

CAAD: FOUR DECADES THAT TRANSFORMED ARCHITECTURE AND BUILDING ENGINEERING

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Introduction

In October 2015, the ACADIA conference was held in Cincinnati, Ohio. Some one hundred plus mostly young people heavily committed to CAAD, attended. Dr Robert Ash presided over a panel discussion 'Pioneers of Design Computation'. It featured Don Greenburg - arguably the father of computer graphics, Chuck Eastman - arguably the father of BIM and the current author - Tom Maver, who in the mid sixties struggled to develop primitive computer software to predict how design decisions - the geometry and construction of the buildings - might impact on their capital cost, their recurring costs, their energy performance (heat, light sound), their efficiency in pedestrian movement, their evacuation in emergency and in every other aspect of their cost and performance. The one hundred plus people accorded the panel a standing ovation in recognition that early endeavours were both welcome and worthwhile.

This paper looks to tell the story of the *early days*, in particular, the design concepts that drove and guided the development of CAAD, and more importantly, to provide an overview of the current *state of the art*, and the way forward for the next four decades.

The story of the *early days* is based primarily on the research group ABACUS - the Architecture and Building Aids Computer Unit, Strathclyde - set up around 1969 in the Department of Architecture and Building Science at the University of Strathclyde in Glasgow under the Directorship of Tom Maver. The story of the *current state of the art* is based largely on the highly successful international company - Integrated Environmental Solutions (IES) - a spin-out consultancy from the original research group ABACUS and now employing in excess of 170 professionals in offices on four continents.

Early Ideas and Concepts

A number of critical factors were relevant around the 1950s.

In the UK, and in other European countries a massive building programme

was underway to replace the housing and public sector building stock destroyed as a result of the bombing and shelling activities of the combatants on both sides of the World War II conflict. In the UK, there was no shortage of ambitious ideas about the “brave new world”. Sir Basil Spence spoke of rebuilding the Gorbals area of Glasgow as “billowing sails” – a massive redevelopment that was to be demolished a few decades later because it condemned the occupants to the misery of fuel poverty. This wide-spread failure of design competence is hardly surprising: the plan and elevation had been the stock-in trade of the profession since time immemorial and hand-drawn perspective geometry, discovered in the Renaissance, was the most recent innovation (in 400 years) in the practice of architectural design. Scant attention was paid to the energy behaviour of buildings; at best the calculation, if done at all, was to multiply the external wall area by a crude measure of thermal conductivity. Little wonder that the buildings, certainly in parts of North Europe were, to all intents and purposes, uninhabitable in winter and unaffordable to residents in the social housing arena.

A few academics – notably Tom Markus and Peter Manning – took the view that what was needed was what came to be known as “Post Occupancy Appraisal (POA)” whereby – unlike the cuckoo behaviour of most architects (deliver, then clear off) – responsible professionals sought to investigate what had worked, and (more importantly) what had NOT worked in existing buildings; a most worthwhile but very long term endeavour. A more radical notion – about which this paper is concerned – is: *supposing* it were possible to *anticipate* the cost and performance consequences of alternative design options *before* the building was *actually* built? The question was how?

A further important factor in the equation, as the authors understand it, is the emergence, in the mid 1960s, of a renewed interest in the whole idea of **design** – what the philosopher Herbert Simon described in his seminal book *The Sciences of the Artificial* (1968), as ... “a science of design, a body of intellectually tough, analytic, partly formalizable, partly empirical, teachable doctrine about the design process”. A number of thinkers – J.C Jones, Hors Rittel, Geoffrey Broadbent, Bruce Archer – played significant roles in establishing such a science. Archer, already dissatisfied by the notion that human endeavour could be mapped on a linear dimension between the poles of what C.P Snow called “The Two Cultures” – the Humanities and the Sciences – proposed a triangle in which DESIGN formed an apex. Whereas the Humanities were driven by Natural Language, the Sciences by Mathematics, this new third culture – *design* – was underpinned by Modelling.

