CAD tool a higher score on helping creative decision making than users of non-parametric CAD tools. This result can be explained by the fact that 'creativity' as a concept is 'generative' in terms of ideas and parametric tools are also 'generative' by their nature. In other words the generative ability of parametric tools to create alternative and multiple design variants by changing the rules and sometimes numbers makes the iterative process more innovative in finding the most efficient design. Furthermore, the impact of parametric tools on creativity in real life projects has been described as follows: 'the Bishopsgate tower by KPF, and the Dostyk Towers by NBBJ and E/Ye Design - demonstrate tremendous creativity based on a highly developed sense of intuitive design.'(Chadwick 2007)

Table 2. ANOVA results on CAD's impact on creative decision making by office type. P (significance) <0.05 means that the difference is statistically significant and not due to chance

ANOVA Table

			Sum of Squares	df	Mean Square	F	Sig.
CAD does enhance Creative Decision Making * Nature of CAD use in the office	Between Groups	(Combined)	7.875	1	7.875	7.875	.009
	Within Groups		30.000	30	1.000		
	Total		37.875	31			

Finally we wanted to calculate how much a variance or a change in one variable (from parametric to non-parametric) can cause a change in another variable (creative decision making). The paper used the Spearman rho correlation test in SPSS to establish the magnitude of association between the two. The results are presented in Table 3.

Table 3. Correlation of parametric/non-parametric CAD's with creative decision making. P (significance) <0.05 means that the difference is statistically significant and not due to chance

Correlations

			Nature of CAD use in the office	CAD does enhance Creative Decision Making
Spearman's rho	Nature of CAD use in the office	Correlation Coefficient	1.000	.449**
		Sig. (1-tailed)	.	.005
		N	32	32
	CAD does enhance Creative Decision Making	Correlation Coefficient	.449**	1.000
		Sig. (1-tailed)	.005	.
		N	32	32

**. Correlation is significant at the 0.01 level (1-tailed).

The correlation between the two variables, Table 3, is significant at the 0.01 level which means that this relationship is 99% logical or causal and has a very slim probability of only 1% that it occurs due to statistical chance. To calculate variance the value of correlation coefficient (0.449) has to be squared, which gives a value of 0.201. This implies that a change from a non-parametric CAD tool to a parametric one will produce a 20% increase in creative decision making. However, one has to accept the limitation of this assertion in that it is mathematical and statistical, thus it is valid in theory. However, one may not get the same result in real life situation in architectural practice, as there could be so many intervening variables that will affect this relationship.

4. CONCLUSION AND DISCUSSION

A single case study with a limited number of variables can at best refine a hypothesis than establish new knowledge. The study also has some other limitations. For example, the sample size was too small to arrive at any firm conclusions and thus any conclusions drawn from this study have to be taken with due care. Unlike a large sample, a small sample size is also very prone to statistical errors since a small change in a response to a question either way can swing the results significantly. Additionally, the author could not find any surveys of parametric practices to compare the results with and tone down the findings, despite repeated literature searches.

Having stated the limitations, some tentative conclusion, though, can be drawn from this study. First, parametric CAD tools were found lacking at the conceptual design stage. In fact non parametric tools fared better in this regards. The author is a competent user of parametric tools such as Grasshopper and it is his belief that parametric tools are complex, difficult to learn by a novice CAD user and arduous to use at the early design stage. They don't lend themselves to be used like traditional CAD software where the generation of 2D and 3D entities is straightforward, quick and direct. The illustration in Figure 3 may explain this better. In a non-parametric CAD system such as Rhinoceros, you can draw a line easily and directly by choosing the line button and clicking on two points on the screen. This is similar to the way we draw a line with pencil on paper. In parametric software such as Grasshopper, you need to create 2 point components and a line component and drag a line (wire) from each point component into each of the two input channels, A and B, of the line component, Figure 3. This is not a straightforward procedure.

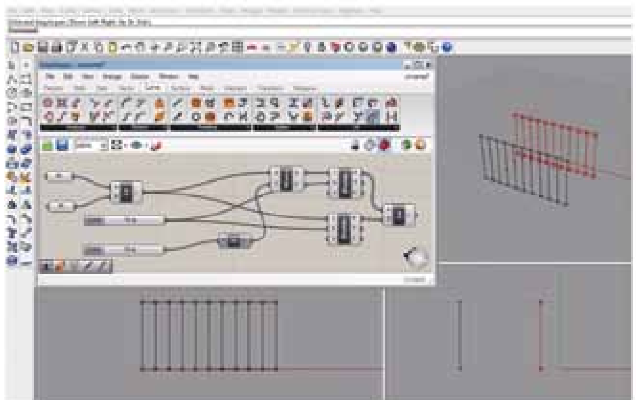

Figure 3. Direct drawing in Rhinoceros and indirect drawing using components and parameters in Grasshopper

