distributed intelligence in design

edited by Tuba Kocatürk and Benachir Medjdoub

WILEY-BLACKWELL

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This edition first published 2011

Blackwell Publishing was acquired by John Wiley & Sons in February 2007. Blackwell's publishing program has been merged with Wiley's global Scientific, Technical and Medical business to form Wiley-Blackwell.

Registered Office:
John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Offices:
9600 Garsington Road, Oxford, OX4 2DQ, UK
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2121 State Avenue, Ames, Iowa 50014-8300, USA

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Library of Congress Cataloging-in-Publication Data

Distributed Intelligence in Design Symposium (2009 : Salford, Greater Manchester, England)
Distributed intelligence in design / edited by Tuba Kocatürk, Benachir Medjdoub.
p. cm.
Includes bibliographical references.
ISBN 978-1-4443-3338-1
1. Building–Information services–Congresses. 2. Architecture–Information services–Congresses. 3. Distributed artificial intelligence–Congresses. I. Kocatürk, Tuba. II. Medjdoub, Benachir. III. Title.
TH216.D57 2011
720.285′63–dc22
2010029073

A catalogue record for this book is available from the British Library.

This book is published in the following electronic formats: ePDF [9781444392371]; ePub [9781444392388]

Set in 9.5/12pt Minion by SPi Publisher Services, Pondicherry, India

1 2011

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Note on editors

Dr Tuba Kocatürk is an architect and a Senior Lecturer at Salford University, UK. She currently leads the MSc Programme in Digital Architectural Design at the University of Salford. Her previous academic appointments include Middle East Technical University (Turkey), Delft University of Technology (The Netherlands) and Harvard Graduate School of Design (USA). She has taught, conducted research and published extensively in the areas of digital architectural design. Her current research interest is the emergent socio-technical and cognitive frameworks in architectural design and production.

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Foreword

Paul Richens

The symposium at Salford in May 2009 brought together around 100 experts on the use of digital technology in architectural design. They included architects, CAD experts, people from the software industry and academics. The overwhelming impression was one of transition: people are experimenting, techniques and tools used last year will be superseded by the next, each project is handled differently from the one before. Everything is fluid: representations, tool sets, workflow, team structure, personnel and even philosophy. Consensus was certainly far away, but two ideas were clearly gaining significant traction. One was building information modelling (BIM) and the other parametric design (PD). As the symposium got under way, it became clear that there was considerable polarisation: most speakers (those from the software industry excepted) were proponents of one or the other.

BIM was described as bringing the discipline of database design to bear on the documentation of a building prior to construction. The model is shared by the entire team, describes everything just once, and includes semantic as well as geometric information. It facilitates interoperability, and avoids the inconsistencies that easily arise from multiple redundant representations. It is seen by its proponents as a platform for all kinds of analysis and production processes – and why not design as well?

PD is fundamentally a geometric technique. A design is represented as a Euclidian construction, where certain relationships are fixed, but other quantities (the parameters – positions, angles or lengths) can be varied. PD software allows the parameters to be adjusted and works out the consequences.

Support from speakers at Salford was measured; unlike BIM, PD is not seen as a universal problem-solver but as one of many tools useful for conceptual design and the geometrical aspects of design development. Their disagreement with the BIM people centred on the issues of multiple as opposed to single representations. Models, they say, are abstractions, and you need to use different abstractions for different purposes, different modes of thinking; a 'federation of models', as Hugh Whitehead eloquently said. Ambiguity is rather a benefit when you are working things out. BIM is an abstraction highly suitable for ordering materials and constructing a building, but not for designing it, and should perhaps be built by the contractor (as we heard was happening in Hong Kong) rather than the architect.

PD is clearly generating a lot of excitement. It offers an essential plasticity (easier to manipulate than clay or a sandbox) while simultaneously enforcing rules of arbitrary sophistication. This is what interactive CAD was always meant to be and, having at last got there, several distinct ways of using it are emerging. One is to explore many variants of the same basic design, by altering the parameters in a systematic way and inspecting the results, perhaps through drawings, 3D printing, or some kind of environmental or structural analysis. When coupled to analysis, this leads to the possibility of some sort of optimisation, or at least sensitivity analysis. In the design of tensile structures, engineers call the analogous process 'form finding', and it was interesting to hear the term being used in the seminar by architects.

A second use is to defer certain decisions, perhaps quite important ones such as controlling dimensions, to late in the design process. If a thoroughgoing PD model is employed, the change can be made and the consequences computed automatically. This can be very important; indeed, at Foster's 'change propagation is the issue'. There are many ways to construct and parameterise a model, and the choice you make encapsulates a decision as to which kinds of future change will be facilitated and which not.

A third use is within a design, to represent elements that are repeated not exactly but with some systematic variation in size or shape. It is striking how architecture has for thousands of years depended on regular repetition of identical elements – columns, arches, windows, vaults. The very first PD building (Grimshaw's Waterloo Station) demonstrated systematically varying trussed arches, and the considerable potential PD has for revolutionising architectural language is increasingly being recognised – perhaps most eminently by Zaha Hadid's office.

Another entrenched architectural tradition, a dependence on straight line and circle and the simple extrusions and surfaces of revolution they can generate (the Phileban solids), has already yielded to some extent to PD with the rather controversial development of 'blob' architecture. This new-found freedom is being exploited rather tentatively, for reasons of constructability. 'Design for manufacture' has entered the conversation, and a new process called 'rationalisation' is everywhere under discussion, meaning the breaking up of curved elements into pieces which are piecewise developable, and preferably cylindrical or plane. Two approaches are available under PD, and the preferred mode is becoming a rather significant differentiator of design style. In 'pre-rationalisation' the parameterisation is based on lines and tangential arcs, so that only simple surfaces can emerge. In 'post-rationalisation' an arbitrary doubly curved surface is processed into simpler panels by an optimisation procedure.

The theme of the seminar was distributed intelligence, and quite a number of views emerged as to where intelligence is to be found. For the BIM people intelligence is in the data; for PD it lies in the system of constraints and freedoms that 'capture the design intent'. For Chris Williams it lies in the software, a sharing of knowledge by the programmer who put it there for the benefit of the user who employs it. As for the network, 'information systems reflect management systems' we were told, so perhaps the PD/BIM divide is a reflection of the shift in design/build responsibilities that has come from modern methods of procurement. Designing a team organisation and workflow is seen as crucial to the delivery of a project (particularly for the propagation of change), so in that sense there is intelligence designed into the network.

Peter Brandon discussed the nature of expertise. Bryan Lawson reminded us that intelligence resides in the people, and that design intelligence is peculiarly hard to characterise. One thing is certain: expert designers think in substantially different ways to beginners, and the kinds of cognitive support an individual finds helpful change as experience develops.

Several speakers from practice reported on how they are forming specialist modelling groups in order to deploy PD. It is possible that a distinct discipline is beginning to emerge, that of architectural geometer, with a rather wide range of modes of interaction with other design team members. Indeed, designing the workflow for a particular project is perhaps the major responsibility, ahead of construction of a parametric model. Students are emerging from the universities with a high degree of fluency in scripting and parametric tools, but they need to acquire a considerable amount of architectural or engineering project experience before they can fill the specialist role.

As to the future, there seemed to be agreement that the next step in PD is to integrate some structural, environmental and constructional intelligence into the underlying geometrical framework, so that form-finding can proceed in a balanced way, following the principles of concurrent engineering rather than the sequential processes encountered most often in architectural practice today.

Introduction: Distributed intelligence in design

Tuba Kocatürk and Benachir Medjdoub

In the world of architecture, the emergent digital technologies have taken a significant role in how we create, collaborate, design and produce. This book attempts to address the current socio-technical transformation in the architectural industry, as a new paradigm. The increasing use of advanced 3D knowledge-rich parametric/generative tools, combined with information modelling systems and digital prototyping technologies, is already enabling radically new ways of designing and coordinating among the many actors in architectural design and production. Architectural and engineering design is becoming more and more a digitally networked practice. This has led to more distributed activities within and across disciplines and involves embedding intelligence in the formation and actualisation of spaces. Innovation in design is no longer recognised as the creation of a single product by a single designer, but as the outcome of an iterative and dynamic coordination of a cross-disciplinary intelligence that is distributed across various digital tools, people and organisations in a social context. The book tries to uncover the ways in which digitisation and digital tools have recently been adopted within the work practices of multidisciplinary firms and the evolving socio-technical networks and organisational infrastructures in architectural practice.

For quite some time now we have been debating the impact of new technologies on architectural practice and the emergent formal vocabularies. The generative, representational and collaborative potentials of various digital media and embedded computing are already well documented and discussed in various conferences, biennales and publications. Yet it would be fair to say that although the potential is huge and endless, the technological transformation the architectural profession is going through at present has not been as smooth as one would have hoped. The institutional and social structures of the building industry, as well as the high variation in its technical systems and practices (e.g. construction technologies, fabrication tools, computing software etc.), build up multiple barriers to utilizing the collaborative potential of new digital environments fully (Shelden 2006). Moreover, different digital media and collaboration styles offer radically new and, most often, varying methodologies to merge design with execution. Many practices struggle with the adoption of technologies into their work, as there is not yet any formulated method or theory of how to choose the best possible tools and organisational structures that will suit the designers' preferred design approaches or preferred set of media. Moreover, there are more fundamental issues in the utilisation of these diverse sets of digital media. For example, although BIM (building information modelling) systems provide better data transfer and integration, they do not entirely support the creative processes occurring during the conceptual design stages. Similarly, there is a computational limitation in the design aspects that cannot be addressed parametrically with the current capabilities of various parametric and generative software packages.

How is the architectural industry responding to the possibilities offered by these technologies? How is the industry adopting and utilising these technologies and how is this adoption transforming the dynamics of practice? One obvious observation is that innovative practices are not necessarily merely adopting design technologies but are finding innovative mechanisms to structure and coordinate multidisciplinary design intelligence through various media, customised workflows, organisational structures and complementary activities. With this book, we are not aiming to start yet another anachronistic debate on 'architectural design' and technology, as the two are already inseparably linked. The book rather attempts to discover the controversial relationship between design innovation and technology. Technology is indeed a critical enabler of innovation, however new human networks and work practices, in their turn, facilitate the emergence of new methods to deal with the emerging knowledge and complexity affecting the ways in which the technology is adopted and used. This instrumentalisation entails the ways in which humans mediate between different media, facilitating new coordination mechanisms across various interdisciplinary actors and representations. Consequently, we can observe the spontaneous emergence of highly complex socio-technical systems where both the human/organisational structures, and the IT capabilities are distributed, diverse and heterogeneous. In these varying socio-technical formations, the interaction of the architect(s) with different project participants through different media at different stages of the design process and the extent to which this interaction contributes to product and process innovation both vary.

We introduce the concept of 'distributed intelligence' to further investigate the socio-technical and techno-organisational repercussions of digitally driven processes in building design and production at large. Here the use of the term 'intelligence' has been a very careful and conscious selection which has become the current 'intellectual dominant of early twenty-first-century post-vanguards', as famously put by Michael Speaks in his *Intelligence after Theory* article (Speaks 2007). In this text, Speaks mentions a new group of intelligence-based practices and their unique design intelligence that enables them to innovate by learning from and adapting to instability. This group is more concerned with 'plausible truths' generated through prototyping than with 'received truths' of theory and philosophy. Here, plausible truths refer to a quick way of testing ideas by doing, or making them (prototypes), and are thus the engines for innovation. In other words, prototypes create a 'design intelligence' by generating plausible solutions that become part of an office's overall design intelligence. For example, a series of rapid prototyping models or generative design codes can enable the mass production of unique design solutions invented and deployed by an architectural design firm. In such a practice, design becomes more than a problem-solving exercise and creates new questions and solutions simultaneously, where the creative process is driven by an embedded intelligence.

We add a 'distributed' dimension to 'design intelligence' to end up with an even more complex entity with multiple interacting dimensions which need to be managed and coordinated accordingly. An important aspect of this complexity is the distribution of 'design knowledge' – the availability and orchestration of tools and ideas from different disciplines. Another aspect is the spatial distribution of 'interacting agents', which could further be distributed temporally when an artifact is being repeatedly modified by different user-creators over time. Finally, technological distribution involves understanding and distinguishing which medium, tool or technology is better suited for particular phases of a design. It is also important to note that architectural production is not just market, theory and/or technology driven, it also has a critical socio-cultural dimension which typically changes more slowly and incrementally than science and technology.

The change is continuous, incremental and multifaceted. Therefore, in the context of this book, the uncovering of distributed intelligence refers to a multitude of interdisciplinary design knowledge constituted by different individuals with different backgrounds and experience, the media and technologies that support their individual thoughts and inter-individual communication and the social network that links them together.

The chapters in the book are compiled from the presentations and discussions of the Distributed Intelligence in Design Symposium which was organised in May 2009 by the Mediated Intelligence in Design (MInD) research group at Salford University. The symposium brought together some of the best practitioners, thinkers and educators from around the world to discuss and debate the emerging concept of distributed intelligence in design as an attempt to answer the following questions:

- How have parametric and generative design tools moved the boundaries offered by conventional CAD tools and enhanced creative thinking?
- How is cross-disciplinary intelligence distributed and dynamically coordinated across different design/modelling software packages, actors and organisations?
- What are the characteristics of the evolving creative and collaborative practices (e.g. emerging skills, organisational and cognitive structures)?
- How can architectural education adapt to this digitally networked practice and highly distributed intelligence in design?

The chapters are grouped under four main sections, each addressing a combination of methodologies and theoretical arguments, academic research work, innovative developments and state-of-the-art applications and industry experience.

From a future-oriented perspective, the book aims at presenting where we are and what can be expected in the next generation of architectural and engineering design as a collaborative practice.

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Part 1

1 Of sails and sieves and sticky tape

Bryan Lawson

This chapter concentrates on creative conceptual design and will not deal with downstream issues of detailed technical development or the generation of production information. The title of the Distributed Intelligence in Design symposium used only the word 'design'. It is not until we got into the description of the conference theme that the word 'production' appeared. From then on 'design' and 'production' were as inexorably linked like 'love and marriage', as the song would have it. I challenge that assumption, all the more dangerous because it is implicit rather than explicit. In particular, I am concerned about the dangers of developing knowledge structures and applications for the production stages of construction that then wash back into design.

In a paper very well known in the design research world, Nigel Cross asked us: 'Why isn't using a CAD system a more enjoyable, and perhaps, also more intellectually demanding experience than it has turned out to be?' Nigel argued that CAD may in some cases be quicker, but it is more stressful and there is no evidence that the results are better (Cross 2001).

I have taught in schools of architecture that are privileged to have the most able students of their generation. Whether in Sheffield, in Singapore and China, in Holland and Norway, in Sydney or America, I find the same thing. Students no longer think computers are either difficult or extraordinary; they are just a fact of everyday life. Many architecture students find that computers are not a very appealing part of their design lives. My graduates regularly give voice to a tormenting dilemma. Listing their considerable CAD skills in their CVs often helps them to get a job. But they live in fear of their project leaders discovering this, especially during their years of practical training. They return telling tales of being sat for months in front of a computer exploited as 'CAD monkeys'. They have a plethora of terms for the abuse of computers in design, from 'Photoshop rash' (the over-application of textures and photorealistic skies) through 'Macfontopia' (indiscriminate proliferation of fonts made so easy by the Mac) to 'Modelshop bargains' (an over-reliance on 3-D modelling forms). I have censored the names they have for principal partners who insist on all this nonsense to impress their clients but are unable to do it themselves.

Our students were further discouraged when one of their number won a major national award for his use of CAD and yet, with the same submission, failed his master's degree.

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

My professional experience is hardly more encouraging. I am part of an international consortium that won the competition to masterplan about 100 hectares of central Dublin known as Grangegorman. The lead architects, Moore Ruble and Yudell, are in Santa Monica; the transportation planners, Arups, and conservation consultants, Shane McCaffrey, in Dublin; the landscape architect, Lutzow 7, in Berlin; the sustainability engineers, Battle McCarthy, in London; and I am in Sheffield. We met as a team roughly once every six weeks, but otherwise relied entirely on IT to communicate across continents and time zones.

What software did we use? Obviously we had an FTP server that held jpegs, Microsoft Office documents and pdfs. The size of such files was already a problem and exchanging CAD files or other active documents was impractical. We largely relied on Word and Acrobat Reader. We used some very basic 3-D modelling software but created inert pdf files for exchange. We often sketched over them by hand, digitised and returned similarly dead files. It worked OK, but relied heavily on the trust established in the face-to-face workshops where we sketched by hand and looked at physical models. How disappointing after all these years!

The vast majority of the software most architects use today is generic. We manipulate pixels and vectors and occasionally use crude solid modellers and generic word processors and spreadsheets. The few big CAD systems are not specifically architectural, although some have what you might call an architectural accent such as the Bentley suites. Even these are really AEC rather than architectural in their way of thinking and working. When we recently did research with architects in the UK using the Bentley suite, we struggled to find any operating the latest version or making sophisticated use of its supposed architectural features.

Design as a cognitive task

From a psychologist's perspective, our view of the possible role of the computer has changed and I want to suggest it is now in need of another paradigm shift to take us forward. The first people in this field (Whitehead and Eldars 1964, Auger 1972) expected that long before now computers would be designing buildings.

More recently, I have worked with cognitive scientists who are in what we might call the 'computation theory of mind' camp. This artificial intelligence theory in essence claims that eventually we will make computers do what our brains can do; the only problem is we have not yet got big enough and powerful enough machines and sufficiently sophisticated software languages. Many of us have felt uncomfortable about this for a while, but each time we threw a new challenge down they would eventually rise to it. 'OK,' we said, 'computers can play noughts and crosses, but they can't play draughts.' They did, so we challenged them to play chess. Of course they did that too. Then we cheated and demanded they beat the best human players. Guess what? They did, although no one seriously claims the software uses human-like cognitive processes.

At last cognitive scientists are seeing design as the challenge that collapses this house of cards. You could trace this argument through Jerry Fodor's T*he Language of Thought* (Fodor 1975) and then on to Dreyfus' *What Computers Still Can't Do* (Dreyfus 1992) and Vinod Goel's *Sketches of Thought* (Goel 1995). AI claims that we can represent all useful knowledge through symbol systems and thought through the manipulation of those symbols. Our view now is that it does not seem possible to represent design knowledge and processes in this way. The leap from chess to design is not the same sort of thing as the step from draughts to chess. It is fundamentally different. This is beautifully illustrated through the famous paradox that Bar-Hillel advanced to show the unfeasibility of automatic language translation (Bar-Hillel 1964).

He asks if we could understand the sentence 'The box was in the pen'. At first it might sound like a transposition error. But if it was in the context of a child looking for a toybox and possibly being in a playpen, then we can work it out. However, there simply is nothing in the symbol collections themselves that gives this away. We have to bring other knowledge into play and the symbols give no clues about that knowledge, what it might be or how it might work. We do not know how to make a computer that could work this out; and yet *we* find it easy. Designing is full of this sort of knowledge and this sort of thinking. In fact, they are at the very heart of creative designing.

At an RIBA CAAD symposium a software developer prefaced many remarks with the phrase 'the trouble with architects is…' I suggested that if the vast majority of architects behaved in the same way there were two possible explanations. The first was that all the most stupid people in the world had by chance chosen to become architects. The second was that perhaps they had adapted to their situation intelligently. So we had better darned well try to understand not just how architects think, but why. This idea offers a small creative leap that may help re-orientate us here. Once we start to think about the cognition of designing rather than of generating production information, we might not see the architect as part of the construction industry but rather as part of the design industry. This is quite a paradigm shift and I think a necessary one.

Lawson and Dorst lay out a description of what constitutes design expertise (Lawson and Dorst 2009). The model we develop shows a series of levels, rising from the novice through the advanced beginner and competent up to the expert and master and, finally, the visionary. One key finding is that designers operating at higher levels of expertise do not simply do the same things as lower-level experts. They are not quicker, better, more accurate or efficient. They actually do quite different things. In a curious way, they think less.

This model fits into a more generic set of ideas about cognitive expertise. De Groot showed that chess grand masters did very little analysis of board situations but rather recognised them (De Groot 1965). Advanced architects similarly recognise design situations. They can see parallels with other situations they know well. That knowledge about situations also incorporates ideas that in chess would be thought of as gambits, or bits of solutions that can be used, each having advantages and disadvantages. Complex situations may be made up of many of these. Architects talk of precedent, by which they mean the panoply of previous situations that can be brought to bear on the case in hand. Unlike lawyers who seek to show the accuracy of precedent, architects seek to interpret it more creatively and to draw it from apparently remote sources. This is a key feature of what we normally describe as creativity.

What this model also shows is that the cognitive support we might need as novices is quite different from that we might need when we are competent and certainly when we are masters or visionary designers. Since I seek excellence rather than the mundane, I am interested in how this affects education and the impact that such ideas might have on the higher levels of architectural design.

What is so different about design?

A key question you might ask here is: 'What is it then that is so different or special about designing as a cognitive task that makes architects think in such peculiar and infuriating but ultimately fascinating ways?' The answer to this question is long and complex, but some key points can be developed here with specific reference to how we might develop computer tools to aid distributed intelligence in design.

Design is not like chess. When I was recently designing a garden shelter, I had just spent time in Bali looking at their special way of designing traditional houses and temples. I had seen the

Pondoks crafted by rice workers to allow them shelter from the intense midday sun in the open terraced fields dug out of the lower slopes of the sacred mountain. Knowing this, it should be clear that the design of my 'pondok' was heavily influenced by ideas from Bali, reinterpreted for our landscape and climate and my purpose. There is nothing clever or extraordinary about this; it is the way architects work. Had I been in Africa or South America rather than Asia, it is likely my pondok would have looked different. Design relies, then, on unbounded knowledge. No statement of the problem can symbolically encode information that gives reliable or comprehensive clues as to the kinds of knowledge that might usefully be employed in solving it.

For more problematic features of this world of design cognition, we turn further east to Sydney Opera House. This building is special because it has become so well loved, memorable and symbolic. It represents the unique place in which it belongs, Sydney Harbour, a new culturally progressive Australia, the time it was built and many other ideas. It is fascinating not just as a product but also as a process that has been well documented and teaches us many lessons about designing.

Central to the design are the great concrete sails that simultaneously perform many tasks for Utzon, the architect. They create a magnificent composition sitting perfectly on Bennelong Peninsula jutting out into the very heart of Sydney Harbour. They act as a perfect counterfoil to the famous bridge against which they are so often photographed for that reason. They subtly reflect the sails of the myriad small yachts that often surround the building. Of course, they also house the great spaces of the opera auditorium, the concert hall, the smaller restaurant and the public domain. They create opportunities for solving the tricky problems of threading services through such a complex and demanding set of volumes. They offer a structural system that is self-explanatory, efficient and beautiful when exposed. I could go on.

How can one mind arrive at a single device that simultaneously does so much on so many levels? In truth, the sails perform far better at some of their tasks than others. They leave spaces that have poor acoustics, though that is not really Utzon's fault. They insult and discriminate against the disabled. They make life hell for stagehands; ridiculously, the public approach is from the stage end of the opera house. It is well known that Utzon designed the sails before he knew how to build or even draw them and this was one of the factors that would drive the initial contractor to financial ruin. Again, I could go on.

And yet we forgive the building all these inadequacies because it is so magnificent in so many other ways. To have become one of the best-known buildings in the world with all these faults shows just what a fantastic achievement it is. It narrates a very human story of genius that succeeded in the face of so many difficulties and yet also failed our unreasonable expectations of perfection.

So what do we learn here? Design depends on integrated responses to many disparate factors in one single device in ways that could not possibly be predicted from any symbolic representation of requirements. These factors cannot be measured against criteria with any common metric for success. Which of us can say how many more stairs we are prepared to walk up in order to get the memorable view that Utzon creates for the interval promenaders out in the middle of the harbour?

New ways of communicating with computers

Architects must be using extraordinary mental gymnastics when designing. This implies the existence of a multidimensional cognitive structure that enables multiple ideas to be considered and developed. So if computers are going to assist us in designing, surely weneed to converse with them in ways that are at least as sophisticated as we might use when working with other designers. Is this realistic?

Some 30 years ago, my research group developed a suite of CAD programs for designing architecture known as GABLE (Lawson and Roberts 1991). They were founded on the principles of intelligent building modelling and on some key ideas about the nature of architectural design processes. They allowed architects to describe buildings in a variety of cognitive modes observed to be in common usage (Lawson and Riley 1982). Thus one could draw elements such as walls, windows and doors and GABLE would infer a spatial model. Alternatively, one could move, combine or divide spaces and GABLE would update the elemental model.

Back in the 1980s this system was in international use in both practice and education. We learned a huge amount from its use, not so much about CAD but about designing itself and about the complexity of knowledge representation in design. Eventually GABLE failed for a number of reasons, but the main intellectual failure turned on some unwarranted assumptions that are still going unquestioned today.

We must decide the extent to which we expect such systems to be central or peripheral to the creative design process. John Lansdown asked this question decades ago, but few have explicitly attempted convincing answers (Lansdown 1969). He pointed out that there were two fundamentally different strategies we could employ, which he called 'ad-hoc' and 'integrated'. He foresaw a wide range of applications, for example thermal evaluation, daylighting studies, visual form, costing, structure and so on. He realised that such applications need different though overlapping sets of data about features of the design.

Assuming that as designers we might like to be able to see how well our design is working on a number of criteria, how do we input the necessary information? In what Lansdown call the 'ad-hoc' strategy, we input the information needed as we use each individual application. So if we want to perform a simple steady-state thermal evaluation, we would need u-values and the areas of the external skin components. If we want a natural lighting study, then geometry, transmission, reflection data and orientations would be required and so on. This means a very halting process for the designer. Every time you want to examine the design along some dimension, you have to stop and input data.

An illustration of how impossible this would be can be seen from simply observing students. They are struggling to develop an integrated response, a task already almost too demanding for their early level of expertise. They need advice from a range of tutors, about architectural form, construction, structures, environmental control and sustainability. At Sheffield we now have this in-house, but previously structures was a service taught by our civil engineering department. To get advice on structures students had to phone up, make an appointment and then go to the other side of the campus. They did not do it, of course, and we saw many projects that were innovative climatologically but very few that were innovative and creative in structural terms. This ad-hoc idea simply does not work for designers. It would not work for the sails of Sydney Opera House. Utzon could never have used it.

So we turn to Lansdown's 'integrated' strategy and link all the evaluation packages to a single database, now variously described as building information models or n-D models. Each evaluation then runs immediately.

Salford and Sheffield universities collaborated on a research project to create support systems to record and make explicit design rationale (Cerulli *et al.* 2001). There were several objectives. First, the need in a multiprofessional, and often not co-located, team to know who is making what decisions and why. This becomes especially important when things happen in parallel. The classic example is the scenario in which the architect issues a general arrangement floor plan and the M and E engineer starts to run services through routes that the structural engineer is busy blocking. The architect is often left trying to spot this and we all think that CAD clash checking would be the answer.

However, things often get even messier. Our drawings show the decisions but not the reasoning. Later on, someone who may not understand the reasons changes things without realising the damage they are inflicting on the design. Being able to see the thinking behind the design at every stage is far more important than just the clash checking. In the design of Sydney Opera House they built a huge perspex model so everyone could see how spaces were interconnected and related. Today we would think of doing this on a computer. Somehow the physical model still does the job better. Incidentally, this model is now seen as a security risk, since the knowledge it imparts could greatly facilitate terrorism.

The Sheffield–Salford project worked with the Bentley software and logged the complete state of the model, traced all additions and changes and recorded the rationale. Instinctively, we decided to plug our software into the CAD software. All very logical: as you called a routine to add, delete or edit a model element, you automatically accessed the rationale capture software. However, field trials revealed that this was hopeless. More often than not, key decisions were taken away from the computer model.

By way of illustration, you can see a most creative process at work in the Philadelphian offices of Bob Venturi when designing his famous extension to the National Gallery in Trafalgar Square (Lawson 1994). One of Venturi's key forming concepts in this design is how the new architecture relates to the existing Wilkins' building, so famously described by Prince Charles as 'a much loved friend'; this, of course, when he so unfairly criticised the previous competition-winning design by ABK. Venturi had the original façade computer modelled, plotted out and cut up into pieces with scissors. These pieces were then stuck around his new physical models with sticky tape. How ironic to see a computer metaphor being used far more creatively in its physical reality.

The normal situation, then, is that key design decisions are often made over sketches or physical models, on telephone calls or at meetings, on drawing boards and sketchpads. Mostly they are the results of 'conversations' involving much talking and waving hands in the air. Often someone is deputed to input the new state of affairs into the computer model. At that time the rationale is either not available or it is incorrectly guessed. The computer model is simply not where the action is.

A further problem with the integrated model is that it quickly becomes a production tool rather than a design aid. Designers find that you have to specify not only geometry but also materials and construction in such depth that you have effectively generated not a design model but a production model. Does this really matter? Well, yes it does. It is simply unfeasible to argue that tools do not have an impact on processes and that processes do not have an impact on the end product, the architecture itself.

Take the representation of free-form design. Surely this must promote creativity? At last, sophisticated mathematics allows us to compute locations on irregular surfaces. Gehry Technologies have contributed to the migration of ideas from aeronautical design into architecture. Bill Mitchell claims that the use of this in Frank Gehry's 'remarkable late projects will ultimately be remembered not only for the spatial qualities and cultural resonances they have achieved, but also for the way in which they have suggested that everyday architectural practice can be liberated from its increasingly sclerotic conventions' (Mitchell 2001).

Of course he is right, Frank has created a remarkable new form of architecture. But look more carefully and there are two problems here. First, Gehry does not himself use this software in design. Indeed, Zeara claims that 'the computer was introduced into Frank Gehry's office in a way that would not interfere with a design process that had been evolving over thirty years' (Zeara 1995). Lindsey tells us that 'Gehry does not like the way objects look in the computer' and that he avoids looking at the computer screens in the office (Lindsey 2001). He not as eccentric as you might think. My work on Santiago Calatrava, one of the most creative minds in free-form design, shows that he also does not like to use computers. This man is even a fully qualified engineer as well as being an architect, but he prefers to sculpt physical models and only relies on computers for finite element analysis.

This is quite understandable, since software driven by the complex mathematics of such esoteric devices as Bezier curves or non-uniform rational B-splines is hardly user-friendly. The input of control point locations and tensions on curved patches is not for the fainthearted! It is certainly not intuitive and far from the 'conversation with the drawing' discussed earlier. So Gehry designs with much more plastic materials such as crumpled paper and other expert users have to negotiate these into the computer. Calatrava collaborates with a Swiss watch-maker turned modeller who has become an integral part of his creative process.

The second problem here is in Mitchell's reference to the sclerotic conventions of architecture. He wants us to believe that all architects, their clients and users are desperate to get away from geometry in architecture. There is no evidence to support such a thesis. Instead, I will present one rather powerful anecdote in contradiction. Having become very interested in what Frank Gehry and Jim Glymph are doing, I realised that a very famous piece of architecture indeed could now have been realised very differently. In his original submission for Sydney Opera House, Jorn Utzon included a model showing irregularly curved surfaces for the sails. It is well documented that once the competition was won, Utzon and Ove Arup puzzled over how to build these (Weston 2002). Eventually they resorted to mapping them all onto the surface of a single sphere. Not long before he died, I showed Utzon that the Gehry technology software would now allow him to build the original design and I asked what choice he would make today. The answer was emphatic. He would keep the geometry and the design as finally realised. He was always looking for some rationality and order. To this day, of course, the stunning result is as he wanted, a combination of romantic reference and yet coherent order. As Utzon said in his response to me: 'I am *not* Frank Gehry.' Thank goodness we have been lucky enough to have both of them, but clearly Mitchell's implied idea that we all want to become just like Gehry is simply another example of technology push rather than market pull.

Unfortunately, that technology push can then extend through into the architecture itself. Take the case of the Opera House in Singapore. The design of this can be summed up as a couple of auditoria in boxes standing inside a huge glazed upturned kitchen sieve. When working at the National University in Singapore, I attended a long lecture from one of the software engineers employed on this project. It was their software that had led the architect to appreciate the feasibility of this design in this context. Remember that Singapore has a hot–wet tropical climate with temperatures around the year in the 30s, very high humidity and often daily torrential rain. A glass dome is hardly the first form that comes to mind in such a climate. Compare such an idea with the environmentally sustainable work of Ken Yeang, who tries to create a new regional identity for south-east Asia (Yeang 2006). In a kitchen sieve every cell is unique, as the square grid is resolved onto a curved surface. So in the Singapore dome every cell must have its own tailor-made shading device shaped to its cell size, and of course orientation in order to avoid unbelievably high solar gain. The software to achieve all this is indeed very clever!

The lecture reminded me of much of the silly technology push that surrounds us. The plethora of applications for the iPhone is a wonderful demonstration. I have an app that gives the phone the wonderful capability of acting as a spirit level. 'Very clever,' says everyone who looks at it. Of course, I have never used it. We still treat computers and their smaller palm-top offspring like circus animals trained to perform apparently clever but pointless tasks.

The nature of the computer model itself brings yet further potential remoteness from real design decision making. The art critic Adrian Stokes introduced the delightful distinction between what he called 'modellers' and 'carvers' (Stokes 1934). These are two distinct forms of thinking about space and form. Modellers would assemble a building from its components; carvers would craft it from its materials. The sculptor, who carves works with the grain of stone or wood, understands the material and even feels the way it wants to be. The great American architect Louis Kahn told us to 'let a brick be what a brick wants to be'. In other words, he called for architecture that was carved, that worked with the grain of its materiality.

Conversations with the situation

We have a further pervasive problem: a fundamental misunderstanding about the nature of design expertise. In the mid-twentieth century when we first started to explore the nature of design processes. the dominant paradigm was that of problem-solving. Those of us who continue to research this field no longer see this as the only, or even the dominant, way of explaining the creative processes used by designers in general and architects in particular. Sadly, the developers of CAD have not caught up. Implicit in so much of the software is a problem-solving view. The newer view of reflective practice, pioneered and championed by Donald Schön, leads us in quite different directions (Schön 1984). In this paradigm the architect is not so much solving given problems as discovering them in parallel with developing solutions and even through the creation of solutions. In fact, already the words problem and solution are uncomfortable in this world. We now prefer to talk of 'situations' in which needs and possible actions are seen as existing in creative tension. Schön talked of reflective practitioners having 'conversations with the situation'. In the case of architects this situation is often assumed to be represented through drawings, though other media are used too.

If we are going to support this process, we need to understand the methods of knowledge representation used in the drawings architects generate, not for others to see, but to develop their conversation.

Goel has compared the way designers work using ordinary manual sketches with the way they work using very simple computer drafting programs of the vectoring type, namely in this case MacDraw (Goel 1995). Six graphic designers were set the task of designing tourist posters while six industrial designers were asked to design a desk clock and a toddler's toy. Goel analysed all the drawings produced by both groups of subjects using both manual and computer-based drawing systems. He showed that the drawings done with MacDraw were less dense and ambiguous than those completed by hand. This will not surprise anyone with any skill in drawing who has tried to use such software.

Disturbingly, Goel also showed that this had an impact on the nature of the design thinking and was in turn likely to affect the eventual outcome. The designers using MacDraw made significantly fewer 'lateral transformations' than their manual sketching counterparts. That is to say, they tended to persist with an idea for longer, 'vertically transforming' it. The inference here is that the less ambiguous MacDraw system allowed the designers less opportunity to 'see' different interpretations of their drawings. As a result, fewer ideas were explored in the process in roughly the same period of time.

Bilda and Demirkan tested designers on an interior design task using both manual drawing and a vectoring-based CAD system known as Design Apprentice (Bilda and Demirkan 2002). A retrospective reporting technique was used to get subjects to recall and describe their intentions by watching a video of the protocol. This study again showed fewer 'cognitive actions' when using the digital media.

A reasonable conclusion is that existing CAD systems use symbolic representations that do not map well onto the mental symbolic representations used by designers. As a result, working with such systems leads to a less rich mental world, since the drawings 'talk back' to us in less suggestive ways. Put simply, the conversation with the computer was less rich than the conversation with a piece of paper.

Kvan demonstrated something that raises other profoundly disturbing questions for the CAD movement (Kvan *et al*. 2003). Architecture students worked in groups using computer-based communications. One group had only text-based technology, while the other could exchange graphical information too. The results of the text-based groups were consistently more creative, original and interesting than those from the groups exchanging graphical information.

A more positive approach

So far my analysis suggests that attempting some computer aid that sits right at the centre of the creative design process is deeply problematic. This is perhaps a rather harsh lesson. First we had to give up the idea of computers designing. Now I am asking you to give up the idea of computers even helping us to design, at least in some central role.

So how can we be a bit more positive? The design expertise model suggests that one of the key tasks at the early stages of expertise development is the acquisition of precedent and of schemata that are used to organise them cognitively. In simple terms, students of architecture need to see and study a wide range of buildings, places, designed and natural objects and other cultural artifacts. While a few geniuses may manage without this, most of us cannot. A student who has not studied the Sydney Opera House, for example, is unlikely to be able to appreciate the ideas that it taught us. These would certainly include the notion of rationalising curved surfaces, how to compose them and the very powerful idea of a free-floating form hovering above a solid plinth. Again, I could go on.

Traditionally students learned these things through extensive travel, scouring magazines and journals and so on. They were always encouraged to carry with them a sketchbook. No architect I admire does not carry such a thing for the immediate and quick sketch to record and analyse. Excellent examples can be found from John Outram looking at Corb's Ronchamp and Bucky Fuller's Dymaxion House (Lawson 1994).

The digital camera, its connection to the computer and all the easy image-manipulation software linked to internet searches make for a different world. This technical advance also poses huge dangers, however. The student who had to travel saw in the flesh, as it were, a totally different experience to a Google Images file. The sketch relied on an eye–brain–hand process that forced a degree of analysis and brought understanding. We now have a generation of students arriving at schools of architecture who have not learned to sketch, have not learned to see, have not learned to analyse, in fact have not learned.

All is not lost. We have used simple solid modellers in exercises with novice students in which they build models of buildings and then deconstruct them to explore the conceptual structures that underpin their design ideas. In some ways this is very successful and illustrates an important principle of using computers that I have always thought desirable: we can actually do something new. Unfortunately, it is also still very crude. The software is far better at some kinds of geometry than others. It works brilliantly in this example with the architecture of the De Stijl movement.

We need to develop software that is specifically targeted for this purpose, not for designing as such but for recording and analysing architectural form.

All this begs another hugely important question about the way we search for information. I used many of the same fundamental concerns to analyse how architects use libraries (Lawson 2002a). There are important lessons that many university librarians find as difficult to accept as some CAD enthusiasts do. My university built a major new library recently, except that we are not allowed to call it that. It is an 'information commons'. The university then wanted to split our collections between the old and new in terms of undergraduate and postgraduate. When I refused to agree to give the librarian the list of undergraduate texts for architecture, he thought I was just being awkward. Not so. First, there is no overall undergraduate subject textbook for architecture and there never will be. Secondly, our students look at the latest journals. You would not expect either of these things in an undergraduate psychology course. Our students take few books out but spend hours in the library scanning, browsing and then sketching and arguing. The library is actually an integral part of the design studio.

Let us see at another example higher up on the expertise development staircase. When studying the work of one of our most successful and creative architects, I visited the office of his practice and heard three different people use the word 'belvedere'. There is nothing extraordinary about this word, but even in an architect's office this seemed too much of a coincidence. It was an example of something we have come to realise more clearly recently: expertise in design is not held only inside single heads but collectively and socially in organisations. This word brilliantly and incredibly efficiently stands for a whole set of architectural ideas that clearly this practice had been talking about. If you were not in on this you simply could not contribute to the design process they were using. This is real distributed intelligence at work in design.

So how do designers search for information and how might we help them? It is, of course, a frustrating process. Even though we now have Google Images, we have search it through words in the titles of the images. How we understand and express our desire for information, use this in conversation and searching and then send ideas to other members of the design team turns out to be a key obstacle. This is hugely challenging and in my view a far more important and interesting problem than most work done currently in CAAD.

At a higher level of expertise we see another problem: the assumption that all knowledge about design is encapsulated in drawings. The wonderful Czech architect Eva Jiricna is widely recognised for her original and creative output (Lawson 1994). I select her as an example because Eva is no Luddite. She is trained as an engineer and is well known for her high-tech interiors for fashion guru Joseph and others. She has described to me how she uses words more often than pictures to discuss ideas with clients until the design is fairly well developed: 'I try to express in words what they want, and then I try to twist it into a different statement and then draw it.' However, this is not some eccentric exception. The very successful product designer Richard Seymour told how he and his partner entered the competition to design the front end of the high-speed train. They astonished the client by not using any images at all at the interview. They merely said that their train 'would make schoolboys want to be engine drivers again and that it would be heroic in the manner of Concorde'. They won the job!

An interest in how we manipulate knowledge in design through words rather than pictures led us to investigate a computer program that could hold a useful and creative conversation with a designer (Lawson and Loke 1997). We wanted to know what building blocks and methods of knowledge representation would be needed. During one research seminar a colleague who is responsible for teaching CAD declared the whole thing a waste of time. 'Go into any architect's office,' he said, 'and 90 per cent of what you see will be drawings.' 'Yes,' I replied, 'but 99 per cent of what you hear will be words.' The problem here is that the words do not get recorded, and the drawings are left behind to claim all the glory. We have become so obsessed by our cleverness at training the circus animal computer to draw that we have missed the point completely about how designers actually think and work and what tools they might want.

From our model of expertise, we can see that software designed to help at one level of expertise may not necessarily be so useful at another level. A generic problem might be that much of the software ostensibly created for architects to design with is actually written by people who are hardly masters of design, let alone visionary architects. Implicit in the resulting software are many examples of assumptions that the users will work in ways far more likely to be seen at novice rather than expert levels of design. No wonder so many great architects choose not to use CAD.

Our model of design expertise teaches us that different construction industry professionals operate in increasingly disparate ways as they gain expertise. Architects' design knowledge is largely about solutions rather than problems. It is what cognitively we call experiential rather than semantic. We know that these two kinds of knowledge are held differently in the brain, have quite different characteristics and are accessed differently. One sad but dramatic demonstration of this is the way people suffering from severe dementia may be quite unable to remember recent events but can still parse a sentence grammatically and perform accurate arithmetic. Designers, it seems, have a far greater reliance on episodic knowledge than on semantic or theoretical knowledge. Architects simply do not have theories that enable them to get from problem to solution. There really is a difference between the thinking of most engineers and most architects. Architects will commonly tell you that an engineer who thinks architecturally is an incredibly valuable asset in the design team. People like Tony Hunt and the tragically departed Peter Rice are often cited as rare examples of such ability. Software that is somehow capable of bridging these gaps might be an exciting possibility. However, here I want to go one step further.

Zeisel perceptively showed us that the most important and critical gap is not between specialist consultants but between us, our paying clients and users (Zeisel 1984). For those building typologies where the complexity of use is both high and critical, this becomes one of the most serious obstacles to really good design. I have spent a good deal of my time working on this problem in the twin areas of healthcare and education. Hospitals have been heavily researched in recent years (Lawson 2002b). We now maintain a research database for the Department of Health and it has in the region of 1000 pieces of work that in some way link architectural design issues to health outcomes, patient satisfaction levels, quality-of-life issues, staff effectiveness and job satisfaction. Others have shown that if we take all this research together and apply it in the design of new hospitals, we should be able to save something in the region of 20–25 per cent of operating costs with an increase at less than 5 per cent of capital costs (Berry *et al.* 2004). For such buildings characteristically the capital cost is exceeded by the operating costs in less than two years (Lawson 2004).

Different kinds of knowledge about all these issues exist in the heads of people with many roles. We have devised a series of web-based tools now used by the Department of Health for the briefing, design and evaluation of such buildings (Lawson 2007). One of these, IDEAs, serves a useful example here.

IDEAs breaks away from the conventional Department of Health structure of Health Building Notes, Room Data Sheets and all those other production-based tools that focus on compliance with minimum standards rather than promoting excellence, that suppress rather than facilitate creativity. Instead of the multiplicity of named rooms, we broke the whole problem down into fewer than a dozen major activities that turn out to account for almost all areas in healthcare buildings. These include quite specific places such as 'consulting/examining/treating' as well as more generic ones such as 'arriving' and 'circulating'. IDEAs has two major panes. The top pane deals with the challenges and opportunities. The challenges show all the research mentioned above as ways of understanding what people are trying to do in such places. The opportunities discuss the features of the designed environment that can be used to affect this. The bottom pane shows bits of designs that other people have already built that seem to work quite well in some detailed way. So what we do here is to bring problem and solution together in such a way that both client and architect can meet on some territory where they both feel comfortable.

Only the interactive and highly graphical capabilities of web-based applications can offer such an environment. Computers really can help designers. However, it is worth noting one further connection back to our model of design expertise. The model shows that expertise can exist in four different ways. We call this Project, Process, Practice and Profession. What we are beginning to realise is that our CAAD efforts might be misplaced not only because we have tried to embed them too much, but because they are too focused on the 'project'. The positive examples I have been giving here suggest that we might help more by concentrating on 'process' and, even more interestingly, on 'practice', realising that students need to develop this differently to competent and expert designers. IDEAs even shows how we can develop a further level of 'professional' expertise that exists beyond a single project, outside any one single practice, and yet it can be used to bring all that distributed intelligence through a new process to individual projects.

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2 Distributed perspectives for intelligent conceptual design

Volker Mueller

Future design

Conceptual design in its essence embodies the anticipation of various futures. In that sense, this chapter presents a scenario of a possible future. The future, for the sake of argument, is considered to be influenced by the choices everyone makes. Since for all practical purposes everyone experiences the same future, one may claim that this one shared future is the commingled, collective result of all the choices everyone makes individually or collectively. This description of the future as the commingled result of all the choices made collectively characterises the design process. Within a project team all team members make choices, individually, as sub-teams or at the full team level. The combined result of these choices generates the future project result. Usually, design choices made at individual or sub-team level are guided by an agreement about the goals for the specific project. In the domain of architecture, engineering, construction and operation (AECO), the general intent is that a facility under design will facilitate human activities in the future, with or without providing shelter for any humans for any extended time span. This also means that the project result itself will in turn continue to shape the future.

As another consequence, the commingling effect influences any individual's or group's plans, with the result that no single person's or group's plans will carry through without the willing or unwitting support of many other people. Therefore, if stronger control over the realisation of one's plans is desired, it is important to be able to make the right arguments to gain support within and outside of the project team, and perhaps even among stakeholders at large. 'Make no little plans' is a quote attributed to Daniel Burnham. The insight he provides reaches deeper:

> Make no little plans; they have no magic to stir men's blood and probably themselves will not be realized. Make big plans; aim high in hope and work, remembering that a noble, logical diagram once recorded will not die, but long after we are gone be a living thing, asserting itself with ever-growing insistence. (Daniel Burnham, cited in Wikiquote)

During the design of facilities, design activities occur at various levels throughout the facility lifecycle. There is certainly the design of the facility, preceded by the design of the overall vision of which the facility is a part – for example a business plan, or a vision for the future of a

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

community – and the design of the larger surrounding infrastructure into which the facility will be embedded. There is the design of project team composition and of workflow and design processes. However, there is also the design of materials and any components or systems from which the facility will be constructed. In addition, of course, there is the design of the multitude of software and hardware, digital and analogue tools with which the facility itself will be designed, its components will be manufactured, and with which they will be installed, erected and built.

Although it appears that we have reached a point in time at which all these levels of design become more aligned, with the goal of highly increased sustainability in the broadest sense of the term, it seems that most of the time, all these levels of design have been cultural expressions of their era. Nevertheless, this has never precluded visionaries from anticipating different futures, like Negroponte in his book *The Architecture Machine* (1970) or Bill Mitchell in *City of Bits* (1995). It is noteworthy that if the alignment of purpose with sustainability appears widespread, then that is a result of many people having worked towards that future for many years. For a scenario of a possible future, it needs to be pointed out that the focus of sustainability will shift once it is established as a facet of a facility's performance, as structural performance is at the current point in time.

Following the theme of distributed intelligence in design, this chapter presents an orthogonal section through the AECO design process and describes the layers of intelligence that enable design projects to escape confinement to conventional approaches and the discovery of opportunities for improved approaches and potential innovation.

Facility performance in a vision framework

In response to the progressively increasing recognition of global resource limitations, there is a growing demand for understanding of the overall performance of a design. Currently most analysis or simulation tools that provide the material from which an understanding of the future performance of the designed facility may be developed require data that exist only when the design is relatively well developed (Maile *et al*. 2007: 3). That state of design is reached at a point in the design process at which changes to the design become cumbersome and their cost would be substantial, often prohibitive (Construction Users Roundtable 2004: 4). Thus the effects of the analyses or simulations are limited to a theoretical validation of design assumptions with only little room for improvement. Therefore, feedback about a design's performance must be provided as early as possible to affect the design.

The vision for the facility develops within the larger framework of the vision of the enterprise or community or other types of clients who commission the project. It is possible that the larger vision framework is adjusted as a consequence of the discussions that hinge around the specific project. The original or adjusted vision framework provides the guiding principles to which the project team members align their vision of and goals for the facility that they want to achieve (Chachere and Haymaker 2008).

Intelligent design team configuration

The structures mentioned are predominantly networks, even if of very different natures. Most infrastructure systems are physical networks of artifacts such as roads, cables or pipes. Some of the networks are determined by the project's site location, or by its position on the site.

However, some of these networks may be networks of ideas, or networks of relationships without physical expression. For example, relationships among members of a project team form the social fabric or infrastructure of the project team and often influence communication behaviour among team members. As an extension of the social infrastructure internal to the project team, project team connections to outside stakeholders connect to similar internal networks at the stakeholders' institution or agency. These stakeholders may influence the design, such as representatives of surrounding neighbourhoods that may need to be convinced of the project's benefit to them. Also important are good connections and communications to the various agencies that may regulate, review and approve the design; issue permits for and inspect the project during construction; or inspect the project at the end of construction to issue permits for the operation of the finished facility. Many of these networks are part of or exert an influence on the design process. While the networks per se may be independent of each other, they are interconnected in the project design process. For each project these networks and relationships change.

Conceivably, each new configuration requires the design of a new approach, which seems inefficient. Therefore, there is an urge to reduce complexity through standardisation. Standardisation stretches across physical and virtual networks, and from loose, guideline-like standards to very tight, mandatory standards. Standardisation is a matter of convenience; however, standardisation inhibits innovation, because as a methodology standardisation is the codification of existing knowledge or practice. Most standards organisations are based on the agreement of the majority of members, or even require full consensus of all members, further delaying the standardisation of innovative approaches. In any case, innovation attempts to go beyond existing knowledge and practices and in the benign case can utilise standards as a starting point.

Similar challenges exist at the project team member level and their direct or indirect involvement with the project work flow and project work product. On any one project a project team is configured, through various project-specific choices and mechanisms. For most projects the specific configuration of the project team changes. However, in conventional practice, the constituent project team members represent the same types of project partners, for example structural engineers, mechanical engineers and so on (Construction Specifications Institute 2005: 1.2). Even in the best case, such a team searches for design solutions in the combined discipline space, well within the AECO domain. Figures 2.1–2.3 show the recent transition from traditional to integrated teams.

Some design firms are actively looking for modifications of those conventional approaches in an awareness of the confinement they impose, for example by eschewing standardisation at the immediate work process level and instead using a standardised process design methodology (NBBJ 2006). So far only as rare exceptions, project teams may also organise based on the project requirements at the much more fundamental level of first principle investigations, thus opening up the potential of innovation at that basic level (Barlieb *et al.* 2009). This shift in how teams are composed is a high-level shift in practice models from a domain-specific, discipline-centred approach to a project-specific, interdisciplinary approach, potentially reaching far outside the traditional AECO domain (Figure 2.4). This is a significant step, from designing an intelligent work flow within any given project team to designing an intelligent project team in the first place. In this future scenario, highly dynamic team composition across a wide range of disciplines within and outside of the AECO domain becomes a more common practice, especially for projects in search of intelligent, innovative solutions.

This establishes the first two levels of distributed intelligence: the intelligence represented by individual designers and the collective intelligence represented by a distributed design team (Fig 2.5). Each design team member brings their unique perspective to the design investigation,

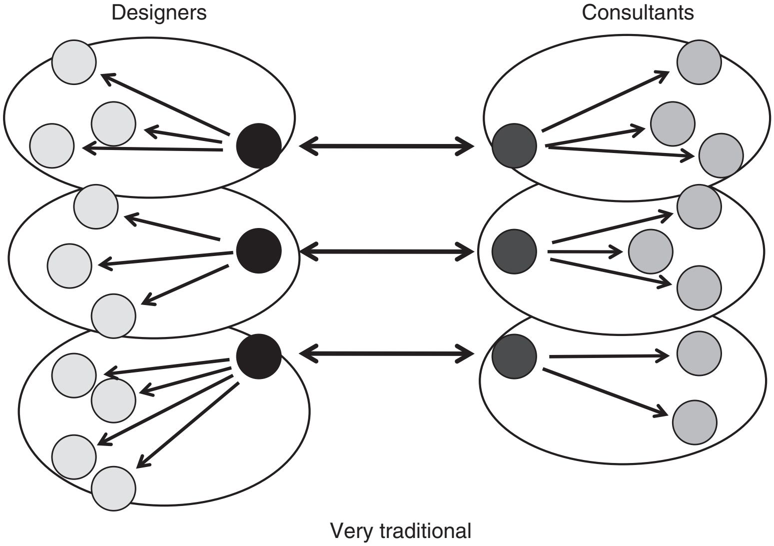

Figure 2.1 Very traditional teams.

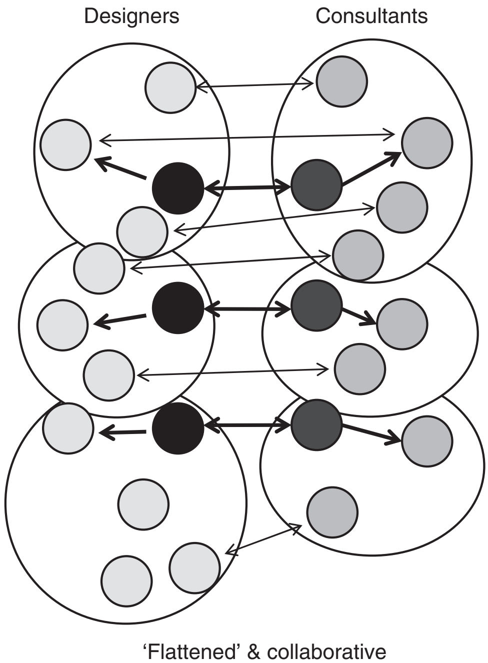

Figure 2.2 'Flattened' and collaborative teams.

whether based on distribution across socio-economic or educational backgrounds, discipline-specific areas of expertise, geography, life experiences or other knowledge and understanding. The skilled collection of these individual intelligences into functioning, intelligent teams lays the

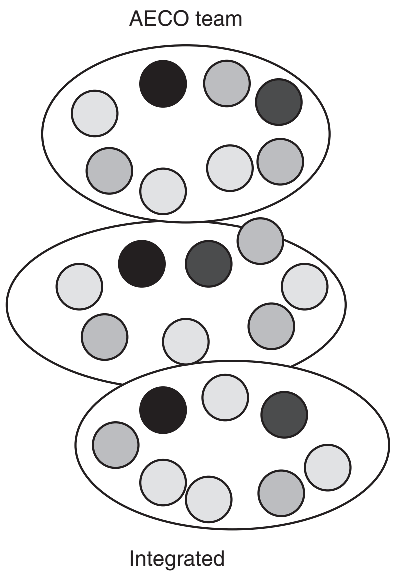

Figure 2.3 Integrated teams.