The advancement of this ‘science of design’ was supported, undoubtedly, by the availability in the mid 1960s of digital computers. Originally massive in size, expensive, difficult to interact with and modest in capability, their development was extraordinarily rapid, and with the advent of colour graphics, their relevance to the modelling of buildings was assured. The significant advances in the application of computers to building design can be summarised as follows:

The first primitive software to predict the cost/performance consequences of design decisions (Maver,1972).

Encoding of the laws of perspective geometry to allow representation of 3D “wire-line” views of buildings

Introduction of colour graphics to allow the first colour images of buildings

Visual Impact Analysis of constructions in the urban and rural landscape (Petric, 1991).

The advancement in scale from the representation of individual buildings to entire cityscapes (Maver & Flying Dreams, 1987).

Animation: the change from stop-frame film-based technologies, set up to run all night, to real time dynamic interaction

The huge increase in the sophistication of the modelling of the dynamic thermo-fluid behaviour of buildings as they respond hourly and annually to weather and climate (Clarke & Maver, 1991).

The application of multimedia software to explain our cultural patrimony (Maver & Petric, 1995).

The evolution of virtual reality and virtual worlds Ucelli at all, 2002).

Current State of the Art

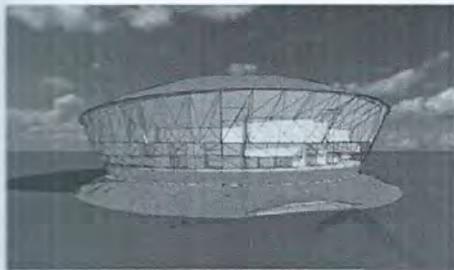
The current state of the art of computer aided architectural design (CAAD) has been summarised in the document authored by Maver and DiMascio. The areas of application, some well established and some still emerging, are:

- Information management and collaborative design
- Simulation of environmental performance
- Parametric geometries
- Space syntax
- Generative design
- Precedence, prototypes and shape grammars
- Digital fabrication, rapid prototyping and shape grabbing
- Large urban databases and smart cities
- User participation in design
- Multimedia in heritage and patrimony
- Virtual reality, virtual environments and virtual worlds

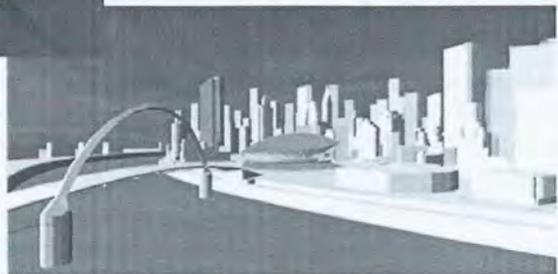
For the purposes of this paper, the authors have chosen to illustrate the power of computer based modelling through the work of the company IES – Integrated Environmental Solutions (www.iesve.com) – which came into existence in 1987 (originally as Abacus Simulations Limited) as a spin out from the highly successful

is expected to host the MTV Music Awards and was the venue for Boxing and Gymnastics during the Glasgow 2014 Commonwealth Games.

IES Consulting performed detailed dynamic simulations to investigate the operational energy usage of the SSE Hydro arena when in its normal concert mode, as well as predictions towards its use as a venue in the Glasgow 2014 Commonwealth Games. Secondly, IES Consulting produced Building Regulations simulations to investigate compliance for Section 6 and assess the rating for the EPC (Energy Performance Certificate).



THE SSE HYDRO, GLASGOW



- Capacity - 13,000
- Construction Cost - £125 Million
- EPC Band B
- Commonwealth Games Glasgow 2014

Figure 1. The Hydro in Glasgow

The Solis Hotel, Qatar

This 400 room hotel (Figure 2), of 82,000 square metres, features a wrap-around organic shading form.