In one operation, you can also divide the line into several pieces using the divide command in Rhinoceros, copy it and move it upwards on the screen using the mouse. In Grasshopper the procedure is far more complicated. First you need to create the divide component and link it to a slider that controls the number of divisions. Then you will have to create the move component, specify the direction (x, y, z) of the move by creating a vector, another component, and a slider to specify the distance for the move. One could argue that this process is cumbersome and incompatible with the conceptual design stage where the link between thinking and drawing on the screen has to be immediate rather than convoluted.

Further, parametric tools were considered to be slightly better than non-parametric regarding the way they deal with complex surface geometry, but the difference was not found to be statistically significant (P=0.147, >0.05). On enhancing creative decision making in design, parametric CAD tools again proved to be more desirable aids than non-parametric ones despite their weaknesses at the conceptual stage. Evidenced by several P values <0.05 and coupled with the fact that parametric CAD tools were perceived, on average, as having a higher performance and being more supportive of the design process than non-parametric tools, this research has to reject the null hypothesis and accept the alternative conjecture that parametric CAD tools do in fact differ from non-parametric tools in offering designers more potential and opportunity to enhance design performance. Table 4 gives a summary of findings.

Table 4. Design process variables: differences between parametric/non-parametric CAD, based on levels of P (significance) <0.05, obtained in previous tables

Variables where differences existed between Parametric and Non-Parametric CAD= Reject the Null Hypothesis		Variables where differences DID NOT exist between Parametric and Non-Parametric CAD= Confirm the Null Hypothesis
Façade design	Type A	Use at the early design stage
Digital fabrication		Use for exploring complex surface geometry
Generation of design variants (an indicator for creativity)	Type A- indicator to double check Type B	
Improve work flow between design teams	Type A	
Use for structural optimisation		
Use for environmental analysis and optimisation		
Enhance creative decision making (4 dimensions of creativity)	Type B	

In closing the findings from this study on parametric CAD can also be useful to disciplines other than architecture, for instance textiles. Collaboration and cross-over of ideas between the two disciplines is well documented in the literature, i.e. project Listener, which is labelled as 'an architectural research probe' by its authors. (Ramsgard-Thomsen and Karmon 2012) They state:

> '*In developing the textile pattern and material specification for Listener we created our own interfaces between architectural design software and CNC knitting. Listener is developed across a diagrid base pattern. The diagrid defines the holding pattern creating a base diagram from which the deformations of the pattern can be determined. Responding to an imagined scenario of occupation and interaction, our aim was to distort the diagrid creating fields of varying intensity, suggesting a higher degree of responsiveness around particular areas of the body. The pattern is designed using parametric software that allows us to interactively programme the design environment.*'
> (Ramsgard-Thomsen and Karmon 2012)

Perhaps this is just the beginning, where the digital fabrication of materials in architecture and the architectural articulation of patterns in facades, both inspired by parametric software, can stimulate information based thinking in textile knitting.

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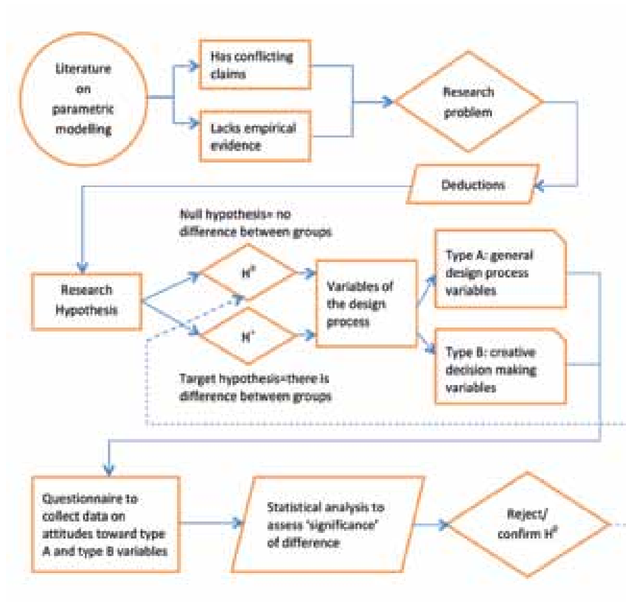
Appendix 1: The research design.



Appendix 2: Relationship between Torrance's 4 creativity dimensions and the research design.