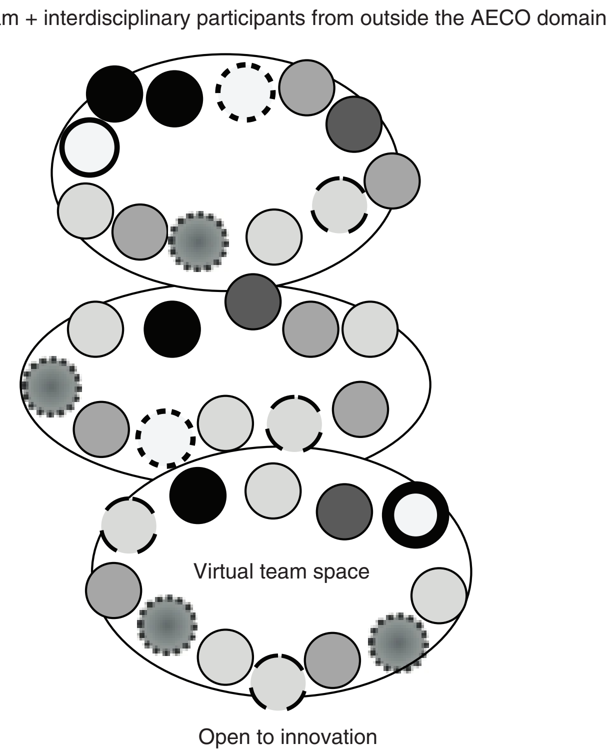

Figure 2.4 AECO team including interdisciplinary participants.

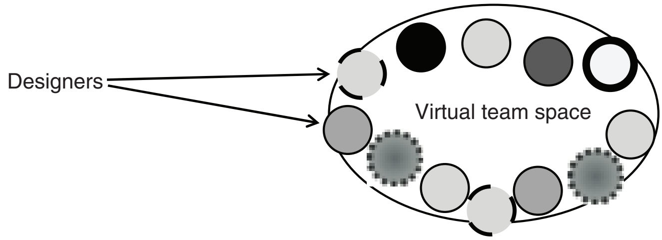

Figure 2.5 Distributed design team.

foundation for exploring a virtually infinite design space, with insights that help generate potential design responses more quickly and then accelerate convergence on effective solutions with more focus.

Intelligent design tools

The third level of distributed intelligence derives immediately from the second level: the intelligent design tools used by the team members (Figure 2.6). In this context these tools are digital tools, hence the potential that they may have developed some intelligence. Intelligent conceptual design tools will support early design as the anticipation of various futures in multiple ways. They will include parametric engines for rapid development of design variants that allow exploration of a larger solution space at a finer granularity, and perhaps encourage parametric extrapolation beyond the pre-design or preconceived solution space (Monedero 1997). They will allow the capture of design intent in diagrammatic form and direct manipulation of it. They will easily combine with simulation and analysis engines that provide performance predictions. Simulation and analysis software will cover an increasing collection of performance criteria that may need to be validated in support of an assessment of the facility currently under design. This validation of design assumptions will occur at the highest possible verifiable and scientifically sound level. Comparative tracking between design alternatives and across iterations will support design team decision making (Flager *et al.* 2008). With early design information lacking or sparse, these tools will offer those analyses or simulations that can be run based on the available information. This may be achieved through a higher level of modularity, plug-ins or other, service-oriented architecture, or simply by developing software packages to be able to respond to a varying availability of inputs. Allowing for uncertainties, performance prediction will include a clear indication of their level of certainty (De Wit 2003).

Slightly 'intelligent' tools will also be able to help designers identify information that can be provided with only little additional effort, while it will enable valuable additional insight into the future performance of the options being investigated. Tools will find this information in and pull it from geospatial, materials and other resource databases. Performance prediction will span a wider range of performance criteria than is at the cutting edge in current practice. The underlying scientific and mathematical models that are used by simulation and analysis tools will evolve further to become more accurate, more robust and faster. At this level of intelligence, tools still need to remain highly extensible, so that intelligent project teams are enabled to implement their own design generation, analysis or simulation and evaluation methods; and, where

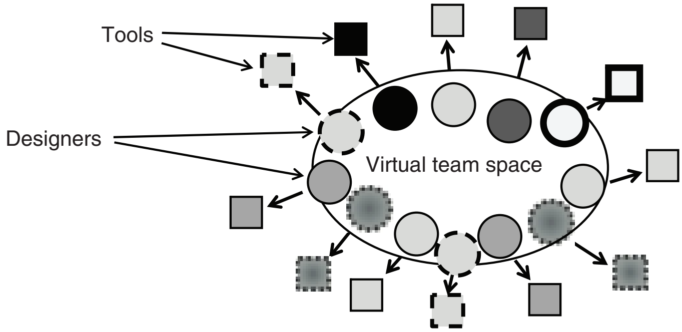

Figure 2.6 Intelligent design tools used by the team members.

possible, close the loop for at least some of the performance criteria for automated design improvement based on weighted performance criteria. Such processes are often called 'optimisation' processes, implying that an optimum can be found. While this may be true for some cases, multivariable cases in particular require some compromise, some decision about which variable design response takes precedence based on the higher weight assigned to it. Supported by visualisation tools for design decision support, Pareto front will become a standard term in design assessment, until made obsolete by improved decision support technology.

Cognitive agents will provide an additional increase in tool intelligence. Cognitive agents will be able to learn (Sarkar *et al.* 2007), with additional opportunities for the inference of design performance based on comparable projects, pulled from data repositories like CarbonBuzz hosted by the Royal Institute of British Architects (RIBA), the Chartered Institution of Building Services Engineers (CIBSE) and the British Research Establishment (BRE), or the United States Green Building Council's (USGBC) and similar organisations' project libraries. These project libraries will include future designed and predicted facility performance, as well as an operational track record of actual performance for the rest of the facility's lifetime, allowing validation of design solutions, as well as further validation of the analysis and simulation tools used to predict the designed facility's performance. Cognitive agents will exceed any sole practitioner's or collaborator's expectations by learning about design from all designers with whom they interact, and across all disciplines with which they are involved within or outside the domain. Perhaps through self-improvement cognitive agents will be able to render tool extensibility moot. If cognitive agents become part of the team, these intelligent agents will be distributed across the design team, or gravitate to those locations where they have faster access to data, or find sufficient computational resources to work and learn quickly.

Intelligent models

A fourth level of intelligence will be created by deliberately designing how the digital representation of the facility models the design and performance goals into parametric behaviours (Gane and Haymaker 2007). Eventually at least some of the behaviours will migrate from analysis and simulation tools into the data objects themselves as embedded behavioural models (Breider and Coenders 2008). Constituent components of a design or entire building systems composed from such components will model their own accurate behaviour, which is a change from the current

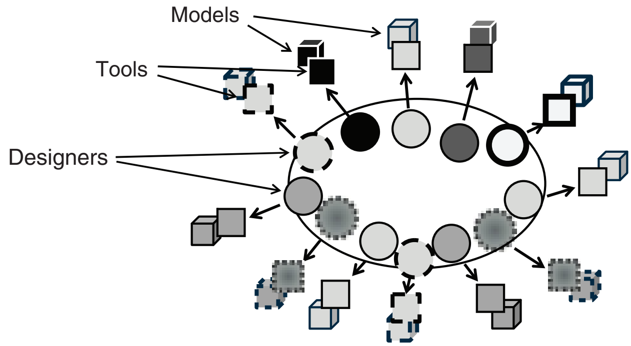

Figure 2.7 Load cases investigated by the design team.

approach of mating geometry with properties which then ultimately let procedural processes evaluate the performance of the assembly. Thus the design model will represent the behavioural model of the facility, and simulations will be triggered by applying the use or load cases that the design team wants to investigate (Figure 2.7).

It is conceivable that analogous to the development of facility designers into tool makers for the utilisation of tool extensibility there will be a development of facility designers into designers of model behaviours. Those models will exhibit generative capabilities which will allow designers to seed sites, neighbourhoods or cities with those models' germs. Then designers will sit back and observe how those germs populate the sites, neighbourhoods or cities to grow design solutions. Designers will continue to change or tune the models' behaviours to create alternative design approaches and grow more solutions with them. The selection of design solutions will again be based on evaluation supported by intelligent, accurate simulation and analysis tools.

Intelligently interoperable data

At the fifth level of distributed intelligence are intelligently distributed – perhaps otherwise rather pedestrian – data repositories, considering that distributed, intelligent team members work on the design project with their similarly distributed, intelligent conceptual design tools (Figure 2.8). Involvement with the project may be only periodic and not necessarily across the entire design process, making collocation a proposition of little meaning. Therefore, these distributed, interdisciplinary teams with their pursuit of non-traditional design investigations require an innovative data infrastructure. This data infrastructure will further evolve in the form of a flexible, federated data repository or a collection of federated data repositories in which the design data persist. It becomes obvious that homogeneity must not be a requirements for the data contained in such a data repository. Data repositories need to be able to store vastly heterogeneous data considering the diversity of projects, project goals and interdisciplinary project teams. Analogous to the current expectation that design tools are extensible by designers, there will be the expectation that designers will be able to add any data they need to become part of the project data repository. Nevertheless, the nature of the data repository ideally remains transparent to the designers.

Supporting the intelligence of a distributed design team, data development over time will be traceable, including iterative or concurrent explorations of many design alternatives and variations

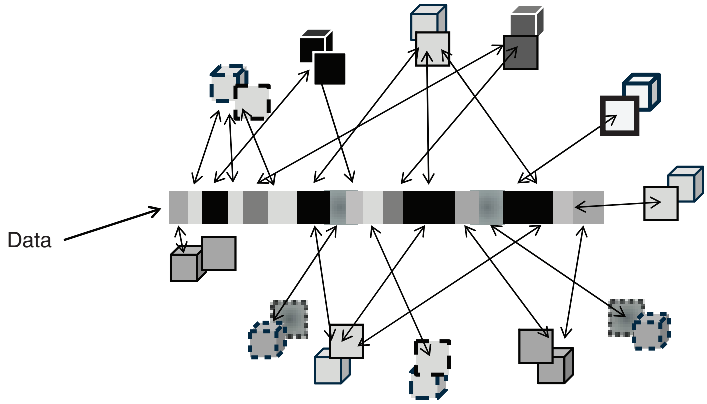

Figure 2.8 Distributed, intelligent conceptual design tools.

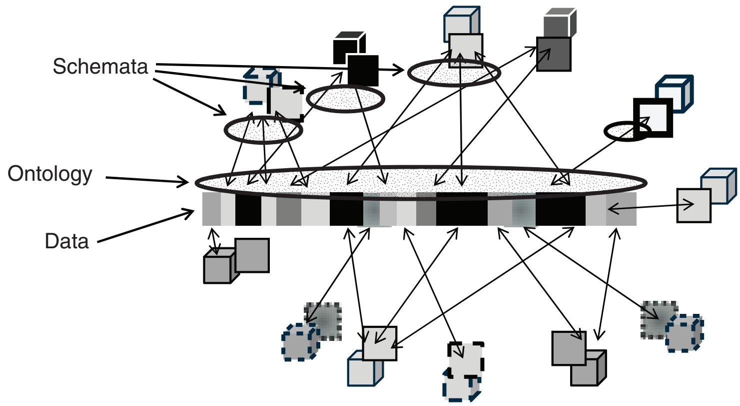

Figure 2.9 Schemata mapping from the individual tools into the data repository and vice versa.

within those alternatives. In support of asynchronous work processes, data can be parcelled out in configurations as requested by the design tools. Towards milestones and the end of the process, the repository technology supports teams in the collection of their asynchronous and disjointed work results in some meaningful fashion and in presenting the design coherently to the client.

This type of highly interoperable data repository replaces the many one-to-many and many-to-one data mappings that are otherwise necessary to support the interoperation of many design tools (Cleveland 2008). For each tool only one mapping into and out of the repository is needed. There are two fundamental requirements: a robust ontology that supports straightforward mapping procedures (Maier *et al.* 2008) and easy extensibility to support new team and tool configurations. This approach corresponds to the modular design analysis and simulation tool architecture. In addition to data manipulation, this data architecture supports data persistence and exchange. The core intelligence in this data-persistence architecture is then in the ontology, which imbues meaning and its capability to evolve over time; that is, to reflect the accumulated learning from all projects that have contributed to its growth. The peripheral intelligence is in the schemata that map from the individual tools into the data repository and vice versa (Figure 2.9).

The physical future of design intelligence

This data-level intelligence in both the design data as a whole and any digital components or systems contained in them will be mirrored by corresponding expressions in the materials used for construction, the physical components or systems that constitute the facility, and the constructed facility itself, respectively. These are additional levels of intelligence on the physical result end of design. These levels of intelligence will also be highly relevant for improved facility performance, maintenance and re-use or disposal.

Considering materials at various levels of intelligence, they may be enabled at a low level of intelligence to track and report their embedded energy from initial extraction through processing, including all transportation to final installation, the lifetime of the facility and beyond. Such materials could be deemed to be lifecycle enabled. At any point during the design lifecycle, the enabled materials will allow design teams to make well-informed decisions about material use (Griffith 2008); at a high level of intelligence, materials are enabled to react to local conditions during construction and later, during operation. Similarly, intelligent components or systems aggregate their constituent materials' intelligence and add their own creation, transportation and installation history. They know their semantic position in the facility as well as their physical location and, therefore, can direct their installation, double-check their installed position, and during operations report on their actual performance. Especially at the systems level, this will allow for continuous monitoring and operational tuning. At the end of a facility's lifecycle, its systems, components and materials will advertise in a materials, components and systems marketplace their future availability to projects that are in the design phase of their lifecycle. Intelligent design tools will note their availability and intelligent designers will include them in design options.

Conclusion

This orthogonal section through levels of intelligence offers a different perspective on the distribution of intelligence in design. The hypothesis is that increasing the intelligence at each of these levels will improve design results and their performance throughout the facility lifecycle. Eventually, the physical facility may evolve into a hybrid analogue and digital computer that contains a computational model of itself, rather than being a reflection of virtual, computational models housed in a digital network of computers. Ultimately, the facility may thus be enabled to continue the design process for further improvement of its own design, which was terminated at some rather arbitrary point in time in order to finish construction of the facility and start operations in it.

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3 Distributed intelligence or a simple coherent mental model?

Chris J. K. Williams and Roly Hudson

The word 'intelligence' comes from the Latin 'to understand' and whatever other interpretation we may put on the word intelligence, understanding must be the starting point. Understanding is at many levels: one might speak of superficial or deep understanding. The deeper the understanding, the more irrelevant details are stripped away. Understanding involves producing a simple, coherent mental model or framework to which new pieces of information can be appended, including design decisions. If a new piece of information does not fit in the frame, either the new piece of information or the frame has to be modified or abandoned.

Understanding is passed from person to person and from generation to generation in many ways: speech and writing, drawings, mathematics and objects. In engineering each generation learns from the past by looking at objects, carts, pumps, mills, bicycles, bridges, dams, cars or aeroplanes. The Fiat 128 of 1969 differs from the 1938 Volkswagen Beetle (largely copied from the 1936 Tatra T97) in thousands of ways, yet the application of intelligence will rank those differences, probably starting with the fact that one has the engine in the rear. The Fiat itself was inspired by Issigonis's Mini of 1959. Volkswagen engineers chose the Fiat as the starting point for their design of the Golf and the Beetle design became extinct, at least for popular cars. The Citroën GS of 1970 (Figure 3.1) grew from the DS of 1955 and the 2CV of 1948. But modern small Citroëns are descended from the Fiat, mainly because improvements in roads mean that ride quality is now less important. So the genetic lines of the Beetle, 2CV and DS are extinct.

Models

An individual or group can represent their understanding as a model. Models are abstractions of reality and can be used to represent things that exist or to capture an idea. A map is a simple example of a model used to capture an existing situation. Only the detail that is required to convey particular information is used and this is represented in an abstract form. For example, a road map and a terrain map show significantly different detail. Roads can be expressed as lines

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

Figure 3.1 Citroën GS (1970–86), engineer Jean Dupin, designer Robert Opron.

connecting points which define locations, whereas landforms can be described with shading or contours.

In the design process, models are used to represent ideas that do not yet exist in a material form. This provides a means for testing an idea before it is realised. In this sense, drawings serve the same role as physical models and computer models in the design process.

The objects described above that capture engineering knowledge can also be considered as models. Their current configuration has emerged from a series of tests and modifications that have occurred incrementally. They represent intelligent input distributed over time. This kind of development can be seen in vernacular buildings: each new version is improved slightly as a result of observing flaws in the previous one. Eventually a coherent model emerges that represents the object, its function and its environment. The Scottish croft is an example of this. Its massive construction, small rooms that are easy to heat and a low surface area-to-volume ratio reflect the need to retain heat in a cold climate.

Innovation

The Wright Brothers were bicycle manufacturers, a mature technology at the turn of the twentieth century. Wilbur Wright explained countersteering as follows:

> I have asked dozens of bicycle riders how they turn to the left. I have never found a single person who stated all the facts correctly when first asked. They almost invariably said that to turn to the left, they turned the handlebar to the left and as a result made a turn to the left. But on further questioning them, some would agree that they first turned the handlebar a little to the right, and then as the machine inclined to the left, they turned the handlebar to the left and as a result made the circle, inclining inward. (Crouch 1990)

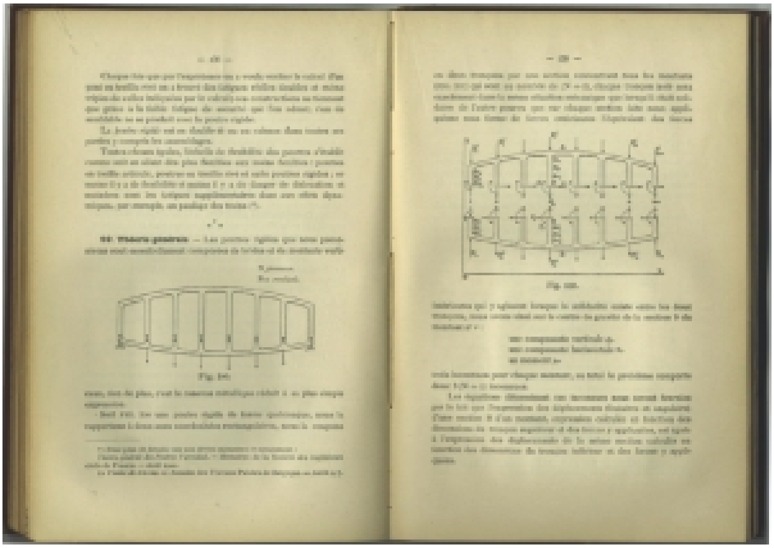

Figure 3.2 Arthur Vierendeel, *Cours de stabilité des constructions*, Tome V, A. Uystpruyst, Louvain, 1906.

This type of understanding was crucial for their design of a powered aircraft for which there are three problems to solve: power, lift and control. Over the next 50 years thousands of engineers, scientists and mathematicians improved the design of aircraft to produce the Boeing 707 by 1957, which, externally at least, looks very much like a modern airliner. Even though we now think that a computer is indispensable in the design process, the 707 would have been designed largely without computers, although Boeing had begun to use analogue computers in the mid-1940s and took delivery of an IBM 701 digital computer in 1953. IBM produced the first FORTRAN compiler in 1957, and FORTRAN is still used, primarily for science and engineering.

Each area of technology goes through periods of rapid advance and relative stagnation. The shift from a purely craft-based approach to construction to one where objects were drawn before they were built is an example of this. The rapid advances correspond to the role of designer becoming distinct from that of builder. The drawing provided the designer with a level of abstraction that escaped physical laws, material difficulties and the constraints of labour. New ideas could be developed on paper and tested theoretically without fear of wasting time and money. The draughtsman still required a coherent understanding of construction, but was in a position to experiment.

Specialisation of labour later formalised and separated the roles of engineer and architect, which corresponded roughly with the development of structural design theory. By the time that Arthur Vierendeel published Tome VII of *Cours de stabilité des constructions* in 1908, pretty much all there is to know about the theory of structural design in iron, steel, concrete, timber and masonry was known. Vierendeel himself built many bridges, and there is no doubt that Alexandre Sarrasin must have had copies of Tome V, *Pièces courbes et polygonales, ponts suspendus rigides, poutres rigides* (Figure 3.2) and Tome VI, *Maçonneries, fondations, béton armé* when he designed the Pont de Naou-Hounts, which was completed in 1931.

Figure 3.3 Newport Transporter Bridge, Ferdinand Arnodin, 1906.

Like Vierendeel and Sarrasin, Ferninand Arnodin had a clear understanding of the relationship between design and structural behaviour. One can look at the reinforcement in Sarrasin's Pont de Naou-Hounts, or the arrangement of cables and struts in Arnodin's Newport Transporter Bridge (Figure 3.3) and immediately see how the structure works. Further than that, the calculations to establish these forces would be very simple, based mainly on a thorough understanding of the principles of static equilibrium.

Theory

Mathematically, the theory of shell structures (Figure 3.4) and the General Theory of Relativity are very similar. The General Theory of Relativity is quite brief; Dirac (Figure 3.5) is only 70 pages long and much of the material has been presented by page 30. The General Theory is about curved space–time and employs the same mathematics that is used in shell theory to describe curved surface structures. In the General Theory force is dimensionless because mass, length and time share the same units. The relationship between structural theory and mathematics has always been close, and mathematicians and scientists from Galileo to Maxwell were involved in the development of structural theory.

Thus it could be argued that one should study Dirac before designing a shell structure. On the other hand, it is true that if one can produce a 3-D computer model of a structure, then it is easy to put it into a commercial finite element program to see whether the stresses exceed certain values. So it could be argued that you don't need to know anything about shell structures before designing one, in the same way that one can safely drive a car without having any knowledge of car mechanics, or even Newton's laws of motion. There is no logical way out of the dilemma, although common sense says that there must be some middle way. Computers, like any technology, have a great impact on people; new skills are needed while others wither.

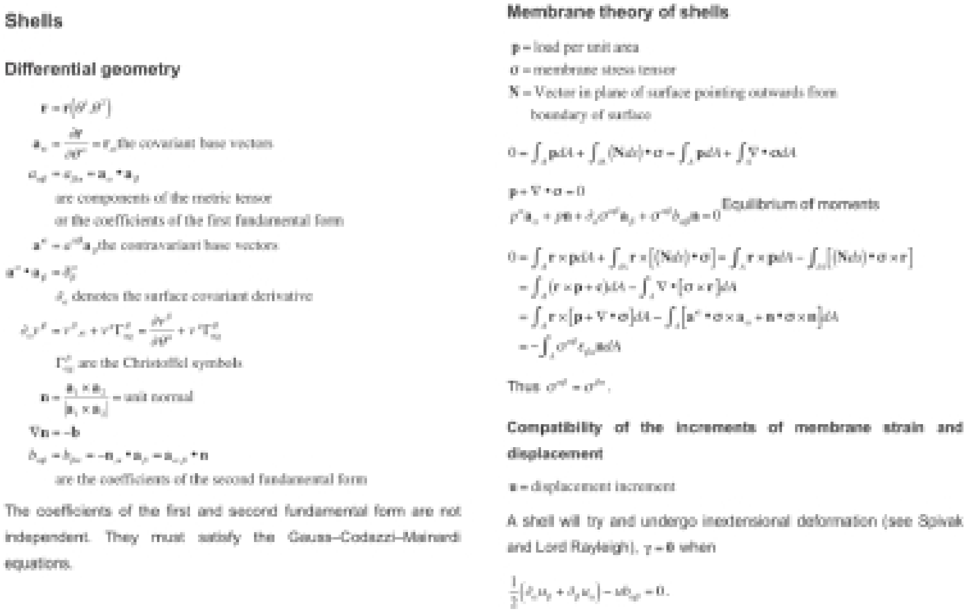

Figure 3.4 Theory of shell structures. (Figure supplied by Chris Williams.)

The middle way indicates that we need to develop some new sensibilities for working with new modelling methods. Common sense tells us that every time we want to drink something we do not make a new drinking vessel. Instead, we pick one from the shelf which is suited to our level of thirst, the temperature of the drink and the quantity. If an appropriate vessel is not on the shelf we have several options: we might try to use an inappropriate one, we might buy a new one, we may make one or we may choose to drink something else. This suggests that we need to develop skills in determining when to use existing methods, software and models, when to question them, when to adapt them, when to start from scratch and when to question what it is we are trying to do.

Calculations and safety

Engineers traditionally (up until about 1980) did calculations on a slide rule, invented by William Oughtred in 1622. The slide rule has two logarithmic scales. Adding these two lengths multiplies two numbers. The relatively laborious nature of these calculations meant that engineers thought about what they were doing before embarking on too much arithmetic.

The simulation of the workings of a nuclear power station involves the same sort of calculation as the simulation of the world in animated films such as *WALL-E*. They both make use of disciplines such as CFD (computational fluid dynamics; Figure 3.6).

The connection between the real world and calculation is always tenuous; it is not possible to prove that a structure will not fail. All that one can do is to postulate all the possible ways in which it can fail and try to convince oneself that each failure mode is sufficiently unlikely. That is why engineers are pessimists.

which is the Bianci relation for the Ricci tensor. If we raise the suffix σ, we get

$$(R^{\mu\sigma} - \tfrac{1}{2}g^{\mu\sigma}R)_{:\sigma} = 0. \qquad (14.3)$$

The explicit expression for the Ricci tensor is, from (11.3)

$$R_{\mu\nu} = \Gamma^{\alpha}_{\mu\alpha,\nu} - \Gamma^{\alpha}_{\mu\nu,\alpha} - \Gamma^{\alpha}_{\mu\nu}\Gamma^{\beta}_{\alpha\beta} + \Gamma^{\alpha}_{\mu\beta}\Gamma^{\beta}_{\nu\alpha}. \qquad (14.4)$$

The first term here does not appear to be symmetrical in μ and ν, although the other three terms evidently are. To establish that the first term really is symmetrical we need a little calculation.

To differentiate the determinant g we must differentiate each element $g_{\lambda\mu}$ in it and then multiply by the cofactor $gg^{\lambda\mu}$. Thus

$$g_{,\nu} = gg^{\lambda\mu}g_{\lambda\mu,\nu}. \qquad (14.5)$$

Hence

$$\Gamma^{\mu}_{\nu\mu} = g^{\lambda\mu}\Gamma_{\lambda\nu\mu} = \tfrac{1}{2}g^{\lambda\mu}(g_{\lambda\nu,\mu} + g_{\lambda\mu,\nu} - g_{\mu\nu,\lambda})$$
$$= \tfrac{1}{2}g^{\lambda\mu}g_{\lambda\mu,\nu} = \tfrac{1}{2}g^{-1}g_{,\nu} = \tfrac{1}{2}(\log g)_{,\nu}. \qquad (14.6)$$

This makes it evident that the first term of (14.4) is symmetrical.

15. Einstein's law of gravitation

Up to the present our work has all been pure mathematics (apart from the physical assumption that the track of a particle is a geodesic). It was done mainly in the last century and applies to curved space in any number of dimensions. The only place where the number of dimensions would appear in the formalism is in the equation

$$g^{\mu}_{\mu} = \text{number of dimensions}.$$

Einstein made the assumption that in empty space

$$R_{\mu\nu} = 0. \qquad (15.1)$$

It constitutes his law of gravitation. "Empty" here means that there is no matter present and no physical fields except the gravitational field. The gravitational field does not disturb the emptyness. Other fields do. The

Figure 3.5 P. A. M. Dirac, *General Theory of Relativity*, John Wiley & Sons, 1975.

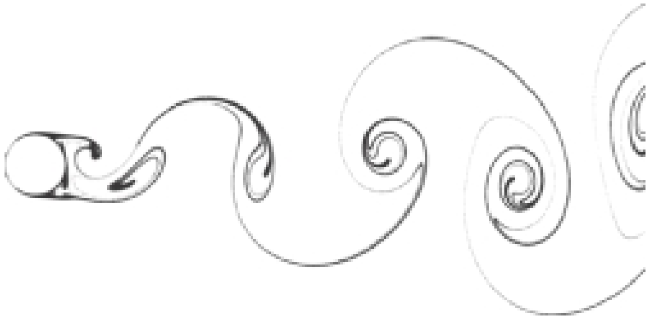

Figure 3.6 Computational fluid dynamics.

Convincing oneself that the structure will not fail requires a coherent mental model. The structural simulation model is based on some abstraction of reality which is informed by assumptions. The coherent mental model consists of a combination of understanding the assumptions made in the simulation and careful examination of both the input and the results. One way of developing knowledge of fundamental principles is to create physical models that provide a tactile way of understanding how a structure performs and how it is likely to fail.

Physical models

Physical models were used to design the Mannheim gridshells (Carlfried Mutschler + Partners, Frei Otto and Ted Happold, Ian Liddell and Chris Williams, then at Arup). Figure 3.7 shows the hanging model used to define the shape (based on Gaudi's techniques) and Figure 3.8 shows the load test of the finished structure. This was in 1974 and in fact Büro Linkwitz did a computer form finding based on the hanging model and it was Linkwitz's model that was used for erection. There were also load tests done on small models and a computer analysis done on a CDC computer that cost in the order of $7 million and filled a large room. Gridshells of the Mannheim type are extremely non-linear and even today there would be aspects of structural behaviour that can only be fully understood by feeling a physical model on the point of collapse.

The program written for the structural analysis of the British Museum Great Court roof (Figure 3.9), which now runs in a minute or so on a laptop, could not have run on the CDC: it would have required too much computer time and storage. This program was written specially for the project, but usually one has to use off-the-shelf software, even if it is not really suitable.

Other worlds

Thus far we have discussed the use of computers in ways that mimic earlier, non-computerised methods, doing drawings, performing calculations and so on. The computer is simply a labour-saving device that is not directly involved in the creative process. It may help 'optimisation', but only by making more information available. The computer is kept under strict control, only doing exactly what it is told.

If computer programs are less rigidly structured, unexpected results can emerge. Emergence is the production of complex behaviour from simple rules, involving the production of order

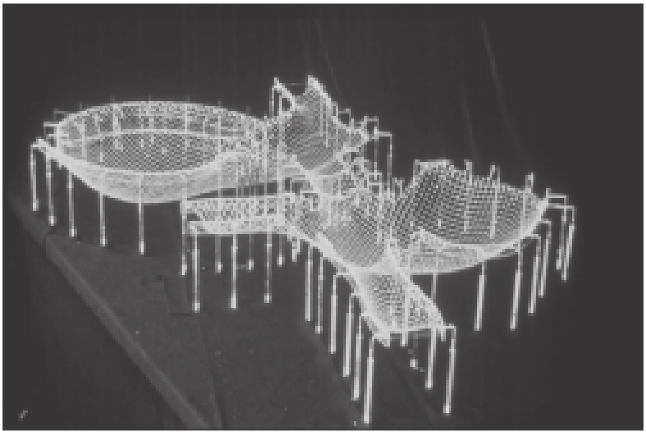

Figure 3.7 Mannheim gridshell hanging model, Frei Otto, 1974.

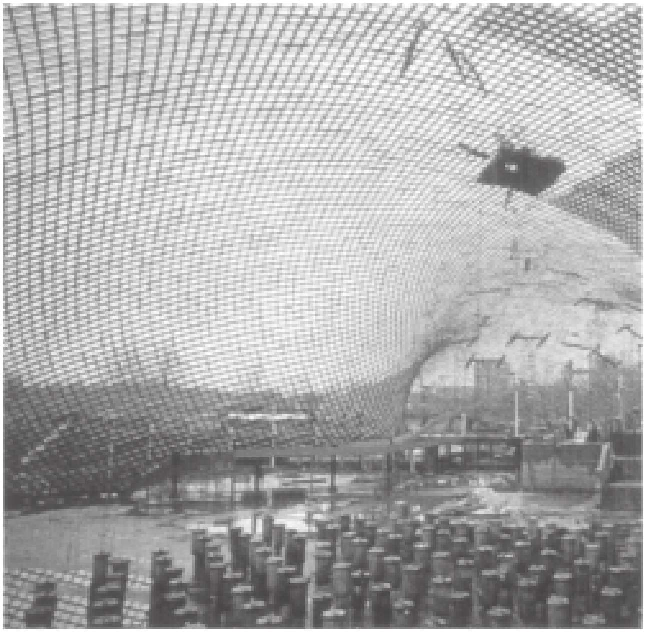

Figure 3.8 Mannheim load test. (Photo supplied by Chris Williams.)

from disorder. These rules can be 'real' in that they are based on the real world, or they can be purely imaginary and only exist in a computer calculation. The form in Figure 3.10 emerged or 'evolved' out of a calculation in which nodes were given a fictitious tensor mass associated with structural stiffness. Thus this form could not have been produced in the real world.

Iannis Xenakis (1922–2001) was an architect, composer and theorist. As an architect he worked with Le Corbusier on the Philips Pavilion at Expo 58 in Brussels and the Sainte Marie de La Tourette

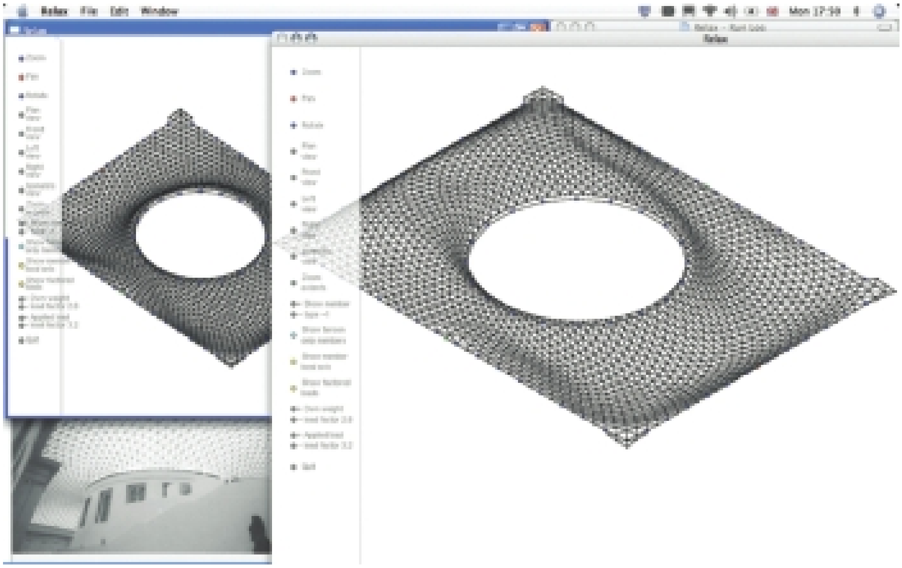

Figure 3.9 Structural analysis of the Great Court roof. (Figure supplied by Chris Williams.)

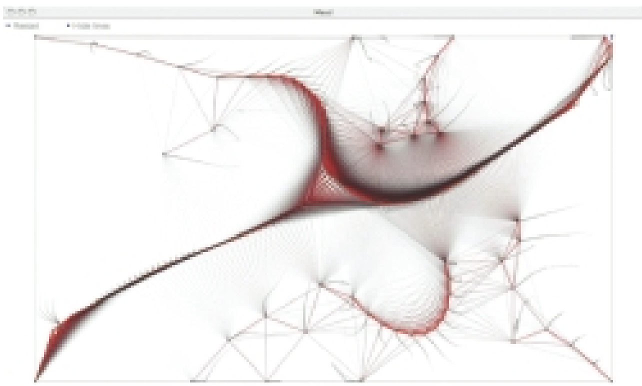

Figure 3.10 Maud algorithm – emergence. (Figure supplied by Chris Williams.)

(1960). The geometry of the Philips Pavilion was based on Xenakis's musical composition, *Metastaseis*. Xenakis was a pioneer of electronic and computer music and the application of mathematics and physics to music. Thus he was able to attempt the integration of sound and architecture. It is perhaps only through such avenues that computers can have a truly creative influence.

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4 Sharing intelligence: The problem of knowledge atrophy

Peter Brandon

This chapter explores the issue of combining design intelligence across a multidisciplinary design team. It will call on the experience of the author in developing so-called expert systems in the 1980s and the development of integrated models and databases through the 1990s. It will then explore the new forms of communication being developed in the University of Salford 'Think Lab', of which he is Director, using ambient and immersive technologies. It will draw conclusions from this experience as to where we should place our effort in the future for developing distributed design intelligence.

The act of design

We are all designers in one sense or another, in that we all contribute to the act of design in different ways. Design is to 'work out the structure or form of something … to plan or make something artistically or skilfully … to form or conceive in the mind' (*Collins English Dictionary* 2000). According to our role we may specify the requirements, we may suggest new approaches, we may constrain, we may stimulate, we may negotiate a compromise and, in each and every case, the design is affected by what the intervention contributes. Thus engineers, architects, planners, clients, contractors and even quantity surveyors have a role to play in the creative act. It is a team effort and has been so for many centuries, ever since complexity and scale became an issue in the design and construction of buildings. The rather strange phenomenon in the construction industry is that the process of design is often seen as something separate from the manufacturing process, whereas in other industries there is a natural flow from one to the other. It has created an unnatural interface which, in turn, creates additional problems and a culture of litigation.

There is, of course, a 'mind' or brain, composite or individual, which brings all these interventions together and makes sense of the information in order to make a decision or sign off a design. In terms of the brain's physiology, there are millions of connections between the neurons which allow the neurons to act together to synthesise, analyse, remember and store in one person or persons the aspiration for something new, the structure to solve the often conflicting issues,

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

and the knowledge to make the new creation realisable. This is normally referred to as intelligence – 'the capacity for understanding' (*Collins English Dictionary* 2000). However, in many areas of complex problem-solving it is a joint effort by many people who act together using their brainpower, and who have been educated in a particular way, to solve the problem as a team.

The human brain is a significant and remarkable entity. The Mind Zone at the Millennium Stadium in London in 2000 likened the connectivity of neurons to every man, woman and child in the world making 200 000 telephone calls, all at the same time! The incredible thing is that it works as a whole and can interact with other brains which have different knowledge and skills to produce something together which is better than one brain acting alone. This is so obvious that we often take it for granted. Two or more brains can collaborate together to produce something new.

Complexity and wicked problems

The problem domain in building design is difficult to formalise except in very constrained circumstances. Rittel and Webber (1973) suggested that the problems that planners face are inherently different from the problems that scientists and engineers deal with, which they consider are mainly 'tame'; that is, they are clearly defined problems with a clear mission and clear indicators for when the problem has been solved. There is a parallel with architectural design. Some of the differences they suggest are as follows:

- There is no definitive problem formulation, instead 'the formulation of a wicked problem' *is* the problem.
- There are no criteria to indicate when a solution has been found and the eventual solution is decided through reasons external to the problem, such as time or cost constraints.
- Solutions to wicked problems are value based; that is, they are not true or false but good or bad.
- There is no way of testing and fully appreciating the consequences of a solution as the full scope of its repercussions cannot be traced.
- There is no opportunity for trial and error; every solution has an immediate and irreversible impact on the system.
- There is no fixed number or set of permissible solutions to a wicked problem; they tend to be unique and, therefore, there are few replicable solutions.
- Wicked problems are nested across levels, in the sense that every problem can be considered a symptom of a problem at a different level.
- The usual rules of science to formulate and test a hypothesis cannot be applied and the explanation of a discrepancy, and hence the proposed resolution of the problem, is mainly determined by the 'worldview' of the analyst.
- Unlike a scientist, whose hypothesis can often be refuted without major consequence, the planners cannot afford to be wrong, as the solutions to their problem have direct and irreversible impacts.

There are clear parallels with architectural design and from this definition it is possible to see the difficulties that the human brain(s) has to deal with. The more the intelligence in design is distributed, the more these issues become magnified. If one person has difficulty knowing when a problem has been solved, then how much more difficult is it for a team to agree? Hence, there is a desire for hierarchies in design decision-making, which also tend to be reflected in information support systems (e.g. version control and internal security). Distributed intelligence may not make the solution to a problem any easier and, indeed, may make it considerably more difficult.

The interface problem

At the root of the team problem is the interface. Over the past two centuries the number of specialisms has increased enormously to cope with the complexity of the design/construct problem and the technologies available to provide the solution. Innovation has led to reductionism, whereby smaller parts of the problem can be sub-optimised. This innovation is now seen to have led to fragmentation and in many cases an adversarial position between the team members. As soon as adversarial positions are taken, the overhead increases. Each interface needs management and management is engaged with negotiation; this often requires contracts specifying what is in the mind of the parties, standard methods to assist understanding, decision-making tools and risk assessment and a whole variety of other issues/tools, culminating in the project manager who 'manages the managers' (Brandon 2008). This complexity adds enormously to the cost of a project, not only in the increased chance of litigation but also in simply the time and cost involved in managing the interface.

In a perfect world we would have one person or team thinking clearly and acting together as one. The overhead of understanding each other's point of view, getting it agreed and acting on it would disappear and efficiency and effectiveness would increase. The challenge for research and technology is to get us close to this point without the downside of a potential loss of creative thinking which can bring the 'joy of the new' to the design solution.

Knowledge atrophy

The interface also creates another problem. At each interface there is a transfer of knowledge. The Latin verb for 'to transfer' is *tradere*, which means the action of something on something that transforms a state. It is at the root of Italian words such as *tradizione* (tradition), *traduzione* (translation), *tradurre* (to translate) and *tradire* (to betray). It could be argued that if *tradurre* and *tradire* are from the same original root, we can see that when we translate (in the widest sense, not just language) there is also a sense of betrayal. In other words, when something is communicated and explained then there might be a loss of something, which could be interpreted as a betrayal of the original meaning.

This loss of meaning which can lead to loss of understanding can be found across the spectrum of professions which engage in the building design process. As knowledge is passed from one to the other and back again the following can be observed:

- The provider of knowledge has to structure their knowledge in a form which they think the receiver will understand. Sometimes this is standardised to make the understanding easier through specified practice.
- The receiver of the transferred knowledge has to interpret the information given, restructure for their own needs and incorporate within the models being used in their part of the process, before restructuring the outputs for the next person in the chain or for communicating back to the provider for them to use as part of their (now better-informed) activity.

- The communications between people are usually through models of one kind or another, e.g. drawings, information models, formulae and so forth. Models by definition are representations of reality and, therefore, a simplification. In the simplification there is a loss of knowledge. When a participant acts as receiver, they often have to expand the knowledge provided through their own knowledge and experience before simplifying it again for the next person, who repeats the process.
- By the time the knowledge has gone through several of these iterations, there is the possibility of a major loss of knowledge from the starting point, but also the possibility of a fairly substantial growth in other knowledge which may no longer be available to the original provider. This breakdown in communication (hence the betrayal) can result in the kind of litigation which pervades the industry.
- The breakdown has many side effects, in that it can break feedback chains so that participants do not learn from experience. How often do we hear of site personnel who adapt architects' drawings which are not practical but do not communicate back to the design team? Consequently, the architect repeats the same error. It can also create mistrust, encourage malpractice and stifle innovation.

Knowledge atrophy is a serious problem and if intelligence is to be distributed then dealing with this problem is a key issue. In the single human brain all aspects of the brain function appear to have access to the same knowledge. That knowledge is constantly reviewed and updated and the brain neurons act as one. Replicating this with the physical, cultural and technical barriers in a construction design team is the challenge that distributed intelligence must face.

The problem has been faced at each stage of human technological development where knowledge has had to be shared. For example, in 'expert system' development in the mid-1980s it was a key element of the interface between the human operator and the expert system itself. In fact, it led to the rejection of the term 'expert' in preference to the term 'knowledge-based system' (KBS), recognising the limits of any system built around rules and heuristics.

'Expert' systems and the knowledge paradigm

In 1985 the University of Salford, in collaboration with the Royal Institution of Chartered Surveyors (RICS), undertook a research project within the Alvey Programme for the Department of Trade and Industry in the UK (Brandon *et al.* 1988). This programme was instigated in response to the Japanese 5th Generation Project, which was to develop knowledge- and intelligence-based computing for solving problems in a number of application areas. The RICS was approached to undertake the work and it had a relatively free hand on what application area it should focus on. It decided after consultation with Salford to provide an 'expert system' for giving strategic advice at the conception of the project. The idea was that a client would specify the kind of building they required (e.g. an office block of a certain standard on a particular site) and the 'expert system' would provide a report on what was an appropriate budget, the best procurement path, the time scale for design and construction and a simple development appraisal, if appropriate. It was to be used before the designer put pen to paper and it needed around 20 questions to be answered for each module, but these were linked through a common knowledge base which avoided repetition of the questions when the machine already knew that a question had been asked and answered.

The budget module had approximately 2000 rules for assessing the cost of the project and could provide up to 40 screens of report on what it had assumed. The other modules had fewer rules but were more qualitative in their assessment. Behind the idea was that a client or an architect could consult with the 'expert system' which now contained the quantity surveyor's expert knowledge and establish a sensible approach without the need for the expert to assist. Here was an opportunity for a major step forward for architects, clients and others to determine their own strategic approach. The expert system, known as ELSIE (after the initials LC or lead consultant), was sold commercially and over 1000 licences of the administrative office system were sold – to quantity surveyors! Other systems for housing and industrial buildings were also sold in similar numbers. For the quantity surveyors it speeded up their work at this stage of the project by a factor of 10, allowed them to work closely with their clients over short time scales and generally performed better than humans, as it did not forget things and it encompassed the knowledge of at least a dozen 'experts' related to the problem in hand. Indeed, there were several cases where the program found errors in other experts' work. In tours round the country the program responded correctly for many projects brought in to test the system. This is a credit to the quantity surveyors who provided the expertise and knowledge.

However, ELSIE was seldom used by those whose expertise was not in the realm of quantity surveying or project management. In the context of these professions it was a success, but in terms of distributed design knowledge and intelligence it could be considered a failure. The reasons for this might be summarised as follows:

- The user had to have *trust* in the system and this was hard to gain from people whose expertise was not in this field.
- The legal repercussions of being wrong (particularly on cost) were such that no other profession was prepared to take the *risk*, possibly because of professional indemnity insurance issues.
- The expert system was fine provided that it was transparent and that the user had a detailed knowledge of the processes it was undertaking and was able to *steer* the solution.
- Much more *knowledge* was required about the industry context to trust the system. For example, the procurement path for large projects was suggesting 'management contracting' as a procurement path, based on the experience of the knowledge providers, until one of them found that this approach was now costing more than 17 per cent in the market and this had not been picked up by the others. The machine had no way of picking up changes in the market.

From this, we can discern that there may be some real, fundamental issues in trying to bring together distributed knowledge, namely:

- Contextual and particularly 'common-sense knowledge' is outside such systems and it may not be clear who owns that knowledge in a particular context.
- Market knowledge where major shifts can take place cannot be easily assessed without some form of self-learning by the machine, which would be beyond most systems at present.
- Legal and regulatory constraints may stop designers' willingness to share or even gain expert knowledge.
- Strategic design knowledge and intelligence at this conceptual stage belong to many participants, but even so there is a high degree of reluctance to share or engage with the territory of others.

- The distribution of design intelligence already exists, but the real issue is how it can be effectively synthesised to act in an integrated way.

This would suggest that an approach engaging a common source of knowledge had much to commend it, even though complete knowledge involving tacit knowledge may well be outside the scope of any formal system. After the KBS period, when a number of knowledge-based systems were developed at Salford, the move was towards object-orientated programming and integrated databases, partly as a means of handling shared intelligence.

Integrated databases and objects

If intelligence is 'the capacity for understanding', then part of the intelligence contribution is to provide information and memory and structure, which enables 'understanding' to take place. The development of object-orientated programs and the associated databases provided such a facility. Objects, whether they are physical or conceptual or abstract, can be viewed from different perspectives. These perspectives can be the viewpoints of members of the design team. In one sense they are all looking at the same object, but their orientation is different (see Figure 4.1). An architect may look at a beam from an aesthetic and space viewpoint, whereas a structural engineer might consider it from its load-bearing performance, a mechanical engineer as a hurdle which has to be overcome and a quantity surveyor as an item of cost. It is the same item but it has different meanings to each participant, except that each of them would be aware of the understanding and needs of the others and be able to make adjustments to their own work and understanding accordingly.

The degree to which these professionals can adjust their own thinking is, to some extent, a sign of each individual's intelligence. However, awareness of the other person's problem is not the end of the track. Usually some form of compromise is required, which involves negotiation and the ability to understand the underlying objectives and values of the stakeholders, and particularly those of the client. It is further complicated by the 'wicked problem' domain described earlier, since it is not possible to know what is right, only good or bad. This aspect of design intelligence is difficult to distribute!

Nevertheless, the early 1990s and the growth of object-orientated database development began to develop the concept of the common model, whereby all participants could share the same root model and adapt it to suit their own requirements. The knowledge suddenly became more transparent and it was possible for all to see (within the limits of security and protocols) what each contributor was doing and an instant update was always available. At Salford the approach was to develop n-D modelling (Aouad *et al.* 2005), whereby not only the geometric and time dimensions could be modelled (4-D modelling), but this could be extended to include other major aspects of design including acoustics, heating and ventilation, site planning, briefing and indeed any other aspect which could have an influence on the combined design intelligence. This was taken a stage further in the large scale European Divercity project (The DIVERCITY Handbook 2003), whereby the ability to work across national boundaries to create, examine and evaluate design solutions was developed to the point where it could be taken up by industry.

This approach has grown over the years and the concept of a building information management model is now being taken up by industry as the way forward. The One Island East project in Hong Kong for Swire Properties, developed by Gehry Technologies (Riese 2008), is a leading

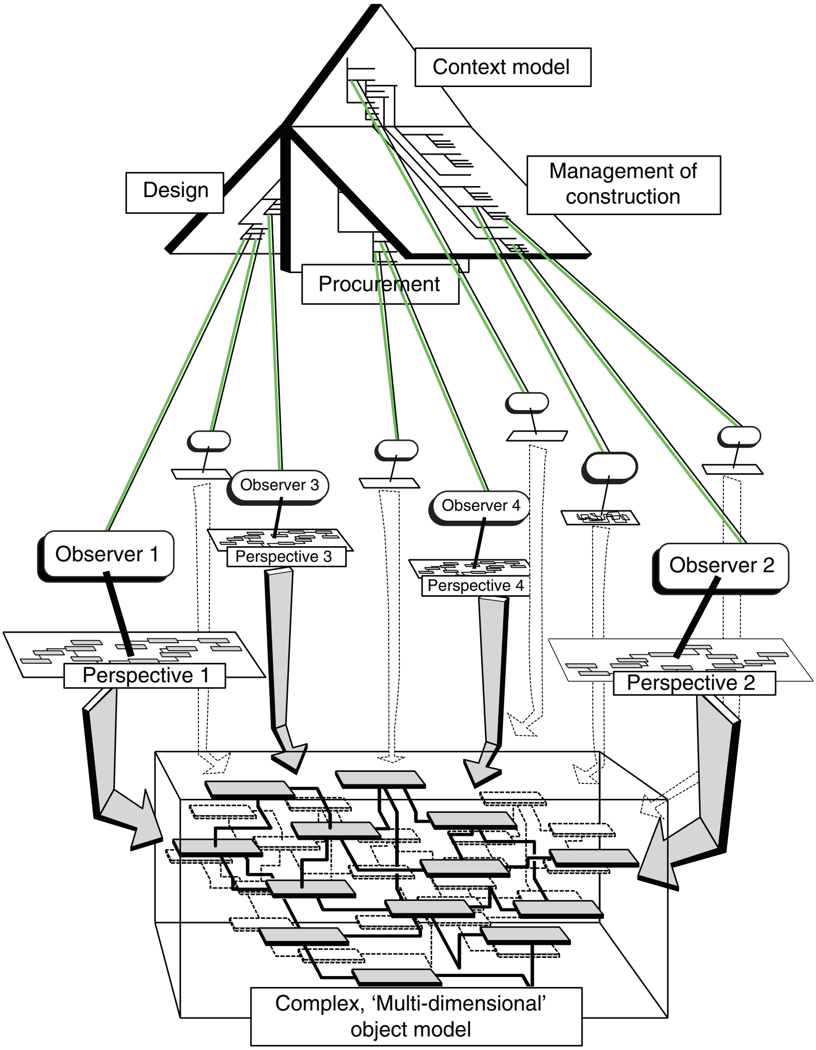

Figure 4.1 Integrated databases showing different perspectives on a common database. (Diagram developed by Grahame Cooper at the University of Salford.)

example (and won the award for BIM at the American Institute of Architects in 2008). This is a very advanced model, which can also be seen in stereo at the University of Salford Think Lab (Figure 4.2), and largely focuses on the interaction between the architectural and structural engineering design and the mechanical and electrical services. In the period before work on site 2000 clashes were evident and identified through the model, but as design developed around 1500 clashes a week were identified and rectified. Some of these would have been extremely costly if this checking had not been undertaken. The machine model acted as an enhancement and integrator of knowledge (and, therefore, some aspects of intelligence), which then enabled the designers to undertake their work more efficiently and effectively.

The firms associated with this project have now said that they will continue to use this approach to modelling on the grounds of 'Why would we now go back to inefficient procedures?'.

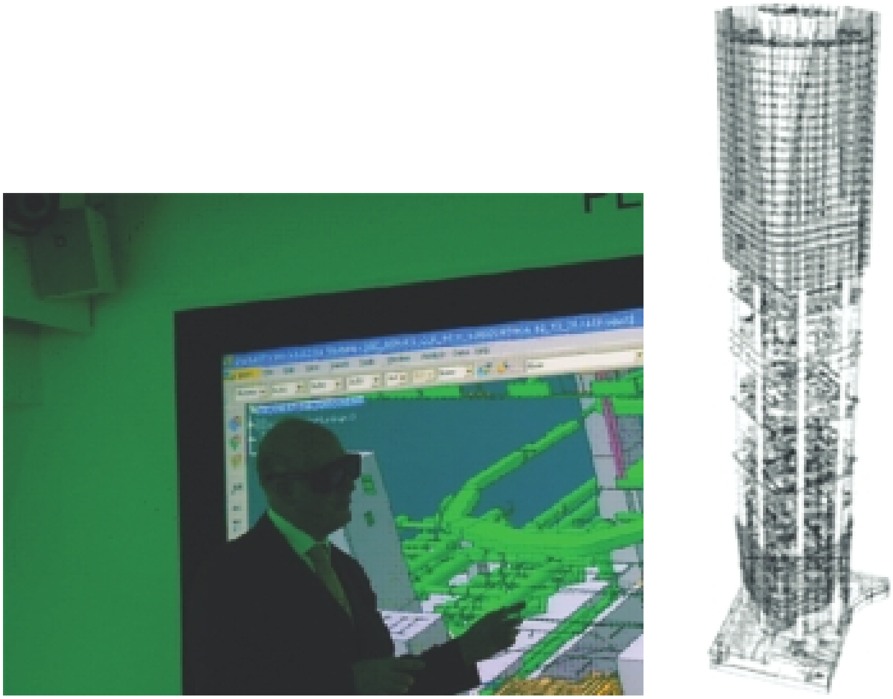

Figure 4.2 One Island East Model being shown in stereo in the University of Salford Think Lab (photo by Martin Riese) and One Island East perspective view (courtesy of Swire Properties and Gehry Technologies).

The experience has convinced them that this is the way forward. Claims of a saving of 10 per cent on initial cost and even more for future occupation cost are regularly made by the clients who authorise these systems.

There is little doubt that such models also begin to break down the traditional barriers between professions and other contributors. The islands created by professions become 'exclusive repositories of knowledge' (Evans 1979) and each profession defends its island through examinations, fees, membership requirements and other artificial boundaries. The creation of building information models begins to break down these boundaries and a different relationship between the participants is created. The integration of distributed knowledge through the model has enabled an improved dialogue. As the model is virtual, so the problems of geographic location begin to disappear and as far as the team are concerned it is not distributed, it is synthesised. To take this a step further, the human communication between participants needs to be addressed.

