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# Modelling Sustainable and Optimal Solutions for Building Services Integration in Early Architectural Design

## Confronting the software and professional interoperability deficit

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**Abstract:** Decisions made in the earliest stage of architectural design have the greatest impact on the construction, lifecycle cost and environmental footprint of buildings. Yet the building services, one of the largest contributors to cost, complexity, and environmental impact, are rarely considered as an influence on the design at this crucial stage. In order for efficient and environmentally sensitive built environment outcomes to be achieved, a closer collaboration between architects and services engineers is required at the outset of projects. However, in practice, there are a variety of obstacles impeding this transition towards an integrated design approach. This paper firstly presents a critical review of the existing barriers to multidisciplinary design. It then examines current examples of best practice in the building industry to highlight the collaborative strategies being employed and their benefits to the design process. Finally, it discusses a case study project to identify directions for further research.

***Keywords:* building services, decisions, integration, multidisciplinary, design modelling**

## 1. Introduction: Services Integration in Early Architectural Design

Given contemporary awareness of global environmental concerns, the imperative to reduce energy consumption and associated carbon emissions can no longer be ignored by stakeholders and practitioners in the Architecture, Engineering, and Construction (AEC) industry. The effects of global warming demand that increasing attention be given to the procurement of buildings that are more sustainable in both their construction and operation. Despite this, building services, one of the major components of energy usage and cost, are rarely considered as even constraints in the early stage of a design, let alone as potential driving factors for form and spatial configuration.

Presently, on a global scale, the buildings sector is responsible for 33% of all energy-related carbon dioxide emissions (Intergovernmental Panel on Climate Change, 2007). Furthermore, in Australia, 18% of the nation's emissions can be attributed to commercial buildings (Intergovernmental Panel on Climate Change, 2007), with the ongoing operation of heating, ventilation and air-conditioning

(HVAC) systems accounting for over 60% of the energy consumption responsible for these emissions (Department of Sustainability and Environment, 2006). However, it is atypical for the implications of either passive or active thermal comfort strategies to be explored in any detail in the early modelling of a building proposal, despite the possible environmental and financial benefits that stand to be gained from this approach (Drogemuller, Crawford, & Egan, 2004). In order for the form and geometry of buildings to be considered in response to performance-based considerations, such as energy efficiency and building services optimisation, multidisciplinary integration is required in the early stages of the design process when the proposal is still flexible and malleable (Tavares & Martins, 2007).

In this paper, the term *interoperability* refers both to the technical ability to exchange and use information across a system, as well as the capacity of professionals in diverse organisational structures to work together. This social capacity to *inter-operate* is vital in *performance-based design*, where the building form is not developed solely according to architectural considerations, but is instead generated in response to performance factors such as energy consumption and comfort control strategies, and requires simulation and analysis throughout the design process to be evaluated effectively (Kolarevic, 2003). The idea of performance-based design is considered distinct from the concept of *building information modelling (BIM)*, which has a more technological basis and is defined as the development of a digital representation of the physical and functional characteristics of a facility, serving as a shared knowledge resource for information that is more than simply data concerning geometry (Aranda-Mena, Crawford, Chevez, & Froese, 2009).

## 2. Barriers to Multidisciplinary Collaboration

The increasing complexity of sustainability and building performance issues requires multidimensional tradeoffs across a range of disciplinary objectives, rather than simply experience-based guidance towards a solution (Clevenger, Haymaker, & Swamy, 2008). This necessitates a shift away from present information-oriented methods, toward process-oriented methods that encourage a dialogue between all parties involved, in order to formally and accurately capture design intent and information interdependencies for exploration and optimisation (Haymaker & Suter, 2006). Both architects and engineers must learn how to modify their tools and their skills to accommodate the significantly different types of knowledge and work processes being brought together (Frazer, Tang, & Gu, 2001). Only by engaging in this manner can an integrated, collaborative design process emerge that has the capacity to resolve performance and design constraints simultaneously, and subsequently catalyse innovative building solutions (Holzer, Tang, Xie, & Burry, 2005).