IES Consulting performed the LEED energy and daylight modelling for this 5 star hotel development at Education City in Qatar at both early and final design stages. The final energy modelling indicated a 25.4% cost saving which demonstrated the pre-requisite for EAp2 (Energy and Atmosphere - LEED Credit) and a total of 7 credits for EAc1 (Energy and Atmosphere - LEED Credit). IES worked with the client to streamline the model building stage and reduce time pressures by utilising BIM capabilities to share and import aspects of the building geometry, in particular the shading structure as much as possible. This

was achieved through file imports staged from Rhino3D to SketchUP and then the plug-in connection to the Virtual Environment.

IES then completed the model build phase within the ModelIT interface and produced rendered 3D visualisations to facilitate model checking. In addition to visual checks, IES utilised tabular room data to export schedules on room grouping, floor area, room volumes, glazing area and much more.

IES used cloud computing to calculate the SunCast solar shading impression due to the complex relationship of the wraparound shading and protected glass and stone facade. This high performance computing was the perfect solution for expediting the calculation and meeting the client's design schedule.

Prior to energy simulations IES produced 3D rendered data visualisations of the model layered to display fabric, room activity and system assignments across the multiple floor plates. This provided IES the ability to reduce the model checking stage by ensuring the client had rich visual access to the complex model setup. With this integrated data sharing approach it ensured a substantial risk reduction when managing the high levels of data and built confidence in the accuracy of the simulation results.

IES used the ApacheHVAC module to define the hotel's HVAC (Heating Ventilation and Air Conditioning) setup which included a mixture of FAHU's (Fresh Air Handling Unit), fan coils, VAV (Variable Air Volume) and CAV (Constant Air Volume) systems. With the large number of guestrooms IES employed the 'Multiplexing' feature within ApacheHVAC to specifically replicate common zones and speed up the modelling as a whole. In addition the networks modelled the hotel's connection to the Education City district cooling network and the hotel's own ~1,100m² solar collector array which was linked to the domestic hot water loop.

IES used the VE Navigator for ASHRAE 90.1 PRM 2007 modelling to complete all steps required for the LEED energy model credit. The energy simulation process included integration of the following stages within the ApacheSim; utilising IES-Radiance to model the daylight sensors for room daylight dimming, as mentioned previously the SunCast solar shading and then the ApacheHVAC network integration.

Lastly IES used VistaPro to interrogate the model results and produce tables and charts highlighting the energy breakdown and informing where the building's dominant loads existed and hence where opportunity for savings existed. With the power VistaPro capability it allowed IES to drill into energy use profiles for the floor, network and zone levels. This meant no data was hidden on the building performance and design optimisation.



THE SOLIS HOTEL, DOHA, QATAR

Figure 2. The Solis Hotel in Qatar

London Heathrow Third Terminal

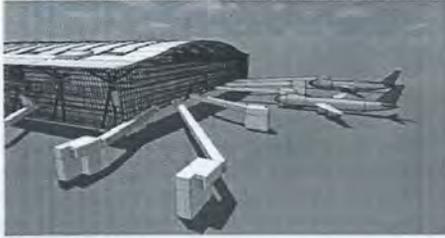
This massive project (Figure 3), designed by the Richard Rogers Partnership, cost in excess of 5 billion EUR and occupies an area of around 50 football pitches. It won the RIBA National Award in 2008.

IES was asked to apply the Virtual Environment software to analyse critical design factors including: the building's thermal comfort, airflow, energy consumption, daylight and glare, from concept through to production design.

The Virtual Environment software provided the design team with accurate performance information on aspects of the building's design such as form and fabric of the roof, facade and solar shading. The selection and sizing of the heating, cooling and ventilation system design could also be examined. Finally, at a later stage, the Virtual Environment was used to check and provide compliance with Part L of the Building Regulations. DSSR and BAA selected IES Consulting and the IES Virtual Environment Building simulation software for a number of important reasons. These included:

- The Virtual Environment was the most powerful modelling tool available.
- The unique integrated data model meant that the simulation processed faster and the data and analyses were managed in a controlled and structured manner.
- The software allowed DSSR to view, query and edit the model and simulation results at any time, providing tremendous flexibility.