Immersion: The social impact on design intelligence

It is likely that for some time to come there will still need to be human intervention and dialogue in determining the building design and implementation. The intelligence will still remain with the participants and a small amount will be shared via models such as BIM. A new project with a new team inevitably means a new model and probably new intelligence, but the real integration requires more than just a sophisticated knowledge base. This dialogue is built around conventions and culture: conventions in terms of the way communication takes place in the industry; and culture in terms of the way in which human beings communicate and build relationships which enable decisions to be made and actions to be taken. These are not purely verbal or textual and sometimes engage other forms of negotiation involving body language and social understanding and skills.

It follows, therefore, that these methods of communication need to be able to be replicated in the virtual environment if we are to take full advantage of integrating distributed intelligence. In recent years this has been a focus for several research groups who are trying to make the interface between the machine and human beings as natural as possible. In many cases they are trying to make the machine disappear as a physical entity and to encourage the development of ambient technologies. These are in the background, but the interface may be by spoken word, a remote sensor or other device, which creates a world in which the role of the machine may be important but it, nevertheless, does not interfere with normal communication between human beings.

At Salford the focus has been on addressing some of these issues through immersive technologies. These are technologies where the human can engage directly with virtual objects.

Tele-collaboration and immersive technologies

If the intelligence is distributed, then we need to provide efficient and effective ways of bringing it together. This has, of course, been the role of the architect or engineer leading the team and the other professions provide support. The designer asks the questions, creates a proposal and then the others provide the knowledge and intelligence to make it happen. The designer then synthesises the knowledge for the final solution.

The new technologies for integrating knowledge and information go some way to make the understanding of each participant transparent. This transparency allows the interfaces between knowledge to be accommodated and efficient but, as explained earlier, there is a loss of knowledge as information is transferred, even in a common model. The different geographic locations of the various parties can make the linking together more difficult. The building information model assists in this process, but often vital aspects can be missing. These tend to relate to the way in which humans interact and to the dialogue engaged in making a decision, which can be lost in matching the various models together. If a more natural virtual environment could be developed whereby the participants meet in virtual space and conduct their meetings as if they were co-located in the same room, then trust and confidence may be further enhanced.

Key aspects are eye contact and pointing and body language. There are a number of ways in which the virtual space can be displayed and used (see Figure 4.3).

Each method has a different impact as a means of communication. The access grid is two-dimensional and has the attributes of any screen display. Tele-immersion allows exchange of virtual objects in three dimensions, which enhances the communication. A visual and knowledge interchange takes place at whatever level is thought appropriate and verbal/visual communication can be used to explain and add meaning. In an immersive collaborative environment the participants can be immersed in the visual space and interact together in a similar way to real-life situations. These technologies are still in their infancy, but already avatars can adopt the facial characteristics and expression of a participant and mechanisms can be used to aid pointing and eye contact to make the experience more real. The knowledge of human communication is thus restored and the knowledge about the building enhanced.

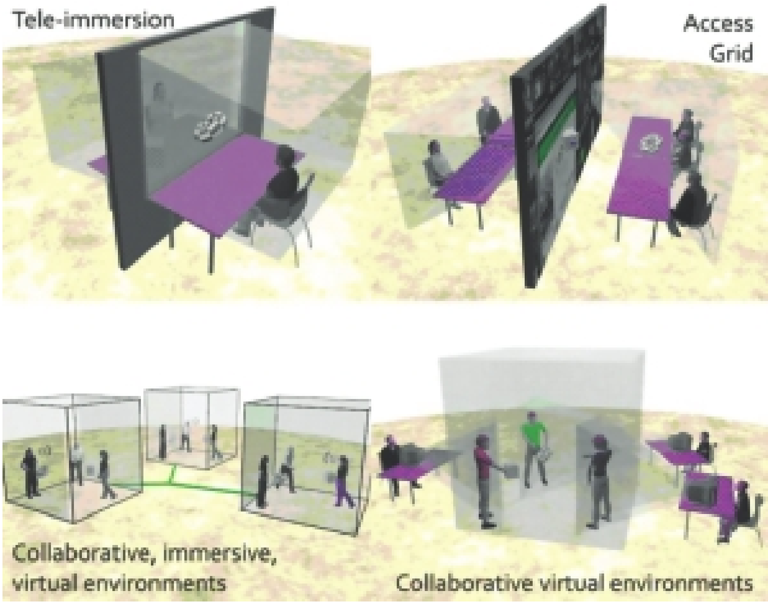

Figure 4.3 Sharing space for tele-collaboration. (Courtesy of Professor David Roberts and The Think Lab, University of Salford.)

These technologies are further advanced when the physical presence of the machine is hidden and communication is by sensors and other devices which capture performance, speech and recognition automatically. The additional intelligence is then found through the sensory data or the captured speech. The more these ambient devices are empowered, the more natural becomes the interface and the more the distributed intelligence is enhanced and possibly integrated, although in complex systems with complex interaction and analysis, it might be more difficult to determine the source of the increased intelligence. This leads to future expectations.

Future expectations

In 2007 Grady Booch, the Chief Scientist for IBM, provided the annual Turing lecture at Manchester University (Booch 2007). His context was the prediction of what might happen to software engineering over the next three decades. His forecast was as follows:

- *Decade 1*: This will be characterised by greater transparency in software engineering, presumably to make explicit what has been programmed, how it has been programmed and why it has been programmed. This would allow the increasing level of machine intelligence to develop without concerns about in-built bias which is not made explicit.
- *Decade 2*: This will be characterised by increasing machine dependence. It will not be possible to write the kind of software required for this decade without the support of the machine itself. It will deal with inputs, outputs and analysis and synthesis, and will enhance the programmers' ability to fulfil the software demands of this decade.

- *Decade 3*: This will be characterised by what he calls 'the rise of the machine'. This is not well defined, but it is a signal that instead of merely supporting human endeavour, the machine will begin to initiate and enjoy a degree of autonomy which may well compete with human intelligence.

These suggested epochs in software engineering have an underlying theme, which is the development of machine intelligence. We make things explicit so that we know what the machine is doing. We allow the machine to support us where we know our capability is suspect. We allow the machine to develop because we recognise that its power to create is approaching or overtaking our own. Distributed intelligence now encompasses the machine! This would be a very significant development and has major issues associated with it which are not always benign.

Construction tends to lag behind and follow the technological developments we see in everyday life and in other industries. So what might we in construction see in the corresponding periods identified above? The following is speculation, but is based on what we can foresee at present:

- *Decade 1*: The transparency will come from the increasing development of 'deep' building information models. These will provide all participants with an insight not only into the data sets needed for them to contribute, but also into the meaning and understanding behind the data that has been produced. It will see a shift from hard systems thinking to soft systems. These will cope more with the qualitative issues in construction decision-making and avoid the knowledge atrophy identified earlier.
- *Decade 2*: The dependence on the machine will arise from the increasing complexity of the unified construction systems engaging all aspects of construction work, from design to manufacture and occupation. This will include increasing remote sensing of both physical and human performance to avoid the expense of data capture and analysis. Initially, sensing is likely to be embedded in remote-input devices, but as time goes on it could also result in more outputs and real-time control throughout the development, preparing the way for an autonomous machine-led construction process. There is an obvious link here to distributed intelligence as far as devices are concerned.
- *Decade 3*: By this decade the use of BIM and CAD/CAM will be well established and the machine will be in competition with the human in many areas. It may not be possible to allow the machine to create at this stage (except for simple buildings), but the level of support to design through such means as 'intelligent agents' could be well advanced.

The uniting theme throughout these developments is the dissolution of the interface. First, the interface between people, as the machine begins to enhance communication and unite activities. Secondly, the interface between human and machine, as the interaction between human and machine becomes more natural and ultimately more intimate (possibly 'jacking' direct to the brain). Thirdly, the interface between machine and machine, as direct linkage is obtained and we move towards more autonomy for the machine and in the longer term towards robotic assembly.

These interfaces are the major stumbling blocks to efficient design and manufacture in any case, but the developments in ICT are beginning to offer the solution to the problems these interfaces cause (Brandon 2009). This reduction or removal of obvious interfaces allows the distribution of intelligence to be made 'invisible' to the participants. It probably has its ultimate progression when the computer is 'jacked' directly into the brain to enhance performance.

Already this is occurring for people who have visual and hearing impairments, but whether it will help designers is another matter. More likely the use of knowledge grids to combine the performance of computers and the knowledge they hold is going to have a major impact on making distributed intelligence more integrated and more coherent.

Conclusion

This chapter has tried to provide an overview of the issues and trends in harnessing intelligence which may be distributed across several contributors to the design process. It has identified the problem of the dilution of knowledge across these interfaces and the approaches which are beginning to be used to remedy the situation, as we progress towards ambient technologies where the distribution of knowledge is less evident to those within the system. It holds out the promise that the next working lifetime is going to be an exciting place to be for both researchers and practitioners. More importantly, it is likely to provide a better environment for design which, in turn, will produce better buildings for all stakeholders in the building process.

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Part 2

5 Pedagogical frameworks for emergent digital practices in architecture

Brent Allpress

The diverse roles of digital design and communication technologies are converging through the development of parametric modelling systems that offer flexible generative design capabilities and enable highly efficient design development documentation and fabrication functionality. The process of design development and articulation no longer involves shifting from a malleable generative medium to a more rigid and instrumental documentation medium. A parametric model sets up parameters for a design project that are both calculable and alterable. These mutable models are already compatible with digitally controlled manufacturing machinery. Design generation, design development and fabrication production can potentially be brought into an intimate dialogue. The relationship between digital representation and materialisation has become a significant practice and research question. Designers are also increasingly scripting the functionality of design software, opening up new applications tailored to specific project contexts.

These rapidly changing technologies and practices are challenging established approaches to architectural design, communication and technology teaching within academic institutions. This chapter addresses the issues at stake for architectural education in engaging with the rapidly shifting role of emerging digital technologies in architectural design, professional practice and industry. Pedagogical approaches being employed by RMIT Architecture in Melbourne, Australia are discussed as a case study (http://architecture.rmit.edu.au/).

Tri-polar scholarship

A number of institutions internationally have developed 'Digital Architecture' degrees offered at a post-professional level as a specialisation. RMIT Architecture has taken a different approach and sought to integrate project-based teaching that engages with digital design technologies and practices as one of three key streams within the Architecture professional degree programmes. These currently include Urban Environments, Expanded Field and Advanced Technologies.

Urban Environments has as its focus a concern for architectural design precedent, type, infrastructure and the urban scale. This is not urban design with a planning focus but rather architectural design situated in relation to urban, historical, contextual and civic implications.

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

Expanded Field involves the production of new design knowledge through the transfer and application of interdisciplinary practices across adjacent fields, including landscape architecture, public art and fine art. This involves collaborative practice models and architectural responses to diverse modes of cultural production. The *Advanced Technologies* stream, which is the focus of this chapter, engages with the application of advanced digital design, communication and fabrication technologies and techniques, and emergent design processes and practices. These complementary approaches all share the common characteristic of engaging with and exploring bottom-up, emergent practices. Questions of environmental sustainability and social justice are treated as ethical concerns located across and through all areas of enquiry.

The aspiration for this tri-polar pedagogical model has been to sustain three contested areas of scholarship and research. Holding multiple, articulated positions fosters a productively dynamic scholarship environment. The three poles act as clusters of intensity within a constellation rather than as fixed positions. These streams are not exclusive. They interact and overlap and remain in question. Over time as they are challenged they will change. This approach offers a provisional and flexible framework for the curation of commissioned design studios and electives, and for shaping the consolidation of research activities.

Practice-based teaching by project

This section discusses the distinctive practice-based pedagogical framework of the RMIT Architecture professional degree programmes and outlines how the tri-polar model is implemented. The term practice-based, as used here, is not intended to be limited to industry-located teaching models. Instead, it refers to project-based practices specific to the broad discipline of architecture, a dynamic and open field of knowledge shared by a diverse community of practice located across institutional and industry contexts.

The RMIT Architecture programme has recently restructured to align with the nationally adopted 3+2 model, with a three-year undergraduate Bachelor of Architectural Design degree followed by a two-year Master of Architecture professional degree. Design remains the primary focus of student learning activities across both degrees, with design studio courses making up 50 per cent of full-time student enrolment. Core courses in history/theory, communications and technology are primarily located in the first three years of the undergraduate pre-professional degree, freeing up the Master of Architecture professional degree for a diverse patterning of specialised and advanced elective offerings. Students investigate architecture and learn to design by designing from the outset.

A foundational first semester gives students a grounding in three distinctive paradigms of design thinking and practice, focusing on contextual, cultural and material questions and thematics, acculturating students to the tri-polar Urban Environments, Expanded Field and Advanced Technologies streams. Students in semesters 2–5 are subsequently grouped into a vertically integrated lower pool design studio cohort of students from mixed semester levels. They ballot for a place in a thematic design studio selected from around 15 studio offerings commissioned each semester that are aligned with one or more of the tri-polar streams. A studio leader runs each studio independently. The staff to student ratio is kept at around 1:14.

Design studio leaders are drawn from RMIT Architecture academic staff and visiting academics, and from innovative architectural practices in Melbourne. They set out an autonomous studio brief of teaching and learning activities for the semester, with the range of studio topics reflecting a diversity of emerging architectural practice and design scholarship positions across the tri-polar streams. The introduction of selective skills, techniques and practices are integrated as a thematic focus of the learning activities for each studio.

In the final, sixth semester of the undergraduate Bachelor of Architectural Design, a portfolio course provides a vehicle for a critical reflection by the students on their emerging body of design work. Semester 6 design students join the Master of Architecture (Professional) students in the vertically integrated upper pool design studio cohort, consisting of semester 6–9 students. Students again ballot each semester for around 16 studios, offered by architecture academics and innovative local and visiting practitioners and researchers. The staff to student ratio is around 1:12. These studios are more specialised and engage with more complex design questions involving emerging practice and research concerns associated with one or more of the tri-polar streams.

The vertical integration of students from different semester levels working together in small, focused studio groups fosters mentoring of lower-level students by more experienced students and the transfer of practices among students through collaborative learning activities.

A diverse array of around 25 project-based electives are also commissioned each semester, with the tri-polar categories providing the guiding curatorial framework. These courses offer students opportunities to extend core course interests at a more advanced level, gain an introduction to practice and research specialisations, and be exposed to the practices of other disciplines through interdisciplinary and collaborative projects.

This model of studio and elective commissioning and balloting differs fundamentally from the dominant competency-based approach to architectural education found in most Australian universities, where students are in stratified whole-year-based studio groups with a fixed curriculum and recurring studio brief, set and overseen by an academic staff member supported by low-paid tutors who service the teaching with little autonomy.

The RMIT Architecture programme structure supports a dynamic diversity of studio and elective offerings. The flexible commissioning process allows the curriculum to be very responsive to the emergence of innovative practices, techniques and technologies such as parametric modelling or scripting. The educational aspiration is not simply to service current standard industry practice, but rather to give students the agility and critical skills to be able to engage effectively with rapidly changing technologies and practices that are likely to shape and redefine future professional roles and responsibilities.

Academics and practitioners teaching at RMIT Architecture are able to harness the studio and elective groups as a vehicle to investigate and trial questions that are of direct relevance to their research and practice interests and activities. This fosters a unique community of practice of teaching staff, bridging between the university and industry, who lead and drive the learning activities. Studios and electives also provide visiting academics and practitioners with teaching vehicles that are tailored to their specific interests and expertise.

The flexible approach to commissioning courses also allows the institution to partner readily with industry and community groups in cycles of smaller live and applied projects. Groups of students can be aligned with larger funded research or practice consultancy projects. Studios and electives that introduce students to research methods and practices specific to key research clusters, such as the Spatial Information Architecture Laboratory or the Urban Architecture Laboratory, provide a pathway for students to undertake subsequent postgraduate research in digital design technologies or urban architectural design research.

The Master of Architecture (Professional) degree culminates in a final semester design thesis major project through which students are able to reflect on, consolidate and extend the knowledge they have gained in the programme. Students set their own design research questions and parameters in consultation with an individual supervisor, opening up future practice and research trajectories.

Advanced technologies and emergent practices

The Advanced Technologies stream allows any professional degree student to engage with or specialise in this area of study. This provides pathways to dedicated postgraduate research by project supervision within the RMIT Spatial Information Architecture Laboratory (SIAL; www.sial.rmit.edu.au/), a facility for transdisciplinary design research and education with a particular focus on the role of digital technologies across the design industries. SIAL supports diverse modes of enquiry, from highly speculative project-based design research through to industry-situated applied research undertaken with linkage partners.

Design studios and electives offered by RMIT Architecture academics and SIAL researchers anchor the Advanced Technologies stream. Recurring cycles of courses are offered in parametric technologies, spatial sound, virtual environment design, scripting and other digital design practices, and culturally situated discourses on digital design technologies.

The *Flexible 3D modelling* elective (www.sial.rmit.edu.au/Projects/Flexible_3D_Modelling.php), led by SIAL Research Fellow Jane Burry, is offered to an interdisciplinary cohort that includes architects, designers, engineers and artists. It aims to give students expertise in creating flexible associative geometry computer models for design, linking these to physical modelling and prototyping through the application of parametric software systems such as Digital Project. Parametric technologies such as CATIA and the more bottom-up Grasshopper generative modelling system for Rhino are also a recurring focus of SIAL design studios offered within the Architecture professional degree programme.

SIAL Sound Lab Director Lawrence Harvey leads the interdisciplinary *Spatial Sound Composition and Diffusion*, and *Soundscape Studies* electives (http://sound.sial.rmit.edu.au/Single_Subject_Electives.php), which focus on the investigation of complex spatial sound composition and the design of physical or virtual soundscape environments. A specialised digital sound laboratory and a range of sound studios support these courses, including the Pod, an eight-channel, near anechoic space designed by Paul Morgan Architects in a literal homage to Stanley Kubrick's *2001*.

The *Atmospheres* electives and related studios led by SIAL Research Fellow Greg More (More n.d.) have been trialing cross-disciplinary teaching models for digitally networked design collaboration between architecture, interior design and landscape architecture students. They utilise gaming and online 3-D community platforms such as Second Life and VastPark as speculative vehicles for designing co-authored virtual environments that can be scripted live from within. This approach is not focused on prototyping physical buildings. It is more concerned with acculturating students to the virtual realm as a collaborative platform for the design of meaningful virtual environments, promoting the development of new spaces synthesising cinema, architecture and video gaming. Participants are encouraged to explore innovative notions of space through the digital medium, spaces that are informational and atmospheric. These design projects are sited on RMIT University's Francis Ormond Island in Second Life. Over time this precinct has amassed a collection of distinctive projects and developed its own unique design culture, developing environments designed for digitally mediated and immersive visual, spatial and auditory experience (see Figure 5.1). Design and communication skills gained by students working in teams within a virtual communal medium are readily transferable to other collaborative practice contexts.

The *Visualising the Virtual Concourse* (http://architecture.rmit.edu.au/Projects/biacs3.php) electives led by RMIT Architecture Professors Tom Kovac and Leon van Schaik explore

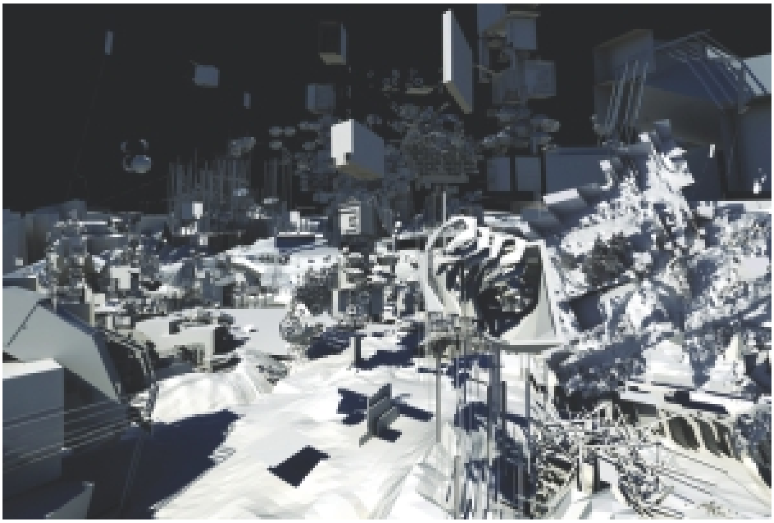

Figure 5.1 Design Archipeligos, RMIT Ormond Island, Second Life. RMIT Architecture and Interior Design students. No Country for Old Avatars & Meta Make, Architecture/Interior Design Lowerpool Design Studios, 2008. RMIT Bachelor of Architectural Design, Bachelor of Design (Interior Design). Studio Leaders: Greg More, Andrew Burrow, Edmund Carter & Louis Wong.

data-generated collaborative virtual environments, with a focus on public behaviours that sustain creative communities. This is a digital infrastructure for distributed communities that can be both more dispersed and more intensely interrelated through spatially unifying digital environments (see Figures 5.2 and 5.3). This ongoing research project has been exploring relationships between real environments, rich in sensory and spatial information, and virtual environments developed around communication software applications such as Quick-links that are information-rich interactive models for community engagement and self-monitoring. The aspiration here is for the gathered data of user interactions and information exchange sourced from collaborative software systems to inform a dynamic spatial environment, transforming information to make legible a more qualitative shared spatial intelligence.

Tom Kovac has also led the series of *Extremes* (http://architecture.rmit.edu.au/Projects/Extremes.php) design studios with Wolf D. Prix, bringing together students from RMIT Architecture and Studio Prix at die Angewandte, Vienna to investigate architecture and building in extreme environments. The functional focus of the buildings ranged from a small research station, as a single highly specialised live/work unit, to a hotel as an agglomeration of these units. The technical focus of the Extremes Studio was on adaptable and responsive structures that react to external dynamic forces. Adaptation to, or deformation by, external influences is driven by energy use and information, in connection with sustainability and performance (see Figures 5.4 and 5.5). Students have experimented with Surface Evolver, employing the Evolversaurus plug-in for Rhino developed at RMIT, and have explored evolutionary structural optimisation (ESO) software as both a structural and formal compositional design generator. Kovac has run subsequent iterations of this studio at SCI-Arc in Los Angeles.

The *Cloudnets* architecture electives (http://architecture.rmit.edu.au/Projects/cloudnets.php), led by RMIT Architecture Associate Professor Paul Minifie, SIAL Research Fellow Andrew Burrows

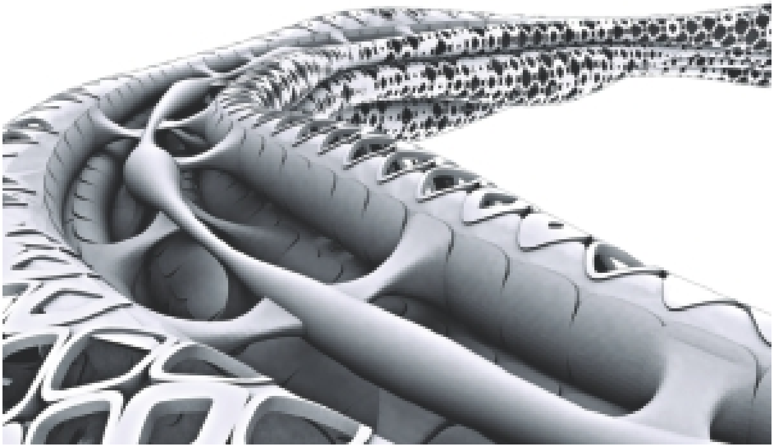

Figure 5.2 Virtual Concourse. Daniel Griffin, RMIT Architecture student. Visualising The Virtual Concourse, Architecture Elective, 2008. RMIT Master of Architecture (Professional Degree). Elective Leaders: Tom Kovac, Sean Kelly, Alvin Low and Leon van Schaik.

Figure 5.3 Virtual Concourse. Daniel Griffin, RMIT Architecture student. Visualising The Virtual Concourse, Architecture Elective, 2008. RMIT Master of Architecture (Professional Degree). Elective Leaders: Tom Kovac, Sean Kelly, Alvin Low and Leon van Schaik.

and PhD candidate Tim Schork, focus on the role of scripting in design generation and composition. Students undertake investigations into emergent urbanism and architectural form through the use of RhinoScripting. Cities consist of discrete buildings set in relation to one another, responding to existing situations. A type of specific shop responds to adjacent shops. Convenience

Figure 5.4 Equipoise. Tom Frauenfelder, Will Hosikian, Jessica In, Sarah Papadoupollous, RMIT Architecture students. Extremes, Upperpool Design Studio, RMIT Master of Architecture (Professional Degree), 2008–09. Studio Leaders: Tom Kovac, Wolf D. Prix, Reiner Zettl, Niels Jonkhans, Jerome Frumar, Farzin Lofti-Jam.

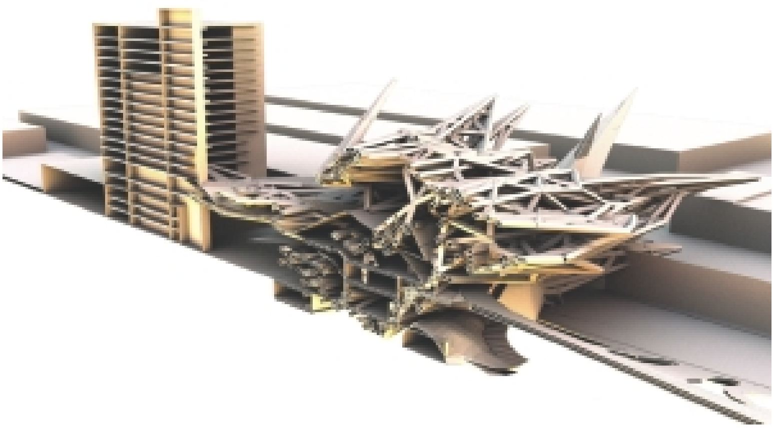

Figure 5.5 Xplicit. Hally Ongkosandjojo, RMIT Architecture student. Extremes, Upperpool Design Studio, RMIT Master of Architecture (Professional Degree), 2008–09. Studio Leaders: Tom Kovac, Wolf D. Prix, Reiner Zettl, Niels Jonkhans, Jerome Frumar, Farzin Lofti-Jam.

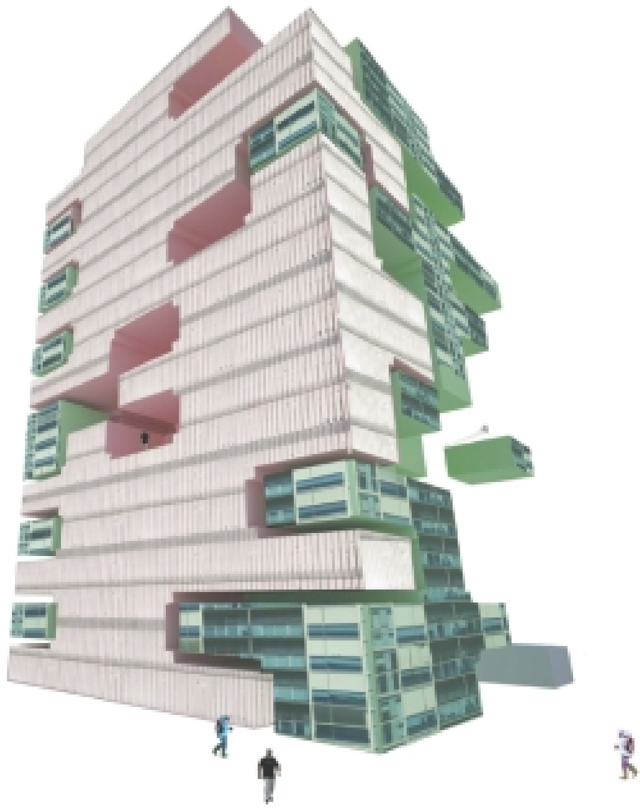

Figure 5.6 SiteGraph Tower. W. James Goscinski, RMIT Architecture Student. Cloudnets, Architecture Elective, 2008. RMIT Master of Architecture (Professional Degree). Elective Leaders: Paul Minifie, Ross Heywood, Luke Howson.

stores want to be far away from other convenience stores, but fashion stores want to cluster close together. Other attributes such as typology, height, colour, material and programme similarly have relationships to other buildings within the city. Graphs are a general way of describing the overall relationships of connectedness (cities) in a system of nodes (buildings). Cellular automata (CA) are a grid of entities where the state of each entity responds to the state of adjacent entities and have properties of emergence. Low-level rules by which each entity (buildings) decides its current states do not describe the higher-level phenomena of the overall system (cities).

The Cloudnets electives experiment with making graphs of relationships and deriving emergent properties based on those relationships via Rhino NURB modeller software. Scripts build and visualise structures controlled by the attributes of each node. A city can be grown and regrown with different rules of emergence or starting conditions. Beginning with a map of an existing city, new elements can be grown to relate to these existing patterns. Landscapes, spaces within a building, elements of a façade or abstract representations of data can be similarly represented. Cloudnets is intended to be a workbench for exploring emergence in general three-dimensional space. Students employ scripting techniques to give form to these relationships and examine how they could lead to certain patterns within cities. Outcomes are visualised and rendered using the AIR plug-in for Rhino to test architectural and urban implications (see Figures 5.6 and 5.7).

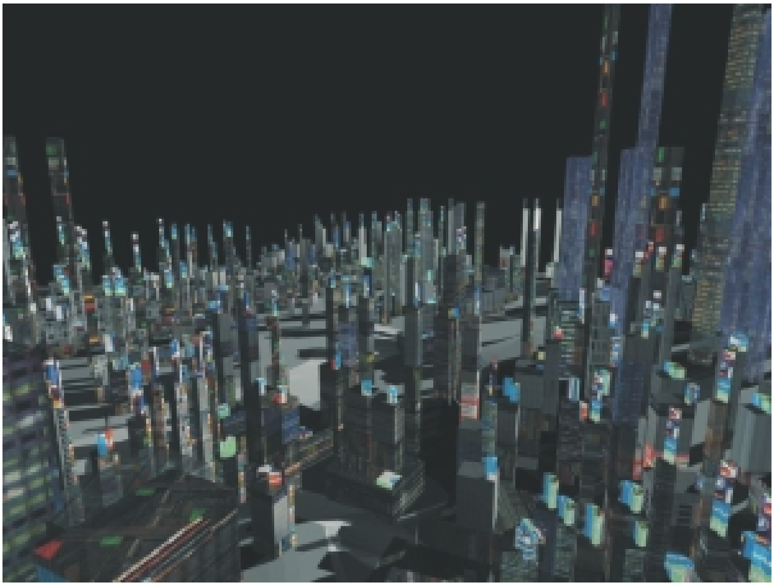

Figure 5.7 Hitogahitoyobu. Jessica In, Peter Charles, RMIT Architecture students. Cloudnets, Architecture Elective, 2008. RMIT Master of Architecture (Professional Degree). Elective Leaders: Paul Minifie, Tim Schork.

RMIT Architecture Associate Professor Pia Ednie-Brown leads a cycle of design studios and electives exploring contemporary emergent design and digital practices that draw selectively on biological models and transdisciplinary art practices. Students are encouraged to forge a dynamic dialogue between design discourses and practices, situating emerging technologies against a range of ethico-aesthetic cultural and social concerns. A recent studio entitled *Plastic Futures* run in partnership with the SymbioticA biological art research laboratory at UWA, Perth, posited that digital and biotechnological innovations will become increasingly intertwined and infused throughout the realm of domestic everyday life, incurring quite radical alterations of the familiar. The utopian modernist account of the progressive role of technology is open to critique when we are faced with environmental degredation as a consequence of development driven by instrumental industrial technologies. This studio focused less on technical solutions to problems that have not happened yet, and more on how to work constructively with emergent environmental, technological, aesthetic and cultural conditions that could transform our future quality of life (see Figure 5.8). This teaching forms part of an Australian Research Council (ARC) Discovery Grant-funded research project, 'Ethics and aesthetics as criteria for innovation: A design research study of biological art and digital architecture' (http://architecture.rmit.edu.au/Projects/Grant_Funded_Projects.php).

A diverse range of other design studios and electives are offered every semester in the *Advanced Technologies* stream by RMIT academics, researchers and commissioned practitioners, extending their research and practice projects and concerns. A final semester stream within the professional degree allows students to consolidate a position on the role of digital technologies through a culminating design thesis project, opening up possible practice specialisations and providing a pathway to further postgraduate research in the RMIT Spatial Information Architecture Laboratory.

Figure 5.8 Installation model. RMIT Architecture students. Plastic Futures, Upperpool Design Studio, RMIT Master of Architecture (Professional Degree), 2009. Studio Leader: Pia Ednie-Brown. (Photograph courtesy of Brent Allpress.)

Practice-based research by project

Professor Mark Burry, the Director of SIAL, leads a team of researchers working on a range of projects that include the design development and construction completion of Gaudi's Temple Sagrada Familia (http://www.sial.rmit.edu.au/Projects/Sagrada_Familia.php). This ARC Discovery Grant-funded research focuses primarily on the role of parametric modelling technologies and digitally controlled fabrication systems. Related consultancy projects and collaborations with practices such as dECOi, Gehry Partners Architects and Arup situate the work of SIAL researchers within an international practice network.

This agenda is being furthered through the ARC Linkage Grant-funded SIAL research project, 'Technology transfer through embedded research within architectural practice: The creation of an Australian practice-based architectural research and development network' (www.sial.rmit.edu.au/Projects/Embedded_Research_within_Architectural_Practice.php). This incorporates an innovative embedded practice model of postgraduate PhD research by project supervision. Candidates were situated within four Australian architecture and engineering practices of differing scales, to explore and capture how their design practice processes could be mapped onto and transformed by new digitally supported and supportive ways of working. Linkage partners included the small architectural practice BKK and a larger practice MGS, both in Melbourne, the distributed practice Terroir based in Hobart and Sydney, and the engineering firm Arup.

Practice research within architecture schools internationally has primarily been in the field a building science and rarely undertaken with a design focus. The SIAL embedded practice model is an extension of the primary mode of architectural enquiry promoted by the RMIT School of Architecture and Design, which is research by project and through design.

Across most universities, postgraduate research within architecture and design has traditionally involved a written dissertation employing research methodologies drawn from the adjacent disciplines of art history, cultural theory, building science, environmental science and sociology, with arguments presented through the established conventions and methodologies of the sciences or humanities. While this approach can be effective in research for design and about design, it generally precludes the possibility of engaging with research through design (Downton 2003). RMIT Architecture was one of the first architecture programmes internationally to develop and offer a postgraduate design research by project model in the 1980s under the leadership of Professors Leon van Schaik and Peter Downton.

The foundational Master of Architecture group was the invitational Reflective Practice stream, where practitioners who had received the acclaim of their peers through awards were invited back into the academy to reflect on and extend their mastery through design research by project (van Schaik 2004). The innovative community of practice formed by this programme extends beyond the duration of candidacy. Alumni have been commissioned to design innovative campus projects and have gone on to take up academic and adjunct professorial roles and key leadership roles within the profession (van Schaik 2005). The research by project model has subsequently been adopted by all the design disciplines in the School of Architecture and Design and diversified to include the Urban Architecture, Expanded Field and Advanced Technologies streams. It has also been adopted and adapted by other institutions internationally, such as the Bartlett, UCL, in the UK.

The practice-based research approach at RMIT emphasises the undertaking of research by and through design projects, exploring and extending design practices and methodologies relevant to the discipline. Postgraduate candidates engage in a series of project-based design investigations and speculations conducted by employing disciplinary design practices and techniques such as design drawings, diagrams, models and prototypes. These may involve speculative unbuilt works or built projects in an industry context framed as case studies. This research activity does not readily follow the hypothesis-testing model of the sciences. It involves, but is not simply reducible to, problem solving. Design research is necessarily exploratory and iterative. It occurs through cycles of performative creative investigation and critical reflection, in response to a selective framework of focusing concerns or problematics. Key design relationships are framed and brought to the fore. Productive design responses to particular situations or concerns are trialed, seeking qualitative improvement. The research by project model provides an effective methodology for practice-based research into the design application of new digital technologies that could not be readily undertaken otherwise.

Research embodied within project investigations is framed by an accompanying exegesis, with examinations occurring through exhibition and an oral presentation to a panel of examiners. This mode of assessment differs from the sciences in that it focuses primarily on qualitative criteria. One of the key responsibilities and challenges for the reflective and generative practitioner is effectively to make available knowledge that arises through practice to a broader community of design practitioners and scholars. Michael Ostwald and I founded the first international project-based refereed design research journal, *Architectural Design Research*, to facilitate this emerging research economy (Allpress 2005).

RMIT Architecture academic Paul Minifie, who is a director of the Melbourne practice Minifie Nixon, undertook an exemplary Master of Architecture (research by project) in the Advanced Technologies stream (Minifie 2001). This research examined architectural composition in the context of emerging digital technologies and practices through the undertaking of a series of design project case studies. These projects approached the doing of architectural design as a kind

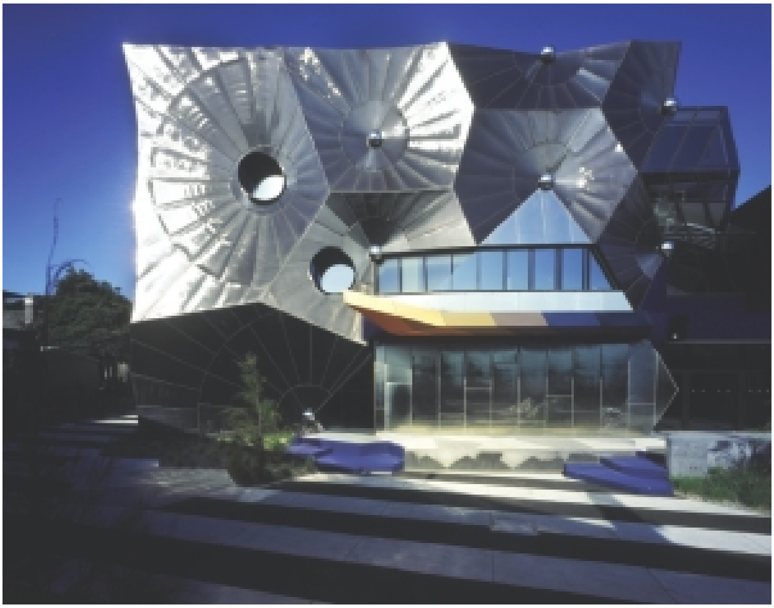

Figure 5.9 Victorian College of the Arts Centre for Ideas. Minifie Nixon. (Photograph courtesy of Derek Swalwell.)

of *techne trouvé* or strange procedure, enacting a dialogue with digitally enabled methods. The Centre for Ideas at the Victoria College of the Arts in Melbourne by Minifie Nixon was a key case study project vehicle where Voronoi diagramming was trialed as a compositional procedure, providing a digital means to organise adjacency relationships in the arrangement of architectural elements and conditions (Minifie 2005; see Figures 5.9 and 5.10). Minifie gives priority to relationality as an account of our mediated engagement with the world, with design reframed as the curation of relational domains.

Co-rational practices

The ARC Linkage Grant-funded SIAL research project *Delivering Digital Architecture*, led by Professor Mark Burry and Professor Mike Xie of RMIT Engineering, investigated architect/engineer collaborations using structural models, prototyping tools and parametric digital design tools. The study identified that co-rational collaboration with specialists early in the design process offered the greatest opportunities to harness parametric optioneering. The co-rationalisation of qualitative and technical criteria can be distinguished from pre-rationalisation, where technical criteria pre-determine design outcomes, and post-rationalisation, where technical considerations are addressed after key design decisions have already been made.

Re-Engineering was a related studio led by Jane Burry and Andrew Maher of SIAL, with Professor Mike Xie (Burry and Maher 2007). A group of RMIT Architecture design thesis professional degree students formed teams with engineering students to collaborate on

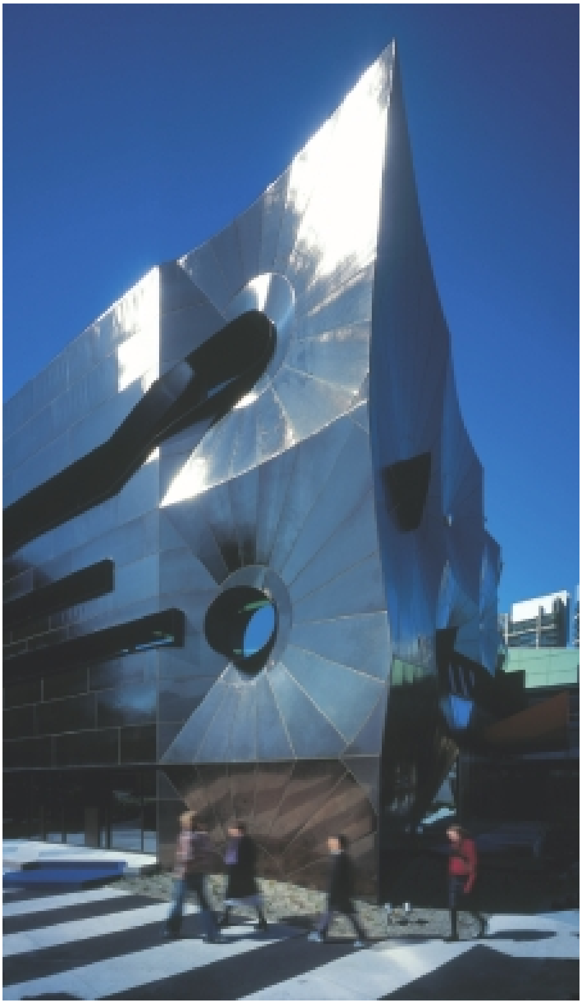

Figure 5.10 Victorian College of the Arts Centre for Ideas. Minifie Nixon. (Photograph courtesy of Peter Bennetts.)

'co-rational' approaches to the integration of digital technologies from design conception through to design development. They employed optimisation methods such as evolutionary structural optimisation (ESO), using finite analysis to remove the least-stressed material in a structure. The more successful projects were notable for demonstrating a sensibility for the curation of the spatial scale and material qualities of highly efficient performative geometries (see Figure 5.11).

This followed on from the *Digital Mockups* studio (www.sial.rmit.edu.au/Projects/Digital_Mockups.php), run between RMIT Architecture, SIAL, MIT in Boston and Gehry Partners in Los Angeles. Architecture students at RMIT and MIT formed teams and undertook collaborative design development projects employing CATIA. All communication

Figure 5.11 Geelong Bypass Bridge. Steven Swain, RMIT Architecture student. Re-engineering, Pre-Major Project Design Studio, RMIT Bachelor of Architecture (Professional Degree), 2005. Supervisors: Jane Burry and Mike Xie.

occurred online and via video, including teaching and assessments involving critics from RMIT, MIT and the Gehry office.

Scripting practices

The *Delivering Digital Design* project identified the lack of inter-operability between software systems as a major industry obstacle. Bottom-up scripting tools are arguably the most flexible and feasible means to address this. Paul Minifie engages with scripting as a core design practice, employing his own plug-in tools for Rhino. Ken Brakke's Surface Evolver, a minimal surface (soap film) generating software, has been made accessible in Rhino3D via Evolversaurus, a plug-in coded by Kynan Woodman, to a design by Paul Minifie with RMIT student Jono Podborsek.

In his RMIT Architecture professional degree design thesis, 'Highly evolved' (Podborsek 2006), supervised by Minifie, Podborsek employed a custom-made cellular automata program to curate and model programmatic relationships in a high-rise tower through differential attraction criteria. The resulting topologies were inserted into Evolver to generate evolved program distributions and relational surface configurations (see Figure 5.12). Podborsek contrasts this with the common approach to developing form digitally through emergent pattern making.

Minifie also supervised the professional degree design thesis by Farzin Lofti-Jam, entitled 'Systems of exchange', that involved the curation of a system of particles that interact with each other in ways

Figure 5.12 Highly Evolved. Jono Podborsek, RMIT Architecture student. Major Project Design Thesis, RMIT Bachelor of Architecture (Professional Degree), 2004. Supervisor: Paul Minifie.

governed by thermodynamic forces using RealFlow software and custom scripts developed at RMIT (see Figure 5.13). Programmatic and formal intention was seeded as a set of rules and parameters in a cloud of particles that responded to each other and the site. In moving towards a dynamic equilibrium, a threshold was negotiated between programs that act as a new vertical public realm – one not based on precise programmatic placement but a mapping of variable intensities. This public space is an infrastructure of spatial and surface manipulation that does not dictate programme specifically, but rather encourages or enables certain types of activities and events to emerge. Form follows intensities, but so too does activation and occupation. The urban image of the project is articulated by unruly ornament that is not applied but emerges from the generative process, with form and ornament operating on different gradients that shift out of phase.

Parametricism

At the 2008 Venice International Architecture Biennale, Patrik Schumacher of Zaha Hadid Architects promoted 'parametricism' as a new stylistic term (Schumacher 2008). This polemic implied a predisposition in parametric technology towards formal configurations involving continuous and continuously differentiated surfaces conceived as field conditions. This was argued for as a break from modernism and offered a counter-position to the assimilation of parametric technologies as a new means to achieve instrumental efficiencies within a 'late modernist' economy. The compositional criteria of surface continuity in their Biennale installation project imposed a unifying framework for the incorporation of differentiated elements and provided a legible case study for testing and demonstrating the resolution of complex relationships through parametric technologies (Zaha Hadid Architects 2008).

Figure 5.13 Systems of Exchange. Farzin Lofti-Jam, RMIT Architecture student. Major Project Design Thesis. RMIT Master of Architecture (Professional Degree), 2008. Supervisor: Paul Minifie.

If style is viewed as a shared framework for the curation of architectural relationships between constituent elements and systems across the scales for a given grouping of projects, parametric technologies that set up reconfigurable relationships between design elements provide a particularly effective means to enact that curation, whatever the particular stylistic conventions and aspirations. Rather than privileging 'parametricism' as a style, these new technologies enable and provoke a renewed engagement with style and composition as fundamental design research questions.

Anachronistic practices

The work by SIAL researchers offers a very different test case for the role of parametric technologies in the design development of Temple Sagrada Familia. Gaudi's project is characterised by a conjunction of efficient structural performance and complex ornamental surface figuration. Parametric tools enable the trialing of options for arranging relationships between new design

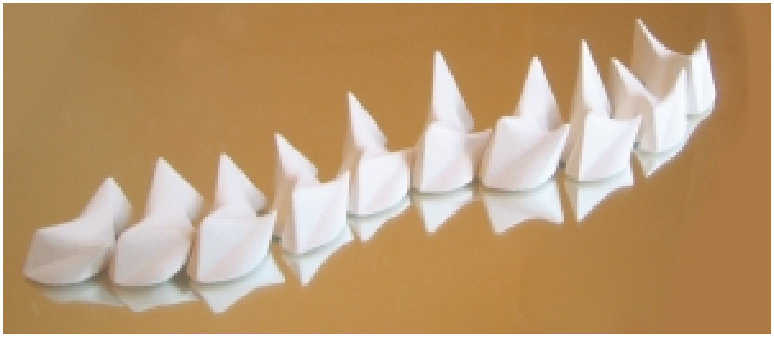

Figure 5.14 The Trilateral Dynamic. Tamara Friebel, RMIT Architecture student. Major Project Design Thesis (History and Theory). RMIT Bachelor of Architecture (Professional Degree), 2007. Supervisor: Brent Allpress.

elements, drawing on evidence for Gaudi's approach extrapolated from the existing building and surviving design documentation.

Tamara Friebel is a final-year RMIT Architecture professional degree student I supervised who undertook a project-based design research investigation in the history theory stream (Friebel 2008; Figure 5.14). She investigated the collaborations between Le Corbusier and the composer/architect Iannis Xenakis, culminating in their design for the Philips Pavilion. Friebel employed CATIA as an analytical tool to reverse engineer the various permutations of the pavilion. She retraced the compositional pre-history of the geometry of the pavilion back to the diagrammatic schema of Xanakis's *Metastasis* music composition. She then undertook a comparative analysis of the role of the modular proportional system across the differing sketch design variants of the pavilion and in the design development of the built project. She also reconstructed the curatorial schema of the multimedia promenade as vertical montage sequences. Friebel argued that this project offered a modernist precedent for processes of parametric collaboration.

Non-standard technologies that employ digitally controlled fabrication challenge the long-established economy of modular prefabrication that conflates standardisation as an efficient means of mass production with a reductive formal aesthetic accepted as an authorised default. My design studios and architectural theory electives at RMIT contend with contemporary ornamental practices and techniques that revise modernist prescriptions.

I was the supervisor of the RMIT Architecture professional degree design thesis major project by Suzannah Waldron entitled 'Australian Network for Art and Technology (ANAT)' (Waldron 2008). This project deployed non-standard cladding panels as a means to frame and unify complex stacked programmes within a singular orthogonal volume that met the urban scale and robust texture of the massive adjacent bluestone walls of the old gaol on the RMIT campus (see Figure 5.15). Variable perforations and deformations in the cladding partially masked glazed volumes, void pockets and promenade circulation zones behind. The screens created incidental texture and shadow effects that would animate the spatial experience of moving through the complex, giving oblique perspectives a haptic dimension.

One precedent for this approach was Melbourne architect Shane Murray's RMIT PhD research by project case study design for the Brisbane Gallery of Modern Art competition. Murray

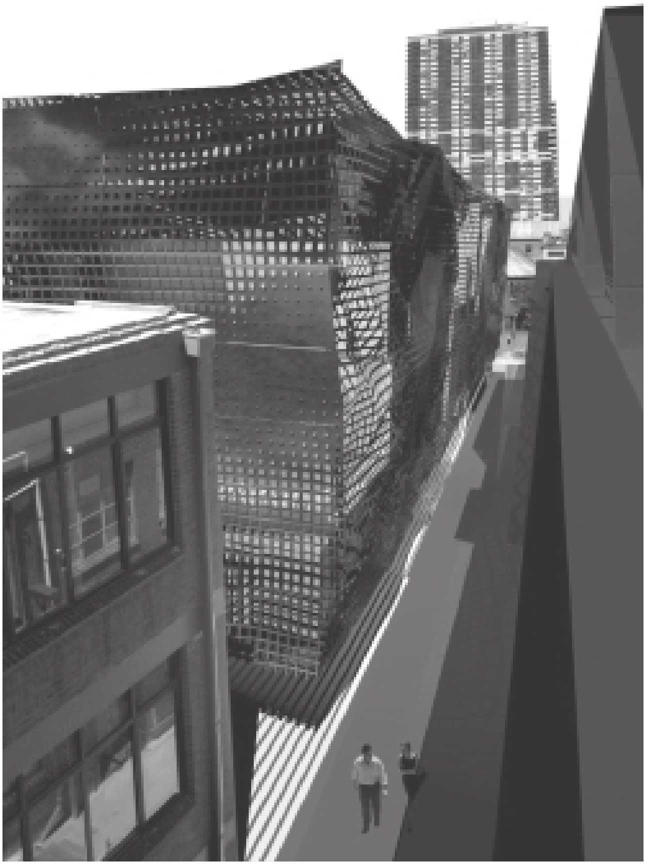

Figure 5.15 Australian Network for Art and Technology (ANAT). Suzannah Waldron, RMIT Architecture student. Major Project Design Thesis. RMIT Bachelor of Architecture (Professional Degree), 2006. Supervisor: Brent Allpress.

Figure 5.16 Volume Up. Mocape-Shenzhen International Museum of Contemporary Art & Architectural Planning Exhibition, Shehzhen Competition, China, 2007. (Image courtesy of Suzannah Waldron, www.searle-waldron.com.)

employed a framing envelope of variably folded fins unifying new and existing structures on the site. This was a mutable composition that could accommodate revisions in the brief during implementation (Murray 2004).

Waldron tested the durability and adaptability of her own schema when she teamed up with architect Nicholas Searle and reworked the design strategies of the ANAT project as an entry for the Mocape-Shenzen International Museum of Contemporary Art and Planning Exhibition Competition (see Figure 5.16). Searle and Waldron were selected as one of four first-stage winners of the competition along with Coop Himmelb(l)au, which subsequently won the second-stage commission.

Non-standard pedagogy

The convergence of new generative digital technologies with emergent design processes and practices offers unforeseen possibilities. Claims that new technologies will simply supersede existing practices and disciplinary modes of knowing should, however, be treated with scepticism. The relationship between emerging digital technologies and techniques and anachronistic disciplinary practices is a promising area of enquiry, particularly where design considerations previously marginalised by cost and complexity are now technically feasible and economically viable through developments in non-standard fabrication.

In order to explore the integration of digital technologies as an avenue for discovery without prescribing the outcomes of an engagement with emerging design practices, pedagogical frameworks are needed that bring together differentiated, contested positions on the role of digital technologies, situated in relation to other core architectural scholarship concerns.

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6 Emergence and convergence of knowledge in building production: Knowledge-based design and digital manufacturing

Eduardo Lyon

Advances in computation, both regarding its treatment and technology, have stimulated the design and implementation of an ever-growing number of computer-aided design (CAD) and computer-aided manufacturing (CAM) applications. Application elaboration both responds to and generates new conceptualisations of architectural knowledge, in a body of principles, rules and regulations which commands the building's design and its realisation, therefore it constitutes a preliminary datum for its comprehension, and thereby is of theoretical importance (Lyon 2006). Until recently, the use of CAD systems[1] in building production was limited to drafting systems. The introduction of solid modelling and recently the development of parametric three-dimensional modelling are providing a new platform for embedding design and fabrication knowledge. Despite the continuous increase of power in computers and systems capacities, the creative space of freedom defined by them acting as cognitive instruments remains almost unexplored. Therefore, I propose a change from a design knowledge based on objects to one focused on design as a cognitively distributed process.

Design is a cognitive process that consists of the consensual production of meaningful artifacts through a knowledge capture, generation, manipulation, synthesis and communication process (Lyon 2005). Designers investigate certain topics; through them the design problem is defined and its fundamental aspects are organised. Those topics establish the design knowledge. Afterwards potential design solutions are formed, composed, decomposed, analysed and finally the relevant knowledge produced in the process is codified in the form of design representations. Relevant knowledge comprises not only knowledge to describe different parts and multiple aspects of the artifact, but also knowledge to describe the process to build it. The design process is also a negotiation process between multiple actors and several related aspects flowing together along time. In addition, the design process consists of the transformation of concepts and

[1] For the purpose of this research, a CAD system is a combination of hardware and software that allows three-dimensional modelling of physical artifacts, enabling engineers and architects to design artifacts from simple parts to airplanes. Consequently, a CAM system is a combination of hardware and software that enables engineers and architects to communicate work instructions directly to CNC manufacturing machinery.

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

relations of high abstraction into relevant knowledge about production processes and its resulting artifacts with a high level of complexity and specificity. Understandably, design rather than an artifact-production process is a knowledge-production process and that knowledge is what makes it possible to realise the artifacts that we design. Unfortunately, designers ignore what mechanisms and strategies are effective and efficient in producing that knowledge, and unintentionally we throw away an significant portion of that knowledge once it is produced. Finally, a small portion of it is possible to obtain from studying the artifacts that we produce.

The relevant knowledge required for the design process (design knowledge) and parameters needed to guarantee its coherence (design rationale) are manifold, while its conception mechanism (design thinking) remains ignored (Lyon 2006). Coherently, in exploring the concept of intelligence in design (design intelligence), we need first to enquire into how intelligent behaviour in design is generated, and then how that behaviour is related to improvements either in the design process or in the design solution.