However, there are a number of social and technical barriers inhibiting multidisciplinary design collaboration, most of which are focused around how and when information is shared between the different parties involved in the delivery of a project (Haymaker et al., 2006). To date, research has tended to focus primarily on finding solutions to only the technical problems, specifically, looking to improve issues of interoperability through the refinement of data exchange standards and customisation of application programming interfaces (Boddy, Rezgui, Cooper, & Wetherill, 2007). One of the fundamental downfalls of this approach, however, is that the design tools that have emerged from this direction of enquiry tend to favour documentation and management tasks that arise once the design of the building is already substantially underway (Lawson, 2005).

The subsequent result is that the current suite of computational tools available to designers are lacking in their ability to support decision-making and supplement tasks associated with resolving interdependencies between performance criteria and form in the early stages of projects (Schlueter & Thesseling, 2009). Performance-based simulation tools are largely discipline-specific and primarily used by engineers to substantiate a chosen proposal late in the design process, rather than to explore alternative solutions through analysis and evaluation early on (Flager, Welle, Bansal, Soremekun, & Haymaker, 2009). While there is the capacity to provide high resolution analytical data, the concurrent lack of ability to seamlessly integrate with software packages from other design domains means that computational advances are not being utilised to their full potential, and can actually inhibit the multi-objective exploration of possible solutions (Kolarevic, 2003).

The underlying problem that is evident is that the design software available exacerbates the lack of communication currently already existing in conventional practice. The tools that support high resolution design solutions have developed more rapidly than the framework of communication that is supposed to be sustaining them, and the result is a lack of cohesion between overarching project objectives and the computational methods for achieving them (Holzer, 2007). Paradoxically, collaborative design endeavours have been demonstrated to be more successful when integrated design infrastructures and communication networks are in place prior to the implementation of multidisciplinary technologies (Nikas, Poulymenakou, & Kriaris, 2007). It thus becomes crucial to acknowledge that design strategies must be established in response to knowledge and process interdependencies, and not dictated by the use of generic computational tools, so that information is placed in a context easily understood by the whole design team (Cheng, 2003). A refocussing of collaborative tactics is therefore called for that reflects support for process integration, as well as technological integration, in the early design stages, to ensure the integration, rather than dissemination, of knowledge (Augenbroe, de Wilde, Moon, & Malkawi, 2004).

## 3. Current Multidisciplinary Practice

Current practice is supporting a transition away from a linear work flow that promotes engineering as mere support for architectural design, toward a multidisciplinary approach where performance-based tools and processes provide the mediation between the participants and the design (Janssen, Frazer, & Tang, 2002). More consideration is being given to whole of building lifecycle considerations earlier on in the design process, which is necessitating the embrace of integrated design policies, technologies and processes (Succar, 2009). The two approaches that have gained acceptance in current research on these collaborative initiatives are the development of virtual design and analysis tools (Shelden, 2009), and the implementation of integrated communication and information management strategies (Haymaker et al., 2006). The first of these approaches relates to the idea of technical integration, while the second relates more to the concept of social integration.

One Island East is a seventy storey commercial office tower in Hong Kong that was procured through substantial implementation of virtual 3D building lifecycle tools (Figure 1). Gehry Technologies were consultants to the design and construction of the virtual model for this development, the complexity of which can be seen in Figure 2, which depicts the mechanical, electrical and plumbing services (Gehry Technologies, 2009). In this project, Building Information Modelling (BIM) facilitated a high degree of information integration and data exchange between members of the design and construction teams and the client, to improve the integration of building components (Boddy et al., 2007). The objective of this process was to minimise cost and construction time, which was achieved through the use of multidisciplinary integrated modelling tools that allowed for the optimisation of the sequencing of construction stages (Gehry Technologies, 2009).

Figure 1: One Island East, Hong Kong (Gehry Technologies, 2009).