In addition, IES was the only organisation which could provide the level of expertise and staff to handle the wide range of design and performance issues involved in such a consultancy role. Although no special customisation was required, IES had the capability of adapting the software if the needs of the project demanded.



- Architect - Richard Rogers Partnership
- Size of Interior Space - 50 Football Pitches
- UK's Largest Free-Standing Structure
- Cost - £4 billion
- RIBA National Award Winner 2008
- Skytrax Awards - World's Best Airport Terminal 2012

LONDON HEATHROW TERMINAL 5

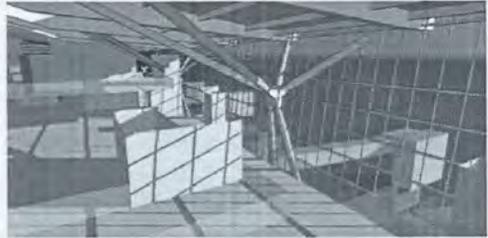


Figure 3. Heathrow Airport's Third Terminal

The Dubai Opera House

This innovative Opera House (Figure 4) seats 2,500 and occupies 300,00 square metres. The analysis focused on the energy performance of the façade in this demanding climate.

The Dubai Opera is a multifunctional building with several operational modes to include for opera, theatre and banquet usage, each having different design criteria, space usage and thermal conditions.

IES performed energy modelling to assess the foyer space which forms the glass facade of the building. The foyer wraps around the front and sides of the building and therefore experiences a varying cooling demand due to the changing solar gains distribution through the day. The assessment focused on selecting an optimum glass and shading performance through a series of collaborative energy and solar shading simulations. This provided the client with a numerical understanding on the foyer performance but also a strong visual communication where the solar exposure can be easily demonstrated from the building's curved form and its external shades.



- Seating Capacity - 2,500
- Floor Area - 300,000 sq metres
- Analysis - Facade Energy Performance

DUBAI OPERA HOUSE



Figure 4. The Opera House in Dubai

The Grand Mosque, Abu Dhabi

This is the third largest mosque in the world (Figure 5) and, with the help of IES was designed to be evacuated in 7 minutes or less, in the event of fire or other issues.

IES Consulting were appointed to conduct performance analysis to improve thermal performance, internal environment and safety. The process was to firstly create a Building Information Model (BIM) which accurately captured the architectural, structural and thermal aspects of the building. IES software allows geometry to be created from scratch in the same way as a conventional architectural CAD package, but also offers unique import/export links with market standard BIM platforms to facilitate information transfer.

Once the building model geometry had been created the next step was to begin populating the model with the necessary thermal information and HVAC data. The thermal behaviour of a building is the result of complex interaction between the structure of the fabric, internal lighting/equipment profiles and occupancy patterns, combined with the external environment. The software allowed for all of this information to be input dynamically and assigned to the model, enabling accurate capture of these complex interactions as they change over time.

With the geometric model populated to an appropriate level of information, the transition from a basic 3D model into a multi-dimensional building information model which could be used to inform the design team on key decisions was well under way. Initially, a dynamic thermal simulation was conducted in order to

focus on the potential effects of a proposed high level induction air-conditioning solution.

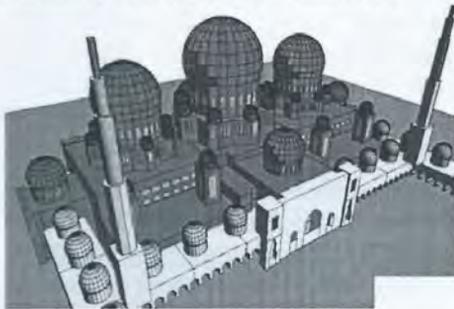
Further simulations were performed to accurately determine the magnitude of air-conditioning load requirements needed to maintain comfortable occupancy conditions within the building.

Another key output from the dynamic thermal simulation was the estimation of internal CO₂ concentration levels, of particular interest during Ramadan, when there could be as many 9000 occupants inside the main prayer hall simultaneously.