Design intelligence can be described as the ability of designers to acquire, generate and apply design knowledge. But rather than a manifestation of a property of the designer, design intelligence needs to be reformulated based on two fundamental aspects: first, that there is a class of behaviour exhibited by humans in general, and by designers in particular, that involves the interactions of at least one individual designer – and more frequently multiple designers and consultants – and the design context (design environment); and second, that the design intelligence designation is used to make a connotative reference to the relations and changes of relations in the design process within a specific design environment, without denoting a particular attribute of individual designers, or without denoting a particular feature of the object being designed (Maturana 2008). Therefore these relational changes are directly related to design knowledge production that constitutes the fundamental purpose of the design process; and to the design environment, which is the main context in which the design process occurs and where design knowledge is found.[2]

The distributed cognition approach emphasises the context–distributed nature of cognitive phenomena across individuals and instruments (Hutchins 1995). A main point of departure from the traditional cognitive science framework is that, at the 'work-setting' level of analysis, the distributed cognition approach explores how intelligent processes in human activity transcend the boundaries of the brain (Minsky 1986). Consequently, instead of focusing on design activity in terms of mental processes acting on internal representations, we propose to apply the same cognitive concepts in distributed cognition to the interactions among a number of designers, consultants and the design environment (Lyon 2005). Finally, we explore the concept of distributed cognition in order to redefine the use and role of CAD and CAM systems within the design process as 'cognitive instruments' (*ibid.*).

As result of the previous statements, we can affirm that design intelligence is distributed in at least three different ways: first, design intelligence may be distributed among multiple designers and consultant members of the design team; second, design intelligence may be distributed among multiple representations of knowledge; and third, design intelligence may be distributed thorough time in the way in which knowledge created earlier transforms the knowledge that is

[2] These concepts are based on the idea of autopoiesis, proposed by Humberto Maturana and Francisco Varela in 1970. They argue that a living system embodies a continuous process of self-organisation and emergence. According to Maturana and Varela, living systems are self-producing systems. In contrast to assumptions that viewed living systems as generators of something different from themselves, autopoiesis approached systems as simultaneously producers and products.

being produced later in the design process. Accordingly, this research explores new ways to capture, systematise and integrate manufacturing knowledge into the design phases. Through the use of the design for manufacturing (DfM) concept, and looking at relations between its potential application in component design and its implementation using digital manufacturing technologies, the author implemented a DfM model that varies from previous models by incorporating learning in the process. This process was based on a knowledge-capture and systematisation process and the incremental development and refinement of design heuristics and metrics. The aim of this research is twofold. The first is to realise a process to capture and organise manufacturing knowledge, and the second is to organise that knowledge and make it available as a DfM model for component design using digital manufacturing.

The division between design and construction

From its origins, building production has been characterised by an intricate relation between construction techniques and a specific image of the building. Since the Renaissance the production of drawings, or design activity, has been at the centre of this process, and has delineated the architect's role within the building production process (Perez-Gomez and Pelletier 1997). Since then, drawings have been the instruments by which architects have provided the knowledge necessary to construct buildings, and it is in drawings where design and construction knowledge happen together (see Figure 6.1).

By the eighteenth century the discipline of architecture had been profoundly affected by the demands for the reorganisation of knowledge (*ibid.*). The questions that confronted the discipline involved not only ontological queries regarding disciplinary boundaries or the matter that constituted architecture's body of knowledge, but also a growing demand for an epistemology of architectural knowledge that would allow architecture to be taught as a formal discipline. Changing social structures reinforced such abstract questions by requiring the removal of the vestiges of past practices. This new order provoked a deep and still open incision into the body of the discipline and was clearly noticed not only in the division of the practice according to

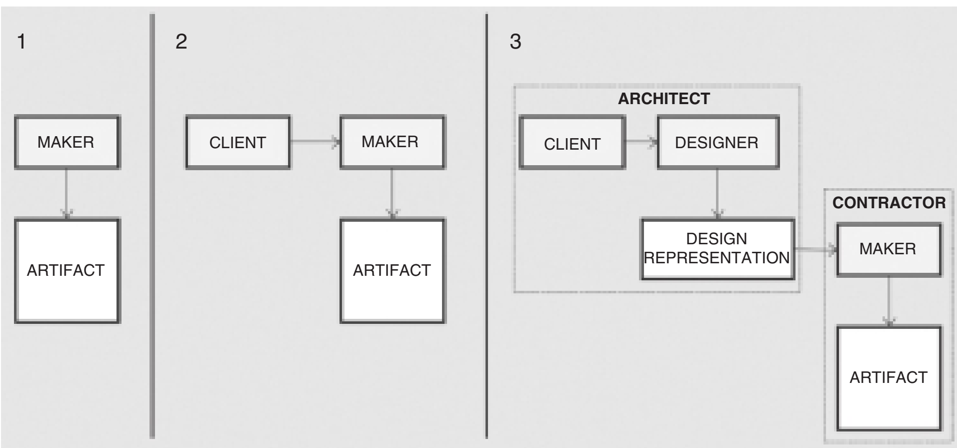

Figure 6.1 Division between design and construction evolution.

design and construction activities, but also in the division of the newborn formal architectural education following the distinction of architecture as a science or as an art (Groák 1992). As a result, design activities have been based on a sequential process model, with a clear-cut division between the generation of information to describe artifacts and the provision of information to construct them.

The benefits of integrating design with construction knowledge can be understood through a study of the cost of resolving problems as they occur early or later in the design process. Problem resolution late is expensive, early is cheap (Ahmadi and Wurgraft 1994; Anumba and Evbuomwan 1997; Pasquire and Connolly 2003). In addition, considering construction knowledge during design becomes especially important when exploring alternatives to traditional construction methods, where the space of construction alternatives is not well understood.

The core problem is that architects ignore the fact that up to 70 per cent of production cost is determined at design stage. Moreover, designers are concerned with describing and placing artifacts in space. Meanwhile, contractors are concerned with producing components and locating assembly processes over time. Better integration is needed (Groák 1992, 2001; Fox 2002; Hill 2005). Design for manufacturing (DfM), on the other hand, tries to resolve within the design process how the artifact is to be constructed. The benefits of using the DfM approach come from shortening the design and production cycle, improving component quality and reducing manufacturing cost (Dertouzos 1989; Susman 1992; Fox *et al.* 2001; Boothroyd *et al.* 2002).[3]

Production of space vs building production

Architectural design's ultimate aim is the production of space. However, since space is not a malleable matter, structures are needed not only to define the space but also to produce and control the specific spatial conditions that are required. Consequently, structures, because of their dimensions, are not producible directly, and representations are needed not only to scale down the artifacts to describe them but also to encompass their complexity, coming out of the multiple systems that constitute them.

Design can be thought of as a process of composition and refinement of concepts and technologies, while construction is the decomposition of design units into their producible components and execution processes. Both design and construction are included within the building production process, but they present discrepancies in its objectives, as seen in Figure 6.2. If the units of design also support analysis and decomposition for construction, then the space for construction alternatives and potential errors is greatly reduced, as is the risk of later changes. This is particularly relevant if we realise that the proportion of construction productivity and quality problems attributable to inadequate design is still about 50 per cent (Fox *et al.* 2001).[4]

The advent of CAD and CAM technologies and associated manufacturing technologies in architecture has not only introduced a twist in traditional separation between 'design intent' and 'means of construction', but has also exposed inefficiencies coming from the division of design and construction. Furthermore, these exceptional circumstances offer the opportunity to architects to be leading this new form of architectural production, recovering to some extent the role

[3] These authors reported product cost reduction in using DfM methods ranging from 50 to 70 per cent. There is no equivalent data in building production, but the potential benefits of applying DfM to building have been recognised for some time; see Anumba and Evbuomwan (1997).

[4] This information is referenced by Stephen Fox from two sources: Barber *et al.* (2000) and BRE (1981).

Figure 6.2 Discrepancies between design and construction.

of master builder[5] and re-establishing the connection between design and construction (Kolaveric 2003; Kieran and Timberlake 2004).

Design for manufacturing (DfM)

Design for manufacturing, or DfM, is an important area in product development and application in all manufacturing sectors (Bralla 1999; Boothroyd *et al*. 2002). The objectives of DfM are to develop and organise information to produce knowledge that can be applied in designing products to improve their manufacturability. DfM has led to important improvements in manufacturing effectiveness, resulting in cheaper products, of higher quality, that are fast to produce and that are easier to service, maintain and replace (Poli 2001). These improvements have been achieved while product quality has been raised. The benefits of applying the DfM approach come from shortening production cycles,[6] improving part quality and reducing manufacturing cost (Dertouzos 1989; Susman 1992; Fox *et al*. 2001, Boothroyd *et al*. 2002). DFM benefits have often been quite remarkable and production cost reductions of up to 50 per cent have been widely reported (Ulrich and Eppinger 1995; Boothroyd *et al*. 2002).

DfM is also a major aspect of productivity improvement in such global areas of manufacturing as automobiles, electronics and aircraft. Companies like Ford, General Motors, Xerox and Boeing have applied DfM and obtained benefits from reducing product cost, reduction in the production cycle and quality improvements (Boothroyd *et al*. 2002).[7] Improvements come

[5] Kieran and Timberlake (2004: xi) state: 'Hundreds of years ago, all of architecture could be held in the intelligence of a single maker, the master builder. Part architect, part builder, part product and building engineer, and part materials scientist, the master builder integrated all the elements of architecture in a single mind, heart, and hand. By recognizing commodity as an equal partner to art, architecture is made as accessible, affordable, and sustainable as the most technically sophisticated consumer products available today.'

[6] For clarification purposes, a production cycle includes design, analysis, optimisation, manufacturing and assembly stages.

[7] Boothroyd provides a comprehensive review of DfM and DfA from its origins in the mid-1970s to the present day. They include several case studies and experiences from different manufacturing areas and companies, including Ford, GM, NEC and Xerox. They also produce one of the leading DfMA software packages in the industry. For them DfM and DfA are part of the same process, but they recognise that there are conflicts between manufacturability and assemblability objectives. Their method and its implementation have been also subject to enquiry by Stone *et al*. (2004).

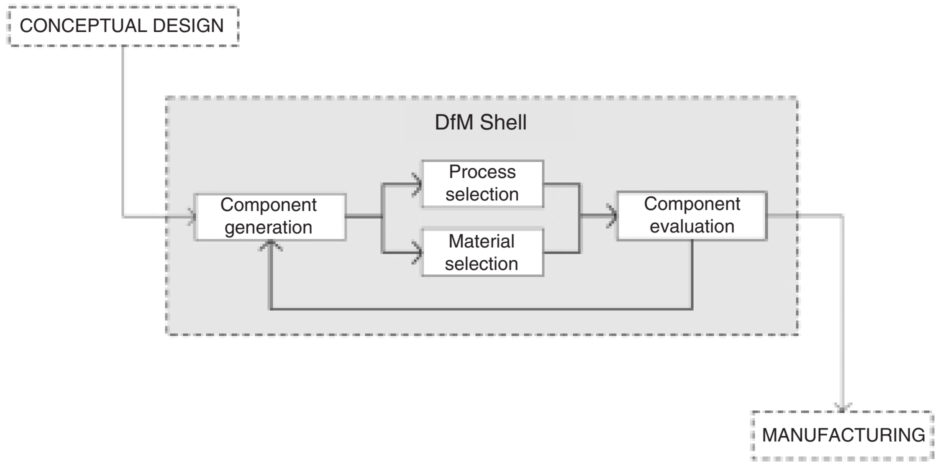

Figure 6.3 Generic design for manufacturing process model.

from reducing assembly times, reducing the number of different parts, optimising the total number of parts, reducing the number of manufacturing operations and reducing manufacturing time.

DfM is a well-structured research area in product development. In this area it is possible to find not only abundant literature but also DfM systems that support design (Susman 1992; Vliet *et al.* 1999).[8] According to Shah, most of these systems have a limited scope, because they either focus on material/process selection or they perform detailed analysis for a specific manufacturing process (Shah and Wright 2000). Most importantly, people do not have an overview of manufacturability analysis and there is little work completed on specifying the generic steps to perform manufacturability analysis tasks irrespective of a particular technology (Shah and Wright 2000).

DfM is an approach that emphasises the inclusion of manufacturing knowledge during the design phase. Consequently, DfM is a process-centric approach and targets the design process, shown in Figure 6.3. Subsequently in applying the DfM approach it is important to consider that designers are required; to design products that structure design information properly, in order to integrate production knowledge in design; to select adequate materials and processes; and to evaluate alternative design solutions in relation to their manufacturability (Boothroyd *et al.* 2002). Normally, the literature in DfM tends to address the integration of these issues, focusing on a single one in isolation, and ignore the interactions between them. Additionally, it is important to realise that many products are manufactured out of two or more processes and this increases process complexity.

The fundamental strategy in DfM is first to verify a potential product design or alternative ones; second to select material and a feasible manufacturing process or vice versa; and then to analyse the product's manufacturability, determining potential design improvements. Improvements are implemented through DfM metrics, DfM methods and DfM tools (Vliet *et al.* 1999; Shah and Wright 2000; Boothroyd *et al.* 2002).

[8] Vliet *et al.* (1999) provide a comprehensive revision of DfM tools.

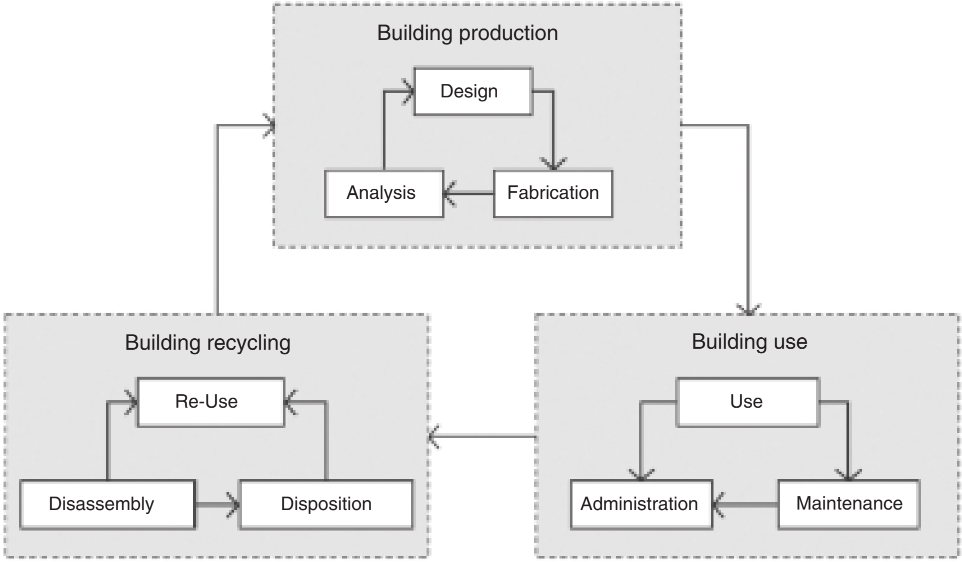

Figure 6.4 Building lifecycle diagram.

Building production

The previous section was a brief introduction to the DfMA approach in product development. In this section I examine building production, looking for its similarities and differences in relation to product development. Product development comprises conception, design, analysis, manufacturing and assembly processes and is part of a general process-denominated product lifecycle, which is integrated in an approach called product lifecycle management (PLM). A conceptualisation similar to PLM, denominated building lifecycle management (BLM), is proposed as a framework for DfM implementation in building production, as shown in Figure 6.4. This approach is extensively based on building information modelling (BIM).

If we assume that construction is an industry (Groák 1994),[9] the most relevant discrepancy between product development and building production arises from the differences between the manufacturing and construction industries. As we reviewed in the previous section, in many manufacturing areas DfM has became an important approach in improving product development productivity through design. By contrast, in the construction industry, building designers have not been provided with equivalent methodologies, and the integration of production knowledge into the design stages continues to rely on the experience of individuals in an increasingly fragmented work environment (Anumba and Evbuomwan 1997).[10] Fragmentation is due to two major issues: one coming from the division between design and construction; and the second from the increasing number of disciplines, consultants and specialists coming together in the building construction process (Yates and Battersby 2003).

[9] Steven Groák (1994) discusses intensively the notion of conceiving construction as an industry and states that the parameters for looking at the existing paradigm are buildability, fragmentation and feedback.

[10] Nevertheless, architectural graphics standards and other construction standards in text form are provided to illustrate some forms of best practice for conventional construction systems.

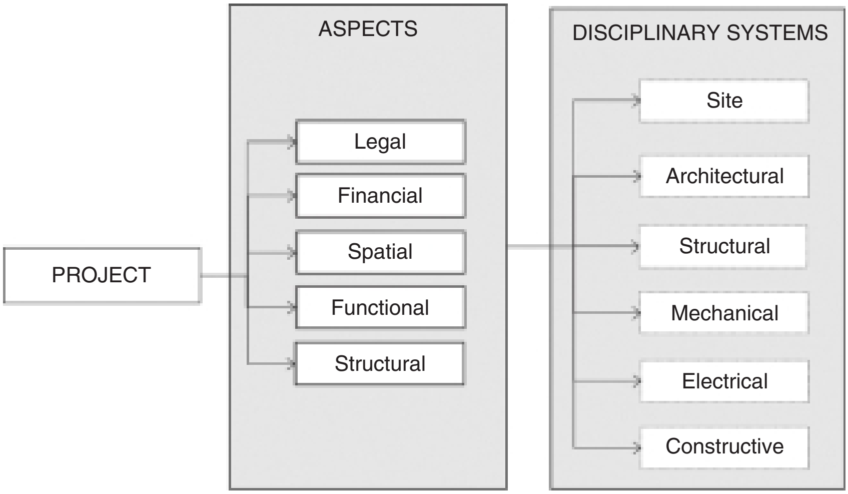

Figure 6.5 Project's aspects and disciplinary systems.

It has been recognised in both the manufacturing industry and the construction industry that productivity and quality can be enhanced by integrating production knowledge into the design stages. Within the manufacturing industry, different forms of production knowledge integration have led to radical improvements in productivity and quality. However, in the construction industry, low productivity and poor quality continue to be extensively found and no comparable improvements have taken place in construction (Fox *et al.* 2001; Teicholz *et al.* 2001).[11] A number of recent studies have indicated that construction productivity has stayed even or declined slightly, although there are also counter views (Goodrum *et al.* 2002). What is not in dispute is that construction has not achieved nearly the same productivity improvements as manufacturing.

Traditional design documentation produces detailed knowledge representations organised in systems and sub-system descriptions; that is, spatial, structural, mechanical, electrical and acoustic. Multiple aspects considered in the project are distributed along different knowledge representations and managed by multiple disciplinary systems, as delineated in Figure 6.5. Interaction between these systems is assumed to be coordinated by the designer. Consequently, component production and assembly processes are implicit until bidding and sometimes until execution.

The core problem is, ignoring the fact that up to 70 per cent of production cost is determined at design stage (Giachetti 1998; Boothroyd *et al.* 2002), that designers are concerned with describing building shape and space allocation. Consultants are focused on placing systems and sub-systems in space, while contractors are concerned with producing components and locating assembly processes over time. Better integration is needed. Accordingly, Stephen Fox states:

[11] In relation to increasing productivity and quality by design methods in the manufacturing sector, see Peck (1973). On the same topic but related to the construction sector, see Emmerson (1962). For improvements in the manufacturing industry, see Dean and Susman (1989). For a review of productivity decreases in the construction industry in the UK, see DETR (1998). For reviewing the issue of productivity decreases in the construction industry in the US, see Allmon *et al.* (2000).

> Architects are held responsible for the deficiency of this unsystematic approach. Architects' 'typical lapses' include: specifying inappropriate materials, lack of knowledge of basic construction techniques, and not understanding buildability. (Fox *et al*. 2001)[12]
>
> As we can conclude, the core issues are architects' lack of methodologies equivalent to DfMA; poor understanding of buildability; difficulties in production knowledge integration into the design stages; and the disproportionate dependence on individuals' experience within an increasingly fragmented work environment.

Manufacturability vs buildability

One of the most important purposes of applying the DfM approach is to allow manufacturability analysis in product design. Fundamentally, DfM considers manufacturability as part of the design constraints. Consequently, in applying DfM to building production, it is important to discriminate between manufacturability and buildability. Buildability has evolved from being considered as just a production objective that usually tackles problems in the assembly process in building construction into a concept applied all along the design and construction process.[13] This evolution reflects how building production has evolved from an environment with a clear-cut division between design and construction to a more integrated work environment in recent years.

Traditionally, buildability was achieved based on standardisation and project simplification strategies, expressed as design trade-offs. By contrast, DfM can be described as a design method that incorporates production objectives in generating and evaluating alternative designs. Accordingly, design formulation needs to consider manufacturability and to produce the necessary information to feed manufacturing processes (Fox *et al*. 2001).

Buildability is referred to by Lam as 'the extent to which a building design facilitates efficient use of construction resources and enhances ease and safety of construction on site whilst the client's requirements are met' (Lam *et al*. 2006). Nevertheless, this has not always been the interpretation of the concept; somehow, the term has evolved as the construction industry has evolved. Buildings in the early half of the twentieth century were relatively simple from a systems perspective. In the 1920s and 1930s, for example, a major building could be constructed by stonemasons and carpenters, with a plumber and an electrician (Kostof 2000). It was only in the early twentieth century that structures were quantitatively analysed and the rise began of more complex buildings, including mechanical systems, communication systems, vertical circulation and fire safety.

Traditionally, buildability has focused on problems arising in the design and construction phases. Nowadays it is interpreted from a wider perspective that addresses the entire building production lifecycle. This approach emphasises the applicability of buildability from design to construction phases and to all project participants. Buildability cannot be effective as a stand-alone tool. It has to be implemented as part of an approach that clearly specifies the primary project objectives and the techniques that allow buildability to be assessed (Fox *et al*. 2001). Buildability has been connected to improvements in building quality and ease of construction, and to more efficient and economical construction (Fisher *et al*. 2000; Jergeas and Put 2001; Lam *et al*. 2006).

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12 In relation to this specific issue Fox refers to Harding (1999).

13 For an in-depth review of the evolution of the concept of buildability, including a review of key research centres relevant to that, see Eng (2002).

Constructability is a concept similar to buildability and is defined as the optimum use of construction knowledge and experience at different project stages to achieve the overall project objectives (Fisher *et al.* 2000; Jergeas and Put 2001; Arditi *et al.* 2002; Lam *et al.* 2006; Pulaski and Horman 2005; Pocock *et al.* 2006).

In manufacturing industry, DfM has been used successfully to evaluate and improve manufacturability in different products ranging from computers and cars to airplanes. Detractors from the initial efforts to apply DfM to building production argued that the manufacturing industry is quite different from the construction industry, even affirming that construction is not an industry.[14] Others affirm that DfM is not suitable for building because building lacks the complexity of manufacturing. This is true if we compare an aircraft like the Boeing 777, which contains an average of 3 million parts,[15] with a house, which contains around 30,000 components.[16] However, it is different if we look at cars, which are much smaller and have far fewer components than a house: a car has 10,000 components (Gann 1996; Heisserman *et al.* 2000; Michaels and Lunsford 2005).

Unfortunately, process complexity is still seen as a barrier in defining buildability.[17] Subsequently, production knowledge related to buildability remains largely tacit or informal and reliant on intuitive use. Such informal approaches to integrating design and production may have been effective when traditional craft practices and a few versatile materials were used to construct buildings. Nevertheless, the ubiquity of technological innovation means that building designers now have to select from a rapidly increasing number of building components and innovative manufacturing processes (Groák 1994; Gann 1996; Fox and Cockerham 2000).

To summarise, the incipient efforts to apply DfM to construction have been deferred or disregarded because of the widespread notion that the construction industry is dissimilar to the manufacturing industry. However, in the construction industry, low productivity and poor quality continue to be extensively found and reported (Fox *et al.* 2001). Other counterpoints to integrating DfM into building production affirm that fragmentation in the construction industry is a major obstacle. As we mentioned in a previous section, fragmentation in the industry is due to two major aspects: the division between design and construction activities and the large number of specialists, consultants and technicians that are involved in the building production process, and the resulting knowledge dispersion.

Building production and construction systems

For most of history, construction has been a craft passed on through apprenticeship that relied on fairly static, 'tried-and-true' construction methods. These practices were built into building codes from the seventeenth century onwards, led by the Dutch in New York and Amsterdam. As long as architectural design was based on these methods, the issues of buildability were

[14] Groák (1994) affirms that construction is more a technological paradigm rather than an industry. He asserts that the construction industry is to be defined as a temporary coalition of people and organisations that are essentially organised around a project rather than a firm.

[15] Heisserman *et al.* (2000) state that out of those 3 million parts, 135,000 are unique. Consequently they present a consistent design representation to organise and manipulate them.

[16] These numbers are collected from Gann (1996).

[17] Stephen Fox states, 'there is no simple answer to evaluating buildability because of the complexity of the construction process'.

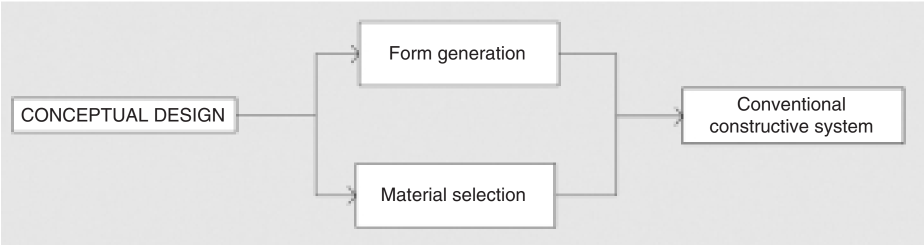

Figure 6.6 Traditional building production process.

embedded in the practices of the different crafts, and not analysed by the designer (Moore 1996). Today construction practices are well known, embedded in Ramsey and Sleeper's series of *Architectural Graphic Standards* (Ramsey *et al.* 2000). These longlasting reference books, developed by teachers at the New York Mechanics' Institute for architectural draftsmen, have captured both the building practices of the day and their appropriate representation for the last 80 years. Updates and new versions have been undertaken regularly, showing the evolution of standard construction practices over the last four decades. They provide detail regulations that prescribe what is within accepted practices and, implicitly, what is outside. Their spanning tables for wood joists and guides for wood framing of different heights and storeys also reflect standard construction practices, although in a less deterministic manner.

Building codes closely reflect standard construction practices in the US and most other countries. Within the shared domain of standard construction practice, architects could define what is to be built simply by providing high-level direction of the extraordinary aspects of a design, without resorting to complete coverage of all aspects of what was considered 'common knowledge'. Reference in the contract documents to 'standard construction practices' was sufficient to address the non-specialised aspects of the design. As a result, any new construction method or material that is promoted for widespread use has as the initial challenge to gain acceptance within the various regional building codes.

During the 1950s and 1960s, traditional construction techniques were systematised around factory-manufactured components and concepts like standardisation, prefabrication, modularisation, quality control and dimensional coordination. Under the pressure of industrialisation, this systematisation process not only gave rise to improvements in traditional constructive techniques but also to new construction systems. The massive post-industrial housing demand in the 1960s provided an adequate testing bed for those systems that became conventional in building production processes, as described in Figure 6.6 (Groák 1992; Gann 1996; Moore 1996).

Out of this review, we strongly support a change from a construction model that has been traditionally based in on-site raw material shaping, assembly and sub-assembly processes to one structured by the component-assembly model (Groák 1992; Gibb 1999; Fox 2002).[18] The component assembly model refers to on-site assembly of components manufactured off-site, and constitutes a basic construction knowledge organisation. Component-based design uses that construction knowledge organisation and facilitates DfM implementation in building production.

[18] Fox terms the assembly component model the 'producer-led model'. Similarly, other authors, such as Groák, use the term 'manufacturer-led model'. All of them refer to off-site production of parts and components in factories and shops, according to design specifications, and on-site based assembly processes. Fox analyses in depth what Steven Groák (1992: 174) defines.

In the next section, three alternative ways to implement DfM in construction are presented and discussed.

Implementation of DfM in building production

DfM in building production has one clear objective: to improve buildability on designs without affecting design quality and fulfilling design requirements. Nevertheless, implementation of DfM in building production can have two different motivations: to address clearly the design and construction of buildings and building components that are clearly outside of standard construction practices; and to improve existing construction practices or existing building components. Improvements are obtained mostly by evaluating the buildability of specific processes and components or by comparing the buildability of alternative processes or components.

To summarise, the definition of a process model that rationalises, optimises and facilitates the fabrication and erection of new or existing building components are the essential goals of DfM in building production, producing the benefits described in Figure 6.7.

In the context of craftsman-based construction, there have always been cases of buildings using innovative construction practices, usually tied to some other form of design innovation, like the use of non-Euclidean geometries. Examples include the Sydney Opera House (Murray 2004; Tombesi 2004), the TWA Terminal at Kennedy Airport in New York (Stoller 1999), the series of buildings by Frank Gehry, starting with the Guggenheim Museum Bilbao (Gehry 1986; Dal Co *et al*. 2003), and the series of buildings by Norman Foster (Jenkins 2005).

In each of these cases, the design was not based on standard construction methods and specialised methods had to be developed. In the first two cases, the costs and construction time were very high. In latter cases, the architects worked out the construction method as part of the design. This is the first way to apply DfM in construction: to define a process for fabrication and assembly of custom-designed components of a building that ultimately leads to the entire building fabrication process design. Each of these projects was considered unbuildable in its day without the special planning inputs of the architect. In each case, the designer also had to plan the construction

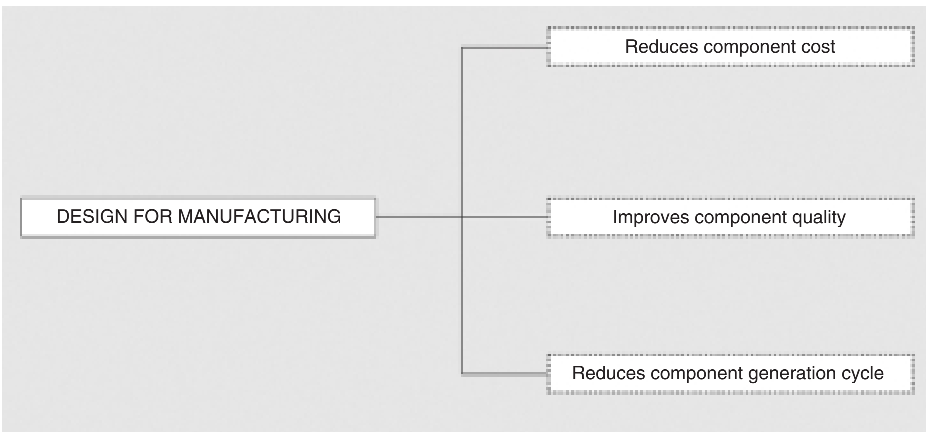

Figure 6.7 Design for manufacturing benefits.

and to evaluate alternative designs and its buildability. The focus of this type of DfM is the definition of a systematic and clear process plan to show that the design is buildable.

A second way to implement is to apply DfM analogically to construction in order to improve productivity. This use of DfM applies rules regarding materials and fabrication practices to an existing process, sub-assembly or component, to systematically evaluate it and improve on it in terms of cost, constructability, reliability or maintenance. This means using DfM to evaluate and assess buildability in a specific design or to compare buildability in alternative designs.

Because most of these buildings are a one-of-a-kind or bespoke type of building and most of the building components are not re-used in future buildings, there are only limited opportunities to refine buildability and to apply improvements.

The third type of DfM implementation is developing large, standard components or sub-assemblies; new prefabricated houses; new prefabricated units such as bathrooms, kitchens and so on; or pre-cast concrete construction and large steel assemblies. Most probably, this is the closest to manufacturing industry that construction industry has got until today. Since these are large components with many parts, they are excellent candidates for buildability evaluation and later optimisation using DfM (Fox and Cockerham 2000). An excellent example of this type of application is the Japanese industrialised housing industry. Manufacturing principles derived from the car industry have been successfully used to produce attractive, customised and affordable homes. Some of these housing industries benefit by using advanced manufacturing techniques developed in other manufacturing industries (Gann 1996). Toyota and Sekisui Heim are two of the biggest industrialised house companies in Japan. Toyota's largest housing factory produces 2000 houses per year. Toyota factory manufactures around 4000 component types for each house type. In doing that, Toyota makes use of production methods developed in its automobile production system, including just-in-time production (JIT) and CNC fabrication. Each house contains around 30,000 items, including 700 different component types (Barlow *et al.* 2003). Another example is found in Sekisui House. This company produces around 20–25 per cent of its houses' value within its factory. About 30 per cent is produced by external suppliers. Site work accounts for 20 per cent of the house's value, and sales, marketing and management operating cost for 25 per cent. Sekisui House's factory is the largest in Japan, producing 750 houses per month and employing 500 people (Gann 1996; Barlow *et al.* 2003).

These implementation criteria proposed above do not apply easily to traditional construction practices. Traditionally architects and contractors have accommodated late changes after construction begins, because they could do so. The predominance of such fabrication techniques as in situ cast-in-place concrete results in production adjustments as fabrication takes place, adjusting pour extents, lockouts and reinforcing. However, new construction practices are quickly making these practices obsolete, with the true cost of late adaptation being recognised and identified. These new construction practices are resulting in important changes in building production. The changes include the use of parametric three-dimensional modelling as the representation of the building, defined as building information modelling (BIM; Eastman 1999); and the parallel move to component-based construction and increased off-site prefabrication (Groák 1992).

The building information model's incorporation in building production could also be seen as a knowledge integration approach in solving construction industry fragmentation. BIM provides a means to support a very accurate three-dimensional integrated model to foster design and integrated analysis and engineering. It also supports fabrication-level models that integrate with CAM software and through that to CNC machinery. Additionally, production management is supported through material tracking and production management software. With this integration, one-of-a-kind products can be produced with similar efficiencies as mass-production products. This new approach is also being adopted in manufacturing, under the moniker of 'mass customisation'.

The next section is a brief introduction to component-based design as the context for DfM implementation in building production is presented.

Component-based design

As was previously discussed, traditional construction systems were based on processes mostly performed on site with high labour use. Since the industrial revolution, this model relying on handcraft started to be replaced by the customisation of previous experiences. In situ activity reduction, standardisation and prefabrication of parts, as well as process mechanisation, became the main characteristics of a new model of the construction industry known as system building.[19]

Component-based design has been part of the reality of industrial design for quite some time; its use in the production of buildings is not new, but is rather underutilised and misinterpreted under more general approaches as standardisation, modularisation and prefabrication. It is important to distinguish component-based construction from prefabrication. Prefabrication relies on the mass production of identical units, in which repetition is the basis of economy. On the other side, component-based production relies on mass customisation that minimises the differential cost between standard components and made-to-order ones. Mass customisation is based on the cost reduction in variation and customisation using computer-aided manufacturing. Component-based production of unique or tailored building components no longer requires an increase in costs due to specialised labour or exceptional manufacturing techniques (Kieran and Timberlake 2004). The origins of component-based design can be traced back easily to ancient Greece and tecent archaeological reconstruction has shown evidence of component-based design in the Parthenon. It is connected with the first steel-frame buildings during the eighteenth century (Groák 1992), and the Menier Chocolate Factory,[20] Eiffel's steel structures[21] and Paxton's Crystal Palace are well-known examples.

After the Second World War the prefabrication movement in the UK and subsequently the US gave birth to the assembly component model (Sebestyén 1998). During the 1960s the concepts of prefabrication were systematised, and they gave rise to 'high-tech architecture'. Architects like Norman Foster, Renzo Piano and Richard Rogers are the best exponents of this style, which is highly connected with component-based design (Stacey 2001).

To summarise, component-based design is embedded in a model of building production based on off-site production of parts and components in factories and shops, according to design specifications, and later takento the site to form specific assemblies (Groák 1992). Within the building, different assemblies organise those parts and components. Parts are the basic units and together form components; components are arrangements of parts; and assemblies are

[19] The system building-based approach is characterised by the reduction of wet site-based activities by pre-manufactured component and dry assembly processes (Perez-Gomez and Pelletier 1997).

[20] Many historians cite Jules Saulnier's Menier Chocolate Works, Noisiel-sur-Marne near Paris, as the first true skeleton structure, with its exterior walls reduced to simple infill (Frampton and Futagawa 1983).

[21] In the case of the Eiffel Tower, all the 18,000 components were manufactured in a factory outside of Paris, where Eiffel's company was located. Each component was designed and calculated to an accuracy of a tenth of a millimeter. Three hundred workers on the building site performed the assembly (SNTE 2004).

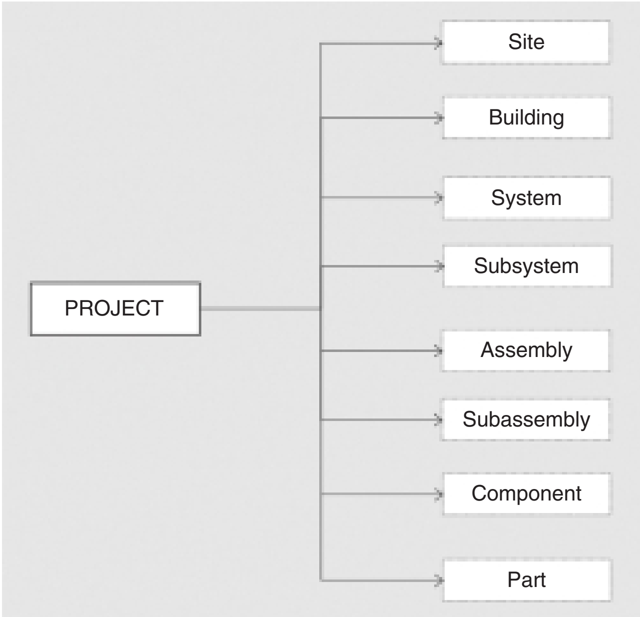

Figure 6.8 Partonomic structure for design and construction.

arrangements of sub-assemblies, parts and/or components. Assemblies, sub-assemblies, components and parts must include connections or joining systems. Connections or joining systems tie together parts and components, and also fasten together and secure assemblies. Design of pre-manufactured components does not distinguish between the use of standard components and the design of a one-of-a-kind component. Because of that, the term component-based design operates in at least three different approaches: standard components from a manufacturer's catalogue, components as a variation of existing ones, and unique or tailored components. In the last two cases it is the designer, not the builder, who becomes responsible for the creation of drawings (now digital) that guide the manufacture of components for the assembly of buildings (Stacey 2001).[22]

The main advantage of the component design approach comes from using a common partonomic structure for design and construction; that is, 'part of' or a knowledge taxonomy. This shared partonomic structure, as shown in Figure 6.8, makes it easy to organise knowledge simultaneously at the design stage and at the production level, in such a way that design units correspond to construction units. Nevertheless, having this correspondence does not guarantee an adequate flow of knowledge along the building production process. In using digital fabrication, this knowledge flows from design to production in digital format. Accordingly, knowledge is encapsulated within the work flow between two major technologies, CAD and CAM. In the next section the use of CAD and CAM in architecture is presented as a way to understand how knowledge is represented and transferred from design to the production of components.

[22] Stacey (2001) provides a description of component design and states the need for DfM use in architecture; see pp. 1–12.

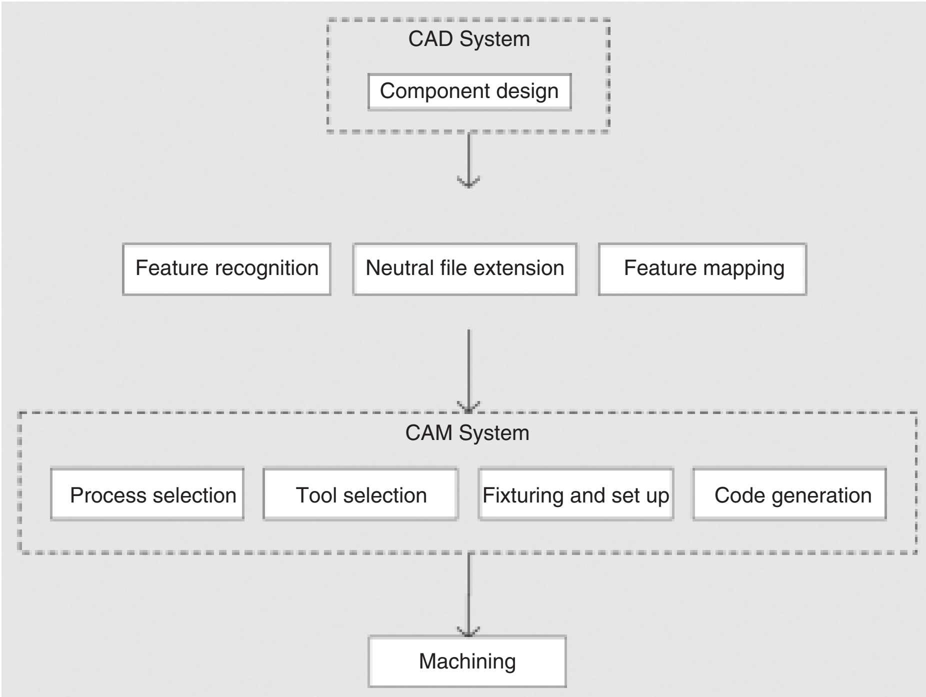

Figure 6.9 CAD-CAM workflow.

Form-generation capabilities and fabrication technologies

CAD systems' expanded form-generation repertoires and enhanced object-manipulation capabilities are providing designers with easier access to more complex geometries. Many forms and shapes produced out of those complex geometries are not related to traditional construction methods. Even though complex geometries were part of the architectural vocabulary, their use was limited by the lack of adequate representations to manipulate geometry. Lately and because of the widespread use of CAD systems, a notable increase in the use of those geometries in architecture has been noticed. Construction techniques for building them are neither stable nor determined and they require the development of a specific realisation process. A good example of this is found in the series of buildings produced by Frank O. Gehry and Associates (FOGA) in the last 10 years. These buildings required not only the deployment of non-traditional construction techniques but also the use of advanced digital technologies, suh as parametric three-dimensional modelling and CNC manufacturing technologies (Dal Co *et al.* 2003; Kolaveric 2003; Schodek *et al.* 2004).

In addition, bridging from a CAD system to a CAM system, as described in Figure 6.9, is mostly performed at the shape-description level based on neutral files or proprietary exchange formats. At the object level, CAM systems rely mostly on feature-recognition algorithms to obtain manufacturing knowledge from the design stages; although feature-extraction algorithms have been improved, they are still inaccurate and incomplete (Miao *et al.* 2002).

The main issue is that integration between CAD and CAM systems remains mostly unsolved (Liu 2000). Even architectural tools now being developed for building information

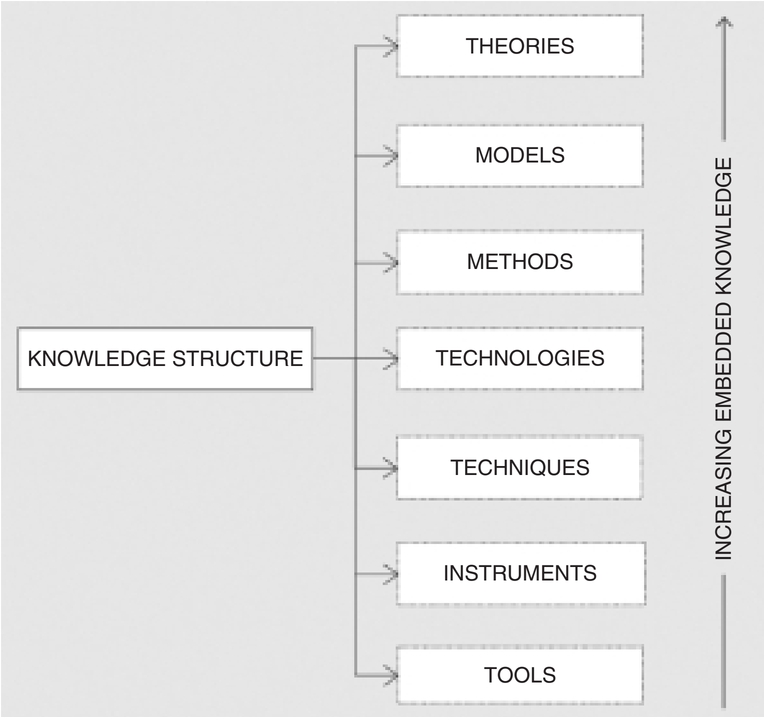

Figure 6.10 General knowledge organisation structure.

modelling (BIM) continue the traditional partitioning between design and construction. That is, they maintain the old stereotype that makes the new integrated conceptualisation difficult.

Knowledge-based design

In implementing the DfM in building production, it is important to consider that designers are required to structure design knowledge properly, to integrate manufacturing knowledge in design, to select adequate materials and processes, and to evaluate alternative design solutions in relation to their manufacturability (Shah and Wright 2000). A coherent organisation of general knowledge is proposed in Figure 6.10. As we can see, DfM implementation in building production is a knowledge-intensive approach and this section is dedicated to exploring the knowledge-based design approach.

According to Tomiyama (cited by Vliet *et al.* 1999), knowledge can be classified as recognised or unrecognised, codified or uncodified. Unrecognised knowledge is related to skills and experience. Uncodified knowledge is typically experience-based knowledge that is recognised and used by humans, but is very difficult to describe. Systemisation of knowledge is a process in which recognised but uncodified knowledge is transformed into recognised and codified knowledge (Vliet *et al.* 1999). Experience-based knowledge can be stored declaratively as facts or procedurally as courses of action. The forms of representation used are rules, predicates, frames, associative networks, model-based reasoning, case-based reasoning, qualitative reasoning, temporal reasoning and artificial neural networks (Vliet *et al*. 1999).

Concurrent engineering, teamwork organisation and expert advice approaches rely on tacit knowledge coming from shared or individual expertise, which is difficult to transfer or re-use in future experiences. Since every building is context specific and frequently designers, contractors and subcontractor teams change on each building, the intent, knowledge and reasoning used to produce the building are lost (Evbuomwan and Anumba 1998).[23] Subsequently, the aim of this research is twofold: to realise a process to capture and organise manufacturing knowledge, and to organise that knowledge and make it available as a DfM model for component design using specific CNC technology. In that context, the process of design generation was characterised as being reliant on a knowledge-transformation process based on specific design strategies or an alternative combination of them (Eastman 1968). This sort of reasoning is concerned with making judgments and decisions using incomplete or uncertain knowledge of the domain, knowledge that has been derived from experience of that domain. This type of experience-based knowledge is often defined as heuristic knowledge (Inhelder 1983).

Design knowledge

Design knowledge can be classified in two major classes: declarative knowledge and procedural knowledge. Declarative knowledge, similar to description, corresponds to knowledge of objects and events and how these are related to other objects and events. On the other hand, procedural knowledge is about tasks that must be performed to reach a particular objective or goal, and it is characterised as 'knowing how'. Procedural knowledge is often more difficult to verbalise and articulate than declarative knowledge. For the purpose of this research three categories of general design knowledge are presented,[24] as seen in Figure 6.11:

- *Object knowledge*: knowledge of the characteristics and properties of components and their materials.
- *Manufacturing knowledge*: knowledge of the various manufacturing processes, plans and steps to be used to realise designed components.
- *Process knowledge*: knowledge of the characteristics and properties of design for manufacturing processes, which can be used to produce a DfM model.

The types of design knowledge identified concern entities, functions, attributes, topologies, relationships and manufacturing methods. The relationships between entity, function, attributes and manufacturing method are particularly important in building production (Pulaski and Horman 2005). Even though design repertoires contain these three types of general design knowledge, the architect's knowledge repertoire consists predominantly of object knowledge (Goldschmidt 2003). In addition, some realisation knowledge, which will be used to realise their designs, is also found (Aken 2005). This knowledge is commonly found as part of conventional construction systems. This recognised and codified knowledge has low potential to be taken into

[23] Evbuomwan and Anumba (1998) refer to design intent, design knowledge and design rationale.

[24] For other knowledge ontologies in the artificial intelligence and design cognition fields, see Potter *et al*. (2003).

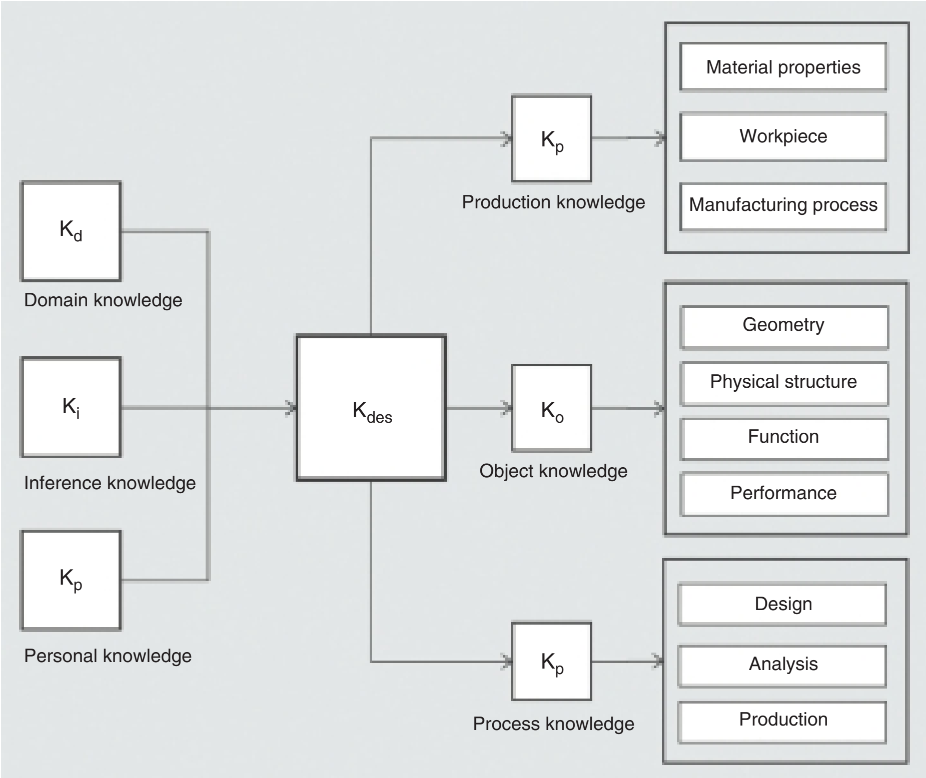

Figure 6.11 Design knowledge organisation structure.

account in component design, as in design for manufacturing. Additionally, it may contain only a limited amount of explicit process knowledge. Most designers obtain their realisation knowledge through their own experience and by re-using it from previous realisation processes. For that reason design knowledge is characterised as being dynamic, unstable, subjective, incomplete and conflicting in nature.

Process knowledge from realisation tends to remain largely tacit; often designers find it difficult to define their approach to realising their designs. Consequently, the next section is focused on manufacturing knowledge as fundamental knowledge to incorporate into the design process to improve the buildability of building components.

Manufacturing knowledge

In the traditional design process, after the design has been created the artifact in question has to be realised through a manufacturing process. Even though the manufacturing approach selected is considered to be a feature of the design, often that process is completely ignored until manufacturing. In building production, the fabrication process is already present as conventional construction systems that can be applied to or adapted to a new design. As discussed in the previous section, the construction process may be the result of the historical evolution of traditional practices and techniques, but nowadays it can also be the result of an explicit and unique fabrication approach (Kolaveric 2003; Schodek *et al.* 2004; Chaszar 2006). Such a fabrication plan is often created as a variant of existing manufacturing processes or a combination of them (Schodek *et al.* 2004; Kulon *et al.* 2006). The fabrication approach, mentioned above, is organised around two basic knowledge categories: knowledge about materials (declarative knowledge) and knowledge about manufacturing processes (procedural knowledge). Material knowledge refers to material and its properties. The most relevant material properties are mechanical, physical and chemical and these define the manufacturing properties. Manufacturing process knowledge specifies the nature of the various manufacturing processes and the equipment used in each one, and predetermines the specific conditions in each of these processes. This manufacturing knowledge is organised around manufacturing plans, manufacturing steps, manufacturing features, tool paths and fixtures (Rosso *et al.* 2002).

Knowledge acquisition techniques

At this point, now that a knowledge-based design approach and the types of knowledge needed have been described, it is necessary to explain how this research will obtain that knowledge. Therefore, it is necessary to introduce some formal, consistent method of capturing that knowledge. Knowledge acquisition is a process of acquiring problem-solving knowledge from human experts, literature, computer files and other knowledge sources. Knowledge acquisition has been recognised by researchers as the key bottleneck in the development of knowledge-based approaches. Knowledge acquisition is an expensive and time-consuming process, and good knowledge engineers are hard to find. In addition, knowledge engineering expertise is not well structured (Potter *et al.* 2003).

Most building production knowledge is obtained from literature and from design expertise, but that is far from satisfactory. The literature in the field tends to be too technical, being merely information referring to either a conventional construction system or a specific manufacturing process. Another drawback is how knowledge is represented in building production. Frequently construction knowledge is presented in the form of tables and manuals, or oriented towards construction management and not very useful for production (Groák 1992).[25] Finally and as mentioned previously, capturing knowledge from experts, a task normally performed by a knowledge engineer, has important disadvantages. Experts tends to structure knowledge based on conceptual schemas that refer to how the task ought to be performed – that is, prescription – rather than how it is performed – that is, description (Ball *et al.* 1996; Ho 2001; Potter *et al.* 2003). Nevertheless, when there are identifiable experts in an area, then the expert knowledge approach is valid and has been used with success (Woodhouse and Nieusma 1997). When the area is ill defined, as DfM in building production is, then other approaches, such as learning by doing, are valid.

A different source of manufacturing knowledge would then be of immense benefit to the development of a DfM model. Accordingly, the alternative method used in this research is to ask students directly, using structured design ‘experiences’ for capturing manufacturing knowledge

[25] Groák (1992) discusses extensively the issue of production knowledge in building production in Chapter 11; technology transfer and specifics about literature on p. 167. In addition, he expands on different forms of building knowledge on pp. 169–170.

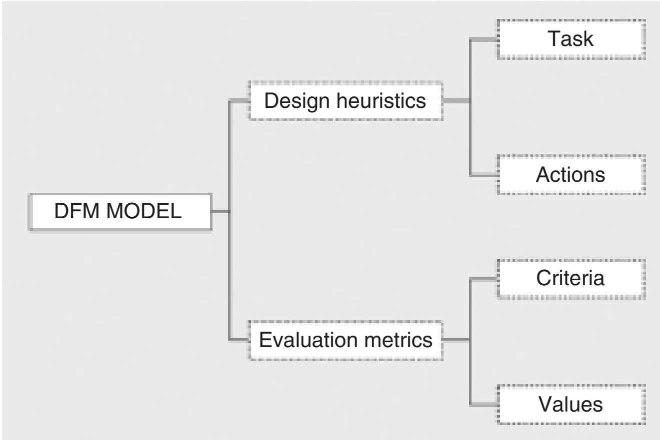

Figure 6.12 Main components in a DfM approach.

(Potter *et al.* 2003).[26] In the context of this research, design experiences with students include a design problem specification and the corresponding design solution (*Ibid.*).

As mentioned before, DfM is a design approach that incorporates manufacturing knowledge in the design stages (Fox *et al.* 2001). Within the DfM approach it is important to properly organise and represent manufacturing knowledge, allowing designers not only to select adequate materials, processes and components but also to evaluate components' manufacturability (Shah and Wright 2000). Consequently, the next section presents design heuristics and design metrics as way to systematise manufacturing knowledge in which recognised but uncodified manufacturing knowledge is transformed into recognised and codified manufacturing knowledge in the form of design heuristics and design metrics, as described in Figure 6.12.