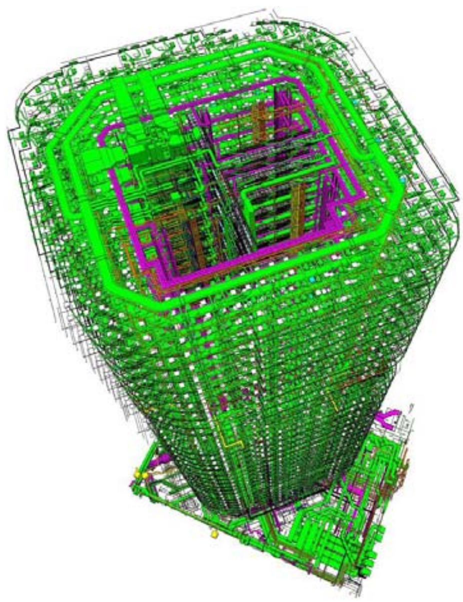

Figure 2: Mechanical, electrical and plumbing model for One Island East (Gehry Technologies, 2009).

In this case the decision to implement a computational tool that integrated immensely complex and detailed building information compromised the ability of the design model to remain flexible to design modifications and alterations (Shelden, 2009). Collaborative design exploration and optimisation in the conceptual phase was restricted in favour of efficiency in the management of documentation and detailing tasks late in the design process. This clearly demonstrates the inability of existing collaborative technologies to support multidisciplinary design prior to the basic geometry of the building being established definitively (Holzer, 2007). In order to facilitate performance-based design explorations, more flexible frameworks that support the communication and management of multidisciplinary information and processes in the conceptual phase of the design are required (Haymaker & Suter, 2006).

Council House 2 (CH2) in Melbourne, the first six green star rated building in Australia implemented a collaborative design process that commenced with a two week multidisciplinary charrette for the development of the schematic proposal (Figure 3). The charrette process enabled 70% of the design and building systems to be resolved in the initial concept stages, an example of which can be seen in Figure 4. It also improved communication and understanding between the disciplines and professions involved in the project, as well as affecting a six month reduction in design and tender time from what was originally predicted (Hes, 2006b). Although this approach necessitated additional upfront investment, for the design and installation of all the environmental features in the building, it is predicted that this will have paid itself off in six years, through savings on energy and water consumption as well as over one million dollars a year in increased staff productivity (Hes, 2006a).

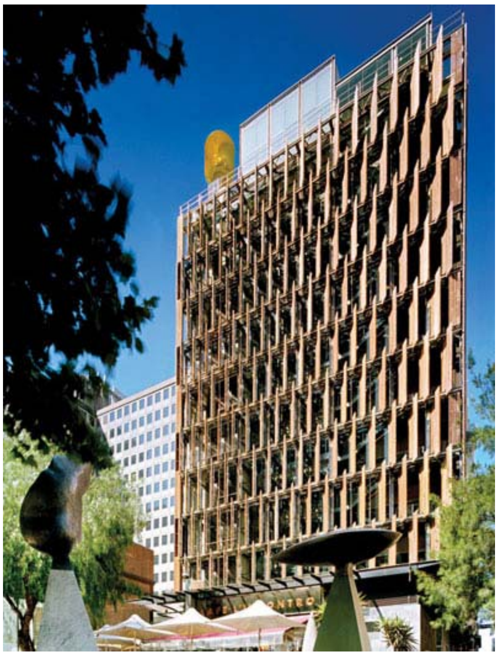

Figure 3: Council House 2, Melbourne (Fortmeyer, 2008).

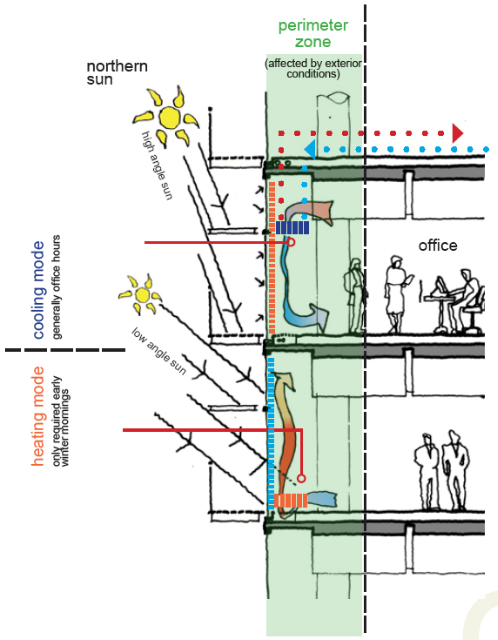


Figure 4: Heating and cooling strategy for Council House 2 (City of Melbourne, 2006).