The dynamic nature of the simulation engine allowed a number of scenarios to be analysed, each with varying levels of fresh air supply from the central air-conditioning induction system. The combined effects on HVAC loads, energy consumption and thermal comfort were analysed for each option, allowing the optimum design to be determined.

In addition to the dynamic thermal simulation, a Computational Fluid Dynamics (CFD) analysis of the main prayer hall was carried out to model thermal comfort and airflow patterns in more detail. By using CFD the distribution from the high level air-conditioning induction system could be visualised in the model. In addition, the effects of extract and supply louvers located at high level around the central support columns could be determined.

The purpose of the evacuation model was to determine how quickly 9000 occupants could escape the building in the event of the break-out of a fire. The Simulex evacuation module of the suite was used and the total evacuation period was simulated at around 6 to 7 minutes.



- 3rd largest Mosque in the world
- Simulated Evacuation Period - under 7 minutes

GRAND MOSQUE, ABU DHABI

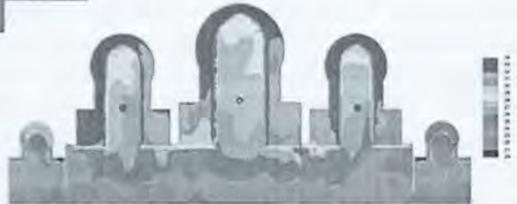


Figure 5. The Grand Mosque in Abu Dhabi

The Way Forward

It is the view of the authors that the advances which have been made in the transformation of the practice and education of architectural design, for the first time in many hundreds of years, have changed radically by the emergence of CAAD. More importantly, authors have the view that the NEXT four decades will see a more profound transformation that only our students will both envisage and create. We hope they will realize this potential.

Acknowledgements

To all the able and far-sighted students we have encountered. They are the future.

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research group ABACUS (the Architecture and Building Aids Computer Unit, Strathclyde) in the Department of Architecture and Building Science in the Faculty of Engineering at the University of Strathclyde in Glasgow, Scotland. The research group, of which the authors were both members, came into existence in 1969 and by 1996 had won the top rank of 5* (the equivalent of International Excellence) in the UK Universities' Research Assessment Exercise. From its origins of a couple of academics, IES has grown to an international organization of over 170 professionals with offices on four continents and a client base of the best known architectural and engineering practices worldwide.

This is how the Company describes itself – a little bit over-blown for the academic mind-set:

“As thought leaders, we are continuously investigating how performance analysis plays a vital role in delivering measurable sustainability, whether that is designing or analysing a product range, regulatory system, building or entire communities/Eco-Cities. Our expertise sits at the heart of the building lifecycle making us the perfect partner to quantify, optimize and verify sustainability objectives through integrated building science analysis.

We can deliver a tailored high-level service to address the individual needs of the many diverse built environment stakeholders. We can provide them with the most appropriate solution, whether that is technology, training, consultancy, research or a combination. We believe we are uniquely placed to help more rapidly deliver a sustainable future for our cities and buildings.

By 2050 cities will contain 70 per cent of the world's population, and ‘we’ need to look at how to make those cities as efficient as possible. IES has the analysis expertise to drive measurable change for sustainability and in conjunction with our partners realise tomorrow's built environment.”

What IES can do, and how its work characterises the current state of CAAD, is best illustrated through a number of case studies that will be more lavishly illustrated in the presentation of this paper. The cases are as follows:

The Hydro, Glasgow

The Hydro (Figure 1), a new facility in Glasgow with a capacity of 13,000 spectators and a construction cost of 150 million EUR, was built in time to provide one of the major venues for the Commonwealth Games in 2014.

IES Consulting carried out extensive energy analysis and 3D modelling during design stage for the SSE Hydro arena in Glasgow using the IES Virtual Environment software. The arena designed by architects Foster + Partners has a 13,000 capacity and has since played host to world famous acts in its short life. The venue