Design heuristics

In this research, the adjective 'heuristic' (or the designation 'design heuristics') is used to represent a process that it is there to understand or to find out about some other process with which it is not identical (Groner *et al.* 1983a, b). Design heuristics provide a framework for solving the design problem, in contrast with a fixed set of rules that cannot vary. In this way the designer uses a set of steps, empirical in nature yet not proven to be always valid, to progress in solving a design task and to successfully find alternative solutions.

A typical design heuristics in DfM is 'to develop a modular design'. This is especially relevant since if a design module is equivalent to a manufacturing module, it means that it can be produced as one manufacturing unit, which is exactly the kind of integration that this research is proposing in using component-based design.

[26] Potter *et al.* (2003) proposed this alternative way to capture heuristics based on design experiences in the form of a design specification and the corresponding design solution, containing the information necessary for deriving the appropriate heuristic knowledge.

Another more trivial but no less relevant heuristics is 'to reduce the part count and part types', which can be translated into architectural production as 'to reduce component number and component types'. Others such as 'to keep wall thickness as uniform as possible in castings' can be adapted in a similar way to building production.

Design metrics

In order to assist the designer to develop components which can be manufactured, a design heuristics must be complemented by design metrics. These metrics would objectively, and quantifiably, contribute to measuring component manufacturability, providing designers with immediate feedback as the design progresses. A good example of efficient and effective metrics in a different domain, which proved successful, is those postulated and validated by Boothroyd and Dewhurst regarding the assembly of products (Boothroyd *et al.* 2002). Their success lies in the simplicity of the usage of the metrics (for example, everybody can count the number of parts in an assembly), connected to the fact that their metrics are valid and indeed provide a good measure for the ability of a product to be assembled.

These design heuristics and design metrics may sound atypical to our field, but once we design a component using digital fabrication they are fundamental in improving component manufacturability. Finally, this research proposed a DfM rule classification, as shown in Figure 6.13, to organise manufacturing knowledge and to link it to different stages in the proposed DfM model.

Type of DfM rule	Example
Generic	Reduce the number of manufacturing processes
Material	Reduce material waste
Process Generic	Avoid double curvatures
Process specific	(3D Surfacing) Best tool path width is 0,1 mm
Machine generic	Compare work piece size with machinable size
Machine specific	(3D Surfacing) Machinable angles can be anywhere between 0 degree and 90 degree minus tool allowances in descending paths
Tool Generic	Reduce number of tool paths
Tool Specific	Ball nose tools provide better finishing that end mill ones.
Dimensions	Use metric system
Tolerances	Match tolerances between processes
Surface finishing	Reduce number of surface finishing operations

Figure 6.13 DfM rules classification for in-building component production.

Conclusions

Traditionally, intelligent design behaviour is conceived as a manifestation of a property of designers, but we need to reinterpret it as conduct whose individuality consists in being enacted in a particular design context as a result of a particular history of interactions of the designers with other designers, consultants, clients or with its context. Design intelligence does not have to do with agreement or with the capacity to solve design problems. Design intelligence is the capacity not only to participate in the acquisition, generation and application of design knowledge but also to expand the boundaries of design disciplines as cognitive domains defined by their relevant knowledge. Problem solving in design takes place as an operation within a discipline that is already established, so it is secondary to the knowledge that defines a discipline, not prior to it. Even though there is an increasing consensus about the significance of re-establishing the connection between design and construction within the architectural discipline, it is still unclear how this change will be implemented.

The DfM model proposed in this research, described in Figure 6.14, is a design process model. And is based in two fundamental design strategies: first a process description that represents an advice for making design decisions in the form of a design strategy i.e. a sequence of procedures that can be repeated and transferred; and second, the implementation of design heuristics that integrate production knowledge and the availability of some evaluation metrics of design related to production.

The key idea is that design is a process of continual inquiry, in which the designer performs actions in the form of design strategies based on the availability of design knowledge. Nevertheless,

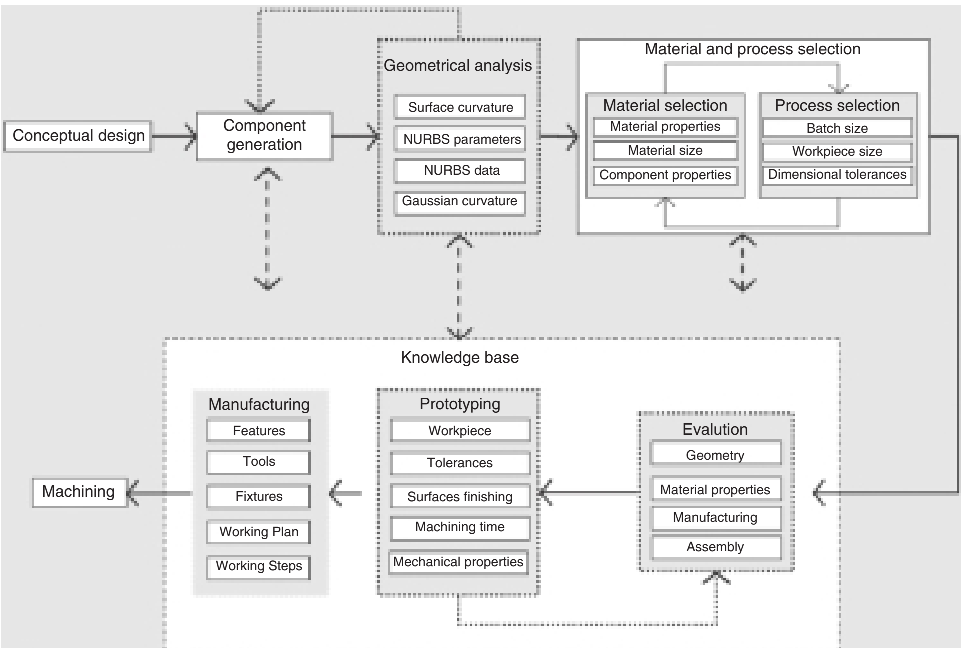

Figure 6.14 Proposed DfM model for building components using digital fabrication.

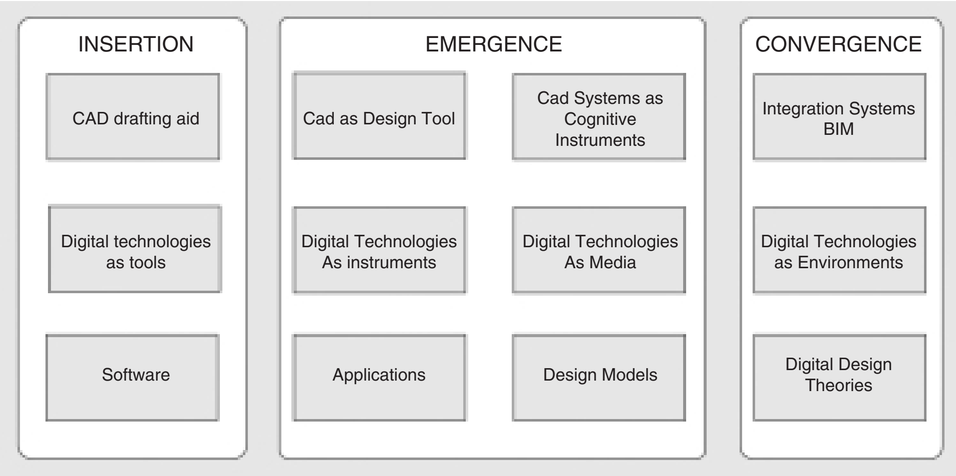

Figure 6.15 Evolution of digital technologies in building production.

the rationale behind these design strategies is commonly ignored.[27] The types of rationale that I looked in this research were not only about what type of design strategies were used, but also what aspects were relevant in design decisions and resolutions of manufacturing issues (Burge and Brown 2000).

Accordingly, capturing manufacturing knowledge in the form of design heuristics and metrics from teaching experiences allows me to enrich the model with knowledge not only about what is being designed but about also how it will be produced. As a summary, within the model procedures are not only the deployment of observable design strategies – that is, design history – but also the inclusion of relevant aspects of those actions for the designer – that is, design rationale. In addition, the model's objective is not only to provide designers or students with a framework to be used as a step-by-step DfM guide, but also to use the model as an analogy to create other DfM models or other DfM teaching approaches. The model represents a process that it is there to understand or to find out about some other processes with which it is not identical.

It is important to realise that design strategies, design heuristics and metrics are the main components within a DfM model, but they do not constitute the model. It is the knowledge that is encapsulated in the model which really constitutes the model. Nevertheless, this knowledge of how to perform the task and indications about the relevant knowledge to perform it effectively are precisely that heuristic knowledge that is required for a DfM approach. Consequently, design strategies, design heuristics and metrics within the model are guidelines representing design experiences and best practices.

Throughout this chapter, I have stated that the architectural discipline needs to reorganise its body of knowledge according to new scenarios within the building production process. This change must start from the core of the discipline; that is, architectural education. Accordingly, this research encourages studio instructors to use more structured approaches to deal with the increasing complexity found not only in the ubiquity of complex geometries, but also in changes

[27] The design rationale is the collection of reasons that lead to the design of an artifact; that is, why an artifact was designed the way it was (Baptista and Simoes 2000).

presented in the building production process itself. Digital design and digital fabrication technologies determine a unique opportunity for new educational approaches, where design is presented as a continuous research process in which designing and making are integrated as one thinking process. See Figure 6.15 for a more comprehensive idea of the evolution of digital technologies in architectural education.

Finally, the proposed use of DfM in building production is not about how DfM must be done. Moreover, it is more a reflection of the nature of design processes and the need for integration between design and construction. We are entering a new epoch in architecture, where we are explicitly concerned with not only the form and function of architecture, but also how it is produced, and this requires new models for design and also new approaches in education.

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7 Artifact and affect: Open-ended strata of communication

Matias del Campo and Sandra Manninger

This chapter explores the manifold planes of possible communication between various fields of expertise triggered by two specific conditions: artifact and affect. The relation between the conditions is described by the application of computer numerical control and the artifacts of the process ground into the surface condition, resulting in opulent novel conditions which can be read in multiple ways.

Perceptions and affect

The Deleuzian differentiation between the disciplines of philosophy, art and science is based on the idea that these disciplines analyse reality in specified different ways. This rigorous differentiation is based on the conclusion that the main task of philosophy is to create concepts, while the arts create novel conditions of perceptions and affects and science produces theories based on quantitative methods that rely on rigid, functive,[1] referential points, such as absolute zero and the speed of light. All three of them – philosophy, art and science – are considered to be diverse ways to organise the metaphysical flux *pari passu*,[2] without hierarchy or supremacy over the other, or, as Deleuze describes it in his book *Negotiations* (1997), 'separate melodic lines in constant interplay with one another'. Consequently, philosophy, art and science can be considered essential and equal as well as creative and practical in a simultaneous manner, resulting in the assertion that Deleuze is asking questions of functionality and practicability akin to 'How does it work?' or 'What does it do?', replacing more traditional inquiries of identity, such as 'Is it true?' or 'What is it?'.

[1] A 'functive' – a Deleuzian term – is any proposition that makes a verifiable truth-claim about actual states of affairs.

[2] *Pari passu* is a Latin phrase that literally means 'equal footstep' or 'equal footing'. It is translated as 'part and parcel', 'hand-in-hand', 'with equal force' or 'moving together' (source: Wikipedia).

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

Figure 7.1 Big Dog rough-terrain robot by Boston Dynamics. (BigDog image courtesy of Boston Dynamics ©2009.)

Rise of the molecular machine

Following the methods of classification mentioned above, the term *artifact* can be described as an object produced or shaped by human craft, in particular objects of historical or archaeological interest as well as tools and weapons. To that extent the example of the BigDog (Figure 7.1) robot by Boston Dynamics (www.bostondynamics.com) serves as a splendid opportunity to speculate on the artifact in intelligent war machines.

Prototypes of predatory machines have already been deployed on a number of battlefields, marking the emergence of autonomous weapons, such as the Talon[3] system by Foster Miller. Contemporary autonomous war machines in fact do not act completely autonomously; although

[3] TALON Operations is in the process of building several distinct 'families' of robots that will be able to perform a variety of tasks, and will all be operated with one universal control unit. Today, TALON Ground Robotics includes four 'families', including the MAARS Robot (Modular Advanced Armed Robotic System).

some robotic UAVs (unmanned aerial vehicle) are capable of executing operations entirely autonomously, there is still a man in the loop,[4] a human being who controls the ethical behaviour of the machine, thus infusing the robot with instances of morality. The decision process between the information delivered by the robot and the human factor is needed in the case of weapons usage and the differentiation between combatants and civilians. This development marks a point of singularity where man and machine cease to oppose each other, resulting in the fusion of both conditions into each other and thus becoming one single war machine, forming a substantial example of artifacts within the *machinic phylum*, as described also by Manuel de Landa (1997).

It should be briefly mentioned that, in fact, this last condition is tightly knotted to Giles Deleuze's idea of the desire for molecular machines (Deleuze and Guattari 1972) formed by social machines, instead of being mechanically composed and manipulated in order to form a complex molar machine. An example of a molecular machine adopted from popular culture is the T-1000 Robot from the James Cameron-directed *Terminator 2* movie. The mimetic alloy composition of the robot allows for a shape-shifting process, giving it the ability to adopt every form it comes in contact with, as long as it is not mechanically complex. The resulting behaviour can be described as a pliant spatial condition created by numerous components forming a collective entity, a population affecting its environment in multiplicitous, intricate manners. The similarities between such a statement as this and the subjective concerns of, for example, Hume, who describes personal identity as a jumble of perceptions; Kant, considering the subject as both a synthetic construct and a construct of synthesis; and even Nietzsche, with his idea of the 'I' as nothing other than a grammatical exigency, are noteworthy. Considering these conditions, the individual subject, the ego, can no longer be perceived as the fundamental basis on which everything else can be built. It is not an *Ursprung*[5] from a special point of mystical origin, but rather emerges from the necessary affects, and capacities for being affected, of bodies (Brasset 1997).

In contrast to the condition represented in the fictional concept of the T-1000, the affect created by industrial robots can be spliced into two components: the machine itself, and thus the moments of affect within the machine; and the artifacts created by the machine itself, which represent pliant conditions, as depicted in Figure 7.2. What enables the machine to produce endless variations within the fabrication process is the numerical code controlling the curvilinear movements of the robot based on calculus. This process possesses a high potential for the creation of ornamented surfaces defined by the milling artifacts, which can be considered an inherent condition of the applied mode of material organisation. The described subtractive method of material organisation converts a spline mesh into a tool path, resulting in corrugated surfaces bearing qualities of corduroy-like patterns, formed by the artifacts left by the continuous tooling path. The ornamentation of the surface does not emerge from a specific design process, but is intrinsic information within the numerical condition of the spline-derived surface, stored

[4] Most countries are bound to international laws of war (such as the Geneva Conventions). These laws govern the conduct of participants in war (and also define combatants). These laws place a burden on participants to limit collateral damage through proper identification of targets and distinction between combatants and non-combatants. It is in this area where the use of completely autonomous weapon systems is problematic, since it is difficult to assign accountability to a person. It is for these reasons that current designs still incorporate an element of human control (a 'man in the loop'), meaning that a ground controller must authorise weapons release. Retrieved from Wikipedia, 23 March 2009.

[5] German word meaning "source", "origin" in English.

Figure 7.2 Kuka industrial robot milling a piece of the Genus 2 Lamp by SPAN. (Photo © SPAN 2008.)

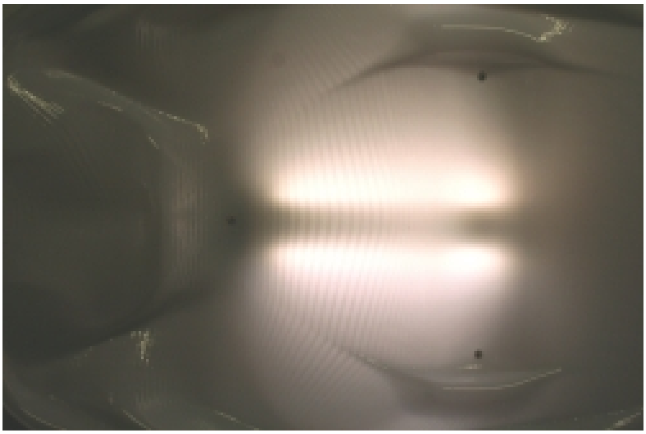

Figure 7.3 The surface artifacts of the milling process pressed into vacuum-formed panels for the exhibition design, *The Austrian Winery Boom* on show in the Austrian Cultural Forum, New York. (Photo © SPAN 2008.)

information within the formal qualities of the object. Like the pattern on an animal skin follows the comprehensive geometry and core information, the corrugation resulting in the milling process follows the constitutive mathematical and geometrical conditions of the surface (Figure 7.3). If ornament were seen as applied decoration, as it has been since the invention of the decorative arts, then it would be transformed by a Deleuzian sensibility. But if it is posed as a question of fused interacting processes, then it is a primary concept for Deleuzian provocation (Leach *et al.* 2004). The trajectory of this narrative is the relation between communication, design and the machine, based on numerical control. The plane of thinking is created by the relation of those to the spliced condition between molecular machine and mole machine and the emergent opportunities in the communication between disciplines propelled by the artifact.

Beyond the description as a physical object, artifacts include products of human conception or agency. Ideas can be described as artifacts of human conception models. Technology has uncovered another stratum of observation, making processes and features previously invisible to the human eye visible with the aid of radiology or electrocardiography; those images can be described as the artifacts of processes unfolding in our cone of vision. Finally, an Artifact can be the result of an inaccurate observation, an effect or result generated by faulty technology or a false assumption in the scientific investigation of a specific experiment. This final definition is able to create unprecedented results, patterns in the data that follow novel conditions in its ballistic trajectories; unfolding in surprising conditions and able to generate affects in the process.

Affect of the plane of immanence

If we consider immanence to be a plane of geometry, we can read it as an abstract or virtual plan unbound from a mental representation, resulting in a formless, univocal, self-organising process differentiated from itself and thus creating qualitative conditions in alignment with Deleuzian understandings of metaphysical and ontological qualities such as transcendental subjects, agency and real structures, as described by Deleuze and Guattari in *A Thousand Plateaus* (1987: 293):

> Here, there are no longer any forms or developments of forms; nor are there subjects or the formation of subjects. There is no structure, any more than there is genesis.

The lineage of this mode of thinking results in a plane of immanence constituted of an intricate relationship between complex networks, intensive forces, particles, connections, relations, conditions of becoming and ultimately affect.

> There are only relations of movement and rest, speed and slowness between unformed elements, or at least between elements that are relatively unformed, molecules, and particles of all kinds. There are only haecceities, affects, subjectless individuations that constitute collective assemblages. […] We call this plane, which knows only longitudes and latitudes, speeds and haecceities, the plane of consistency or composition (as opposed to a plan(e) of organisation or development). (Deleuze and Guattari, 1987: 295)

Artifact, affect and works of art

Artifactuality is often regarded as a defining characteristic of works of art. For example, this is an essential condition in George Dickie's analysis, according to which a work of art is an 'artifact of a kind created to be presented to an artworld public' (Dickie 2001: 7). The condition of artifactuality is plausible only if the concept of artifact is understood in a wide sense in which intentionally created events and processes (e.g. performances) and works which have instances (e.g. musical and literary works) are regarded as artifacts (compare also Figure 7.4). The condition of artifactuality in this sense is equivalent to the requirement that a work of art should have an author.

Some philosophers of art have rejected the condition of artifactuality, using 'driftwood art' and analogous examples as counter-examples. This view has the seemingly paradoxical consequence

Figure 7.4 SCUMAK by Roxy Paine, the artifact of an artistic process. (Photo by Jacques Montel, courtesy of The Wanås Foundation.)

that a work of art need not be a product of anyone's work and need not have an author. Other philosophers have responded to such examples by extending the concept of artifactuality in such a way that the presentation of a natural object as an object of aesthetic appreciation counts as an 'intentional modification' required for artifactuality. If the expression 'artifact' is used in a sufficiently wide sense, the condition of artifactuality clearly holds for artworks, but it is equally obvious that not all works of art (or works in general) are artifacts in the narrow sense of the word. In aesthetic evaluation and criticism, however, they are treated as if they were artifacts. Artifacts in the wide sense form an ontologically heterogeneous collection: some of them have instances (literary works and musical compositions), others are singular objects (e.g. paintings) and there are also abstract artifacts, for example fictional characters, which have authors but are neither concrete particulars nor have such particulars as instances. As Amie has pointed out, abstract artifacts do not fit the traditional division of entities into concrete physical particulars and ideal *abstracta* (*Stanford Encyclopedia of Philosophy*, n.d.)

The relation to affect

Ultimately, the artifact in its representational construction can serve as a launching pad for a twofold process. Primarily it can serve as an interface between disciplines, provided there is a communal etiquette of understanding, a common language. The previously mentioned process of CNC milling, or of numerical control in general, represents one of those opportunities, where a specific aspect of technology serves as a linguistic interface between disciplines. To mention just one example, the authors' communication with a tissue engineering laboratory can form a base for further discussions on the relation between specific technologies and their advanced techniques, computational software artifacts and their potential to generate novel conditions, as well as serving as a universal language between disciplines. In the specific example, the use of advanced software and fabrication tools generates a jargon between the disciplines, which creates an immanence of understanding, enabling both fields to inform each other and thus enrich the potential results of individual or communal efforts. In the process, between material behaviour, processing technique and resulting artifact conditions, the immanent qualities of affect emerge, informing multiplicitous planes of perception and communication. In opposition to the concept of vacuous forms awaiting content to fulfil their destiny, the forms themselves become active productions, affecting and being affected on a constant level by other concepts, representations, images and bodies, thus creating a continuous relation between artifact, affect and the intensive conditions creating continuously varying environmental pressures.

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8 Digital tools for creative hinges

Sean Hanna

Distributed intelligence in design

For nearly half a century, digital tools have been used in design not merely as a means of speeding up or automating various aspects, but to allow us to see, analyse and produce what we are designing in substantially different ways. To the extent that intelligence is distributed across a group of collaborators in the design process, the manner in which communication is mediated by such tools has a marked effect on what they produce. If knowledge and creativity, rather than being products of a single mind, are emergent properties that result from this collaborative work, computation might thereby aid in realising this powerful distributed intelligence in design. But what does design itself involve and what sort of intelligence is necessary?

I propose here that there are two roles for technology in communication and the emergence of design ideas: rationalisation and innovation. The primary focus of our effort and understanding currently and in the past has been on the former role, but perhaps the most interesting and untapped possibilities exist for the latter: innovation. The reason these are as yet underdeveloped is partly technological, but is also rooted in conceptual and philosophical views of cognition and intelligence more generally that were current nearly 50 years ago when the first CAD software was being proposed. We have inherited these, and their very powerful implementation in working software, but they still dominate much of what we associate with the use of computers in design. Intelligence requires both roles to be played, and as our collaboration is increasingly mediated by the tools we have, we require both for distributed intelligence. I will outline this and what the other stream entails, and conclude with a suggestion of some future directions that it might take.

Design is not just production

This chapter is concerned specifically with the act of design: the creative process itself. The later production of buildings and other products after they have already been designed is intimately related to this, but it is not the same thing. It is crucial to make this distinction because production

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

too almost certainly involves knowledge and organisation that is shared among a number of collaborators, and is thus another likely example of distributed intelligence, and because the high-profile tools often said to be supporting design are often only supporting this later phase of realisation. Frank Gehry provides a familiar illustration, as while Gehry Partners and Gehry Technologies are among the foremost users and developers of parametric and related software tools in the making of buildings, Gehry himself famously designs using purely low-tech, manual means. Models are faithfully digitised and post-rationalised only after the fact, and the computational tools are used to work out how to construct the complex geometry. A great deal of communications and information technology is unquestionably useful at these later stages, and this is where it is frequently employed, but this is a separate issue.

The distinction is also relevant because the function of these tools, even when used in design itself, is often the same as their role in production. This is the first of the two possible roles discussed here – rationalisation – and thus only represents half of the picture. Although computers are very good at making models precise, clarifying an otherwise vague concept and ensuring correct communication between individuals, the full design process often starts much earlier. A too common misconception of 'parametric design', for example, is not really design in this full sense. The popular use of this term is itself problematic, as it misleadingly emphasises the adjustment of parameters as the primary feature of such models, whereas in fact by the time this occurs the real work of creating the model is already complete. The core design activity is not the setting of parameters but the setting of the associations and relationships in this model. After these are set the model is a path to production.

Building information modelling (BIM) is also not design. It may be used to visualise the result of decisions or in the management of a complex project, but only after the creative decisions have been made. Nor is optimisation fully design. While it may produce apparently creative results by searching through more solutions than could ever be done by human designers, and stochastic processes such as genetic algorithms might appear mysteriously intelligent in doing so, optimisation relies on objectives, representations and boundary conditions being stated explicitly. This is often the most difficult part of the design task, already complete before optimisation begins. The association of the production of rational solutions is reinforced in the academic literature of design technology, from engineering fields speaking of clearly defined design 'problems' to research on mass customisation that concentrates on a customer's ability to change product attributes as parameters.

The other proposed role of technology – to aid innovation – must also be acknowledged in the context of distributed collaboration. If rationalisation of designs can be loosely associated with the tools for production, this innovation may be associated with quite a different activity of perception and interpretation. Tools to allow distributed intelligence in actual design (not just production) need to contribute at this phase.

The design process: An example

An example design scenario will serve to illustrate the two processes. It is recognisably the work of a single individual – Antony Gormley – at one level, but also the result of a collaboration representative of a distributed intelligence among several people working over a period of time and occasionally in different places. Gormley is a sculptor, winner of the Turner prize, and is concerned with revealing notions of the body's relationship with space that are on the one hand intimately personal (many of his works are his own body) and on the other intuitively understood

Figure 8.1 Antony Gormley's 'Flare' series. The geometry is highly complex yet intuitively recognisable. (Image courtesy of Antony Gormley Studio.)

by others through our common physical resemblance. His 'Flare' series consists of a series of sculptures of the space immediately surrounding a single human body. Each is made from thousands of thin steel rods describing an open mesh of polygons on the body's surface, and radiating outward a constant distance of about 50 cm to an offset surface that is again described by a larger open mesh of polygons (Figure 8.1). Each sculpture is welded by hand and is of a uniquely complex geometry.

The process of design begins with the surface of the body in a given pose, the overall intent of describing the space offset from this body's surface, and a set of tacitly held formal and aesthetic principles as to how this can be done: preferences for angles at which rods should join, the range of shapes and sizes of polygons on the body's surface and so on. It is already a collaborative process, between Gormley and a number of assistants who physically construct the first experiments to realise the geometry, but the precise rules for doing so cannot be stated explicitly. Instead these are gradually refined through a series of iterations in which parts or whole body forms are made, evaluated and adjusted. The process resembles the sketch and reflection phase of almost any design task, only here it is clear that what is being sought is a clear set of geometrical rules by which to realise the complex form. The clear understanding of these rules is particularly crucial for such a project as it will be constructed over several man-months, perhaps by several different people, and it must be coherent to be legible and aesthetically satisfying.

This is where computation (and my personal involvement) comes in. After several experiments and many hours of working by hand a number of rules can be stated explicitly, and these can thereby be coded and tested digitally as more precise algorithms. One of the most important of these concerns the geometry of the rods radiating outward from the surface of the body to define the extent of the expansion. In almost all versions these spring from all vertices of the polygons on the body surface and had been treated as *normals* to this surface – lines oriented in a direction exactly perpendicular to the surface at their point of origin, as in Figure 8.2. These were simply extended outward by a uniform amount and connected on their endpoints by the same topology of polygons as on the body. Unfortunately this leads to several problems in reconciling the geometry. While polygons on the body were approximately uniform in shape

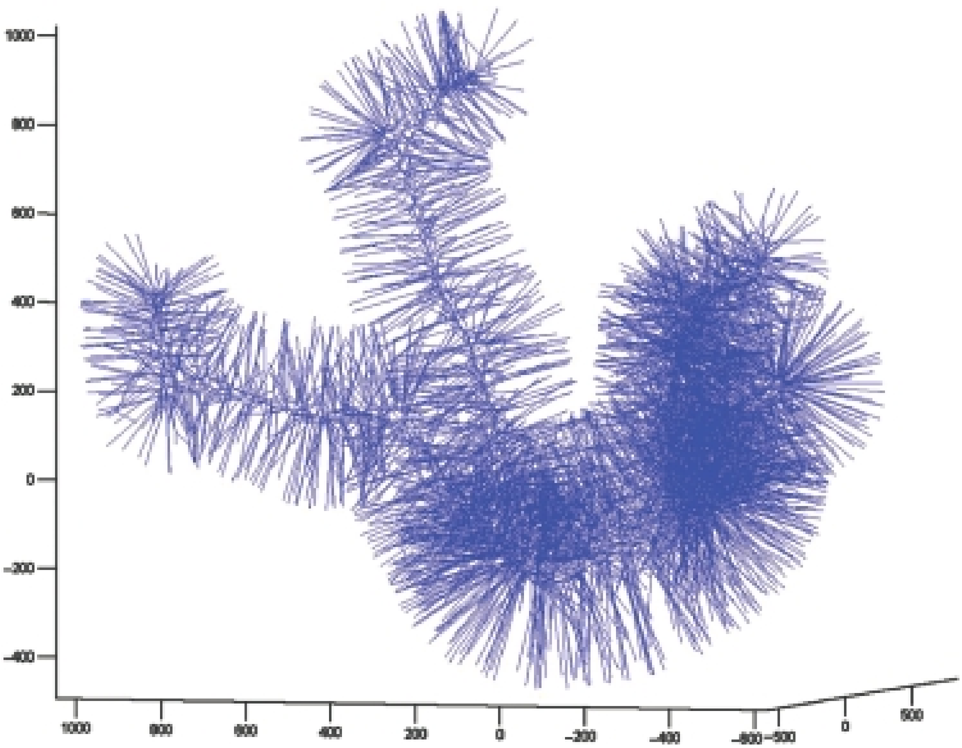

Figure 8.2 Surface normals extended outward perpendicular to a given surface.

and size, changes of surface curvature were exaggerated to severely deform these on the outer surface. For regions in which two areas of surface faced each other at a distance of less than the overall offset (e.g. 50 cm), such as between the legs, between the arm and torso or between the head and shoulder, the problem is most acute as two sets of normals cross into the same space, as Figure 8.3 shows. Additional rules can be applied to remedy this, the normals trimmed at the midway point to suggest an internal surface where the two spatial regions meet. This notion of an internal surface at the intersection of regions appeared to be an integral part of the desired aesthetic, but it required still further rules to cope with the result, as the normals do not intersect one another and must be bent slightly to ensure a clean edge. If the number of rods from one surface is not the same as the other, several further options result: some normals can be simply omitted, some brought together to intersect in groups, or the surface of intersection can moved through the region from its midway position to a new position in which the intersections are realigned. The testing of each new rule or conception of the geometry is easily accomplished digitally, allowing these possibilities to be quickly explored.

However, as it turns out, the solution is in an entirely different concept altogether, one that looks almost identical overall but is based on a completely different algorithm. Rather than constructing normals from given points on the surface, the structure can be conceived as a set of three-dimensional Voronoi cells around the points on the surface of the body. A Voronoi cell is the three-dimensional region defined by all space closer to a point than to any other point, bounded by planes that exactly bisect that point and its nearest neighbours. These extend into

Figure 8.3 Regions in which surface normals intersect one another pose a problem in resolving geometry. (Image courtesy of Antony Gormley Studio.)

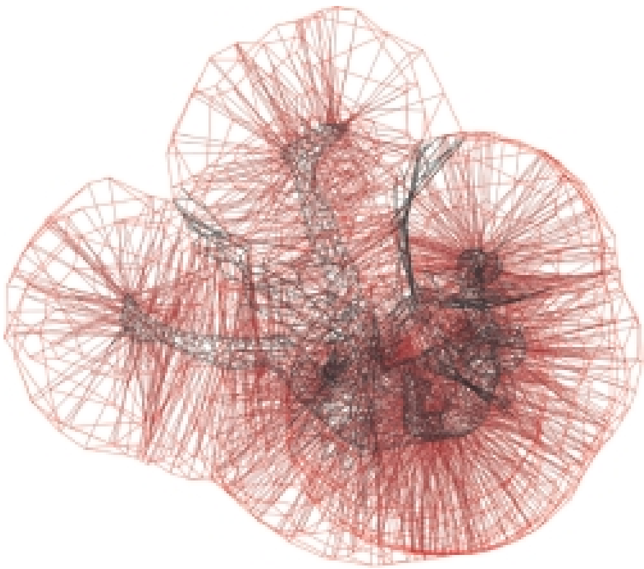

Figure 8.4 A similar geometry based on a different concept: Voronoi regions rather than surface normals.

the body's form and outward an infinite distance, but can be trimmed at the body's surface to yield the open polygons that describe the skin, and at a uniform distance away to result in the same geometry on the exterior of the sculpture (Figure 8.4).

This alternative concept has a clear simplicity. Rather than being conceived as three separate structures with their own rules – the polygon mesh skin, a set of normals of a given length, then a third offset mesh – the entire form is realised from one single rule of Voronoi regions. For all

Figure 8.5 The revised concept elegantly resolves even the most difficult regions of intersection.

the complexity of the final geometry, it is this that ensures its elegance. The complex intersections of regions arise naturally from the rule and form the same graceful surface of open polygons that form the surface of the body and the outer extent (Figure 8.5). Perhaps more importantly, the rule is fundamentally in line with the initial concept of the piece: it is a sculpture of space, and whereas surface offsets are vectors, Voronoi regions are actual spaces themselves. As commonly occurs across a great variety of collaborative design projects, all involved understand the correctness of the correct solution immediately, as it embodies all of the geometrical and aesthetic criteria intuitively grasped while working towards the design for some time.

In terms of the design process, this project illustrates two clearly different aspects (Figure 8.6). On one hand there are the individual instances actually produced, from sketch models and initial attempts to resolve the adequate intersection of rods all the way through to the final piece. On the other there are the abstract concepts – surface normals and Voronoi geometry – that describe precise guiding rules for how these instances should be constructed. The design process can be seen to progress by a repeated oscillation back and forth between these two modes, alternately producing instances of a current concept for test and discussion, then reinterpreting these to formulate a novel redefinition of the concept.

These transitions also correspond with the two design roles discussed here. The first allows instances to be produced from clear concepts. It is this role that requires rationalisation: the precise, explicit definition of a concept – in this case the Voronoi geometry – and the resulting ability subsequently to realise an elegant structure of high complexity. In many ways formulating this is the goal of the design task, after which all the moves follow and make sense. The second aspect allows new concepts to be created. It requires innovation: simply the act of changing concept definitions by interpreting the design as something else. This occurred explicitly in the shift from the 'normal' to the 'Voronoi' algorithm, but also far more often in the earlier stages of sketching and manual experimentation during which the original rules and concepts were formulated.

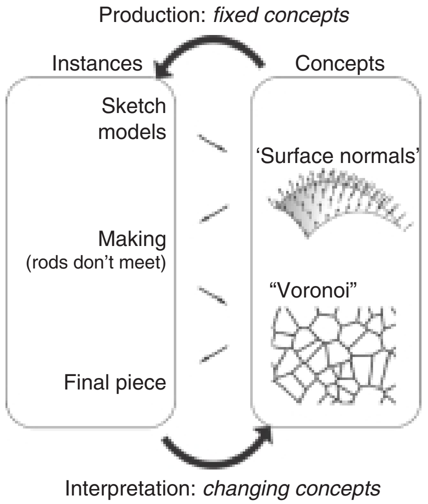

Figure 8.6 Two methods of working. The traditional practice of design sketching works directly with instances (left), the parametric-generative-computational designer is more intimate with clear concepts (right).

Rationalisation and production

Because digital tools allow us to be precise, computation in the design process has traditionally been focused primarily on the fixing of concepts. Parametric modelling tools serve as an illustration of this, but the same applies in varying degrees across the range of digital design technology, from 'straightforward' CAD to the scripting and coding of geometry. The kinds of representation these allow are not *geometric* but *schematic*. Parametric models are often described as providing more flexibility by allowing some decisions – those of dimensions in particular – to be deferred until later in the process. The variables deferred are not the structural relationships that make up the core concept of the design, but the details that are easily modified to produce different instances of it. This is popularly applied to vary modular elements and make something far more complex in form while retaining the same logic. Alternatively, the process is ideally suited to optimisation, by iteratively adjusting parameters and re-evaluating the resulting form.

While this deferral and production are practically useful, it is precisely the wrong way to consider the real advantage of the tools, which lies in the fact that they actually require a far larger investment in time up front in constructing the schema by which the parts of the model are related. They require the designer to consider the logic of the design in advance, and to specify this rigorously. By doing so, they enforce clarity in the design. They don't provide this automatically, but force the designer to construct the associations between the various elements in the model that will provide it. The consideration of these means that the concept is rationalised and the effort expended in constructing the model means – at least for some time until another schema is adopted – that it will be fixed. Associative modelling is perhaps a more appropriate term than parametric, in that it emphasises this point. The associative schema itself is the model of the core concept of the design, and provides structure by which instances of the complex final form can then easily be produced.

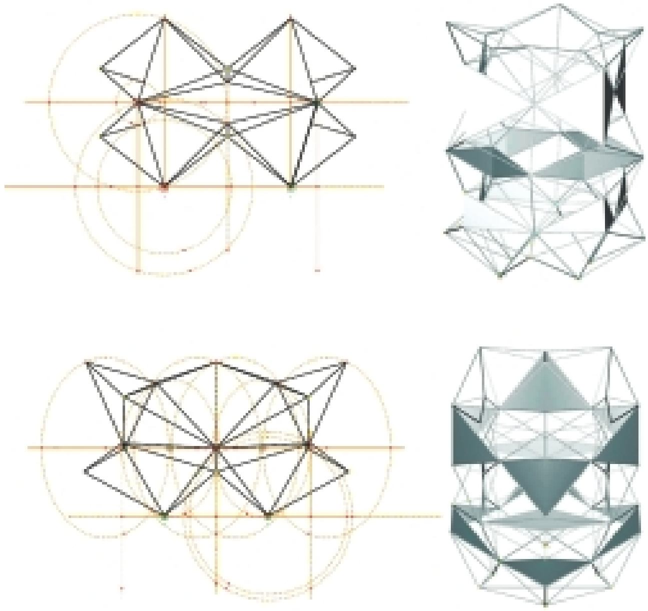

Figure 8.7 A parametric model by Bengt Cousins-Jenvey designed to model the same behaviour of a physical mechanism. (Image courtesy of Bengt Cousins-Jenvey.)

This is not to suggest that the rational concept is an abstract entity entirely prior to considerations about how it will later be produced. On the contrary, at their best, digital technologies for fixing concepts offer entirely new ways to approach design that potentially aid these considerations. Since the origin of the word in the mid-sixteenth century, 'de-sign' has referred to the 'marking out' of the final geometrical form of the thing to be made, with increasingly less emphasis on the process by which it comes to be made. Standard architectural drawings are primarily a representation of this form. As parametric and algorithmic approaches produce that form through a logic that is relational and procedural respectively, they are better suited to engage with the process of building. What the designer plans in rationalising a schema is not just the final form, but may also be the logic that drives the geometry and the means by which construction will proceed. Hugh Whitehead (personal communication) has described this as 'embedded rationale', to distinguish it from the post-rationalisation that often occurs in the translation of a freehand sketch to the hard geometry of a working drawing, and the subsequent interpretation of that to the final construction.

In teaching computational methods in design, this consideration of methods of production and construction has therefore become one of the greatest benefits, and so examples of student work demonstrate the possibility of a close tie between the concept represented in digital models and that on which the real project is built. Bengt Cousins-Jenvey has developed a physical parametric formwork for jump casting concrete columns. The range of possible forms is constrained by the geometry of the mechanism. By setting initial constraints as parameters, the process of casting from the bottom up is modelled in a hierarchical manner using Bentley GC (Figures 8.7 and 8.8). Olivier Ottevaere has used a parametrically driven projection of a

Figure 8.8 The mechanism used as a physical parametric mould to cast concrete. (Image courtesy of Bengt Cousins-Jenvey.)

high-dimensional grid to generate aperiodic geometry, so that a limited set of tiles or formwork can be used to construct an endlessly varying surface. By using a digital model of process into which the method of construction has been functionally embedded, both projects are able to realise complex and varied form from a limited set of parts, economically and efficiently (Figure 8.9).

In terms of supporting a distributed intelligence, the precision this allows facilitates communication throughout the design and construction process, as a clear concept relating form and process is easily graspable and difficult to misconstrue. Mark Burry's work on Gaudí's Sagrada Familia illustrates this over a prolonged time span. The ruled surfaces from which the entire building geometry is produced can be specified mathematically by a schema analogous to the physical process employed by craftsmen turning plaster disks against a straight edge. While few involved in the construction of the project would have had a working knowledge of the mathematical abstractions of the geometry, the physical process was preserved uninterrupted after Gaudí's death. When Burry began to reconstruct the form of the building in the 1980s, it was only because this process described a clear mathematical concept – one which could be realised with a parametric model – that this could be done with precision from the scant basis of photographs of long-destroyed models, and no conventional architectural drawings.

Figure 8.9 Aperiodic concrete tiles by Olivier Ottevaere. A limited set of tiles can tile an infinite surface without repeating the same pattern. (Image courtesy of Olivier Ottevaere.)

Innovation and interpretation

If rationalisation requires fixing concepts for production, innovation requires *interpreting* things in a different way. Changes of concept have been the traditional role of sketching, whether this is taken as pencil on paper, the construction of models or any number of digital representations. Our ability to change concepts, particularly to see existing objects, models or drawings in a novel way, is frequently acknowledged in definitions of creativity as the essential driving principle of innovation. Schön (1963) describes the generation of a new idea as the 'displacement of concepts'. Koestler (1964) calls it the 'bissociation of matrices'. Akin and Akin (1996) explains the process as changing 'frames of reference'. In all cases the point is that we are able to see the developing design in a number of different ways, and explore the possibilities by changing concepts frequently.

Concept creation is also social, and would appear to emerge even unintentionally given the minimum conditions provided by the repeated transition from concept to instance and re-interpretation mentioned above, if it is distributed among a group of collaborators. Balfour (1893; reprinted in Steadman 2008) provides several examples of an imitation game along the lines of 'Chinese whispers' or 'broken telephone', in which concepts change unconsciously over a series of sketches as each is copied by another person. The original sketch is altered almost

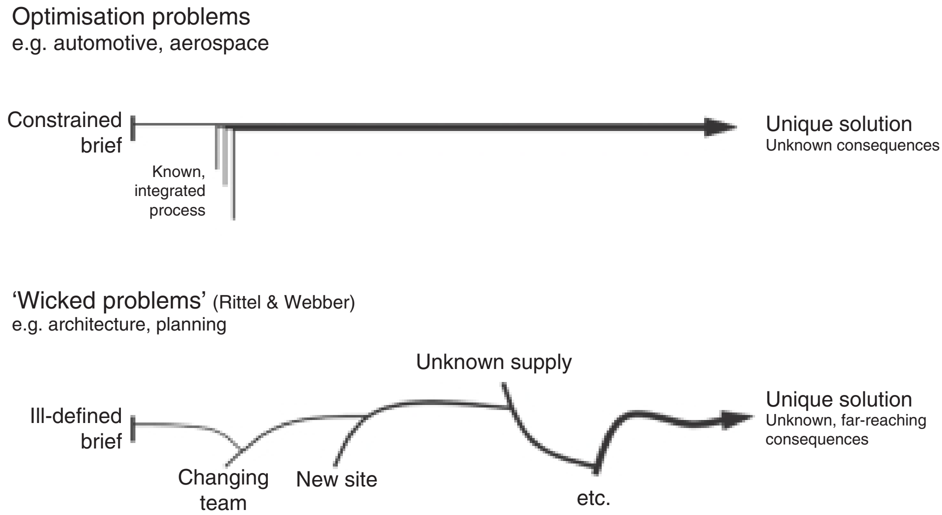

Figure 8.10 Problems that are easily specified lend themselves to parametric representation and optimisation. Design in architecture and many other domains deals with 'wicked' problems that are nearly impossible to make explicit.

imperceptibly by small degrees each time, but what can be recognisably identified as a 'snail on a branch' for the first half of the iterations becomes something entirely different – a 'fish with trousers' – by the end. Here, the sketches themselves are distinct instances of the concept as understood and produced by the artist, and the two clear concepts of 'snail' and 'fish' are interpreted when they view the previous sketch. Although there are gradual changes throughout, only one or two intermediate sketches in the sequence can be seen ambiguously as one concept or the other, and these are what allow the change to take place. These intermediate sketches may be thought of as the hinges on which one concept can change into another. By being interpreted in an different way by different people – the original artist and the copier – they thereby initiate the innovation.

These hinges are particularly important with respect to distributed intelligence because they form an alternative means of communication that is overlooked in many formal accounts. As designers we do not only discuss well-defined concepts, but trade actual instances of drawings, models and prior precedents which potentially convey a far richer and more complex set of ideas than we might be able to make explicit. Different members of the design team will bring their own different conceptual framing of the problems, or a single designer will change their way of looking at it, as Schön and Akin describe.

The need for this is particularly great in architecture, as the particular problems it sets are what Rittell and Webber (1984) call 'wicked problems': they are ill-defined, unique to each job and have far-reaching consequences that are difficult to pin down (Figure 8.10). This may be contrasted, for example, with an engineering optimisation task in which the objective and domain can be clearly defined. The working relationships of the team both in design and construction also change depending on requirements from project to project, and the structure of communication must be reconstructed to some extent. This differs considerably from the automotive and aerospace industries, for instance, in which much more about the design objective, process of manufacturing and channels of communication is clearly defined and constrained in advance, is considered a known variable throughout the process, and can be included in a conceptual schema requiring investment of time and resources at the outset of a new production line. Engineering optimisation and the automotive and aerospace industries are thus ideally suited to parametric and similar methods of working in which the concept is fixed and then explored in detail (and this is where most development of such computational tools originates), but there are a number of tasks in architecture that are not.

The difficulty often shows up when designers first learn to work with parametric tools; wanting to 'just move this element here' in a way that was not foreseen when originally setting up the relationships in the model can be a frustrating experience. Although somewhat obscured by the growing popularity of advanced digital design tools in producing and rationalising complex form, there has traditionally been a division between the mentality of the 'designer' and that of the 'technician', 'researcher' or 'engineer' that has limited the use of many computational processes – from shape grammars to optimisation – in design. This is not a matter of access to technology, but a much deeper conflict between these methods and the designer's need to change concepts with ease.

The current state of CAD and computation

Of the two roles, the latter requirement of innovation and interpretation has been relatively unsupported by computation and related tools. Why this is so is partly historical, as the development of CAD and design computation since the 1960s has primarily been along the former stream: one that fixes concepts, making them clear and rational. Since Sutherland's Sketchpad, generally considered the first CAD software, the form of these tools has typically been a screen-based version of the engineering drawing in which the user can manipulate the precise geometry of points and lines to represent the design in two or three dimensions, but one of the advantages of the computer is that there is a greater range of possibilities for manipulation of these elements. Parametric modelling, for instance, is often considered to be a radical new one of these. As an example of the current state of the art, an introductory demonstration of Bentley's Generative Components typically involves drawing some geometry such as a number of lines between points in a model; then when the points are manipulated the lines are automatically updated to move with them (Figure 8.11). The individual elements are shown to be meaningfully associated with one another rather than the simple, static geometry one might otherwise expect in a drawing. This is certainly useful and impossible to do with pencil and paper, but it is also precisely the same demonstration given by Sutherland of the first CAD software nearly half a century ago. While the technological progress since then has brought us far more power in terms of speed, size and resolution, even the latest developments in modelling are still based on the same underlying principle.

The approach may be called 'symbolic'. The identity or meaning of a given element is determined first – a circle as defined by a centre, radius and plane normal vector – and internally represented in this way by a set of abstract symbols that correspond to each of these. It is only then displayed to the user as a 'circle' in the graphic display of the model. This is the case under the surface of standard CAD software, and new parametric approaches simply advance the same idea by making the underlying symbolic relationships ever more explicit. In Generative Components the 'symbolic model' is even labelled as such (Figure 8.12).

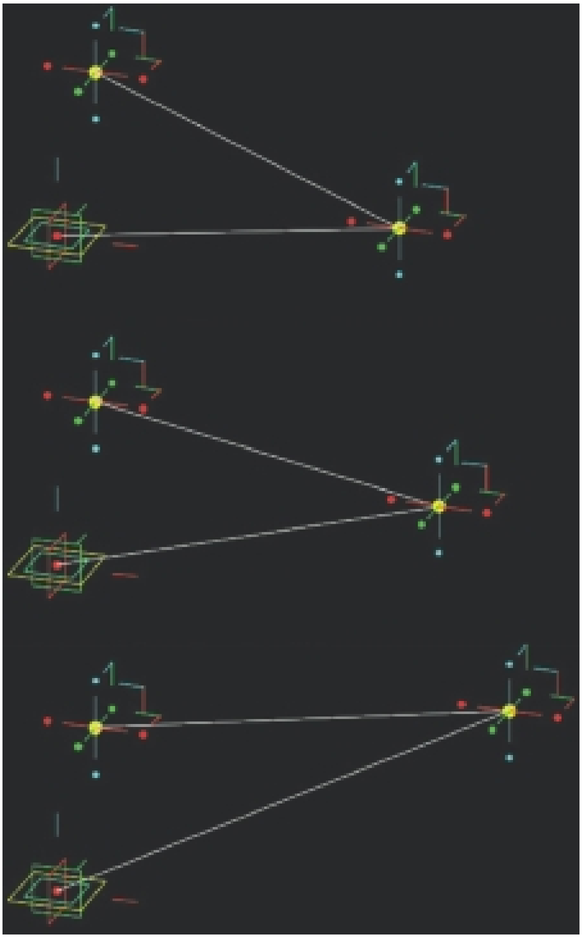

Figure 8.11 Contemporary software updates dependent lines in a model when a point is moved to a new location. The underlying principle of parametric software is unchanged since the 1960s.

This symbolic approach has roots across a number of diverse fields, all represented by major formative activity surrounding the birth of CAD at MIT in the 1960s. The field of artificial intelligence was pursuing the hypothesis that thought itself was itself a symbolic system, and for many years after Minsky and Papert's book *Perceptrons: An Introduction to Computational Geometry* (1969) appeared to discredit the only major alternative, this was almost the only view taken by the research community. In human linguistics, Chomsky (1957) worked out formal rules for generating syntactically correct sentences. Stiny (1976) followed this with shape grammars for generating form, and almost all computer implementations of these have reduced shapes to symbols. In all cases, meaning is assigned to the symbols a priori, and their manipulation then proceeds entirely by concise formal rules. The reasons for this approach were partly philosophical, employing the successes of formal logic practically within each field, and partly simply the limits of the technology at the time. With computational capacity limited and expensive, the only way geometry, words or concepts could be represented in real time and in three dimensions was to reduce them to primitives that could be manipulated symbolically.

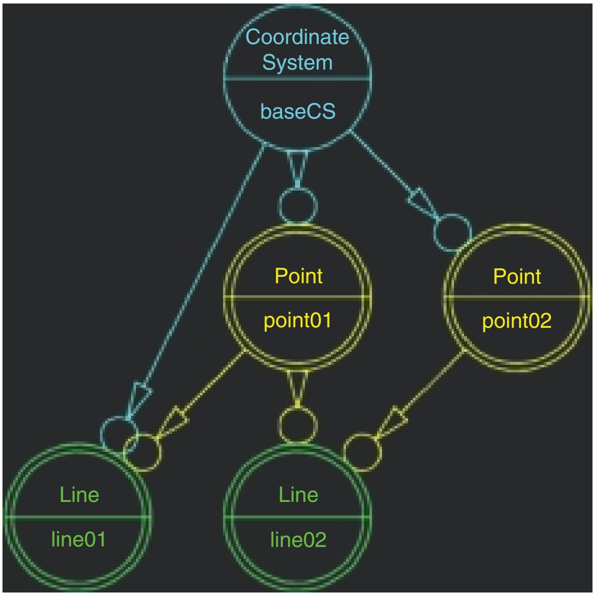

Figure 8.12 The symbolic model shows the real underlying relationships between the elements of geometry.

In theory, there are other ways of looking at these cognitive issues, expressed philosophically for example by Heidegger and later Wittgenstein. As Dreyfus and Dreyfus (1988) note, what the symbolic approach ignores is 'the pre-eminent role of pattern discrimination in human expertise'. Interpretation, rather than simply production, is a fundamental aspect of human thought that simply does not happen once symbols are assigned to each phenomenon. We can define a circle as 'centre, radius, normal vector' or we can define the same circle as 'three points' through which it passes. We can also interpret the same circle in these ways, or as an ellipse (with equal axes), an arc (of 360°) or a limitless number of other things.

Now, alternatives are also possible in practice. We have several things – quantitatively and qualitatively new things – now that we didn't have in the 1960s. The first is the result of Moore's (1965) law. We have faster and more powerful computers: about four million times so in the 44 years since the trend was first noted. The second is the corresponding ability to process much greater amounts of data, not just because of faster hardware but because of the effort that has gone into new algorithms and statistical sciences in the past decades. The inspirations and reasons for these come from new developments that did not exist in the 1960s, such as those of the internet.

So how does Google do it? A search engine that guides navigation through 50 billion pages is simply not interested in algorithms that can't handle vast amounts of data, and with the relatively unstructured information on these pages changing and growing constantly it must be able to change and adapt rapidly, just as the designer does. The new algorithms are becoming better and better at interpreting this data.

The surrounding fields mentioned above have moved on to explore very different basic principles in recent decades. Rather than 'symbolic', these might be called 'messy data' approaches. Instead of predetermining the structure or protocol in advance as in symbolic processing and communication, they leave this open, to be derived from the data. Their base requirement is not the clear concept but the instance. In artificial intelligence, the apparently discredited connectionist paradigm has been found valid after all, and now dominates in many domains. In subfields like embodied robotics, symbols are rejected with the whole idea of representation of any sort, on the grounds that, as Brooks (1991) states, 'it turns out to be better to use the world as its own model'. Chomsky's (1957) hard rules for generating syntax can be contrasted with Elman's (1995) model of a dynamical system, in which words and meanings are overlapping regions in a state space that are passed through in forming an utterance. For Chomsky, the structure of language is innate and so shared by humans even before we begin speaking, while for Elman this structure can be learned. Chomsky's structure can be implemented computationally with relatively low bandwidth, with discrete and fixed units, whereas Elman's requires much higher bandwidth and states are represented by real values that are flexible. The symbolic implementations of Stiny's (1976) shape grammars made the reinterpretation of shapes and the identification of emergent shapes nearly impossible, but the most recent work in the field uses image recognition to interpret the pixels as displayed on the screen, almost as a human user would when viewing the shapes (Prats *et al*. 2009, and personal communication). Each of these requires a significant amount of processing power to interpret and make use of large amounts of data, but that data can be reinterpreted differently many times. It is this sort of model that points the way to an alternative stream of possible design computation, the technical requirements for which we are only now beginning to realise.

Future methods

If such flexible tools have as of yet been relatively unexplored, the question is: Where can we go with them? With research yet to come, it is perhaps too early to make specific predictions as to how much the 'messy data' approaches are capable of in design, but I will conclude by suggesting three general areas that appear to offer potential for development.

The first concerns the crucial issue of the structure of the data itself: what these future methods manipulate. Rather than working with reduced symbolic representations, they may instead use the raw data in all its complexity – point clouds, not primitives. Original data as derived from laser scanning and similar input is currently passed through a series of stages of filtering before it is used, each one fixing and standardising a certain concept of the geometry, and each one losing some information. When that data is used in different contexts, or output (say, to a CNC fabrication process), further processing is required. With computational systems available that do not require the reduction of the data, less standardisation of formats is necessary, less information needs to be lost and communication between parties and contexts is eased.