The success of the CH2 project can largely be attributed to the considerable attention given to thermal comfort schemes in the development of the conceptual design. Rather than acting as a restriction to the design or hindrance to the realisation of the project, the consideration of services in the conceptual design phase became a driving factor in the building's form, to maximise the quality of the interior environment while minimising energy usage and associated carbon emissions (Hes, 2006b). While these outcomes alone are quite an achievement, this process could be further augmented and strengthened through the development of low-resolution integrated modelling tools that permit the iterative testing of design solutions early on, rather than relying on precedence-based knowledge and methods from the consultant team (Nicholas & Burry, 2007).

The following case study from the Queensland Government Project Services demonstrates how similar strategies employing services integration in early architectural design are presently being investigated in Australian public practice. By exploring how the objectives of improving user comfort and minimising energy consumption can influence design, with an emphasis on developing *both* social and technological integration in parallel, this illustrates that more innovative and sustainable built environment solutions can be generated.

## 4. Case Study: JCC Project

The commission of the Joint Contact Centre (JCC), a 5100m$^2$ office located in Brisbane for non-emergency police calls and general government services, provided a unique challenge to the design team at Project Services. Not only did the program call for the accommodation of 375 employees and the operation of the premises 24 hours a day, but the client required a green-star outcome of six stars. Due to the green star rating scheme having a heavy emphasis on energy efficiency, the mechanical and electrical engineering teams were involved in the project from its outset, as part of an iterative design process that also involved architects and structural engineers.

Forty-five different services-design scenarios were modelled and analysed in the conceptual phase, examining variations to the basic form that included orientation, the presence of an atrium, the inclusion of cooling towers, alternative façade designs, alternative roof designs, the use of passive and active chilled beam cooling systems, and changes to the floor to ceiling height. Six of these different variations can be seen in Figure 5. Each of the iterations examined the impacts that these variations had on the somewhat conflicting performance criteria, exploring the tradeoffs required between spatial organisation, and HVAC, lighting and structural systems, to obtain an optimal design solution. For example, in order for the necessary lighting levels to be achieved during the day entirely through the use of natural light, to reduce energy usage, floor to ceiling height would have needed to be 4.5 metres. However, this would have increased the cooling load for the building, as well as placing an increased burden on the structural system, which subsequently would have led to a significant increase in both operational energy usage and construction costs. Further investigation revealed that the placement of an atrium along the building's central axis provided for these lighting levels at only a 3.45 metre floor to ceiling height, with just a negligible increase in the cooling and structural loads.