Another direction might utilise more structure, with CAD tools based not on abstract symbols, but on basic properties that really are intrinsically meaningful in design. Space itself is an option. Standard CAD models place geometry in the Cartesian grid only after manipulating it symbolically, and in parametric models dependent relationships between elements must be determined explicitly. Natural, spatial relationships between elements in real designs, such as 'inner/outer', 'closest to *x*' and so on, have no place in these models. A common frustration is exemplified by a student at a recent parametric workshop, who ran up against such a problem in attempting to get the software to recognise the convex open spaces formed between a set of arbitrarily placed objects. These clearings in a forest are immediately obvious to any designer, but invisible to the symbolic algorithm. While they may be highly relevant to the design, in order to calculate these sorts of relationships the computer must perform exhaustive searches through the symbolic list of elements in the model or employ spatial partitioning algorithms to narrow this search down. Tools that can operate with these kinds of natural relationships, either graphically or in combination with procedural scripting, would more closely resemble our natural spatial reasoning.

The third area of promise concerns the question of whether the computer is able to come up with its own concepts, to read from unfiltered data and make meaningful design decisions. This appears to be possible. In investigating whether various non-discursive properties – properties that can be discerned but not explicitly articulated – of city neighbourhoods can be found, it has been shown that a computer is easily able to distinguish the quality of one neighbourhood from the next (Laskari *et al*. 2008). Perhaps counter-intuitively, this cannot follow from the analysis of any particular variable, but only from the interrelation of large amounts of varied inputs. Similarly, the structure of whole cities can be measured to reveal correlations with geographical or cultural proximity (Hanna 2009). In these cases the computer can evaluate purely geometrical or visual data at its lowest level to come up with meaningful distinctions or concepts of its own. This is entirely the opposite approach to the symbolic marking of semantic properties by tagging objects with metadata, as the concepts themselves are liable to re-interpretation if a different set of instances are involved.

These three areas have implications for designers and collaborators, in terms of how design is progressed and communicated. The 'messy data' approaches have been invaluable in aiding our understanding of language and visual perception when surroundings are unstructured, but are particularly important in design, where wicked problems abound. In design we typically don't have many clear, rational briefs, but we do have a lot of instances of good and bad design. What these approaches point towards are a means for interpreting and communicating these that supplement and extend our private intuition. The dynamics of doing so are even more complex when multiple designers are involved. Collaboration is mediated by the methods and technologies we use to communicate. Concepts must be communicated in different ways, and the methods and technologies used to do so determine the distributed and collaborative process of design.

An important consideration is in the building of non-standard architecture. Any conventions required for effective communication between designers, and between design and construction, must be determined beforehand for communication to take place. When the pace of change is slow, this follows almost unnoticed as new drawing formats, specifications or digital technologies are adopted gradually. Anyone attempting to make something non-standard, which is outside normal practice and therefore more difficult to describe, is faced with the difficulty of communicating this to the rest of the team. The ability to do this has been increased by the proliferation of digital technology in recent years, but the standards of representation and communication here are often not ideal. A fully automated digital fabrication process, for example, can efficiently produce a great deal of complexity, but the design must be entirely specified in the file the designer provides. Many stages of optimisation, material and structural efficiency and knowledge of construction that would be distributed more uniformly along a manual process are compressed into the first stage of file specification. The standard formats used to transfer and manipulate data are also not necessarily suited to the particular task, with many CAD/CAM algorithms having originated for the efficient display of graphics in virtual, not real, physical space. Algorithms that allow one to change from representation to representation, whether standard or non-standard, would allow the flexibility of communication and representation of new and innovative design.

A full definition of intelligence includes both the clear, rational processes of logic, and also the creative processes of intuition. Both forms of working are essential to design. We appear to work by alternatively fixing and then changing concepts, and it is this switching from one mode to the other that propels creative design. In the past this has occurred entirely manually and currently (as in the initial project by Gormley) it involves a combination of manual and digital methods, but these digital methods almost exclusively support production via the fixing and rationalisation of concepts. Interpretation and creativity are more mysterious notions that may appear antithetical to the digital technology with which we are familiar, but the research mentioned above demonstrates that this need not be the case. If the next few years yield tools that not only produce instances of rational concepts but enable the interpretation of instances to produce new concepts, they will be a valuable asset to designers' communication and exploration in an increasingly networked and complex environment. We have tools for the production of concepts, but when we add to these the tools to support the interpretation of instances, our collaboration will approach distributed intelligence in this full sense.

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Part 3

9 The effects of integrated BIM in processes and business models

Arto Kiviniemi

The idea of building information modelling (BIM) was created in the mid-1970s, first under the name of building product modelling (Eastman 1975). It started to become a wider industry issue after 1995, when the International Alliance for Interoperability (IAI) began to develop a standard called Industry Foundation Classes (IFC), a schema and format for data exchange between different software applications used in architectural, engineering, construction, owning and operations (AECOO) activities (IAI 1995). In the first 10 years the main focus in the development of BIM was strongly on the technology. This was necessary since standardised data exchange is a mandatory precondition for an efficient BIM-based work flow between different participants – integrated BIM (iBIM) – and the development and implementation of such a standard proved to be significantly more complex than was believed at the beginning of IAI (Kiviniemi 2006; Kiviniemi *et al.* 2008). However, despite the still existing technical problems and limitations in data exchange (Kiviniemi 2008), the main obstacle to the deployment of iBIM in the last few years has not been the technology, but the old work processes, old business models and conservative attitudes in the industry. The traditional paper-based processes do not utilise the full potential of iBIM and the AECOO industry's business models do not support the necessary development of the processes. Finally, in the last few years the development focus has started to shift towards necessary changes in processes and business models. This chapter is based on several research and pilot projects and the development and use of iBIM in Finland since 2001 and highlights some of the current problems.

Point of departure and main drivers for change

Finland has been one of the leading countries globally in implementing and deploying iBIM in the AECOO industry since early 2000 (Laiserin 2002). The main reasons are that Finland has invested significantly in the research and development of iBIM since the late 1990s (Froese 2002; Uusikylä *et al.* 2003) and the relatively small size of the AECOO market, which enables agile changes (Laiserin 2002). However, the real business use of iBIM is still limited even in Finland, and it is obvious that the technology has advanced much faster than the work processes and business models. This is a problematic situation since, at least based on some studies, the

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

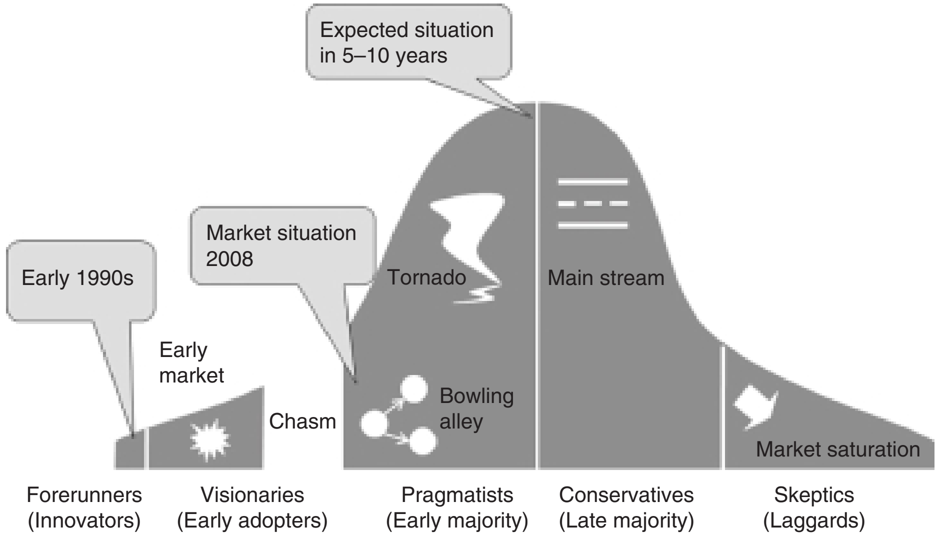

Figure 9.1 BIM Market Situation (Reproduced by permission of AE Partners 2008).

productivity advantages of the R&D efforts in business models and processes are significantly better than the advantages in the development of new products, services or systems (Helin and Lehtonen 2007).

Complex ad hoc delivery chains are typical for AECOO. These chains cause information loss and do not support optimisation of the total solution or an informed and balanced decision-making process, rather sub-optimisation on a company level and decisions based on the direct investment costs only. Integrated BIM is a central element in making the processes and information management more effective and efficient considering the whole lifecycle of buildings. Another, strongly increasing driver for change in the AECOO industry is client demand to be able to predict and compare sustainability issues and the environmental impacts, such as CO_2 emissions, of different design solutions, production processes and lifecycle solutions reliably throughout the design, construction and maintenance phases. Integrated BIM is also a significant enabler in this task because of the virtual prototyping, quick and efficient production of BIMs which can be used to analyse and simulate the different properties and behaviours of possible alternatives.

Interest in environmental issues and the use of iBIM are rapidly increasing, not only in Finland but around the world. It seems that global investors and clients will change the business environment significantly in the next few years. This phenomenon is already clearly visible in the US market, where LEED certification has been a must in projects for some years. Likewise, the penetration of BIM and integrated project delivery (IPD) in the US is growing rapidly. A survey by the American Institute of Architects indicated that in 2006 10 per cent of architects used BIM in billable projects (AIA 2006), but in 2009 over 75 per cent of architects reported that they were heavy or very heavy users of BIM in their projects (O'Brian 2009). In Finland iBIM has clearly moved from the 'Chasm' to the 'Bowling Alley' phase (Figure 9.1). In this phase success in one market segment accelerates rapidly the groundswell of new technologies and processes into closely related segments, leading to the 'Tornado' phase and changing new technologies in mainstream applications.

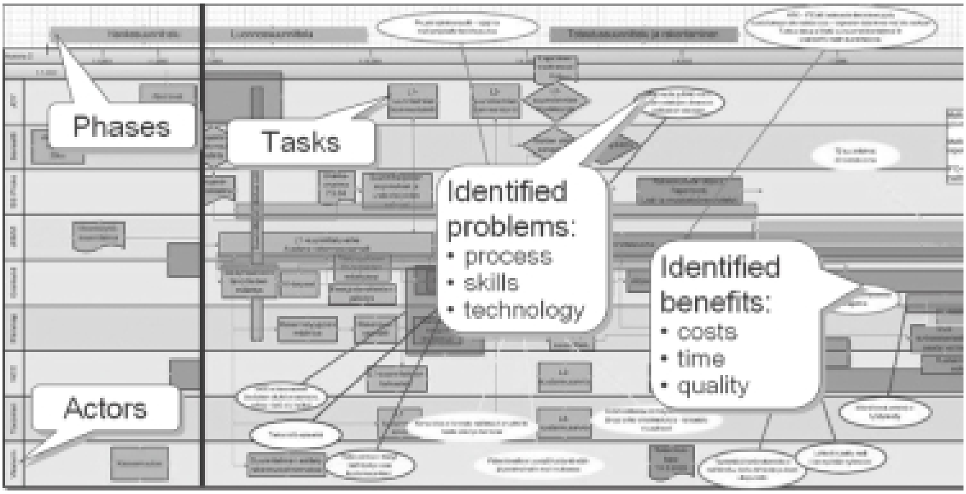

Figure 9.2 Part of the Process Model in Aurora 2 Project (Björkstrand *et al.* 2009, reproduced by permission of TKK/SimLab and Senate Properties).

Current problems in processes and business models

The obstacles to adopting iBIM can be categorised into legal, business, human and technical problems. Among the legal problems are, for example, the undefined responsibilities of data content in BIM, undefined legal status of the models in relation to other documents, and copyright issues. Business problems are mainly related to fuzzy processes and lack of adequate incentives: when and who should deliver what information into the models, who must invest and who gets the benefits, should the roles and awards be based on the added value, and how to measure the added value and performance of the actors. Human obstacles are the general resistance to change and fear of losing the current role and position in the total process (Kiviniemi and Fischer 2009). Technical problems are related to the immaturity of the BIM software, especially in the area of data exchange and interoperability (Kiviniemi *et al.* 2008). This chapter concentrates on the business models and work process issues only.

The main problems in the AECOO industry are created by the fragmented process and low-bid business models, which enforce sub-optimisation on the company level. The lack of real process owners and sufficient business incentives slows down or even prevents systemic innovations; that is, innovations which require changes in multiple organisations along the value chain (Taylor 2005). The efficient use of iBIM is such an innovation. Just changing the media from drafting to iBIM without major changes in the process and an adequate reward system is not enough.

A detailed study of an advanced iBIM project in Finland indicated that, in addition to the benefits from using BIM, there are significant problems in the current processes (Björkstrand *et al.* 2009). These problems can be categorised into process, skill and technology problems (Figure 9.2). The study identified several process problems at different stages of the process. Typically the information was not produced or delivered in optimal sequences; that is, some crucial information was missing when a dependent task had to be performed.

The current design processes are based on tasks which define the required documents at different design stages, but not the needs for actual information flow. In addition, the project

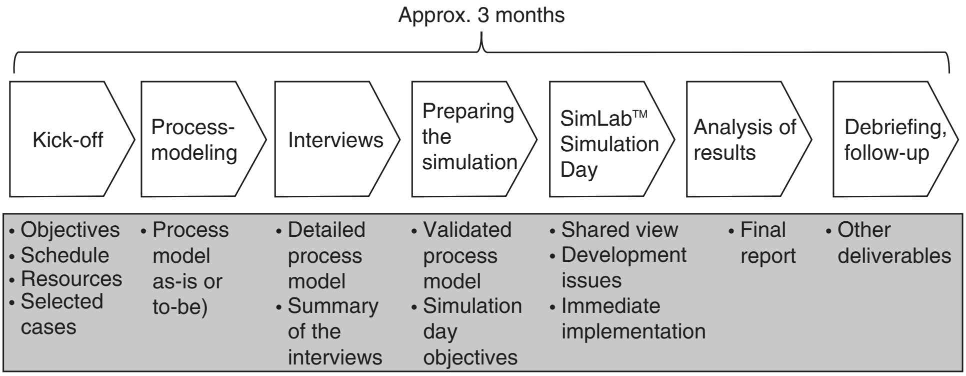

Figure 9.3 The SimLab™ Process Development Method (Hirvensalo *et al.* 2009, by permission of TKK/SimLab).

participants do not sufficiently understand the informational dependencies between the tasks in different domains. The SimLab™ methodology (Figure 9.3) was used to analyse and increase the understanding of these dependencies. The methodology combines efficiently and effectively the scientific research and a learning process for industry professionals. However, currently we are just at the beginning of analysing iBIM processes, and more research and piloting are needed before we know which the optimal new processes might be.

Solutions to the existing problems

Some large public owners, such as General Services Administration (GSA) in the US and Senate Properties in Finland, have made significant efforts to speed up the adoption of integrated BIM by defining specific modelling requirements and publishing BIM guidelines (GSA 2007; Senate Properties 2007). In addition, together with the Norwegian Statsbygg and Danish Enterprise and Construction Authority, in January 2008 they made a public statement of intention to support BIM based on open standards (GSA 2008).

Senate Properties is a government-owned enterprise responsible for managing and letting the property assets of the Finnish state. The property stock includes university, office, research, cultural and other buildings, and its total value, €5.8 billion in 2008, makes Senate Properties the largest building owner in Finland. Senate Properties has been a global forerunner in deploying integrated BIM in real projects. HUT-600 was the world's first IFC-based integrated BIM project. Calvin Kam and Martin Fischer wrote a globally well-known report about the project experiences (Kam and Fischer 2002) and this had a significant impact on GSA's decision to start testing the use of IFCs. Senate Properties' BIM requirements (Kiviniemi *et al.* 2007) in October 2007 were likewise the first global effort to use IFC-based BIM throughout the architectural design process, and this requirement was expanded to cover all design domains in April 2009 (Figure 9.4). The next step, definitions and guidelines for BIM-based facility management processes, started in autumn 2009 and was expected be effective by August 2010.

However, even the largest public organisations, such as GSA or Senate Properties, represent only a very small fraction of the total AECOO market, and therefore the problems described above cannot be solved rapidly by any individual organisation. In addition, public organisations

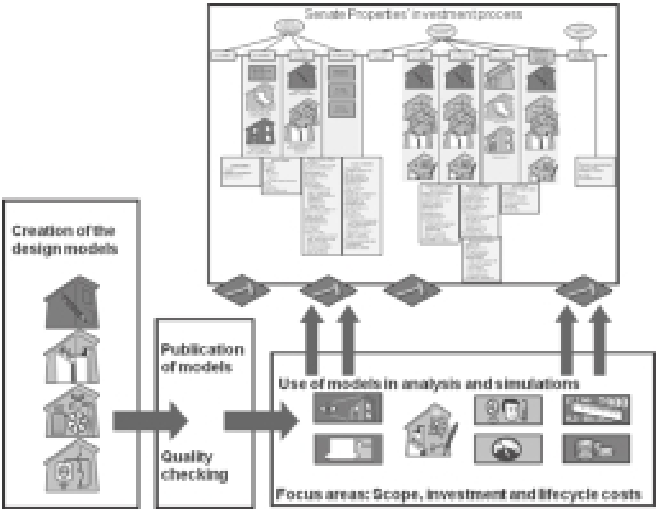

Figure 9.4 Senate Properties' BIM-based Process (Kiviniemi *et al.* 2007).

have to follow strict legal requirements in their bidding process and treat potential bidders in an even-handed manner. This situation inevitably limits rapid process changes and requirements, which could set limitations to the use of different applications. On the other hand, it strongly supports the development of open standards. Because of these limitations in public organisations, the AECOO industry needs also additional efforts to create a new 'business eco-system', a platform that supports innovative changes and advanced collaboration in projects.

One possibility to remove the obstacles is forming private consortiums which voluntarily agree a different way to work together. An excellent example of this is Sutter Health in California. In 2005 it decided to adopt a new process combining integrated BIM and lean construction methods in its hospital projects. The first project using the new process was Camino Medical Group Mountain View in California (Reed 2006; Khanzode 2007). The success of the project created the foundation for a new project delivery method in the US by breaking the traditional legal and business barriers and creating a new contract model for the industry.

> In integrated project delivery (IPD) the disparate legal, design and construction communities have a project delivery model that empowers committed stakeholders to take advantage of design and delivery innovations simultaneously. The keystone that supports the effective and simultaneous use of innovations manifested by BIM and Lean Construction is the new generation of Collaborative Agreements. (Salmon 2009)

A different approach to solving these industry-wide problems is now under development in Finland. The traditional Technology Programmes of the Finnish Funding Agency for Technology and Innovation (Tekes) are now partially being replaced by Strategic Centres for Science, Technology and Innovation (CSTI). The CSTIs are new public–private partnerships which aim to speed up innovation processes in Finland. Formally CSTIs are companies owned jointly by industry, universities, research organisations, cities and other interested shareholders, and their main goal is to thoroughly renew industry clusters and to create

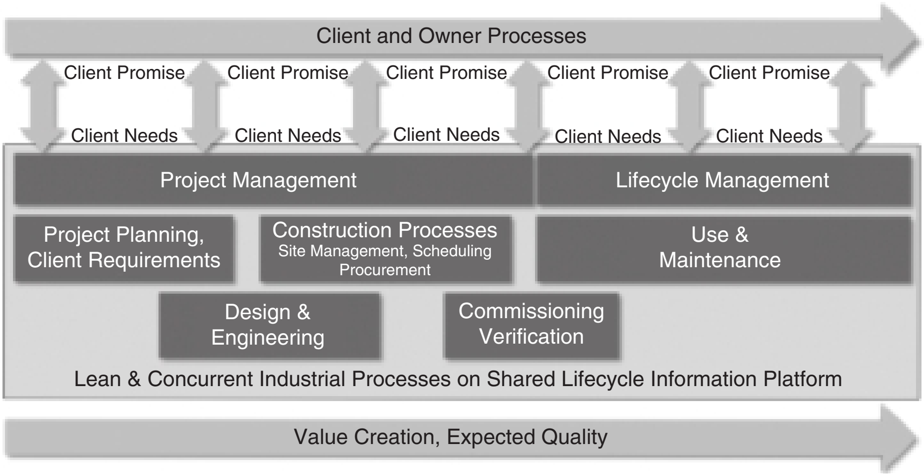

Figure 9.5 Client and Value Driven Processes (Kiviniemi & Fischer, 2009).

radical innovations. CSTIs develop and apply new methods for cooperation, co-creation and interaction. In CSTIs companies and research units work in close cooperation, carrying out research that has been jointly defined in the strategic research agenda of each CSTI. The research aims to meet the needs of Finnish industry and society within a 5–10-year period (Tekes 2009).

The new CSTI for the Built Environment (RYM Oy 2009) began its activities in autumn 2009 and the author is leading the preparations for a large R&D programme called 'B^3 – BIM-based Business' for the Centre. The goal of the proposed programme is to move from the current fragmented and production-oriented processes into new processes driven by client needs; that is, to develop new business models and work processes based on added value for the customer (Figure 9.5).

These processes should be based on open business networks and contracts which enable transparent and supportive compensation for all participants based on the actual value creation. A central element in these processes is the iBIM, based on open standards, flexible sharing of information and delivery of lifecycle information as a part of the product. The vision is that companies can increase their productivity and competitiveness by developing their own internal processes on top of the shared common data and process platform (Figure 9.6).

The programme is planned to cover both building and infrastructure sectors and it is looking also for collaboration with the ship-building industry, which faces many of the same problems as the AECOO industry. The programme will consist of public research accompanied by semi-private 'Aquarium' projects, consortium projects whithatch will be at least partly visible to the other companies and organisations and will support the overall goals of the programme (Figure 9.7).

In addition, the programme will include international collaboration, interdisciplinary research and participation from other than the traditional technical and AECOO domains. The necessary radical changes require 'out-of-the-box' innovations. The aim is to start in 2010 a 4–5-year programme with an annual budget of €5–10 million. Because it is in its early stages, the final content

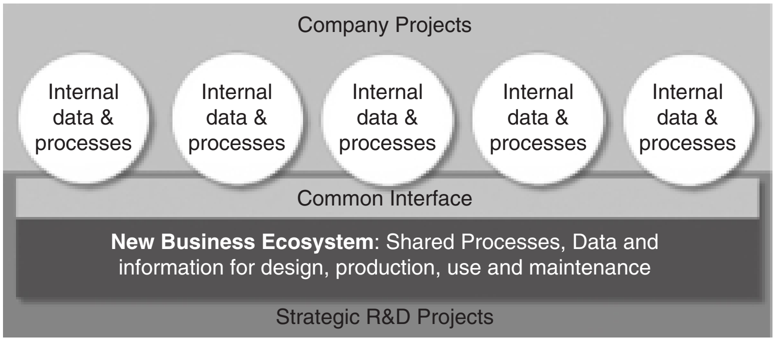

Figure 9.6 Internal and External Processes (Kiviniemi & Fischer, 2009).

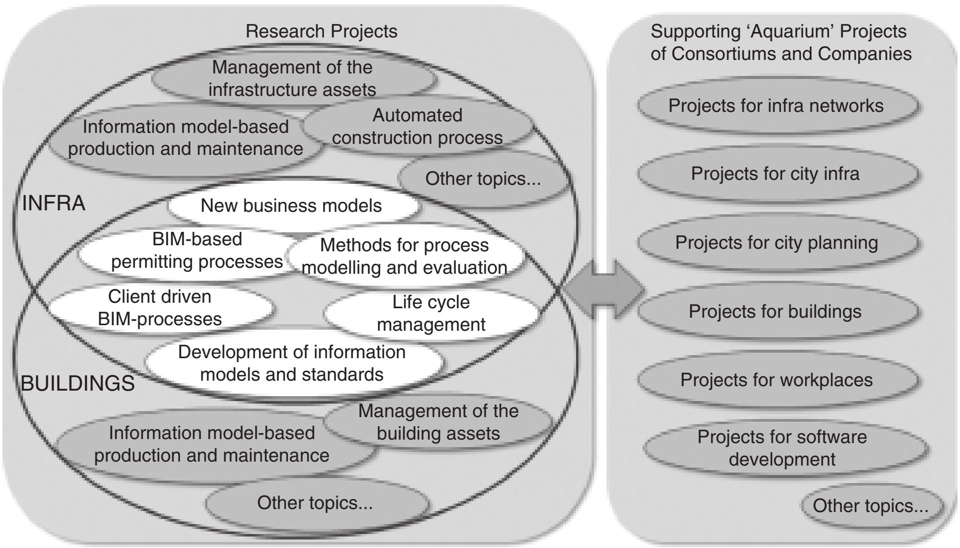

Figure 9.7 Overall structure of the planned programme (Kiviniemi & Fischer, 2009).

of the programme is still open and there are no official references, but the following potential topic areas have been identified in the current project plan:

Acquisition, contracts and management of BIM services

- Bidding process and contract models for integrated BIM services.
- Acquisition of BIM-based project services: design, construction management, other expert services.
- Acquisition of BIM-based maintenance and operation services.
- Quality system for BIM-based processes.

BIM-based processes in different phases of the lifecycle

- Client briefing: functional, financial, energy and environmental goals.
- Design: management and verification of requirements fulfilment, interfaces between models in different design and construction phases.
- Construction and commissioning: management of processes and schedules, interfaces between different designs, production and as-built models.
- Use and maintenance: portfolio management, management of spaces, maintenance and services.
- BIM-based renovation processes.
- Production and lifecycle cost management: BIM-based production and lifecycle cost estimates in early project stages, restructuring of design data for bidding, purchasing and production, comparison methods between cost estimates in different phases.
- Decision making methods in a multivariable environment: decision dashboards for AECOO.
- BIM-based code checking, permit and approval processes.

Development and implementation of open BIM standards, platform and software

- Information platform for real-time information sharing throughout the lifecycle of the product.
- Development of open standards for model structures and interfaces for new process requirements.
- Analysis, documentation and standardisation of tasks and information needs for the whole lifecycle of the built environment.
- Tools for client requirements and change management.
- Tools for process management and simulation.
- Electronic services throughout the lifecycle.
- Data services and registers, access control and maintenance.
- Product libraries based on open standards.
- Equipment, software and methods for digitisation of existing environments.
- Information lifecycle management: BIM archiving and utilisation throughout the whole lifecycle by all shareholders, processes for information updates, management of evolving information structures and user needs.

Key performance indicators for portfolio management in an integrated BIM environment

- Corporate real estate management (end-users).
- Property management (owners).

Overall process development

- Project management methods and tools for BIM-based design, construction and maintenance processes.

- Process modelling and simulation, system dynamics.
- Obstacles and drivers for change: psychological, contractual and legal issues.
- Benchmarking to other industries: ship building, automotive, aerospace.
- Metrics for productivity and added value.

The above lists are a result of the brainstorming phase in summer 2009, and their main purpose was to identify existing problem areas. In autumn 2009 the preparation efforts focused on the selected main topics.

Conclusions

Integrated BIM has created the technical foundation for new business models and work processes in the AECOO industry. The situation is in many ways similar to the mobile phone market, where the new technologies and standards in the late 1980s and early 1990s created new opportunities and fundamentally changed communication services and finally the culture: the way people communicate. In the AECOO industry companies are now starting to realise the new possibilities which iBIM can offer. The market is in strong development turbulence despite of difficult economic situation in the global construction industry. The two main obstacles to the change are old work processes based on the use of documents, not on the necessary information flows between project participants; and low-bid business models, which do not reward actual added value or optimisation of the whole project, but support sub-optimisation on the company level. Companies' internal processes are strongly connected to the legal and technical interfaces between them and the fundamental process changes require a new mindset and collaboration of multiple actors to create a new 'business eco-system'. This can happen either by the pressure from the major clients, such as GSA and Senate Properties; by following success stories of voluntary consortiums, such as Sutter Health has created in California; or by forming industry-wide proactive R&D collaboration, such as the Finnish RYM Oy is trying to establish. Despite the different approaches, all these forces are moving the AECOO industry in the same direction and the author believes that iBIM will cause a true revolution in the business model and work processes in the next decade.

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10 Integrated building design for production management systems

Rita Cristina Ferreira

This work presents the results of a research, development and innovation (R&D&I) project that aimed at creating a web information system to support the development of integrated building design for production. This project has been coordinated by the director of a small building design firm, DWG Arquitetura e Sistemas, and has been granted by the largest research council in Brazil (FAPESP: The State of São Paulo Research Foundation), under a special program for technological innovation in small businesses.

DWG was founded in March 1994 and it was the first independent design office in Brazil to specialise in masonry design for production using 3-D models. The challenge was to break with the traditional methods of producing drawings by linking product information with the specification of the production process at the early stages of design development. It was evident that the development of a masonry production system design played a key role due to its myriad interfaces with other sub-systems. Additionally, the elaboration of masonry design required intense coordination across the detailed design phase and design coordination was incorporated within the scope of the R&D&I project. The initial results of integrating masonry design and design coordination demonstrated increased efficiency in identifying and solving problems related to interoperability, modularisation and technology.

Despite the considerable gains that were obtained from this integrated process, problems emerged related to the remote collaboration and coordination of the different design disciplines. For example, one problem identified was concerned with communication between the independent firms responsible for each discipline, causing a lack of information for decision making. These problems were identified at earlier stages of the R&D&I project, causing the re-scoping of the project. Additionally, the development of the design for production of a real construction project throughout the specification and development of the system prototype led to the identification of unforeseen requirements (e.g. 'following up construction') that were incorporated within the final scope.

The final system (namely Sistema π) was developed to support the management of design for production, adding automation processes to perform remote (via web) collaborative work between multidisciplinary teams using 3-D CAD. The development process had four requirements in its validation processes and consisted of consulting with different stakeholder groups.

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The concept of the Integrated Building Design for Production Management System (IBDPMS) was developed involving 13 major construction companies. The conceptualisation and development phases had a total duration of four years. The development of the system took advantage of a deceleration of the Brazilian construction market and the lack of construction projects to get the attention of potential clients. At the same time, the continual emergence of new technologies for design provided a stimulus to the development of the management system. Currently, the results include a complete software specification and 40 per cent of the functional prototype.

Research and development (R&D)

The research and development of the IBDPMS had three stages: idealisation; planning and conceptualisation (research); and development.

The first stage refered to the idealisation of the product and its presentation to FAPESP (the research council). The idealisation evolved over some years simultaneously with the DWG business strategy focused on exploring this new market opportunity.

At the second stage, the conceptualisation consisted of identifying throughout construction the emergence of design-related problems and proposing ideas to mitigate those problems. This conceptualisation was formalised in a business and research plan that was focused on identifying the main market demands and research and commercial opportunities for building integrated design for production.

The third stage was concentrated on the development and implementation of the software prototype. This stage followed guidance from the rational unified process (RUP) model for engineering software process managing, as well Unified Modeling Language 2.1 (UML 2.1; Booch *et al.* 2005) and Business Process Modeling Notation (BPMN; Owen and Raj 2003; White 2004). The software documentation was developed using Enterprise Architect® 7.0.

The RUP model is divided into four *phases* (Rational 1998): inception, elaboration, construction and transition. Throughout these phases, the process and activities are organised according to eight disciplines: business modelling, requirements, analysis and design, implementation test, deployment, configuration and change management, project management and environment. In addition to phases and *disciplines* (two-dimensional processes), the RUP model considers time as a third dimension that reflects the dynamic organisation of the process along time, called *iteractions*. Due to the complexity of the RUP model its implementation was partial and in conjunction with the software agile development approach (Rational 1998; Wikimedia 2008).

In addition to these approaches for software engineering, investigations were conducted into new information models for construction, such as building information modelling (BIM; Autodesk 2005; Howard and Björk 2007). The investigations were focused on identifying trends in construction related to software development. The investigation led to the realisation of a series of workshops with IT and construction experts (e.g. the AIA group, DWG clients). These workshops resulted in the formation of the BIM research group at the University of São Paulo. Furthermore, the research and development was carried out in a concurrent engineerging (CE) fashion (Prasad 1996; Laufer 1997).

With regard to the IBDPMS, the second stage included the inception phase and the elaboration and construction phases of the RUP model. To increase the iteractions, stakeholders were involved throughout four requirements validations. The stakeholders involved were a customer (investor and constructor contractor); architectural, engineering and construction (AEC) professionals; IT professionals as independent consultants and suppliers, namely from software development firms; independent AEC consultants; and academic researchers. The R&D team was also supported by external consultants/advisers for information technology, civil law, construction production, construction management, knowledge management, construction safety and health management in construction, human resource management and economy.

The first validation occurred in a workshop day with customers' representatives, the consultants, researchers and other invited professionals. This workshop included an extensive discussion about the information system and the application of a JAD (joint application development) session. Throughout the workshop, the scope of the management system was clarified and the IT team began to align it to the business modelling. The initial requirements analysis was also performed.

The other three validations considered the participation of different stakeholders' representatives and these happened as requirements and the solution were getting mature. Surveys with AEC and IT professionals and academic researchers were used as a complementary method for requirements capture. The outputs of the inception phase included the final software specifications, the definition of a clear technological and business strategy (including a risk analysis), and a development programme considering the constraints related to the development of the software on a short-term basis (as per the business strategy).

The management system: Sistema π

The proposed management system, namely 'Sistema π', was designed to manage distributed design for production knowledge, involving product designers (architects and engineers responsible for product conception), contractors and sub-contractors and specialist designers for production who are part of the DWG Arquitetura e Sistemas team. Figure 10.1 shows a diagram of Sistema π and the different stakeholders (actors).

This system was conceptualised to manage those decisions that can be seen through the utilisation of 3-D models, such as how the scaffolding would be strategically positioned, considering the walls and the structure, for external rendering. The system has functionalities to capture the communication between designers, contractors and constructors.

It was critical to this system to design an attractive interface for stimulating actors' participation and increasing the management system's effectiveness. During the system development, part of the research was dedicated to investigating web systems' usability. In this respect, technologies such as Silverlight® from Microsoft were tested, including their application with stakeholders and potential clients and users.

Figure 10.2 shows an example of the time management functionality. The schedule is obtained from the interactive process model. A set of different colours and symbols was tried, aiming to improve the system interface. The green circles indicate finished activities; the grey circles indicate activities that have not been done yet; and the major circles in yellow and red indicate the activity currently being undertaken. Below the circles, the date for completion and a short description of the activity being undertaken are shown. In the upper left corner, the name of the person responsible for completing each activity is highlighted.

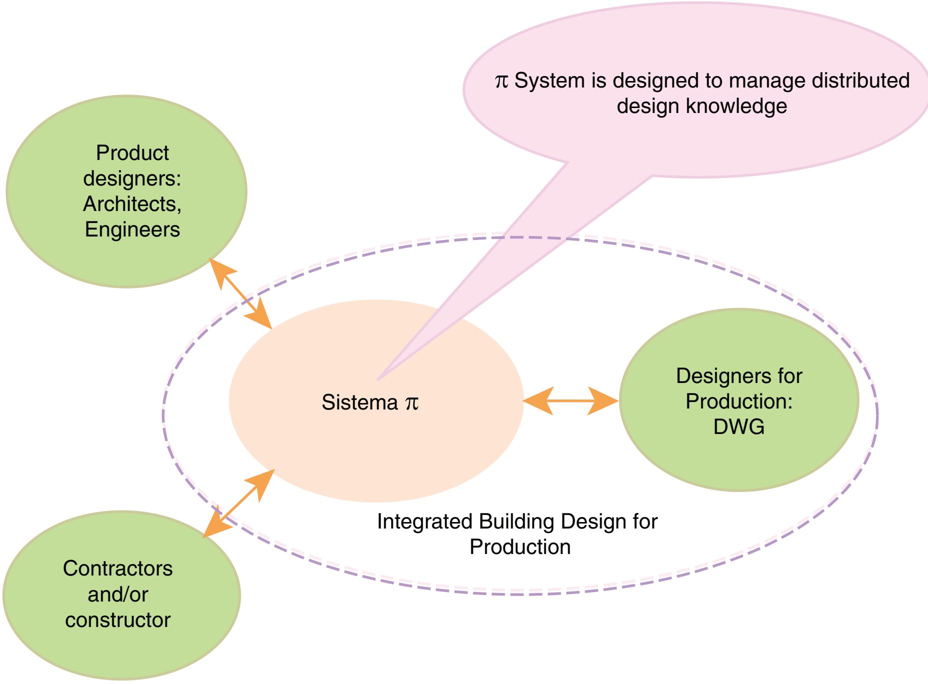

Figure 10.1 View of Sistema π.

Figure 10.2 An example of time management functionality using Silverlight®.

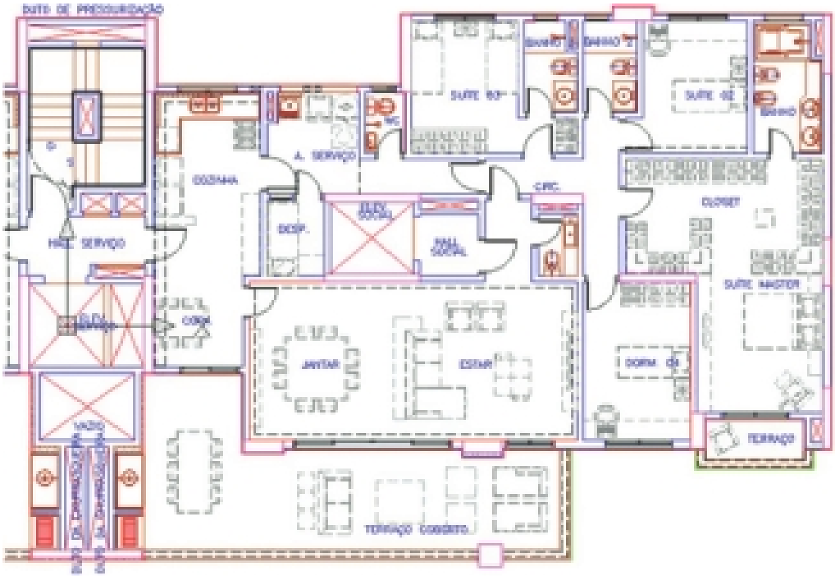

Figure 10.3 Standard apartment.

R&D results

The second phase of the R&D programme was concluded in August 2008. The main output of this phase was the software prototype. Additional outputs of this phase included a pilot integrated building design for production; an information hierarchical classification; a process map for the integrated building design for production; and proofs of concept for the management system. These are further described in the following sections.

Pilot integrated building design for production

Simultaneously with the system development, a pilot integrated building design for production was developed. The pilot study included masonry design, external rendering and plumbing systems. All building systems and sub-systems were modelled using 3-D CAD, which allowed the R&D team to collect information for mapping the management system.

The pilot design was undertaken by the main contractor (one of the largest construction companies in the country, Construtora Cyrela SA). During the design development, 30 professionals of design firms, contractors and constructors were interviewed. These interviews were used to identify requirements that would increase the added value of the system (for example, the willingness to pay a price for offering the management and design service). Further details about these interviews can be found in Ferreira (2007).

The selected pilot project is located in a high-density urban area of São Paulo, Brazil occupied by high-rise residential buildings. The pilot project consisted of a residential building, with 32 floors above ground level and two basement floors. The building has 54 standard apartments (Figure 10.3), 2 duplex apartments and approximately 17,500 m^2 of constructed area.

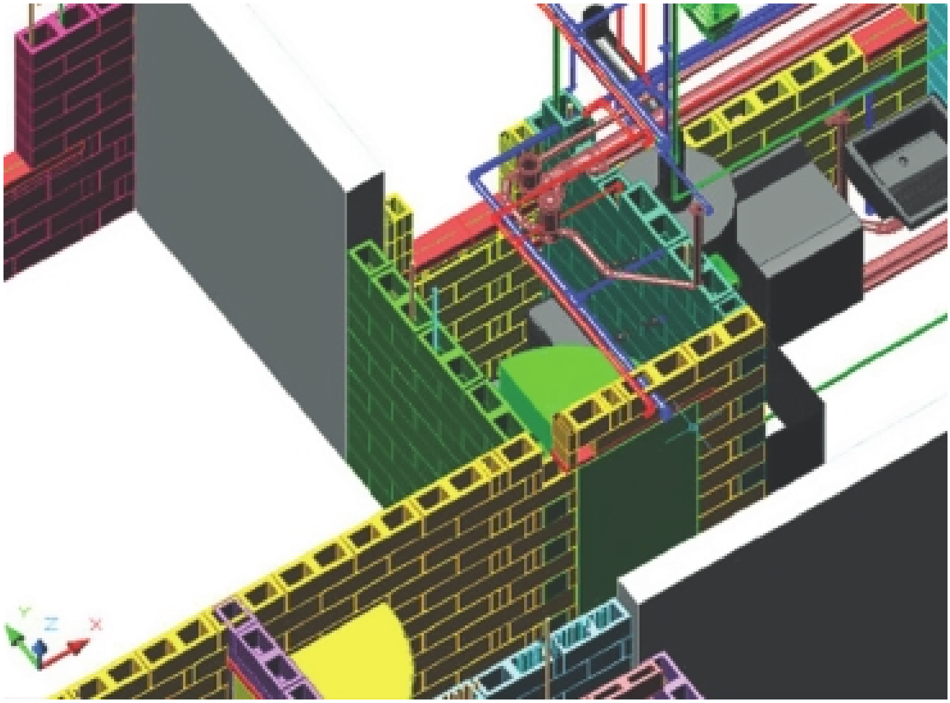

Figure 10.4 3-D model detail shows masonry, part of structure and plumbing kits.

Figure 10.4 represents part of 3-D model with masonry, struture and plumbing kits. Figure 10.5 and Figure 10.6 show details of a plumbing kit and part of the documentation of the plumbing kit for assembly, including item identification according to industry supplier. Finally, Figure 10.7 represents a view of the structure, masonry and scaffolding for external rendering in a single 3-D model.

Information hierarchical classification

Throughout the R&D a hierarchical classification was proposed to identify the level of detailing of the building. This classification was tested in the integrated building design for masonry production with 3-D CAD. The classification and practical examples of its implementation were tested through a workshp with a steering group formed by academics and practitioners.

Figure 10.8 shows the hierarchical classification according to the main knowledge areas (i.e. space organisation, stability and utilities), followed by disciplines, systems, sub-systems, components and elements. This classification provided the R&D team with a clear vision about the level of detailing for production.

In this hierarchical framework, three knowledge areas were considered: spatial organisation, stability and utility. These knowledge areas support the organisation of the different levels of detail and divide design according to product design and design for production.

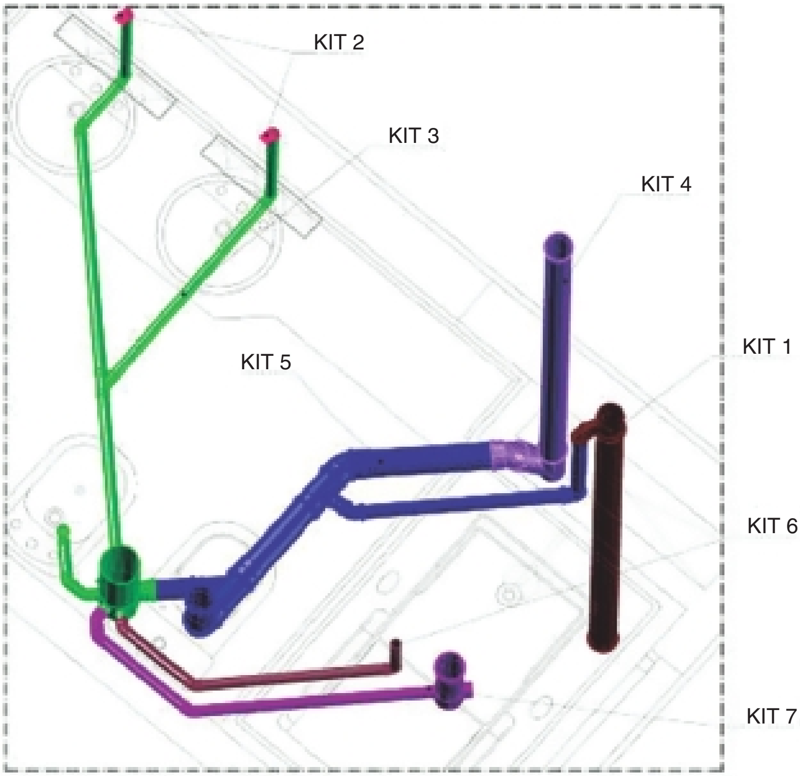

Figure 10.5 Detail of a plumbing kit for assembly.

This hierarchical model can be compared to that used in systems engineering described by Laudeur *et al.* (2003), resulting from concepts by Simon (1981, quoted in Lauder *et al.* 2003). The use of this taxonomy allowed the building sub-systems and their interfaces to be modelled with precision and flexibility.

The management system uses this hierarchical classification for many functions, including those related to communication, decision making, import/export from/to 3-D CAD models and so on.

Process mapping

The process mapping for each sub-system was obtained using a table containing entry data and its outputs (Tzortzopoulos 1999). This table was implemented into the IBDMS and allowed to identify the interfaces between systems/sub-systems and their components/elements. The process is also divided in phases, which will be used by the management system to control the evolution of the design. Table 10.1 presents an example of the process mapping table for masonry design for production, and Table 10.2 that for masonry and external rendering integrated design for production.

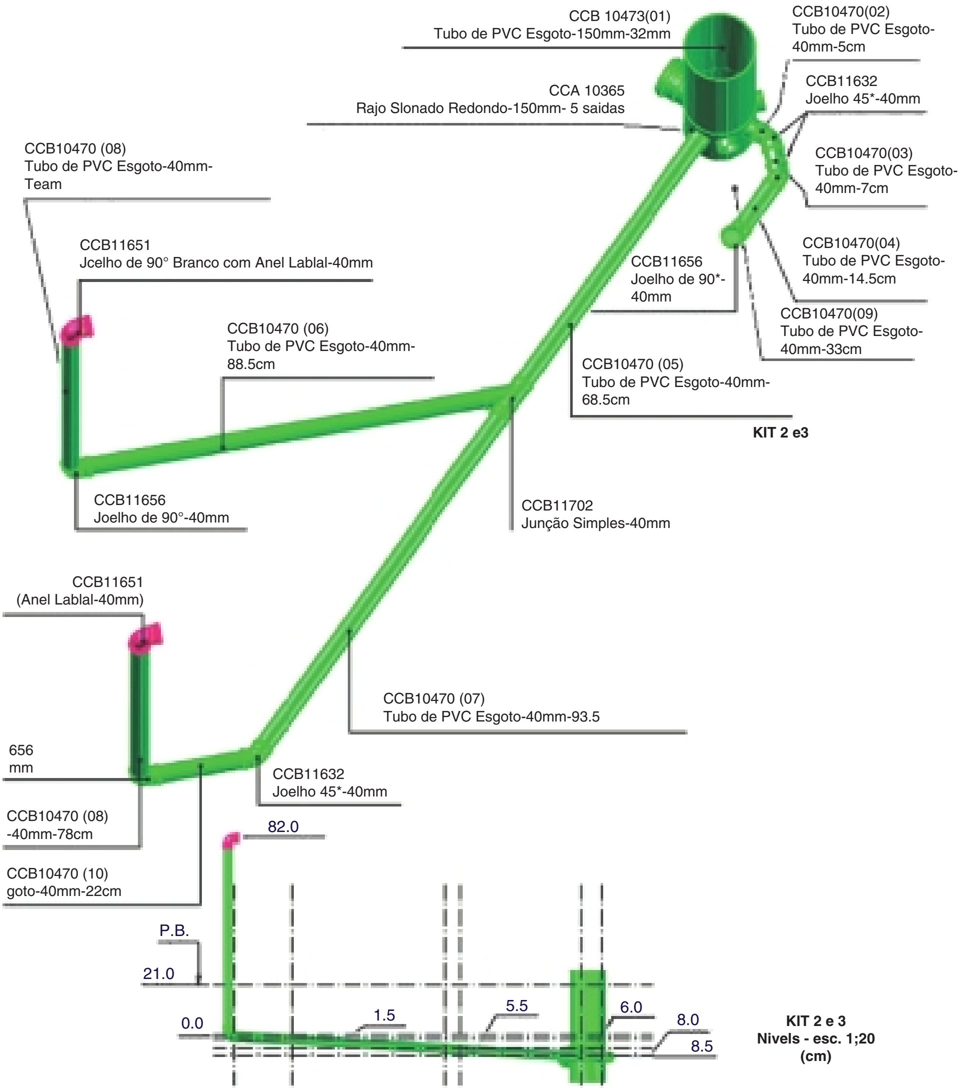

Figure 10.6 Documentation of a plumbing kit for assembly, including items identification according to industry supplier.

System requirements identification from a pilot design

The identification of requirements for the development of the integrated bulding design for production was done by several means, including a real case where the R&D team participated throughout the design development and coordination and followed the use of the design for production on site.

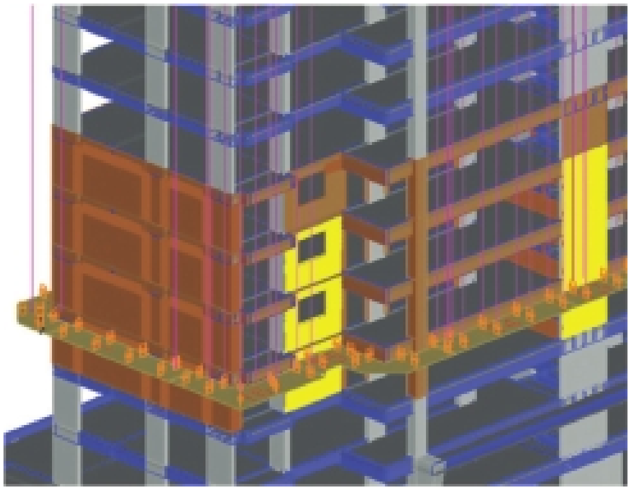

Figure 10.7 A view of structure, masonry and platforms for cladding execution.

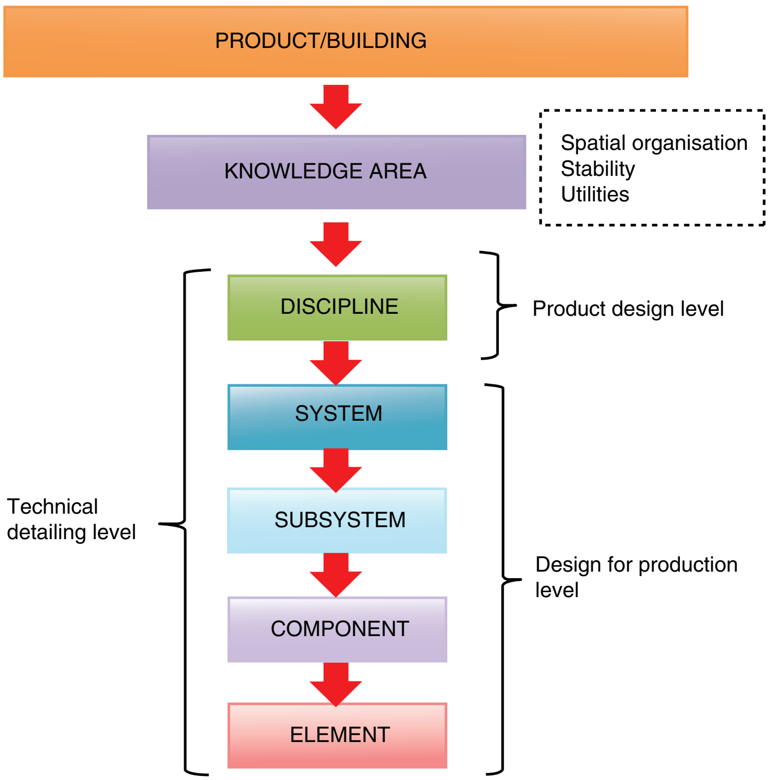

Figure 10.8 Building information hierarchical classification.

Table 10.1 Entry–process–output table for masonry design for production.

Phase	Data entry	Process	Output
Initial	• Technological selection for masonry • Architectural studies • Structural studies • MEP studies	• Horizontal and vertical masonry modulation • Compatibility analysis between architecture, structure and MEP designs • Delivery documentation	• Structural dimensioning directives • Architectural dimensioning directives • MEP directives for designing • Compatibility report
Development	• Previous phase approval • Architectural design • Structural design • MEP design • MEP 3-D models (if available)	• Wall 3-D modelling • MEP 3-D models (if not available from designer) • Interference analysis • Delivery documentation	• Compatibility report • Walls 3-D models • Walls location and distribution plans • Masonry vertical distribution scheme • Walls front views
Finish	• Previous phase approval • Coordination analysis • Architectural design reviewed • Structural design reviewed • MEP design reviewed • MEP 3-D models reviewed	• Critical analysis • Masonry production design revision • Delivery documentation closing	• Walls 3-D models reviewed • MEP location plans on structure • Masonry vertical distribution scheme • Walls location and distribution plans • Walls front views • Quantity report

An example of a requirement identified by this means occurred when it was necessary to make a decision about the technology for the provision of hot water while the plumbing design for production was being elaborated. An earlier decision (perfectly registered in the quality documentation) was made towards the adoption of copper for the hot water system. However, the construction management team decided to change the material and the information did not immediately reach the design for production team.

This event had enabled the R&D team to identify the functionality details for 'technology selection'. This functionality was designed to support approval of decisions by the contractor and/or subcontractor throughout many short cycles, specified in the business process diagram (Figure 10.9).

When a decision is registered (*what*) many other data are included, such as *when* it was decided, *who* decided and if the decision maker has the authority to make decisions. The system

Table 10.2 Entry–process–output table for masonry and cladding integrated design for production.

Phase	Data entry	Process	Output
Initial	• Technological selection for masonry and external rendering • Architecture studies • Structure studies • MEP studies	• Horizontal and vertical masonry modulation • Compatibility analysis between architecture, structure and MEP designs • Technological analysis for integrating masonry and external rendering • Delivery documentation	• Compatibility report • Structural dimensioning directives • MEP directives for designing • Architectural dimensioning directives
Development	• Previous phase approval • Architectural design • Structural design • MEP design • MEP 3-D models (if available)	• Wall 3-D modelling • External rendering 3-D modelling • MEP 3-D models (if not available from designer) • Interference analysis • Delivery documentation	• Compatibility report • Walls 3-D models • External rendering 3-D models • Walls location and distribution plans • Masonry vertical distribution scheme • Walls front views • External rendering execution plans
Finish	• Previous phase approval • Coordination analysis • Architectural design reviewed • Structural design reviewed • MEP design reviewed • MEP 3-D models reviewed	• Critical analysis • Masonry design for production revision • External rendering design for production revision • Delivery documentation closing	• Walls 3-D models reviewed • MEP location plans on structure • Masonry vertical distribution scheme • Walls location and distribution plans reviewed • Walls front views reviewed • External rendering execution plans reviewed • Quantity report

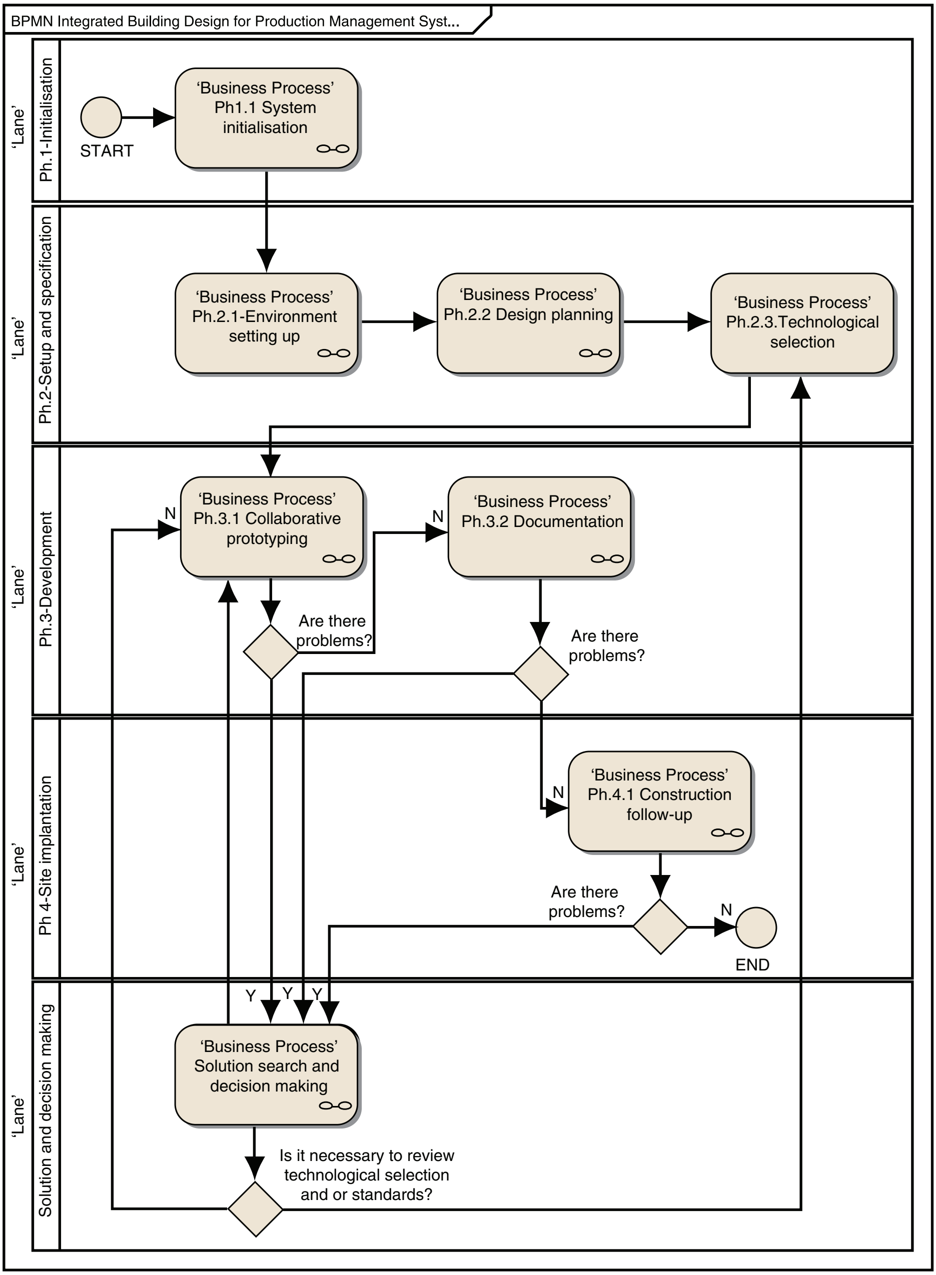

Figure 10.9 Business process diagram for integrated building design for production management system.

automatically prevents changes being made by unauthorised groups. To change a decision, the system will start an automatic notification for all involved with it. A decision has a time within which to occur; it cannot be later or earlier. So Sistema π can be configured to control the time for decisions and to notify all who need to know about them.

The process for 'solution search and decision making' is the most important and was considered by the R&D team the core of the management system. It is possible to see that all complementary processes (Figure 10.9) are driven by the solution search and decision making process. This assumption was validated through the real design for production. Wrong decisions have generated additional costs and/or time for the project.

Software (system) development

The software development was based on an iteractive approach that considered a dynamic requirements identification process. At very early stages of development, usability tests were conducted and the visual identity of the systems and a prototype were developed simultaneously with systems specification.

The results were used throughout the second validation that involved AEC designers, IT professionals and academic researchers. This procedure was repeated three times with an IT consultant and the outputs were:

- A navigable prototype system, containg a mock-up website that expressed the information workflow.
- An executable prototype system for some selected functionalities.
- A second executable prototype system for a group of functionalities.

Business process model

Business process management is considered critical for developing sucessful new products and services (Miers 2007), creating a business commitement to the project. During software development and using a computer-aided software engineering (CASE) tool, it is possible to create a model of a business process.

The business process for the IBDPMS was modelled based on the Business Process Modeling Notation (BPMN) standard, using Enterprise Architect® 7.0. The business was divided into five process groups, as follows:

- *Initialisation*: includes some processes to configure the system.
- *Set-up and specification*: includes 'Environment settings and standards' for design, 'Design planning' and 'Technology selection' for modelling and detailing contracted systems.
- *Development*: includes control tools for 'Collaborative prototyping' (3-D modelling) and 'Documentation' for using at the construction site.
- *Construction site implantation*: includes processes for 'Construction site follow-up'.
- *Solution and decision making*: includes processes for 'Solution searching and decision making' to identify problems during design.

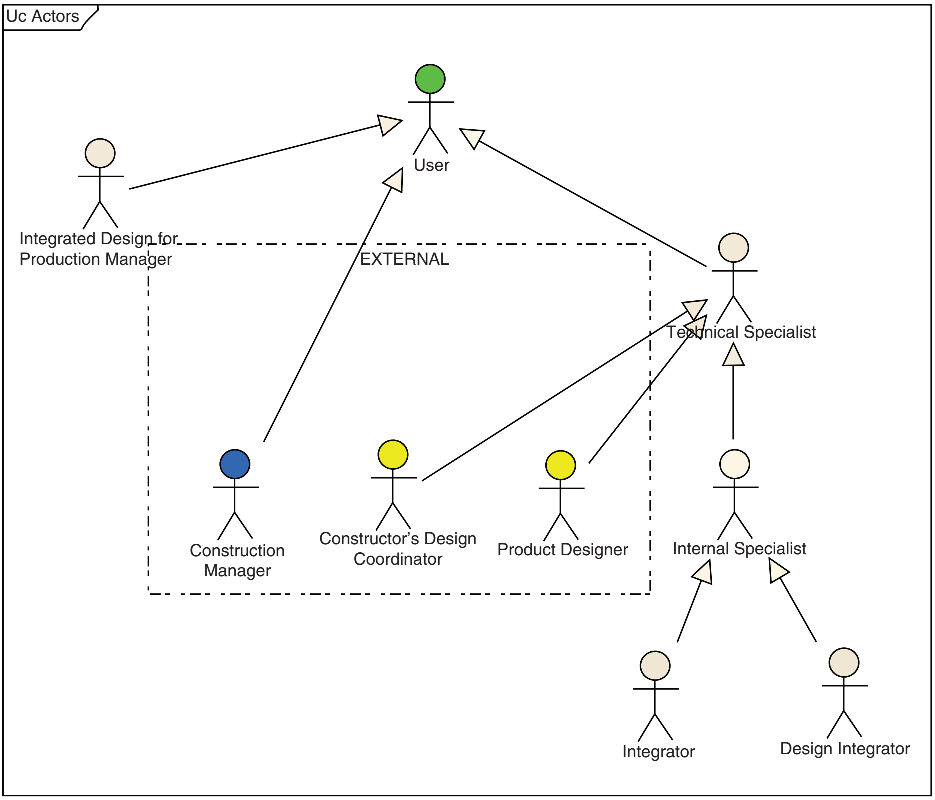

Figure 10.10 Building integrated design for production management system's actors.

Actors

The development of the Integrated Building Design for Production led to the identificaton of new 'actors'. These actors were called Integrated Design for Production Manager, Integrator and Design Integrator. Two other types of actors were also identified from the business model and requirements. These were grouped into external and internal actors. External actors were Constructor's Design Coordinator, Product Designer and Construction Manager. From the DWG side, the internal actors were Integrated Design for Production Manager, Integrator and Design Integrator.

By using UML (Unified Modeling Language), it was possible to identify generic relationships between the actors. In this respect, all actors were generalised as User. Technical Specialist is the generalisation of Constructor's Design Coordinator, Product Designer and Internal Specialist. Likewise, Internal Specialist is the generalisation of Integrator and Design Integrator. The definition of each category of actors and their roles and responsibilities was as in Figure 10.10.

The Constructor's Design Coordinator and Product Designer roles refer to traditional professionals in the design team of building construction, such as the architect, the electrical designer and structural designer. The Integrated Design for Production Manager is responsible for the

Table 10.3 Groups and functional requirements of Sistema π.

Group	Functional requirements
1. Initialisation	Beginning integrated design
2. Set-up	Setting up design environment
	Defining technology scope
	Planning and controlling design
3. Development	Dispensing initial information
	Detailing integrated design
	Searching for solution and decision making
	Validating evolutional stages
	Generating documentation
	Getting final validation
4. Implantation	Following up construction
	Evaluating design changes
5. Mobile device access	Accessing system using mobile devices

system's general administration. The Integrator acts as the technical coordinator for the integrated design and is responsible for promoting integration between the product design (conceptual design) and the design for production (construction).

Requirements

Requirements in the integrated building design for production system are divided into functional and non-functional. The non-functional requirements refer to system quality, involving some constraints, quality attributes and goals and quality of service requirements and non-behavioural requirements (such as usability, testability, maintainability, extensibility and scalability). The functional requirements are those related to general functionalities identified from business processes and reviewed by use cases detailing (such as technical details, data manipulation and processing and other specific functionality). In total, 14 functional requirements were identified and organised into five groups, as shown in Table 10.3.

Use cases

In parallel to business process modelling and requirements specification, use cases for developing the system were identified and detailed. The use cases were grouped into five packages:

1. Managing design and standards
2. Developing design
3. Searching and communicating
4. Integrating CAD with management system
5. Accessing system by mobile devices

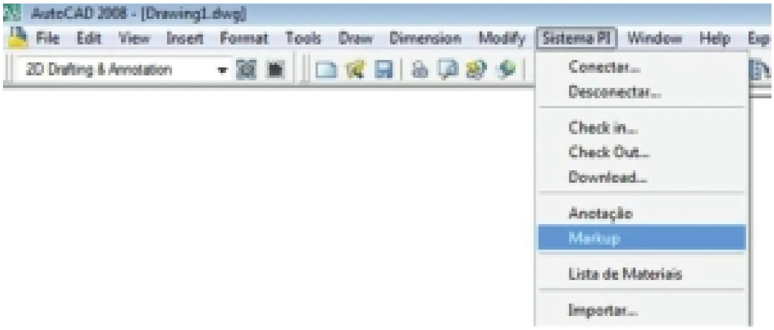

Figure 10.11 Example of markup command in AutoCAD®.

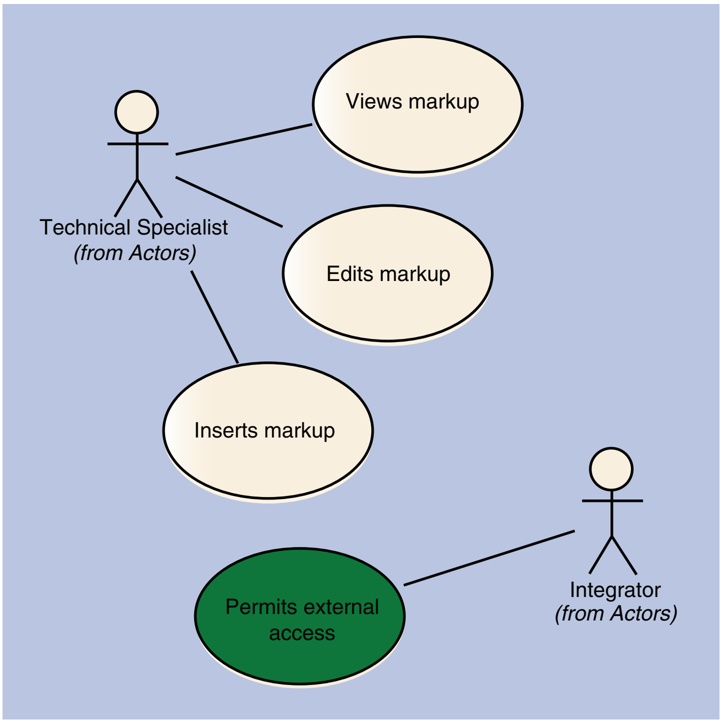

Figure 10.12 Use cases from Integrating CAD with Management System package, for markup functions implementation.

In total, 89 use cases were identified for the management system and these were detailed throughout software development, using concurrent engineering and software agile development approaches. One example of a use case is the markup function implemented into AutoCAD® as a command (Figure 10.11). Figure 10.12 shows the use cases from the 'Integrating CAD with management system' package for markup function implementation.

The above example of a markup command in AutoCAD® displays a screen for the designer to describe the problem identified during the design process. The data is exported afterwards to the IBDPMS and disseminated to others for discussion and decision making.

Final remarks

Integrated design for production was identified as a demand of the building construction market. In Brazil, this demand has increased considerably as investments in the construction sector are continuously rising. This leads to a demand for more effective and efficient production quality control.

Throughout the development of the system, it was identified that there is a professional gap to the support for decisions that involve architectural design, construction technology and the management of construction on site. The Integrated Building Design for Production Management System was designed to aid decision making during designing for production. Simultaneously, it pulls key decisions from product designs at the early stages, because these are entry data to the elaboration of the design for production.

The emergence of new design technologies, such as BIM, were considered at earlier stages of this R&D programme and Sistema π has been adapted and integrated with such technologies, therefore triggering an upgrade to the system.

Finally, additional issues emerged throughout the development process. First, it was identified that the system brings transparency to the decision-making process. However, in some circumstances transparency is not desired. For instance, the fact that the software registers all transactions can inhibit the use of the system. Some of the designers prefer not to have the problems and mistakes registered in a database. Finally, in regard to the role of the integrator, although the system communicates with all designers, there is a need for a mediator when the solution for a trade-off is not obvious. That means that a third party is necessary to bring a more holistic view of the design to support decision making. It is the same when it comes to establishing deadlines for the delivery of decisions.

Acknowledgements

The author thanks FAPESP – Fundação de Amparo à Pesquisa do Estado de São Paulo – for supporting this research through grant no. 01/13304-0, and the design offices and contractor, Construtora Cyrela SA, which participated in the integrated building pilot design for production.

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Trademarks

Enterprise Architect® is a trademark of Sparx Systems. AutoCAD® is a trademark of Autodesk, Inc. Silverlight is a trademark of Microsoft Corporation.

11 Flexibility, semantics and standards

Robin Drogemuller and John H. Frazer

This chapter explores the relationship between flexibility and standards in supporting distributed intelligence in design. The basic question is: If designers insist that their designs are innovative in some manner, how can standards (predefined concepts) be used to analyse designs and communicate about them? This then leads to the subsequent question: How well do digital design tools support the representation, analysis and communication of design information within the constraints of the innovation/standardisation question.

The discussion is framed largely in terms of design for the built environment, but the issues discussed should apply to a wider sphere. The discussion will also consider the pragmatic issue that while current digital tools can support the development of an improved built environment through increasing the information available and intelligence applied to design within the built environment, how can this be improved? We argue that the necessary improvements can be divided into three main groups:

- Improved tools to support the activities of individuals.
- Support for collaboration to improve resolution of multidisciplinary issues.
- Provide access to improved data to support decision making.

The assumption underlying this chapter is that the design problem is being addressed by a design team made up of specialists, each of whom is responsible for particular aspects of the design. As explained later, these specialists cover the facility lifecycle, from cradle to grave. The design team reports to a client and users, as the major stakeholders, with other indirect stakeholders, such as regulators and the public, also involved in some manner. Our major focus is on the members of the design team, each of whom will have access to software to support representation and analysis of the systems within the design problem for which they are responsible, either as producers or for reference. The background for this chapter is a long history of developing leading-edge (i.e. Frazer 1995) and applied (i.e. Drogemuller *et al*. 2009) design support software with close relationships with industry (CRC for Construction Innovation 2009a, b).

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Figure 11.1 Road rules as an example of a 'standard'. (Photo courtesy of Lani Drogemuller.)

Standards

The use of standards for the exchange of information between computer systems is the major issue within the context of this chapter. Standards are important since they provide a mutual understanding between parties. To give a simple example, when travelling in a country which uses the left-hand side of the road, seeing a large vehicle moving towards you as in Figure 11.1 would be a common sight. In a country where people drive on the right-hand side of the road, such a scene should be the cause of some excitement. The rigour with which standards are applied is also important in setting quality standards and expectations. To continue the travel example, driving in some countries where a more 'creative' approach to road rules is taken can be an exhausting process where the driver can place no reliance on the predictable behaviour of other drivers.

Within the construction industry only two standards for information exchange of three-dimensional object models have significant penetration: IFCs (www.iai-tech.org/) and gbXML (www.gbxml.org/). These are both 'industry' standards, set by bodies within the industry without the status of formal international or national standards, although a portion of the IFC model is covered by an ISO Publicly Available Standard.[1] Figure 11.2 shows a snippet from the IFC Express exchange file representing a wall panel (an XML definition also exists), while Figure 11.3 shows a snippet from gbXML. For contrast, Figure 11.4 is a description of the geometry that could be considered as a 'wall' panel, as represented within the Generative Components (GC) software from Bentley.[2] Several important issues can be identified within these examples. The IFCWALLSTANDARDCASE instance in Figure 11.2 contains the string '2OToJKcjrBkvGXkh$ol786'. This is a 'globally unique identifier' that is intended to be unique within the software world. This provides a method for distinguishing between building

[1] This can be found at www.iso.org/iso/catalogue_detail.htm?csnumber=38056.

[2] www.bentley.com/en-US/Products/MicroStation/GenerativeComponents-Extension.htm.

```
#57=IFCWALLSTANDARDCASE('2OToJKcjrBkvGXkh$ol786',#33,'Basic Wall:Brick - 110:116878',$,'Basic Wall:Brick
- 110:99983',#46,#56,'116878');
#46=IFCLOCALPLACEMENT(#38,#45);
... data defining position and direction
#56=IFCPRODUCTDEFINITIONSHAPE($,$,(#49,#55));
#49=IFCSHAPEREPRESENTATION(#27,'Axis','Curve2D',(#48));
#48=IFCPOLYLINE((#4,#47));
#4=IFCCARTESIANPOINT((0.,0.));
#47=IFCCARTESIANPOINT((5000.,0.));
#55=IFCSHAPEREPRESENTATION(#27,'Body','SweptSolid',(#54));
#27=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.E-006,#26,$);
#26=IFCAXIS2PLACEMENT3D(#3,$,$);
#54=IFCEXTRUDEDAREASOLID(#52,#53,#9,3600.000000000001);
#52=IFCRECTANGLEPROFILEDEF(.AREA.,$,#51,9999.999999999998,110.000000000001);
#51=IFCAXIS2PLACEMENT2D(#50,#12);
#50=IFCCARTESIANPOINT((5000.,0.));
#12=IFCDIRECTION((-1.,0.));
#9=IFCDIRECTION((0.,0.,1.));
#53=IFCAXIS2PLACEMENT3D(#3,$,$);
```

Figure 11.2 Portion of IFC file generated from ArchiCAD from a model produced by Robin Drogemuller.

```
<Surface id="obj:002" surfaceType="ExteriorWall"
constructionIdRef="con:043" exposedToSun="true">
<Name>Obj:002</Name>
<AdjacentSpaceId spaceIdRef="zon:001" />
<PlanarGeometry unit="Millimetres">
<PolyLoop>
<CartesianPoint>
…
</CartesianPoint>
</PolyLoop>
</PlanarGeometry>
</Surface>
```

Figure 11.3 Portion of ifcXML file produced from the same model as Figure 11.2.

```
transaction modelBased 'Define Wall'
{
     feature User.Objects.depth Bentley.GC.GraphVariable
  {
     Value = 0.01;
  }
  feature User.Objects.width Bentley.GC.GraphVariable
  {
     Value = 5;
  }
  feature User.Objects.height Bentley.GC.GraphVariable
  {
     Value = 3.0;
  }
  feature User.Objects.solid01 Bentley.GC.Solid
  {
     CoordinateSystemAtOrigin = coordinateSystem01;
     XDimension = width;
     YDimension = depth;
     ZDimension = height;
  }
}
```

Figure 11.4 Portion of Generative Components script produced by Robin Drogemuller.

components no matter who creates them and where and when they are created. This is a critical issue if collaboration is to be supported.

An examination of the gbXML and GC examples shows that they only use simple names to identify instances within the files: *obj:002* and *User.Objects.solid01* respectively. Hence support for uniqueness and collaboration is weaker for these formats.

A comparison of the three examples also reveals that the IFC and gbXML definitions contain some semantic information (meaning) in the descriptions. A human or a computer can infer information about the objects just by reading the files. The GC file gives no indication of what type of object it might represent.

While the three file formats that have been considered are appropriate for different purposes, as discussed later, from a collaboration perspective the IFC format is stronger and from an "intelligence" (embedded information) perspective, the IFC and gbXML formats are richer.

Issue 1: Need to maintain 'identity' of objects when sharing them.
Issue 2: Semantic information within definitions can assist in interpreting data.

Before leaving the issue of standards, a promising area that may resolve some of the issues with standards is the Web Ontology Language (OWL; Smith *et al*. 2004). OWL allows both extensional definitions of membership (i.e. explicitly identifying all walls in a virtual model) as well as intensional membership, where objects are included in a set due to specific properties (i.e. a building component is an external_wall if it is a wall and if it is adjacent to only one internal space). OWL provides a possible means for resolving ambiguities, as identified later in this chapter (Schevers and Drogemuller 2005; Schevers *et al*. 2007).

Design

A broad definition of design is used within this chapter. Design is considered as covering:

- The initial problem specification (the requirements).
- The resolution of the requirements into representations that allow the potential design solutions to be analysed, shared and discussed.
- The development of construction/manufacturing plans.
- The construction/manufacturing operations that result in the physical building or product.
- The management of the building or product during its operational life.
- Planning for disassembly and re-use on completion of the operational life.

While this is wider than the current use within the built environment, we expect that social concerns about sustainability will continue to encourage designers to consider 'cradle-to-cradle' issues. Additionally, research at VTT identified the impact that design has on the lifecycle costs of a building. This indicates that poorly considered design can have an ongoing impact on the financial performance of a building.

Issues that arise from this are:

Issue 3: A problem specification is separate to the (potential) solutions.
Issue 4: There will be multiple uses for the solution representations that may require distinct representations that are coordinated in some way.

Issue 5: Information must be available throughout a product's lifecycle to allow for updates and to inform the re-use/recycle process.

Design in general is acknowledged as a complex activity and a 'wicked' problem (Richley 2008). Herbert A. Simon (1962) defined complexity as follows:

> by a complex system I mean one made up of a large number of parts that interact in a non-simple way. In such systems, the whole is more than the sum of the parts, not in an ultimate, metaphysical sense, but in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole.

This leads to more issues:

Issue 6: Identification and description of individual parts.
Issue 7: Definition of the relationships between parts forming systems and sub-systems.

Rosenhead (1996) (quoted in Richley 2008) identified a number of strategies that should be used to tackle wicked problems:

- 'Accommodate multiple alternative perspectives rather than prescribe single solutions;
- Function through group interaction and iteration rather than back office calculations;
- Generate ownership of the problem formulation through transparency;
- Facilitate a graphical (visual) representation for the systematic, group exploration of a solution space;
- Focus on relationships between discrete alternatives rather than continuous variables;
- Concentrate on possibility rather than probability.'

The issues relevant to this discussion are:

Issue 8: Need for collaboration in problem formulation.
Issue 9: Need for feedback from current solutions to stakeholders to inform the continuous refinement of the design requirements.

Brown and Chandrasekaran (1989) define three classes of design, with the corresponding names (original, innovative and routine) as used by Benaras and Van De Velde (1994).
Class 1: Original Design, occurs where:

- The original design requirements evolve during the design process.
- The design problem is 'ill-defined', i.e. inconsistent, incomplete or ambiguous requirements.
- The design process involves identifying the requirements that the design solution must meet, as well as identifying a solution.

Class 2: Innovative Design, occurs where:

- The problem statement is incomplete.
- The design problem is 'well-defined', i.e. the requirements are fixed.
- The design process involves identifying all of the requirements.

Class 3: Routine design covers problems that have been solved previously, in the same domain, with the same knowledge, where:

- The problem statement is complete.
- The problem statement defines all of the constraints that need to be met.

Intuitively, one would expect that the support for design representation would be more difficult for Class 1 designs and would be trivial for Class 3 designs. This issue is revisited later in the chapter.

Distributed systems

The concept of 'distribution' acknowledges that for all but the most trivial design problems, the requisite knowledge to achieve the design goals is contributed by more than one person or software system. The addition of distribution in geographically diverse locations may change the methods of working and the technologies used to support the work methods, but within the context of this discussion does not have an impact on the fundamental requirements.

Some characteristics of a distributed system, derived from information technology (Ghosh 2007) but selected to suit these circumstances, are:

- There are several autonomous computational entities (including humans), each of which has its own local memory (vision of the problem).
- The entities communicate with each other by message passing.
- Each entity (including humans) has only a limited, incomplete view of the system.

Communication may be required between software packages running on the same computer, or between software packages running on separate computers. With the current state of technology humans will normally be driving the processes and acting as intermediaries between different software packages and between human beings.

The major issues arising from the above are:

Issue 10: Each entity has its own 'view' of the problem and the current range of potential solutions.

Issue 11: Communication is key to shared problem solving.

Intelligence

For our purposes, the application of 'intelligence' is the addition of information to the design problem description or to the potential solutions. This may be done by human beings acting through computer software or by software agents, which are triggered by identified circumstances. The generic term 'actors' will be used where there is no need to distinguish between human or software operations. Intelligence may be applied in many ways:

- Applying knowledge gained from previous work.
- Adding information to the problem description.

- Adding information about how the possible solutions may be configured (adding detail to the design representation).
- Deriving information about the performance of proposed solutions to assist in decision making.
- Adding information about how the proposed solutions may be manufactured/constructed (organisational structures, construction scheduling etc).
- Adding and updating information about how the asset is performing through its life (asset/facility management operations).
- Deciding how potential solutions will be decommissioned, recycled or demolished.

Normal operational changes within a facility that do not have an impact on the fabric of the facility are not considered within this chapter, even though they may benefit from this approach.

No position is taken about whether the data and analysis results are stored in one location, across federated databases or with a hybrid structure of databases and files. A number of issues with the quality of information in BIM models have been identified through examination of models produced by industry practitioners. These issues are also relevant to other domains besides building design. These could be resolved through the addition of 'intelligence' to the source system so that only information relevant to the current exchange scenario is exported.

Spurious or useless information should be automatically identified. Spurious information may be added to systems when two elements, such as windows, are placed on top of each other, or a wall is deleted without removing the windows that were part of the wall. One example of useless information was the addition of 240 wheelie bins to a building model when they were only required for visualisation. These should be automatically removed from any other exchange scenario. These issues are internal to a piece of software and are about the quality and content of a model itself.

A major concern is the ease with which 'invalid' models can be constructed and exported within software. The structure and adequacy of information and representation also increase in accuracy and reliability as the design process continues. At early stages default values may be needed to provide enough detail to perform analyses without overloading users with entering data about decisions that have not yet been made.

Issue 12: Use of knowledge of valid building models to improve the quality of exchange.
Issue 13: Need definitions of stages of design to provide 'context' for information exchange.
Issue 14: Need methods to define and examine assumptions made during information exchange.

Areas of 'intelligence' that are missing from most software packages are the ability to reason about space and access, as is required for disabled access checking and fire escape planning. Some specialist software can handle these issues.

There is a proprietary interface between an engineering design application and a major architectural CAD program where the requisite data for thermal analysis is supposed to pass seamlessly between the software packages. However, problems occur under relatively simple circumstances. If there are two adjacent rooms in the architectural CAD (Figure 11.5) with differing construction materials for the internal and external walls, then the boundaries around the thermal zone (red lines in Figure 11.6) – that is, the thermal representation of the architectural

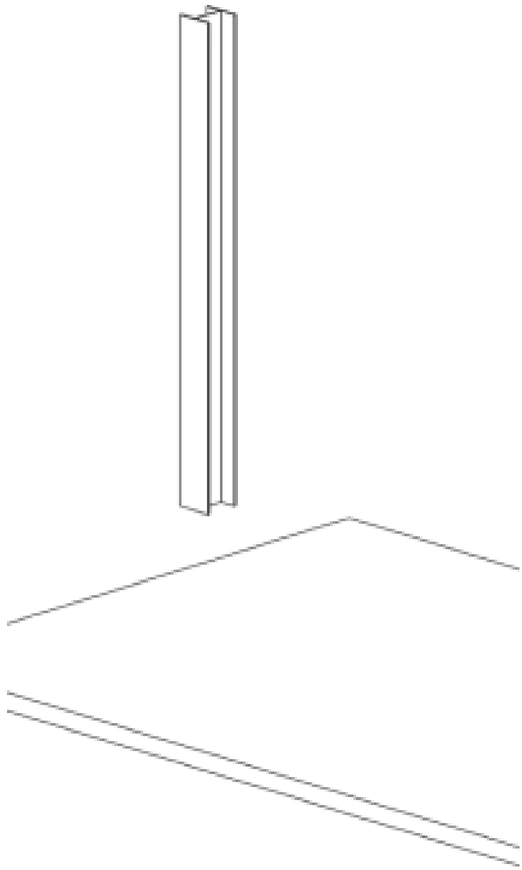

Figure 11.5 Image produced by screen capture from Autodesk Revit by Robin Drogemuller.

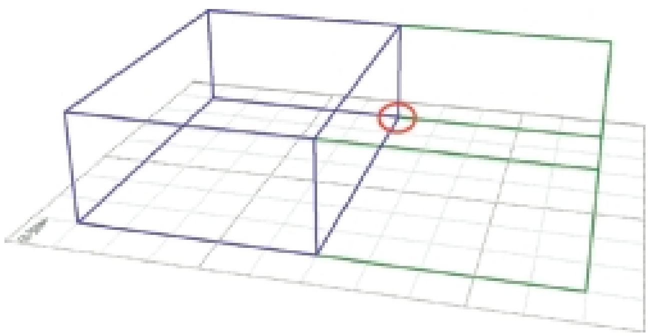

Figure 11.6 Image produced using AutoCAD and PowerPoint by Robin Drogemuller.

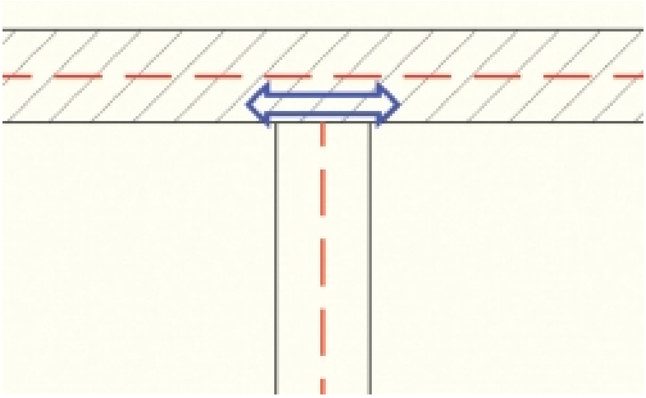

Figure 11.7 Image produced using AutoCAD and PowerPoint by Robin Drogemuller.

room – leave a gap between the internal and external walls. The thermal analysis software 'thinks' that there is a gap between the zones and allows air flow between the zones (the blue arrow in Figure 11.7). This can be fixed by knowledgeable operators but can trap average users.

Issue 15: Average users need assistance in identifying potential problems in information exchange.
Issue 16: How can 'mappings' between domain views (i.e. architectural and thermal) be defined in a flexible manner?
Issue 17: How is knowledge of the data mapping needs between software packagescaptured for potential automation the next time the same process is followed?

Communication

As described in the previous sections, communication is a key capability required for distributed working and a service that needs to be supported through the embedding of intelligence.

The targets of communication reflect the full range of stakeholders within a project: clients, users, designers, constructors, facility managers and the operators themselves. We claim that the operators need to communicate with themselves, since humans can only work on a limited number of concepts at one time (Miller 1956). This means that humans will use their 'scribbling' as memory aids to store partial solutions to problems as they pursue other, related issues. These scribblings will also be used to 'get back into a problem' when returning to it after a break.

Issue 18: Need to be able to review 'versions' of work to re-establish mindset when returning to an old problem.

Collaborators will need full access to the technical information on the project. However, the ability to modify information needs to be distinguished from the ability to merely read it.

Clients and the public will need access to photo-realistic views of the design proposals, while approvals authorities will need to see some level of technical documentation, but only enough to meet their needs for checking compliance.

Issue 19: Need to be able to present 'fit for purpose' views of proposals.
Issue 20: Need to control read, write and visualisation permissions.

Communication also needs to be handled at several levels. Information needs to flow between members of the project team, and between individual members of the team and their own organisation. There will be intellectual property owned by the employing organisation used by members of a collaborative design team to contribute to the shared design outcomes. This private information must be protected, while making the results of its use available to others.

Issue 21: Protection of intellectual property, while sharing results of its use.

Lessons learned within projects should also feed back into the corporate cultures of participating organisations.

Issue 22: Need to capture lessons learned in projects to improve the corporate knowledge base.
Issue 23: Need to be communicated over time, from inception of the project to demolition.

Russell and Norvig's (2003) treatment of communication issues from an 'intelligent agents' perspective assists in examining the major issues. They recognise five 'speech acts':

- *Query*: 'What is the floor construction?'
- *Inform*: 'The floors are concrete slabs.'
- *Request*: 'Calculate the volume of the concrete slab.'
- *Acknowledgement*: 'Data received.'
- *Declarative*: 'We have now moved to the documentation stage.'
- *Promise*: 'If you provide the construction materials for the external fabric, I can provide an estimate for the cost of the air conditioning plant.'

The first four of these speech acts can be handled automatically by software systems. The 'promise' could be handled by systems that support 'service discovery'. This is a goal of the web services developers.

Russell and Norvig (*Ibid.*) give several prerequisites for communication:

- *Situation*: This requires agreement on the roles of the sender and receiver of information and the context for the exchange.
- *Semantic and syntactic conventions*: This requires selection of a communication mechanism, the 'standard' to be used for the exchange and the meanings of the terms used during exchange.
- *Hearer's goals, knowledge base and rationality*: This is about how the receiver interprets the received message.

Issue 24: Need definition of roles of sender and receiver.
Issue 25: Need definition of and agreement on the current stage in the design process.
Issue 26: Need to select mechanism for exchange.
Issue 27: Need to select a 'standard' or 'language' for exchange.
Issue 28: Need to ensure that the 'words' used in the message are interpreted appropriately by sender and receiver.

The stages of communication are (*Ibid.*):

1. *Intention*: The sender wants to inform the hearer of a proposition (statement), such as a change in the material of a structural column.
2. *Generation*: The sender selects symbols (words) from the sender's dictionary to express the proposition within a context, such as 'Change the material of the column at grid A6 on Level 2 from steel to reinforced concrete'.
3. *Synthesis*: The sender creates the message using symbols.
4. Perception: The hearer receives the message as a series of symbols within the hearer's context and dictionary of meanings for the symbols.
5. *Analysis*: The hearer infers possible meanings, such as 'Set the material for the column at A6 on Level 2 to reinforced concrete with concrete grade of N20, N30 etc.'
6. *Disambiguation*: The hearer infers an intended meaning: 'Set the material for the column at A6 on Level 2 to reinforced concrete with concrete strength of 60MPa.' In this case disambiguation may depend on previously agreed values (the context).
7. *Incorporation*: The hearer incorporates the proposition into the building model.

Issue 29: Need agreement on meanings of symbols (words).
Issue 30: Need agreement on the structure (grammar) of messages.
Issue 31: Need agreement on the context of messages – what stage of the design process, setting of default values etc.

There are a number of places where the communication may fail (*Ibid.*):

- The hearer may not believe the message. A message about changing the material of a structural member would be trusted from a structural engineer, but would raise questions if it came from an electrical engineer.
- The message could be ambiguous. In stage 6 of the communication scenario described above, the assumption was made that 60MPa concrete was appropriate based on previous knowledge. What if this information were not available?
- Differing understanding of the current context. What if there was a differing understanding of the appropriate strength of concrete?

Issue 32: Need to know the identity and role of the sender of information.
Issue 33: Methods of setting or clarifying context are required.
Issue 34: Methods of incrementally compiling computer interpretable knowledge are needed to support robust communication between software packages.
Issue 35: In many circumstances the correct interpretation of messages needs to be validated.

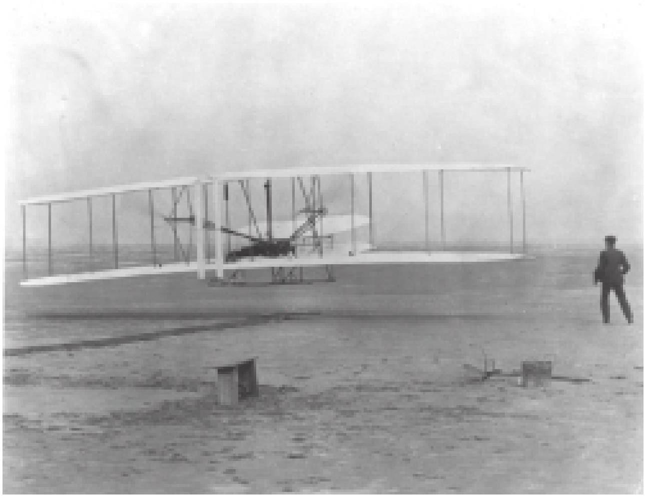

Figure 11.8 Wright brothers' first heavier-than-air flight. (Image NASA/courtesy of nasaimages.org.)

Standards versus flexibility

In order to address the original question 'How can standards support innovation and flexibility?' we will use a historical example of a Class 1 Original Design, the development of the heavier-than-air aircraft (Figure 11.8). The treatment of the history is informal, with the details sourced from Wikipedia.

The design of the first heavier-than-air plane meets the definition of 'original design', since no one knew how to achieve the goal before it was achieved.

This development was the culmination of experimentation with kites and gliders. The Wright brothers manufactured bicycles and were consequently aware of the use of the trade-off between lightness and strength for the materials available at the time. They also read about or communicated with other leading experimenters, such as George Cayley, Samuel Langley, Otto Lilienthal and Octave Chanute.

If a product modelling approach were used to model the Wright Flyer 1, the major systems – body, wings, forward stabiliser, engine and propellers – are all obvious. Many of these were derived from previous work using the flight of birds as a guide and, other than the engine, are not dissimilar to gliders of the same period (Otto Lilienthal Museum n.d.).

The use of timber for the structural parts in compression and metal for those parts in tension also grew out of the kite/glider predecessors. The significant parts of the Wright Flyer that did not have long-term precedents were the spark plugs, which became commercially available in 1902, and the innovations the Wright Brothers made in adapting propellers for use in air rather than water.

In this case, we can claim that while the Wright Flyer was a major innovation, the aircraft could be well described using a merge of information from glider construction and the automotive industry (internal combustion engine).

An important part of design is the exploration of form. The new 'parametric geometry' CAD systems support a wide range of form generation and exploration methods that are often used in the early stages of design to play with ideas. A student project at Queensland University of Technology (QUT) examined how music could be used as a form generator. The notes for the

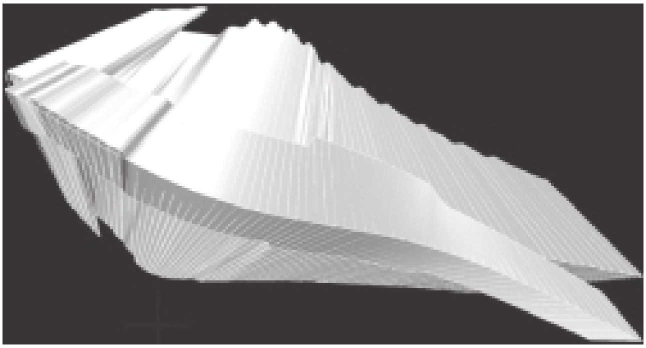

Figure 11.9 Form generated from music. (Image courtesy of Shaun Purcell.)

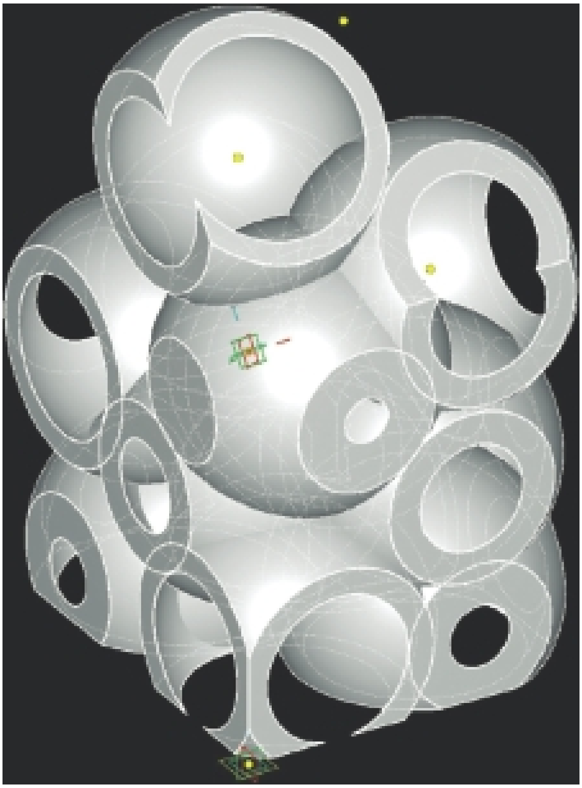

Figure 11.10 Exploration of 'Collision Crop' (Blanciak 2008). (Image courtesy of Camden Cummings.)

two hands of the piano music were encoded in a spreadsheet and the values used as parameters in the geometry generation (Figure 11.9). This type of exercise is useful in exploring ideas on form that may lead to a realisable building design, but in its current form it is only expressible in the internal format of the generating software; in this case Generative Components.

A student explored the ideas behind 'Siteless' pattern 638 (Blanciak 2008), where spheres are 'collided' to form the spaces within a building (Figure 11.10). The resulting forms consist of vaults defined by the fused spheres. Under either the IFC or gbXML specifications, are these walls, ceilings or both? Where does a wall stop and a ceiling start on a continuously curved surface? A possible means of answering these questions in a standard manner would be to use the intension capabilities of OWL (see above), although the authors are not aware of any attempt to do so.

The three examples discussed in this section indicate that it is sometimes possible to represent innovative designs using a standard. The major differentiators between the examples are the stage of the design process: play for the music-generated forms, sketch design for 'Collision Crop' and as-constructed for the Wright Flyer.

Issue 36: Need definitions of design stages to differentiate how much detail is available in a model.

Analysis of current software capabilities

This section analyses existing software against the issues identified previously. The issues are not treated in numerical order, but are grouped to suit the discussion.

The current CAD software offerings are divided into 'component CAD' and 'parametric CAD'. Component CAD is used as a generic label for CAD software that supports the BIM model of working. A pallet of building elements is normally provided from which the user selects and places the components into the internal project model. Parametric CAD covers software where the internal geometrical representations do not have additional semantic value (i.e. identification as a wall or floor slab) attached to them. In the current market there is some blurring between these categories, but they are distinct enough to make a comparison worthwhile.

As Russell and Norvig (2003) point out, some form of standard is a prerequisite for communication. The most fundamental of these are the basic components of the communication process:

Issue 26: Need to select a mechanism for exchange.
Issue 27: Need to select a 'standard' or 'language' for exchange.
Issue 28: Need to ensure that the 'words' used in the message are interpreted appropriately by sender and receiver.
Issue 29: Need agreement on the meanings of symbols (words).
Issue 30: Need agreement on the structure (grammar) of messages.

The mechanisms for exchange currently range from tight integration between a single vendor's products, through exposure to third parties through an API (software interface), file-based exchange and model server (database) collaboration.

While tight integration within a single vendor's products avoids many of the other issues of collaboration, this is not a solution, as no vendor can supply all of the software needs for projects throughout the project lifecycle. At some stage the information needs to be shared with products from other vendors.

Sharing through an API can be direct, with a direct link between programs, or indirectly, through another interface. If there is a direct link, between CAD and structural analysis for example, the users are entirely dependent on the two vendors correctly interpreting the content of their respective models and the users understanding how the software is supposed to be used. This simplifies issues for the users, but does not reduce their professional liability issues in most jurisdictions. This is most appropriate for component CAD systems, where the semantics of the objects defined within the system can be carefully controlled. A common solution for parametric CAD is to export data to a spreadsheet and then import it again into analysis software. This requires the user to mediate between the software, but allows for more flexible solutions. Such users are normally technically oriented.

File-based exchange is the major mechanism supported by the IFCs. However, this is unlikely to be sustainable due to the rapid increase in file sizes as more complex projects are attempted at increasing levels of detail.

Most model servers have significant latency (time) problems, due to the amount of data that has to flow across networks. However, careful design of a new version of a proprietary server has significantly reduced latency and user control issues. This indicates that significant improvements are available in this area.

All of the issues above are givens when using a proprietary exchange mechanism. When using an open standard such as IFC or providing flexibility within a proprietary system, there is considerable negotiation required. The need to add the IFD (International Framework for Dictionaries) project (IFD 2009) to the IFC development is an indication of how difficult this is.

In summary, current systems work well where there is tight control of the communication environment. However, when some flexibility is allowed or required, current systems can be very brittle.

Issue 2, 'Semantic information within definitions can assist in interpreting data', is related to the way information is encoded within the exchange. Both IFC and gbXML (Figures 11.2 and 11.3) indicate that a component is a wall, for example, in contrast to Generative Components (Figure 11.4). The advantages of one over the other will depend on the stage of the design process, the flexibility required and the need to exchange data at the particular stage of the design process.

The final two standards related issues:

Issue 5: Information must be available throughout a product's lifecycle to allow for updates and to inform the re-use/recycle process.
Issue 23: Need to be communicated over time, from inception of the project to demolition.

are both about access to information when the original software is many versions older or even no longer available. It is not always in the interests of software vendors to simplify the use of alternative software. Consequently, users need to maintain pressure on vendors to ensure that the users' and clients' information and intellectual property are always available in the future.

Some issues around content are as much to do with functionality as collaboration:

Issue 6: Identification and description of individual parts.
Issue 7: Definition of the relationships between parts-forming systems and sub-systems.

New knowledge technologies such as OWL (Smith *et al*. 2004) may assist in making content more flexible.

All of the CAD software being considered is capable of defining individual parts and defining some types of relationships between them. Component CAD uses more meaningful relationships than parametric CAD, which is restricted to geometrical relationships. In contrast, the geometrical relationships in parametric CAD are more flexible and powerful. While some analysis software (e.g. some structural software) can be fully integrated with component CAD, other software (e.g. some thermal analysis packages) have very limited internal representations.

Three issues that have a strong impact on collaboration are:

Issue 1: Need to maintain 'identity' of objects when sharing them.

Seamless collaboration is impossible unless a particular object, such as a wall, can be identified all the way through the life of a building. Unfortunately, some software does not guarantee that identifiers will be retained when importing and then exporting information.

Issue 10: Each entity has its own 'view' of the problem and the current range of potential solutions.
Issue 19: Need to be able to present 'fit-for-purpose' views of proposals.
Issue 4: There will be multiple uses for the solution representations that may require distinct representations that are coordinated in some way.

These three issues are related in that each human stakeholder, as well as the software used, has its own interpretation of information. For example, component CAD may have a rich 3-D representation of walls, while thermal analysis software may only use a polygon with an attached U-value. Keeping all of the representations coordinated around a 'definitive' model may not be possible. Achieving this for all but the simplest projects is still not feasible and may never be.

A number of necessary services are not well supported by existing software:

Issue 12: Use of knowledge of valid building models to improve the quality of exchange.
Issue 36: Need definitions of design stages to differentiate how much detail is available in a model.
Issue 16: How can 'mappings' between domain views (i.e. architectural and thermal) be defined in a flexible manner?
Issue 18: Need to be able to review 'versions' of work to re-establish mindset when returning to an old problem.

Using a wall component as an example: At which design stage should a wall be required to have a footing beneath it? How can mappings from 3-D walls to 2-D walls and back again be defined? What alternative wall constructions were tested before the final construction was chosen?

Some issues require storage of knowledge above the project level:

Issue 17: How is knowledge of the data-mapping needs between software packages captured for potential automation the next time the same process is followed?
Issue 22: Need to capture lessons learned in projects to improve the corporate knowledge base.
Issue 34: Methods of incrementally compiling computer interpretable knowledge are needed to support robust communication between software packages.

These are about storing 'industry knowledge' within computer systems. Since artificial intelligence research has not resolved these issues for complex domains such as the built environment, it cannot be expected that these functions will be provided within software.

Context is supported in some areas:

Issue 32: Need to know the identity and role of the sender of information.

User identification is normally supported when using both file-based and server technologies from component CAD. Parametric CAD does not directly support user identification. Most analysis-only software also does not support user identification.

Efforts to set BIM guidelines (GSA 2007; Senate 2007; CRC for Construction Innovation 2009a) have made a start at covering the next four issues:

Issue 13: Need definitions of stages of design to provide 'context' for information exchange.
Issue 24: Need definition of roles of sender and receiver.
Issue 25: Need definition of and agreement on the current stage in the design process.
Issue 31: Need agreement on the context of messages: what stage of the design process, setting of default values etc.

These issues are complex and much more work is required.

Some aspects of collaboration cannot be handled by sending a single message. They require a 'conversation' between the two parties. This is beyond the capabilities of current software. Resolution of this would be a significant research breakthrough.

Issue 14: Need methods to define and examine assumptions made during information exchange.
Issue 33: Methods of setting or clarifying context are required.
Issue 35: In many circumstances the correct interpretation of messages needs to be validated.

Issue 11, 'Communication is key to shared problem solving', captures the motivation for collaboration in the industry. Problem formulation (development of the client requirements) is covered by:

Issue 3: A problem specification is separate to the (potential) solutions.
Issue 8: Need for collaboration in problem formulation.
Issue 9: Need for feedback from current solutions to stakeholders to inform the continuous refinement of the design requirements.

Client organisations are interested in ensuring that their requirements are met. However, as discussed previously, as part of the nature of building and infrastructure projects the project goals will change. There need to be methods to store the initial client requirements and to also modify these as requirements change. Issues were identified by Kiviniemi (2005) and some implementations exist (i.e. GSA 2007).

Some issues of reliability were covered previously. A current challenge at the software–human interface is:

Issue 15: Average users need assistance in identifying potential problems in information exchange.

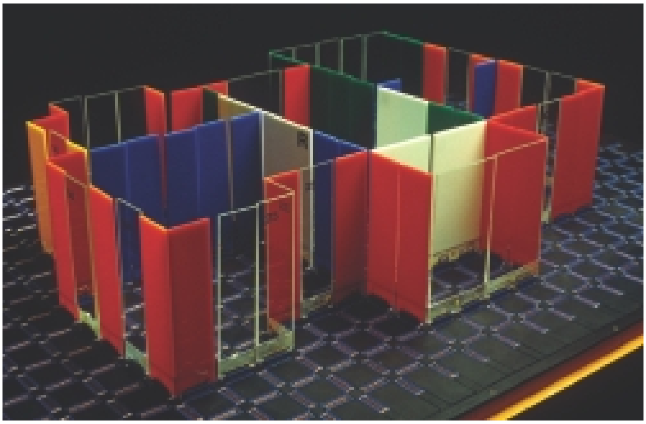

Figure 11.11 The Segal experiment. (Image courtesy of John Hamilton Frazer.)

Seamless (user interaction-free) collaboration is still not available under current systems and may not be feasible. However, research effort into improving the reliability of exchange will improve this.

The business need:

Issue 21: Protection of intellectual property, while sharing results of its use.

and the underlying technical requirement:

Issue 20: Need to control read, write and visualisation permissions.

can be partially addressed by maintaining distinct data sets and software. However, the use of IT for collaboration causes problems for traditional concepts of intellectual property and risk.

Including clients

In the previous discussions the focus has been on serving the needs of the 'technical' members of the design team. Clients and users are currently included mainly through the use of visual representations of the design proposals. These may be three-dimensional and may allow users to 'stroll' through the virtual proposal. However, clients and users are passive recipients. How can clients and users be more directly involved in the design process?

Two ideas that have been explored in the past are described in Frazer (1995). The Segal experiment (Frazer 1982; Figure 11.11) used a specially configured baseboard to allow people to place panels that variously represented walls, windows, doors and so on with a possible suite of 128 different panel types. The baseboard was connected to a computer which was able to provide analyses of various aspects of environmental performance. Multiple breadboards could be used to design multistorey buildings. This allowed students and members of the public to communicate directly with the analysis software and to gain a deeper understanding of the issues.

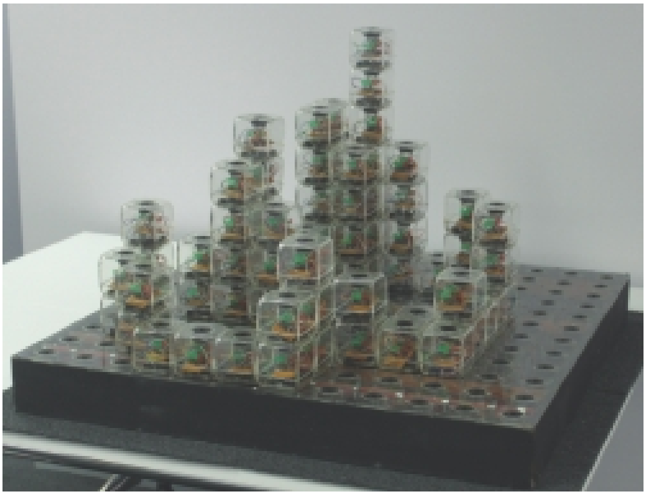

Figure 11.12 The Universal Constructor. (Image courtesy of John Hamilton Frazer.)

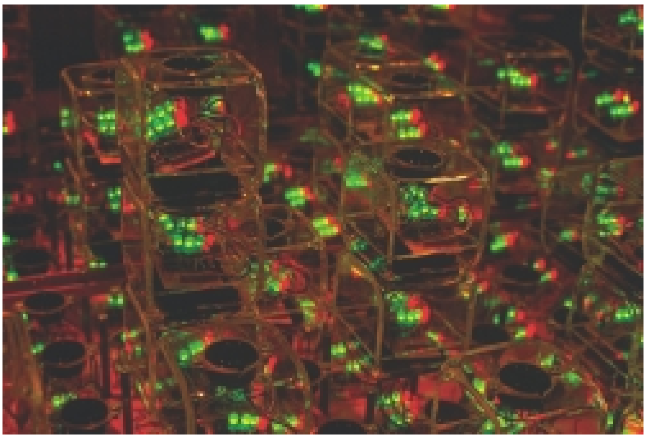

Figure 11.13 The Universal Constructor – detail of cubes. (Image courtesy of John Hamilton Frazer.)

A more ambitious experiment, the Universal Constructor (in deference to von Neumann), was completed in 1990. It consisted of a three-dimensional array of cubes (Figure 11.12). Each cube had an individual identifier, had 256 available states and could communicate with any one of the other cubes (Figure 11.13).

The Universal Constructor was used to explore a wide range of ideas, but from an architectural perspective it could be considered as an expression of 'logic in space' (Frazer 1995). It could be used as either an input device, encoding environmental conditions for example, or as an output device, representing a potential solution to a design problem.

While the Universal Constructor was more abstract than the Segal experiment, it was also much more powerful.

The rhetorical question arising from this work is: 'Why haven't these tangible interfaces been used to improve communication between clients, users, the design team, design representations and analysis methods?'