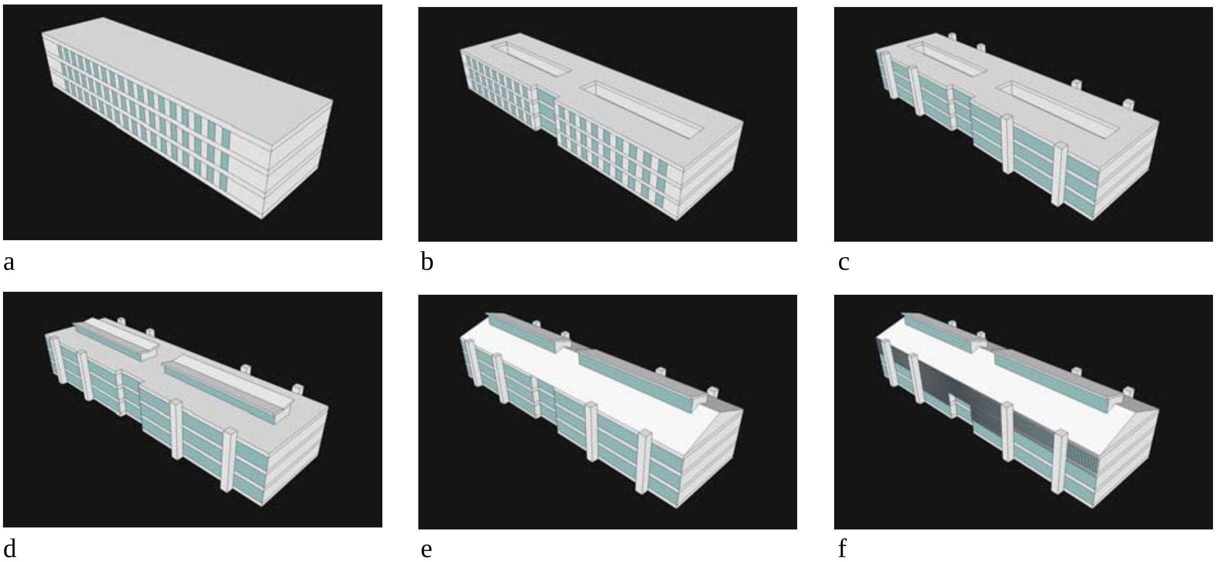

Figure 5: A selection of the various design models explored: a) floor to ceiling height of 4.5 metres; b) floor to ceiling height of 3.5metres with central unenclosed atria; c) addition of cooling towers; d) enclosed central atria; e) roof pitch of 23°; f) addition of window shading.

Once the form of the massing model had been established, more refined iterations were undertaken that looked at the performance constraints of chilled beam cooling systems. Variations considered were for minimum internal temperatures of 18°C and 16°C, and then again for 16°C with a 20% reduction in air speed. The criteria for evaluating the options weighed the quantitative result of total energy consumption against the qualitative measurement captured by the percentage predicted mean vote (PMV) of people considered comfortable. In this case the option that saved the most energy also provided the greatest comfort. It should be noted however that each of these predictions was based on empirical measurements and made certain accepted and standardised assumptions with regards to building usage, which can only ever be an abstraction and estimation of the actual situation. Regardless of these possible discrepancies however, the benefit gained from running a series of simulations arose from the ability to compare the performances of a number of design options.

The JCC building was a pilot project for Project Services that demonstrated an integrated BIM approach to modelling not achieved previously in the practice, combined with a collaborative multidisciplinary approach from the outset of the project. Not only were all disciplines working on the same central model for the design development and documentation of their individual contributions, but analysis software was specifically chosen for its ability to link to the 3D modelling program being used, Autodesk's Revit™, and therefore facilitate performance evaluations of the design as it progressed. In this case, the energy analysis software employed was IES's Virtual Environment™, which has an established link to Revit™, and initially allowed for the architectural model to be transferred with minimal remodelling. It should be noted however that each option had to be modelled individually, as the software being used lacked both parametric capabilities and the capacity to transfer information bidirectionally. In addition to this, the simulation files took some time to set up, as the analysis software required a substantial amount of detailed information regarding building services. The responsibility for these early design investigations fell heavily on the engineers, as opposed to the architects, due to the expert nature of the analysis and interpretation required, making apparent that the tools being used did not adequately support conceptual exploration or multidisciplinary integration.

Despite these obstacles, this strategy proved quite effective in providing information to the designers regarding decisions to be made to improve the sustainability of the building early on. However, as the design began to progress and the solutions were refined, the model became more detailed, as can be seen in Figure 6, and this integration between disciplines became difficult to maintain. Part of the problem was caused by underlying software and hardware incompatibilities that materialised as time progressed. However, the deeper issue that emerged was a lack of interdisciplinary understanding about the process requirements of other design domains. Further to this, what became apparent was that the individual disciplines lacked awareness concerning BIM modelling inputs and outputs at the different stages of the design process, which also explained the minimal involvement of the architects in the initial design evaluations. Models were often overloaded with unnecessary data while simultaneously not containing sufficient information required for analysis when passed from one discipline to another. This was quite obvious when the engineers attempted to use the architectural models for analysis only to find that rooms had not been modelled as enclosed spaces and therefore could not be used to represent thermal zones. In the later stages of this project, the engineers had to remodel the building from scratch to perform the necessary analyses, due to a combination of inaccuracies in the architectural model as well as problems with the file translation between software packages.

Figure 6: Developed design model.

What becomes apparent from this case study is that there is a definite need for the different disciplines involved in the building design process to further improve their understanding of each other's information needs.  The analysis itself is invaluable, but only if there is effective communication and adequate comprehension of the implications arising from specific design objectives.  This must be achieved not only through clearer communication of design intent and improved knowledge integration, but also through more rigorous adherence to the modelling standards set by the practice, so that consistent representations are maintained throughout the design process to facilitate mapping between disciplinary models.  Appropriate levels of abstraction must be negotiated to allow for a more efficient transfer of design and analysis data between the disciplines, rather than continuing to engage building information modelling with the aim of producing a perfect virtual copy of what is intended for construction (Mahdavi, 2004).

While BIM theory dates back several decades, it has only recently started to become prevalently accepted in practice, and as such, it is still falls short of supporting the early design process, in favour of assisting documentation (Holzer, 2007).  As well as the obvious problem of software compatibility, the high resolution data structures lack the capacity to selectively filter or prioritise specific project information, creating conditions of over-constraint that often hinder the early iterative exploration of the most imperative design criteria (Burry & Burry, 2008).  Lower resolution project representations, consisting of lighter data-sets, are required to support early stage design enquiries, when changes to the form of the design can vary dramatically and be quite sensitive in response to the performance variables being considered (Holzer, 2007).  This will involve methods which support abstraction and prioritisation of project criteria in the early design stages, in order to test multidisciplinary optimisation strategies in a manner that promotes creativity and innovation (Mahdavi, 2004).

The issues of integration and interoperability exhibited in this case study, which persist throughout design practice as a whole, must be overcome to provide a means by which to explore the interrelated nature of performance-based criteria in creative and effective ways (Kolarevic, 2003).  By managing the level of detail in building models, there is the potential to be able to explore a greatly increased number of design and analysis iterations in the conceptual stage of a project, through the semi-automation and management of the setup and execution of digital simulation tools (Flager et al., 2009).  This transition to an integrated and iterative process would then lead to design solutions with improved performance outcomes, and result in a more sustainable built environment.

## 5. Conclusions

Appraisal of this case study serves to highlight the difficulties that arise from engagement in multidisciplinary collaboration and makes apparent the areas of the design process that require further work to recognise the full potential of technological advances in the AEC industry. It is becoming increasingly obvious that present information-oriented methods are insufficient for collaborative design endeavours, and that what is needed instead are *process-oriented methods* that support *multidisciplinary design exploration*. If performance-based integration is to be achieved in the early stages of design exploration, then a collaborative strategy is required that focuses on *facilitating the communication and management of processes and knowledge, as well as data*.

If the next generation of tools for multidisciplinary design and optimisation could focus on supporting information interdependencies and design evaluation processes, we might then be able to engage in holistically integrated design practice. To traverse the disparity between collaborative technologies and collaborative processes, these tools will need to have the capacity to negotiate different levels of multidisciplinary information in a manner that is appropriate to the phase of design exploration. This is particularly relevant when considering the process of energy analysis involved with assessing the integration of services and architectural design, where the information is bidirectional between disciplines.

Only by reducing the complexity of these modelling and simulation tools will energy analysis design processes begin to present themselves as potential generators of innovative and sustainable building solutions, rather than act as deterrents to their own use (Ellis & Mathews, 2002). Additionally, given the inaccuracies inherent in these performance evaluation models, it is vital to recognise that overly complicated analyses quite often fail to produce precise performance data, due to small changes in the design having significant impacts on the energy usage (Clevenger & Haymaker, 2006). While they have their place, complex and overly comprehensive simulation tools are not always necessary as comparisons of alternative options can be substantially more valuable than the absolute results themselves (Ellis & Mathews, 2001). This is particularly the case in the conceptual design phase, when many aspects of the form and services are only preliminary, and likely to be modified or altered as the design progresses, especially if performance requirements are tested and fed-back into the design development loop.

The environmental and financial benefits of integrating services design in early architectural conceptual modelling cannot be ignored despite the technical challenges that present themselves. At a time when global ecological and economic issues have intersected in ways that hitherto have not caused such concern, we can react positively by increasing our attention to the procurement of buildings that are more sustainable in terms of their construction and operation. It naturally follows that for building services, as one of the major components of energy usage and cost, to begin to have greater prominence as core driver in the design process, a greatly improved software interoperability will need to be complemented by improved communication strategies between collaborating disciplines.

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