Conclusion

This chapter has examined the issues of flexibility, semantics (meaning) and standards within the context of distributed intelligence in design. This was informed by issues that have emerged in a range of industry design projects and in the development of prototype and commercial software to support building and infrastructure design, construction and management.

Design problems are 'wicked' (Richley 2008) and hence present many challenges. There are indications that some issues may not be resolvable.

Standards are essential to support communication, which is the basis for the distribution of intelligence and collaboration. However, standards are only required when interfacing between software packages. Existing standards, such as IFCs and gbXML, do not cover the entire industry, either in describing the products (buildings and infrastructure) or processes (from inception to recycling). Given than the IFC model, at over 600 entities, is already bigger than recommended in software engineering (Steel and Drogemuller 2009), it is reasonable to ask how scalable is the approach used for defining the IFCs. The use of file-based exchange has inherent limitations, so model servers are the likely means of collaboration between people and organisations, supplemented by direct interfaces between CAD and analysis software on the same computer.

There are some fundamental concepts that need to be supported within the content of information models, the most basic of which is object identity across transactions. The fact that major software vendors do not support object identity is a major impediment to distributed knowledge and collaboration. Methods of storing 'industry knowledge' between and across projects will need to be developed to improve knowledge distribution and collaboration. New software approaches such as OWL (Smith *et al*. 2004) may assist in improving flexibility. The development of vendor-independent 'object libraries' that support the entire procurement process would be a significant start to capturing a corpus of industry knowledge.

Major issues exist in supporting the definition and sharing of the context in which information is shared. 'Conversations' between software packages will be needed to improve sharing and collaboration by raising the quality and reliability of exchange.

Business needs, such as the protection of intellectual property and reduction in risk, will continue to be a major factor in both technical development and uptake of innovation. How will models, process and enterprise change as technology and business methods change?

As a final issue, despite promising work in the 1980s and 1990s, little has been done to support more direct engagement of clients in the design process. Can improvements in collaboration and the design process lead to improved client engagement, and possibly participation?

This chapter started with two questions:

1. How can standards (predefined concepts) be used to analyse designs and communicate about them?
2. How well do digital design tools support the representation, analysis and communication of design information within the constraints of the innovation/standardisation question?

The current answers are:

1. Standards are essential, but require continued research and development to reach their potential.
2. Current tools are improving in their support for representation, analysis and communication, but many more opportunities exist.

Improvements in the areas identified in this chapter will require close collaboration between industry, design researchers and information technology researchers to advance this field.

Acknowledgements

The work in this chapter was supported by a number of projects funded through the Cooperative Research Centre for Construction Innovation and the Australian Research Council Discovery Grant DP0985070, 'Challenging the inflexibility of the flexible digital model'. Bianca Toth, Jim Steel and Ruwan Fernando participated in discussions on issues incorporated in this chapter.

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12 Examples of distributed intelligence on large-scale building lifecycle projects

Martin Riese

The global industry of the built environment has entered a period of substantial transition that is largely being brought about by the implementation of mature technologies and their associated new working practices. Measurable improvements in quality and productivity are being realised in other industries in which such technologies and working practices were implemented earlier on. These benefits are now also coming to the industry of the built environment. This implementation of new technologies and working practices is a key element in the movement to bring about global 'construction industry transformation'. A new generation of project teams is working remotely to create, aggregate and manage large, highly complex, three-dimensional design and construction information databases collaboratively over the internet. Previously, problems resulting from incomplete coordination and errors in two-dimensional project information were almost universally experienced on construction sites. These are now being identified and corrected earlier on in the process. As a result, better-quality buildings are being delivered, on time and with reduced abortive works and post-construction claims.

Emerging advanced modelling and simulation technologies are being connected directly to three-dimensional design and construction databases to enable preliminary designs to be informed by knowledge from downstream processes. This is enabling accelerated and enhanced innovation that is helping project teams to deliver challenging designs that would previously have been impossible. Processes in design and construction that were traditionally the domain of people with specialised manual skills are slowly being augmented and/or replaced by machine automation. The necessary interoperability of these automated processes is enabling affordable mass customisation and the potential for substantial industry supply chain integration. The integration of all aspects of the supply chain will bring additional improvements in efficiency and the ability for project teams of all sizes to explore and deliver highly innovative design and delivery possibilities.

Internet-based collaborative technologies are bringing project teams closer together, and this is becoming a defining factor in distributing intelligence. 'Distributed intelligence' actually implies *bringing together* all project participants to focus, integrate and unify project knowledge long before construction begins. Soon, the relative success of a project may well be determined by a kind of linear relationship between the number of people whose thinking can be directly merged and simultaneously brought to bear on the project knowledge database – and the resulting level of innovation and efficiency that is manifested in the resulting project.

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

This chapter will present a number of examples of large design and construction projects that have benefited from the efficiency of the application of distributed intelligence. The arrival of new collaborative technologies and working practices at this time of the 'coming together' of people in general is not a coincidence. The technologies and working practices that enable distributed intelligence are key tools in the process of the overall management of sustainable development, which, arguably, may be essential for the wellbeing and survival of the growing human population in the immediate future.

The integration and re-organisation of the management of knowledge in the industry of the built environment (including the implementation of distributed intelligence) may be prototypical for the kind of re-structuring of the organisations of human populations in general that will be necessary to achieve a long-term sustainable human existence on the planet. The inefficiencies of non-distributed (or non-unified) intelligence may, in themselves, cause the entire ecosystem to fail. The technology now exists to manage a more coordinated, sustainable existence on the planet and its immediate implementation in the industry of the built environment is now crucial.

Introduction

Over the past three decades there has been a steady increase in the implementation of mature information technologies and working practices in other globalised industries such as aerospace and automobile production. This has resulted in the fact that these industries have become substantially more efficient and effective. Other industries have experienced and recorded a direct relationship between the use of two-dimensional, paper-driven processes and the number of mistakes and abortive works that are experienced in the delivery processes in those industries.

The lack of a comprehensive, integrated three-dimensional design and delivery process has a negative effect on the overall design quality and production efficiency of mass-produced products. The reduction and complete removal of two-dimensional, paper-driven processes from design and production in other industries are making possible increased efficiency, quality and safety in those industries. The industry of the built environment also suffers from reduced efficiency resulting from inadequate information management technologies and working processes.

This chapter will briefly document a number of large design and construction projects that have used the principles of distributed intelligence to begin to realise the benefits of improved information management and work flows that are being achieved in other industries. The industry of the built environment is adopting similar value propositions that are guiding other industries to enhanced productivity and success. Substantial design and construction projects have been optimised by implementing pre-coordination, analysis and simulation of the entire project information lifecycle. New added value is being realised by the implementation of process innovation. Increasingly, improvements in value and quality and safety enhancements will be realised in this industry as a result of the trend towards the virtualisation of the design and lifecycle information management process.

Virtualisation in design and construction

The global industry of the built environment, like most other industries, is at some stage in the overall process of 'virtualisation'. This process is similar to the one that other sectors such as banking implemented in previous decades and is characterised by the following necessary and inevitable industry changes:

- Fully integrated, centralised, internet-based information management.
- Automation replacing manual working practices.
- The removal of paper from working practices.
- Substantial gains in efficiency and quality of delivery.
- New realms of product possibilities and growth enabled by the implementation of new technologies and working practices.
- Enhanced empowerment of decision makers through automation and transparency throughout the process.
- Internet-based information exchange and collaboration enabling accelerated iterative consensus building and innovation.
- Direct connection of the underlying project business model and pro-forma with the actual building lifecycle information analysis and decision-making database.

A brief description of the virtual building lifecycle information management process

The implementation of new technologies and working practices is a trend that is pervasive throughout the lifecycle of buildings. It begins at the formation of the business pro-forma of the project, and continues through preliminary design and coordination, the procurement process, construction and beyond completion into the facilities management phase. Building information modelling (BIM) was an early phase of construction industry transformation which is now evolving into building lifecycle information management (BLM). Building information modelling consists of the three-dimensional geometrical information about the building, but also includes all of the two-dimensional project data such as quantities, costs and engineering information. BLM is a process that is much wider than that. BLM incorporates the integration of all of the data relating to the project business pro-forma, design, fabrication, construction and facilities management phases. BLM can include sophisticated and detailed project knowledge and 'embedded intellectual property' of individuals or groups. It enables automated change management and integrated project controls.

BLM begins at the very inception of the project, when the basic information about the project is being evolved and integrated into one, preliminary, three-dimensional database. The full generating financial pro-forma of the development, site geometry, existing site services, cost information, zoning information, the structure of the project consultant team and, increasingly, specialised 'captured project knowledge', which passes from project to project, are all included in BLM. All of the emerging information about the project continues to be added to the one BIM database as the project moves progressively through the various phases of its development.

It is likely that regulatory authorities throughout the world will soon require fully automated, internet-based, three-dimensional submissions for building code compliance review. This will mean that building permits can be automatically issued over the internet. The functionality of this structure of conformance will be integrated into the preliminary design phase. Partial automation is already being applied to tasks such as net present value optimisation and building core design. Building permit submissions are likely to be made via standardised global, industry-wide formats. An example of what this might look like is Industry Foundation Classes (IFC) compliant three-dimensional data exchange, which already enables efficient and semi-automated code compliance checking. It is likely that building information in general will be shared across the industry using an exchange format like IFC. Sophisticated three-dimensional geometries, spatial relationships and even building methodologies could be reviewed and approved automatically.

When it is time to begin to construct the project, the enhanced building information management process will have provided a detailed automated bill of quantities, improved coordination of information, automated production of two-dimensional construction documents, and a preliminary construction sequence simulation and methodology. This digital information is already augmenting contract documents and will ultimately replace paper-based contractual instruments. Projects which have been fully coordinated with BIM have less risk associated with them. This means that tender prices are lower and have less of a spread between them. BIM can also form the basis of lower negotiated bids with pre-qualified contractors.

Soon, the BLM model will, in itself, become the legal contract document. It is hoped that the legal profession will help to bring this concept into reality, because it will bring added efficiency and accuracy in the underlying legal framework of projects. The constructor can use the BLM model as the central repository of all the project construction information. The constructor's own three-dimensional coordination, supply chain management, cost control, construction process simulation and operating and maintenance reference information can be built up on the BIM created by the design team. Of course, it can also be used to manage 'legitimate' changes to the contract that are not the result of inadequate information. When the project has been constructed, the BIM model can be returned to the owner for use in the facilities management phase. BIM makes the transition into being full BLM at this point in the building process, because it is now used to manage the completed project for its full service life – including eventual modification and/or demolition.

> Using BIM technology has major advantages for construction that save time and money. An accurate building model benefits all members of the project team. It allows for a smoother and better planned construction process and saves time and money and reduces the potential for errors and conflicts. (Eastman *et al*. 2008: 207)

The value of improved building lifecycle information management can be summarised as in Table 12.1.

Example projects using virtual pre-coordination and distributed intelligence

One Island East Hong Kong

Project collaborative metrics: Database size 4.37 GB, 5400 interconnected files, 30 simultaneous collaborative users in 10 companies.

The One Island East Tower project in Hong Kong is an example of the implementation of new technologies and working practices in the emerging transformed industry of the built environment. BLM consultant Gehry Technologies (GT) was commissioned by the owner, Swire Properties Limited, to implement improved building lifecycle information management technologies and practices to reduce waste in the construction of this 70-storey office tower. The owner hoped to increase the quality of the project, save on cost and reduce the construction time. Working together concurrently, many expert professionals contributed collaboratively over the internet to create a single three-dimensional database containing all of the project information.

The challenge of integrating building information modelling into this huge project was successfully met by the consultants and the winning contractor, Gammon Construction Limited of Hong Kong. One building information database integrated every aspect of the building, including

Table 12.1 The value of improved building lifecycle information management.

1	Prior to tender and construction, three-dimensional geometrical coordination of all building elements identifies many issues that would be difficult or impossible to detect otherwise. A significant measurable reduction in waste and construction cost can be realised through this process.
2	Clash lists are generated automatically from the BIM model, which provide detailed, iterative feedback about conflicts to project teams as major systems are developed in a three-dimensional model of the building in the lifecycle design process. An audit trail of errors and resolutions is generated which can be referred to at any stage of the project.
3	Enhanced quantity take-off from the three-dimensional model improves the speed and accuracy of the management of the bills of quantity. Real-time, accurate, complete project cost knowledge can be created and reviewed as often as is necessary, remotely over the internet.
4	By referencing the same integrated and aggregated BLM model, architects and consultants can explore integrated structural analysis and simulation, enhanced energy analysis, fire safety analysis and other factors influencing the quality of the design.
5	The days of human beings manually producing two-dimensional geometrical information for site operatives are over. Two-dimensional documents can be produced automatically from the three-dimensional building information model data. This automated production of general arrangement drawings saves time and reduces errors. Time formerly spent labouring in the creation of two-dimensional 'production drawings' can be better spent resolving the actual underlying design and delivery issues.
6	Lower, more accurate tender pricing results from the significant reduction of contractors' 'unknowns'. A comprehensive model illuminates project complexity and allows risks to be quantified and managed prior to tender. Due to the enhanced quality of the tender documentation, the spread between tender prices on a BIM-led project is normally less.
7	Fabrication-level capabilities such as automated shop drawings, direct fabrication and supply chain integration can be enabled from a single composite model, thereby eliminating the need to redraw. Construction quality information is produced at the pre-tender stage that continues to be developed iteratively during the delivery process.
8	Management and visualisation of construction sequence (4-D) and process modelling and simulation using the BIM elements provide additional reductions in the cost of delivery.
9	Contractors' requests for information (RFIs) and claims on site, which used to result from traditionally incomplete two-dimensional construction information, are significantly reduced in number.
10	Elements of the BIM model can be simply connected to integrated facilities management and facilities maintenance solutions.
11	There is automation in the linkage of the business model for the project to the actual elements of the project design and construction database.

three-dimensional virtual pre-coordination, real-time cost control, and advanced construction process simulation and facilities management. Before the building was constructed, two-dimensional information that was to be used on site was first modelled and checked in the BIM model. Prior to tender, fabrication and construction, thousands of coordination issues and clashes were addressed by the team using BIM. The project was awarded the American Institute of Architects (AIA) BIM Award for Design/Delivery Process Innovation in May 2008. Figure 12.1

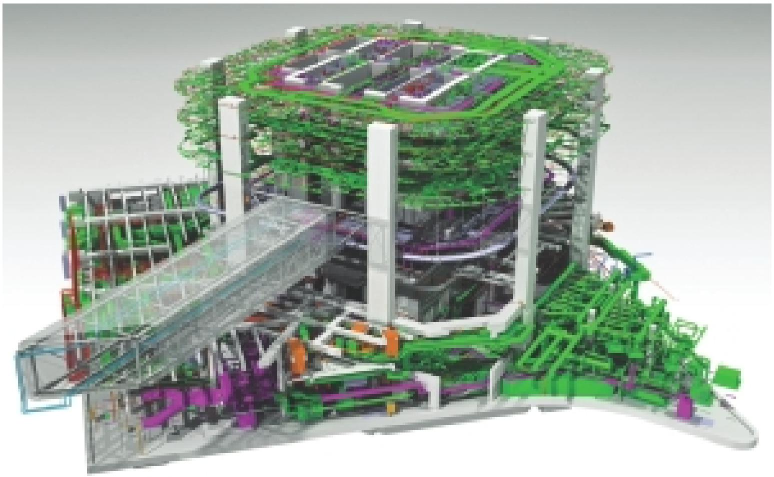

Figure 12.1 Swire Properties Hong Kong One Island East BIM model. (Image courtesy of Gehry Technologies.)

shows a work-in-progress view of the BIM that was created on site by the contractor, who was able to keep to the BIM model ahead of construction.

Taikoo Hui Guangzhou

Project collaborative metrics: Database size 11.5 GB, 18,510 interconnected files, 40 simultaneous users in 8 companies, 65 man-years of database management.

Building lifecycle information modelling has been taken to the next level of scale on the Taikoo Hui mixed-use project in Guangzhou (Figures 12.2 and 12.3). It is approximately 4.5 million square feet in area, which makes it roughly three times the size of the One Island East project. The kernel of this huge model is the automated quantity and cost management of its massive MEP system. 40 users worked concurrently for two years to prepare the single-tender BIM database. The project BIM team identified and managed thousands of clashes prior to tender using virtual pre-coordination techniques. The construction information that is now being used on site is being pre-coordinated in the three-dimensional construction BIM model.

Large networks of collaborators can effectively manage large projects or even cities more effectively using the technologies and working practices that are being employed on this project. Taikoo Hui is exemplary of how large-scale, internet-based construction project teams will be collaborating from now on. Pervasive implementation of state-of-the-art information technology is in itself representative of how the next generation of buildings will be developed and managed.

Sanlitun Beijing

Project collaborative metrics: Database size 35.5 GB, 24,956 interconnected files, 15 simultaneous users in 7 companies, 8.5 man-years of database management.

One of the first city-scale BLM projects to be undertaken is the Sanlitun commercial project in Beijing. Even though the project is nearly 3 million square feet in area, all elements of the

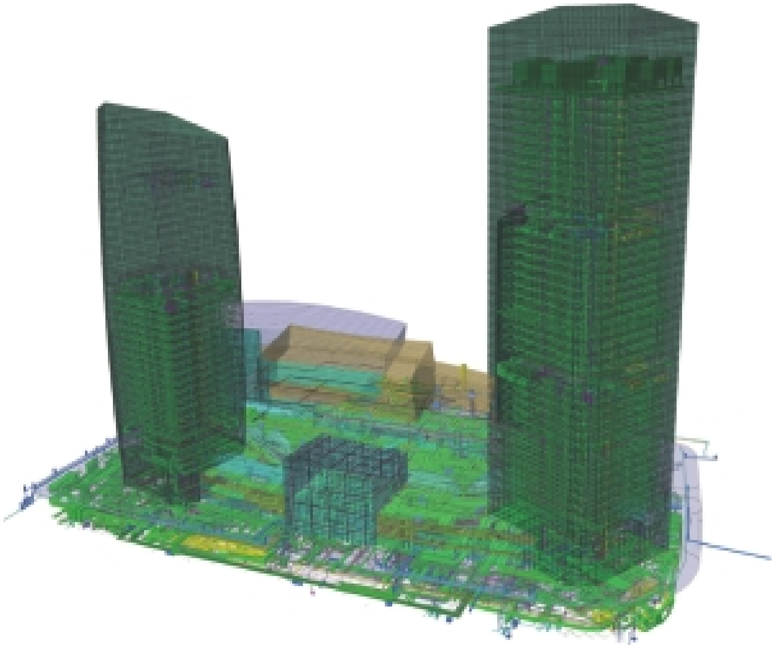

Figure 12.2 Taikoo Hui BIM model. (Image courtesy of Gehry Technologies.)

project were coordinated and integrated into the three-dimensional building lifecycle information database (Figure 12.4). In order to manage connections to the city infrastructure, it was incorporated into the existing infrastructure model as well (Figure 12.5). All building services such as sprinkler heads and lights were modelled and coordinated. Substantial tenant changes were reviewed, analysed and executed by using virtual pre-coordination.

Hotel renovation project

Project collaborative metrics: Database size 6.82 GB, 10,224 interconnected files, 8 simultaneous users in 3 companies, 3 man-years of collaborative database management.

Thousands of detailed MEP coordination items and structural changes were required during the renovation of this large hotel. The owner, consultants, contractor and subcontractors used the BLM modelling process to manage large amounts of design and construction information prior to the actual construction. The project team met regularly to review the BIM model and to review and resolve items that were automatically identified by the BIM technology (Figure 12.6).

Another sophisticated technology implemented in this project was construction process simulation. A number of risk areas were carefully reviewed in advance to ensure that the methodology was optimised. On a number of projects the implementation of construction process simulation technology and working practices has shown that the added value resulting from construction process optimisation can easily be larger than that from the value of geometrical pre-coordination.

Figure 12.3 Taikoo Hui BIM model – basement coordination. (Image courtesy of Gehry Technologies.)

Hong Kong hotel project

Project collaborative metrics: Database size 7 GB, 2,218 interconnected files, 8 simultaneous users in 6 companies, 9 man-years of collaborative database management.

New technologies and working practices can deliver added value at any stage of a project and with any existing level of information. This project demonstrated this principle clearly, as the BIM process began after contract award and yet still delivered a great deal of value. BIM on this project helped the owner and contractor to incorporate substantial design changes brought about by a change in tenant after construction had begun. The Hong Kong hotel BLM model

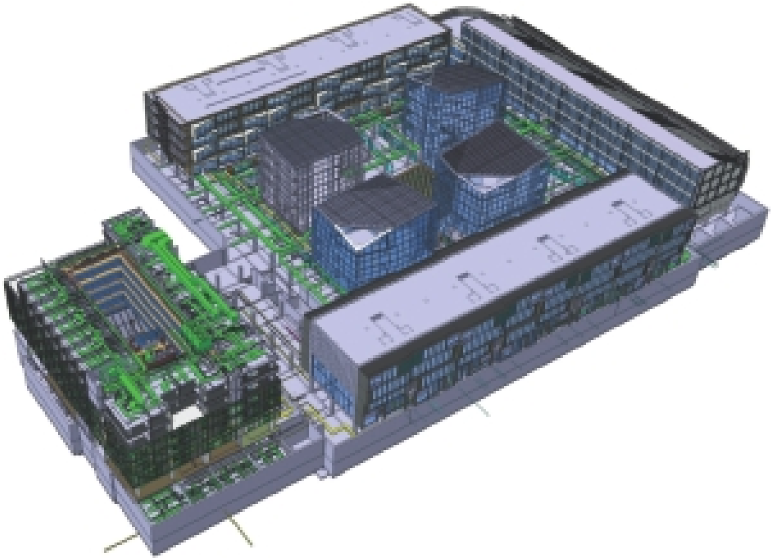

Figure 12.4 Sanlitun North BIM model. (Image courtesy of Gehry Technologies.)

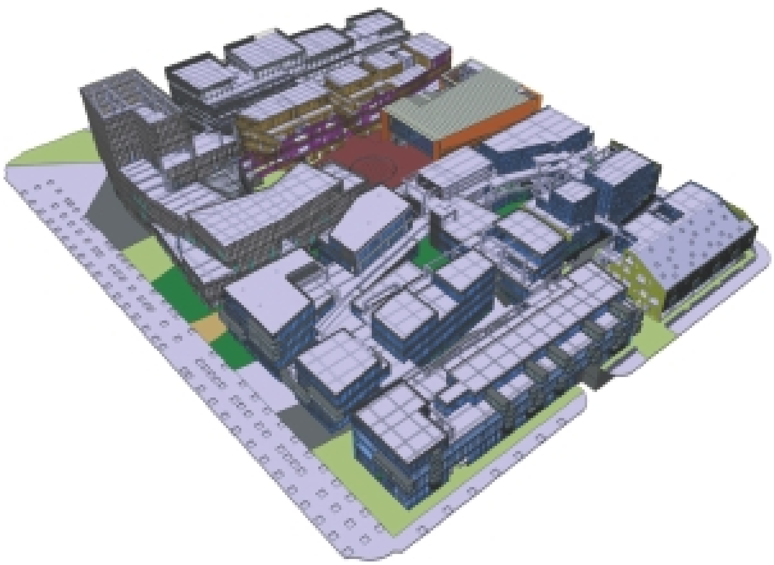

Figure 12.5 Sanlitun South BIM model. (Image courtesy of Gehry Technologies.)

was managed by the contractor, and helped to identify and manage hundreds of clashes and coordination issues before they caused problems on site. The cutaway in Figure 12.7 shows a work-in-progress image of the contractor's BLM model. The cladding and mechanical/electrical/plumbing (MEP) services were modelled to fabrication-level detail and thousands of coordination issues were identified and resolved prior to the actual construction.

Figure 12.6 Hotel renovation project BIM model. (Image courtesy of Gehry Technologies.)

Large existing commercial project – phased renovation

Project collaborative metrics: Database size 9.4 GB, 27 800 interconnected files, 23 simultaneous users in 10 companies, 15 man-years of collaborative database management.

The careful renovation of this Hong Kong commercial project began by creating a BIM model of the existing 2.8 million square foot commercial facility, including the entire existing MEP (Figure 12.8). The substantial sequence of renovation of the project was coordinated in a construction process simulation created by a contractor who was acting as an expert construction consultant. The optimisation of the proposed three-year construction programme was augmented by construction process simulation. Parts of the design were engaged by the designer in London, and remotely located BIM modelling resources progressed substantial portions of the BIM model.

Shanghai mixed-use project

Project collaborative metrics: Database size 29.8 GB, 16,849 interconnected files, 26 simultaneous users in 7 companies, 14 man-years of collaborative database management.

This city-scale building lifecycle management project (8 million square feet) is being carried out concurrently over the internet by project collaborators in at least five different cities. Breakthrough scale and detail have been achieved on this project (Figure 12.9). The model and construction process simulation have extended down to reinforcing bar and coupler sequencing level, finding substantial value in the early identification of previously unforeseen inefficiencies in project detailed design and delivery methodologies (Figure 12.10).

Figure 12.7 Hong Kong hotel project BIM model. (Image courtesy of Gehry Technologies.)

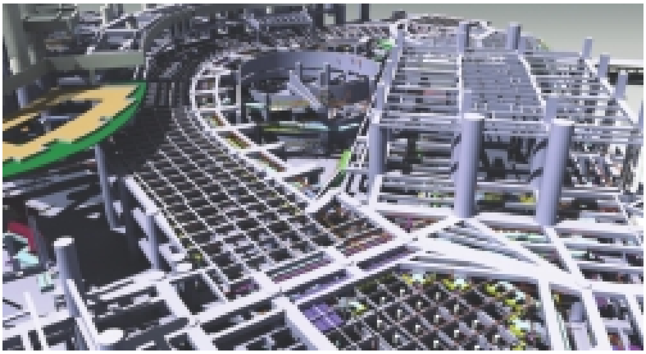

Figure 12.8 BIM model for renovation of existing 3 million sq ft commercial project. (Image courtesy of Gehry Technologies.)

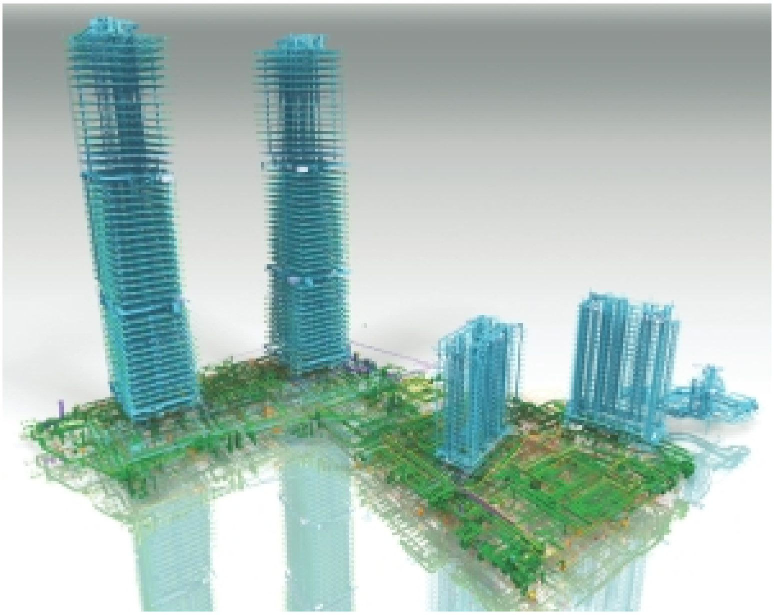

Figure 12.9 Shows work in progress of BLM model of the first phase of an 8 million square foot commercial mixed-use project in Shanghai which is BIM led. (Image courtesy of Gehry Technologies and Shanghai RuiMing Real Property Co., Ltd.)

Marina Hotel, Yas Island – Architect Asymptote

Project collaborative metrics: Database size 3 GB, 1,000 interconnected files, 22 simultaneous users in 6 companies.

The Yas Hotel, designed by Asymptote Architecture, is located in Abu Dhabi and straddles a new Formula 1 race-track. The curving 'grid shell' element of the project is an excellent example of a successful implementation of integrated design and delivery – and distributed intelligence. The project is the result of an extensive and highly integrated collaboration between a number

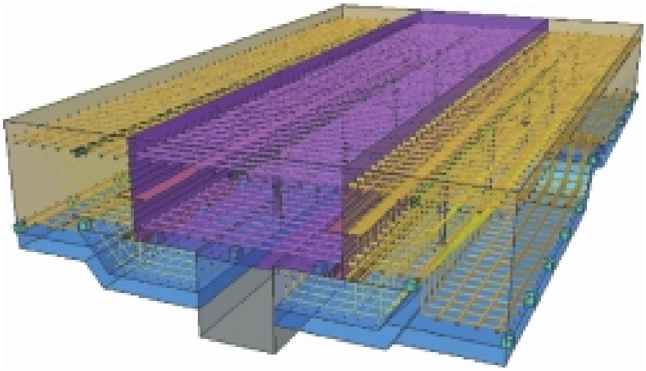

Figure 12.10 Construction BLM model includes reinforcing bars, couplers and their installation sequence. (Image courtesy of Gehry Technologies and Shanghai RuiMing Real Property Co., Ltd.)

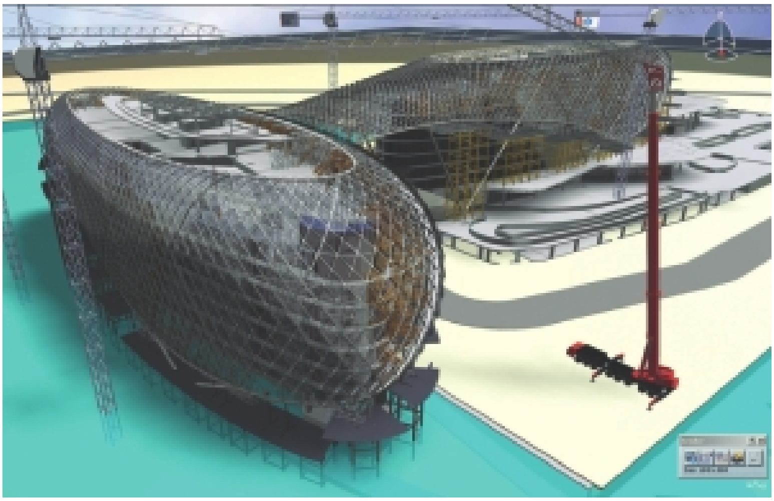

Figure 12.11 Information technology used to explore, manage and progress projects with complex architectural language. (Reproduced by permission of Gehry Technologies.)

of specialised consultants and contractors. The project team evolved and shared centralised three-dimensional design and delivery information (Figure 12.11). This complex and challenging project was completed remarkably quickly, and is an example of emerging projects that are simply not possible without the implementation of BLM technologies and integrated design and delivery working practices.

Dongdeaemun, Seoul, Korea project – Architect Zaha Hadid

Project (in progress) collaborative metrics (estimated): Database size 30 GB, 20,000 interconnected files, 15 simultaneous users in 10 companies, 18 man-years of collaborative database management.

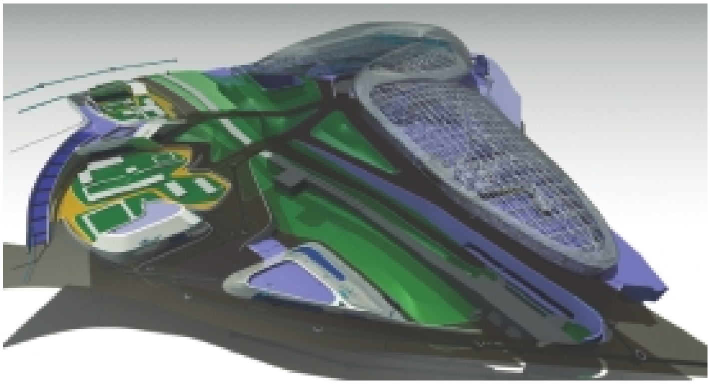

Figure 12.12 Pre-tender BIM model prepared by the architects and the project design team is being progressed into a construction BIM model by the project contractor Samsung and Gehry Technologies. (Reproduced by permission of Zaha Hadid Architects.)

This project is another example of how distributed intelligence enables the broadening of the boundaries of architectural language and delivery. Free-form architecture benefits from and embraces the potentially infinite variations of exploration of form and delivery made possible by parametric object management and enhanced collaboration. This impressive BIM model (Figure 12.12) was passed from the architects and their project team directly to construction teams, who translated and enhanced the data into their preferred construction format.

Foundation Louis Vuitton, Paris – Architect Gehry Partners

Project collaborative metrics: Database size 25 GB, 40,000 interconnected files, 180 simultaneous users in 13 companies, 80 man-years of collaborative database management.

The Foundation Louis Vuitton building is a contemporary art museum with permanent and temporary gallery space, studios for visiting artists and offices for the foundation. Its size is approximately 6000 m^2, on a footprint of approximately 2400 m^2. Probably one of the largest implementations of distributed intelligence, this project brought together 180 people working on one three-dimensional database. This project shows that there need not necessarily be a linear relationship between the size of the team and the area of the project. Here the increase in team size was used to help the project team to manage the complexity and quality of the design. The vast number of project participants (180 people working on the model, 80 designers creating the geometry, 100 people using the model) who were involved during the conceptual design phase brought about a vast number of project modifications that needed to be coordinated and updated simultaneously (6200 modifications in 8 months, 200 modifications per week, 20 modifications per day); see Figure 12.13. This is an example of the emergence of exciting architectural projects that would not have been possible without BIM.

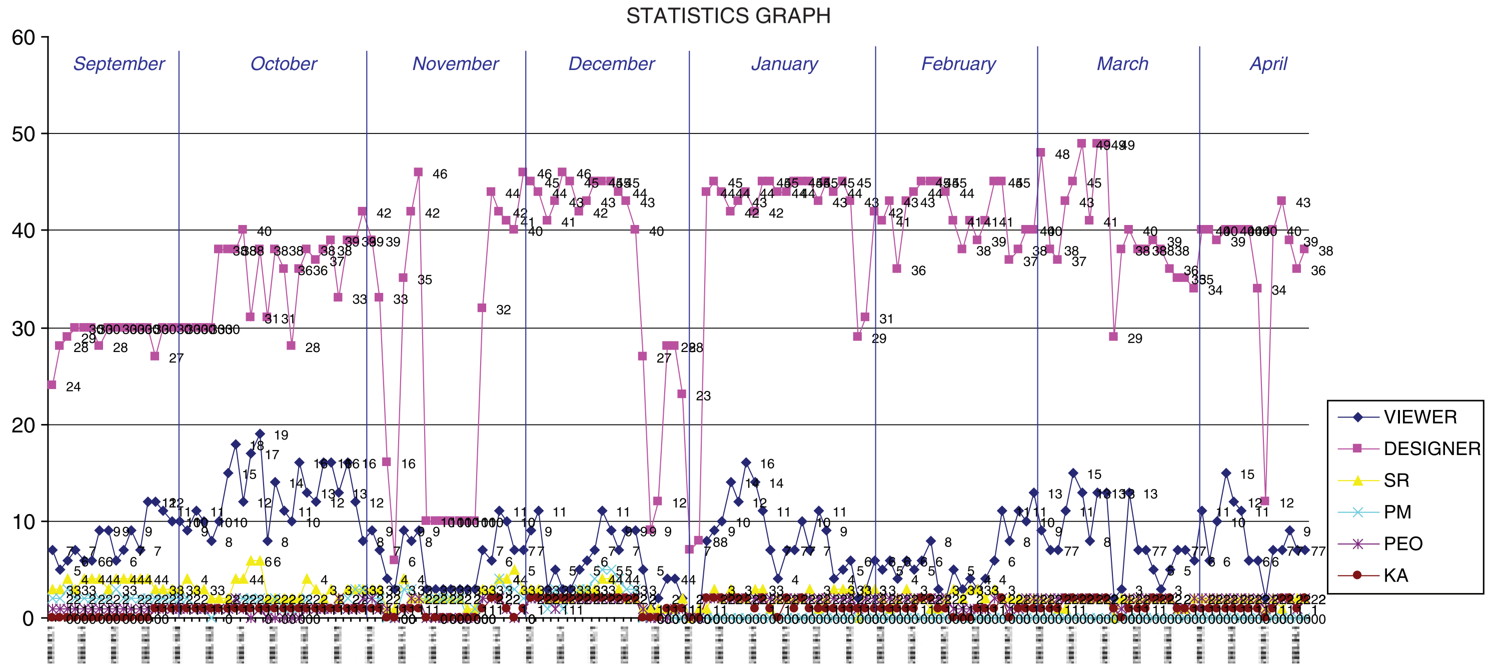

Figure 12.13 Graph indicating number of collaborative BIM project participants over time. (Image courtesy of Gehry Technologies.)

An outline of basic functions of the new technologies and working practices

Automated clash detection and management

An essential fundamental function of distributed intelligence in the industry of the built environment is internet-based automated clash detection and management. From anywhere in the world, owners and project team members can collaborate concurrently over the internet. The image in Figure 12.14 shows how the BIM software can automatically identify and manage clashes and coordination issues.

Fundamental to coordination and clash management is the definition of various tolerances according to site requirements. Cladding tolerances might be 10 millimetres and structural tolerances might be 25 millimetres. The technology is able to adapt accordingly in its clash analysis. (It is interesting to note that almost never is there a zero-millimetre tolerance on a construction site.) The tolerance of clashes can be pre-defined prior to clash analysis and lists of hundreds of design coordination issues are then generated automatically by the software. Precious project manpower previously used to do this work can now be used for the job of actually resolving the underlying design and delivery issues collaboratively and concurrently in the three-dimensional model. Versioning and data access permissions can also be easily managed by the software. Distributed intelligence is both enabled and managed by these frameworks.

Automated two-dimensional drawing extraction from the BIM model

The emergence of distributed intelligence will ultimately bring the end of the use of paper drawings in the production of buildings. By the time a production drawing has been created, the design has usually already progressed beyond what is indicated in that drawing. However, for the

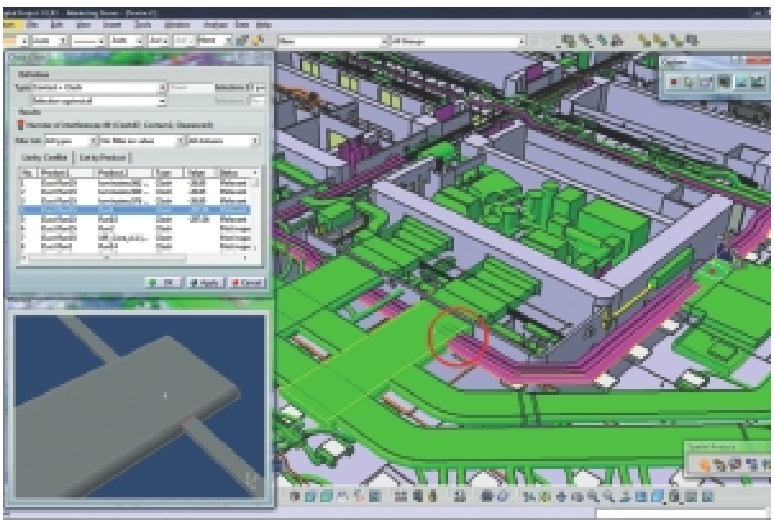

Figure 12.14 Automated clash detection and management. (Image courtesy of Gehry Technologies.)

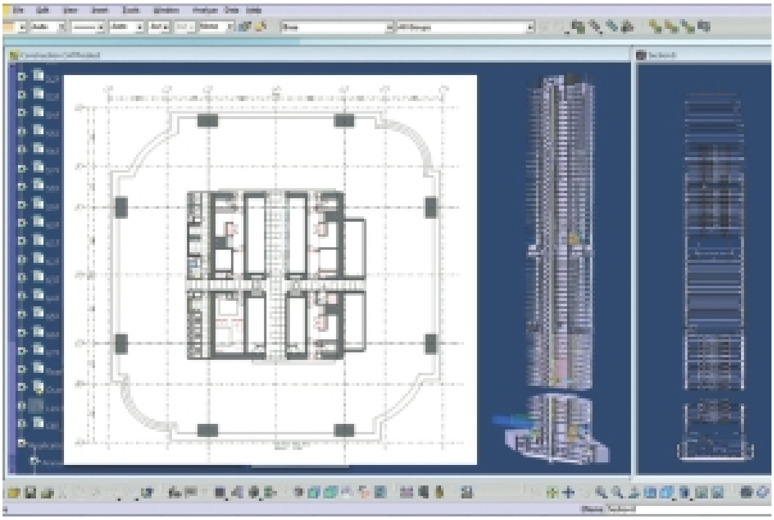

Figure 12.15 Automated two-dimensional drawing extraction from the BIM model. (Image courtesy of Gehry Technologies.)

time being in this 'transitional period', two-dimensional drawings are still required on the construction site. These two-dimensional drawings are better produced automatically from the BIM model because they incorporate all of the coordination information that has been invested in the BIM model by the project team. Two-dimensional drawings created directly from the BIM model contain fewer errors and revised drawings can be produced more quickly because they are generated directly from the BIM model, where the three-dimensional changes are coordinated and validated (Figure 12.15).

Automated quantity take-off and bills of quantity

One of the most important practical manifestations of distributed intelligence is automated cost management. Referring to the Hong Kong One Island East project, for example, all of the defining information about the building's elements, such as size, material, weight, location and sequence, was integrated and aggregated into the BLM model. Using automated scripting functions, quantities taken from the BIM were formatted into Hong Kong Institute of Surveyors (HKIS) format (Figure 12.16). This made it easier to manage and process cost information. The database of quantities was automatically updated as the design developed. During the design process, the quantity surveyors were able to track costs more quickly and accurately.

We have evidence to suggest that, from now on, quantity surveyors will spend much less time trying to measure quantities from different sets of large-scale, two-dimensional paper drawings. Instead, the quantity surveyors will be able to spend more time researching the market to find where the best prices for the project could be obtained. This gives the owners and the design teams quicker feedback on the development of the design and thereby helps to save the project money. Another important advantage is that the entire project team has immediate access to integrated real-time cost information at all times.

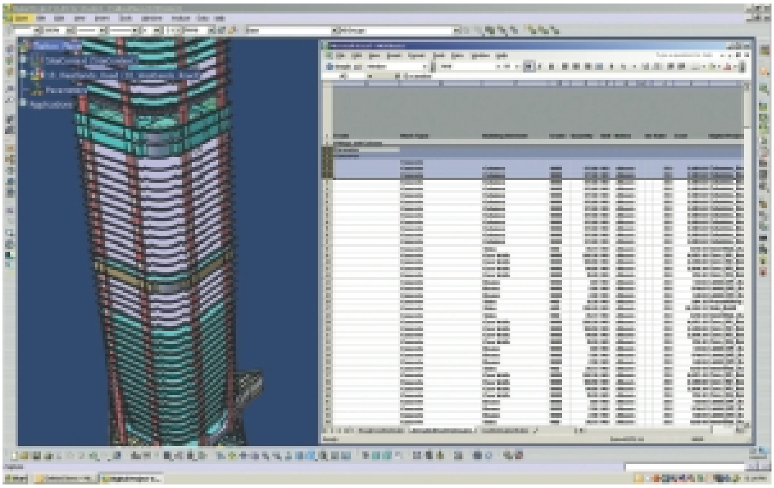

Figure 12.16 Automated quantity take-off and bills of quantity. (Image courtesy of Gehry Technologies.)

Internet-based supply chain integration

As a result of the continuing trend towards distributed intelligence, the entire supply chain of the industry of the built environment will become directly integrated into the rest of the building lifecycle process. Figure 12.17 and 12.18 show part of the three-dimensional geometry information for the cladding of the One Island East tower. These elements of the project were modelled to fabrication detail by the cladding subcontractor, Gartner. Mistakes that might traditionally be found later in the process – even on site – could be eliminated earlier on because the cladding was coordinated with the rest of the building prior to fabrication. The fact that the fabrication, delivery and installation of the cladding were on time was partly the result of this BIM-led pre-validation of the cladding design and installation.

Construction project teams can benefit from the development and sharing of large, complex BIM models over the internet. This is made possible in part by three-dimensional data compression, combined with emerging file-sharing protocols and general interoperability. The virtual project office of any construction team can benefit from the type of highly effective project team collaboration that took place on all of the example projects described earlier in the chapter. Full, continuous and instant visibility into the current state of the project BIM database can be made available to owners and project managers without the need for additional drawing issues or special meetings. Instant collaboration at any level of the decision-making chain – over the internet – is enabled because all elements of the BIM contain hyperlinks to individuals, manufacturers and design teams relating to those elements.

Construction process simulation

Advanced construction process simulation uses state-of-the-art process optimisation and visualisation technologies from the aerospace and automobile industries to simulate and optimise every step of the building methodology. Mistakes or inefficiencies are identified and corrected

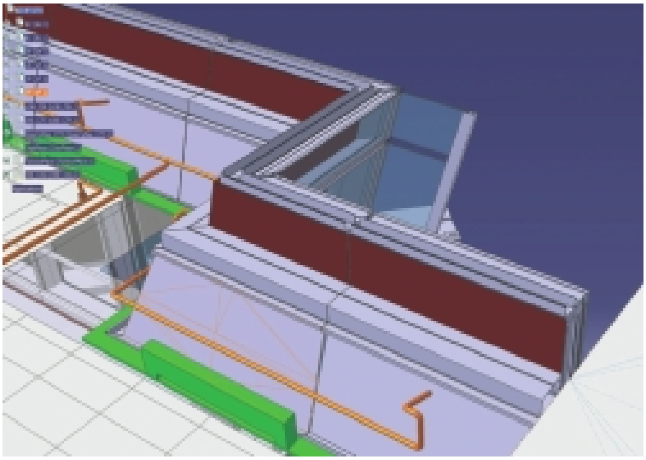

Figure 12.17 Cladding subcontractor modelled all cladding elements in the BIM model. (Image courtesy of Gehry Technologies.)

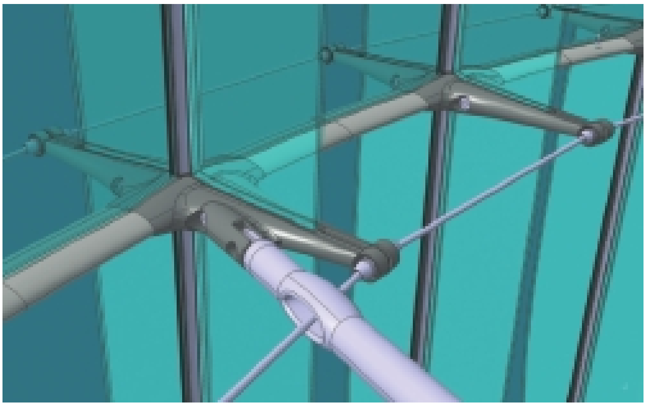

Figure 12.18 Fabrication-level BIM information modelled into construction BIM model by cladding subcontractor Gartner. (Image courtesy of Gehry Technologies.)

prior to construction, thereby reducing the planned construction time. The expensive post-completion claims resulting from cost and time penalties relating to construction information errors can be greatly reduced. Traditionally these claims were ultimately paid for by the owner, but they can now be largely eliminated. An industry culture change will be required to bring this about, particularly from some industry practitioners who have built careers around managing the claims process. The industry as a whole can no longer afford the 'claims culture'. Distributed intelligence enables the effective investigation and management of many risk items before they cause time and cost penalties.

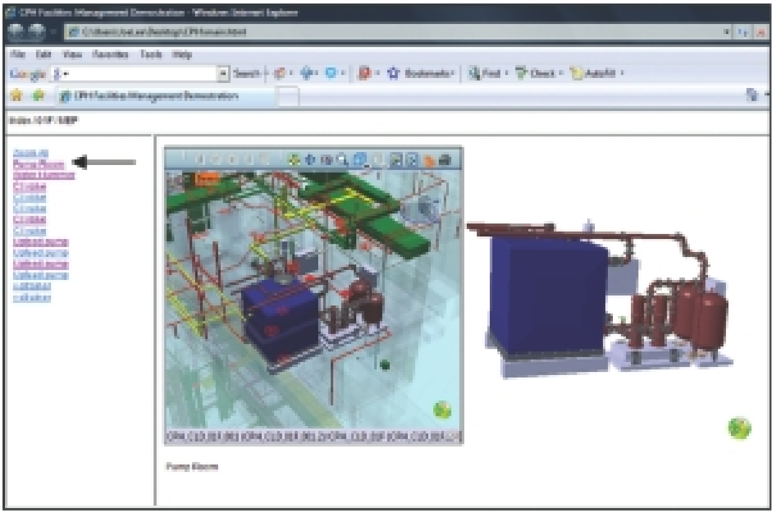

Figure 12.19 Facilities management integration into BIM. (Image courtesy of Gehry Technologies.)

Facilities management integration into BIM

The technology of distributed intelligence is ready to integrate facilities management solutions and infrastructures directly into the BIM process (Figure 12.19). The internet-based BIM model becomes the framework for the management of the project after completion. The BLM model can be 'hard wired' to the building management system (BMS) and the fire control systems. The actual building equipment can be monitored, controlled, optimised and maintained by the owner's facilities management team using the BLM model remotely over the internet where the BLM is connected to and controls the actual equipment in the building. From the start to the end of the life of the building, the same building lifecycle information database can used to manage everything about the project.

Engineering analysis and simulation integration into BLM

Architectural design becomes proportionately more successful as it is directly informed in its earliest stages by a fundamentally integrated and iterative, collaborative exchange of generative project knowledge with the project engineers. The new technologies and working practices that are now being used in the global industry of the built environment enhance and further enable this defining exchange of early project knowledge. This mature, internet-based collaborative engineering-informed way of working has been used in other industries for many years. It is, in itself, opening up many new possibilities for design and project delivery that were not possible before. At the same time, the industry as a whole is beginning to engage and integrate the engineering information infrastructure of its supply chain, so that fabrication and delivery engineering knowledge can impart more influence on preliminary design. The result is a more efficient and influential engineering process that helps project teams to explore new horizons of design possibilities. The technology of distributed intelligence is ready to integrate engineering analysis and simulation solutions and infrastructures directly into the BLM process. The internet-based BLM model becomes the framework for the coordinated exploration and integration of the engineering knowledge of the project.

The emerging integrated digital design process

Experience gained on numerous large BIM technology-enabled projects throughout the world yields some interesting indications about where the emerging integrated design process is going. The notion that information management can be somehow separate from the process of design and delivery is not borne out on site. BIM cannot be 'outsourced'; quite the reverse is true. The information which documents the design and delivery process is (necessarily) becoming ever more integrated directly into that process. The BIM is the integrated manifestation of hundreds of man-hours of direct expert professional collaboration. This does not mean that project team members cannot work remotely – they can. But all team members must be closely connected via a clear collaborative structure of information exchange.

The new technologies and working practices that are transforming the industry of the built environment are helping to better manage highly complex industry issues three-dimensionally. The imagery in the construction industry has moved beyond the production of 'pretty pictures' that are produced to help to convince project stakeholders to spend money. The imagery that is now emerging in the industry of the built environment documents the actual knowledge and information of the project itself. It is a virtual prototype. As such, images take on a greater importance, because they literally *are* the project knowledge. The famous quote from Marshall McLuhan three decades ago still seems to hold true: 'The medium is the message.'

Conclusions and discussion

Distributed intelligence today

Distributed intelligence in the process of building lifecycle information management is changing the nature of the industry, because it is greatly enhancing the ability of project team members to collaborate concurrently and more effectively, thereby reducing waste across the entire industry. The supply chain benefits from this improvement in efficiency, because it is integrally connected into the process. Many thousands of elements of the project are tracked from the factory to the site and then through their service life in the building. The implementation of radio frequency identification (RFID) helps to create the connection between the virtual prototype and the actual elements of the project. On a project such as the Hong Kong One Island East tower, the result is a vastly improved building lifecycle process. This project is typical of the future of procurement and the more sustainable lifecycle management of the built environment.

The future of distributed intelligence in building lifecycle information management

Fifteen years from now, the construction industry will have been transformed into a highly efficient, unified process that integrates design ideas that are fully informed by exhaustive, iterative engineering analysis and simulation with a seamless, factory-based, optimised manufacturing and assembly process. Construction will have become a holistic organism in which all stages in the process inform each other through a technologically enabled network of collaboration and information exchange that is shared by man and intelligent machines alike. Projects will become ever more cost effective, because designs will be informed by optimised real-time planning and logistics strategies. Energy efficiency, lifecycle costs and safety will be greatly improved. There will be one all-encompassing, three-dimensional global asset database of built form, which will be integrated with other rapidly evolving information databases that will be instantly accessible to all.

Through the integration of new paradigms of material and structural analysis and simulation, business management, parametrically driven design analysis and automated generative computer design, construction projects will be more efficient and will take advantage of forms of innovation that are only possible through the use of these new media and tools. The syntaxes of architecture and construction will manifest a higher level of artificially conceived and functionally driven elements and systems that result from this enhanced process. Rather than being limited to semi-arbitrary form-making, the beauty of sophisticated, logic-driven ideas and explorations will become the driving force in design. Individuals will be seamlessly connected to the vast network of global collaborators and will become ever more specialised as the never-ending renewal and evolution of the entire process accelerate exponentially. Construction process dashboard controls will become increasingly simple and yet powerful at the top of the decision-making chain, and increasingly granular, numerous and automated at the bottom. There will be substantial 'feedback' from the site and post-construction processes back into the design and manufacturing cycle.

Ultimately, a perfect union will be achieved between the imagination of the individual designer and a massive interconnected symphony of planning, production and lifecycle management. The process will gain an increased life of its own and will become, in itself, a recognisable revolutionary presence in future society, which will help to empower the political structures that currently define the limits of the industry (Riese 2008: 71).

Acknowledgements

Some portions of this chapter, including some of the images, are based on material that was previously put forward in the following publications: Chongqing Housing Conference proceedings edited by Tsou Jin-Yeu, Zhang Xinggou, Xu Ronglie and Jin Dejun, published by China Architecture and Building Press in 2008; The proceedings document of the Hong Kong Polytechnic University conference on collaborative working practices, *Collaborative Construction Information Management*, edited by Geoffrey Qiping Shen, Peter Brandon and Andrew Baldwin, published by Spon in 2009; *The Handbook of Research on Building Information Modelling and Construction Informatics: Concepts and Technologies*, edited by Jason Underwood and Umit Isikdag, to be published by IGI Global in 2010.

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Part 4

13 Rapid practice expansion through strategic design computation

Cristiano Ceccato

Zaha Hadid Architects (ZHA) is a London-based architecture practice operating internationally with projects under development and construction worldwide. The firm has grown almost tenfold over the past decade in response to market demand. This success presents a very serious challenge in terms of project design and delivery methods, design quality and control, and project management. Together with the ever-increasing demand for extensive and precise information by clients, this has further increased the need for a powerful and versatile computational foundation. ZHA engages in different types of projects, including design competitions, bids and feasibility studies and direct commissions, as well as computational design research, the latter interplaying with actual projects to provide new tools and design methods, which are described in this chapter.

The context of contemporary global architectural practice

Contemporary architectural practice is affected by a number of major factors, which have a combined influence not just on the design practices of architectural offices, but on the allied professions and the architecture, engineering and construction (AEC) industry as a whole. The result is an increasingly complex intersection of economic feasibility, environmental sustainability, physical constructability and (finally) artistic creativity that demands an ever-widening range of solutions, immediate results and the ability to achieve projects both economically and under management of risk.

One factor is the continuous, rapid growth in sophisticated computational technology and creative design tools, and the closely related interest in the use of technology as an active design and design exploration tool. The aesthetics of computation and the myriad forms, patterns and physical constructs that can be generated through parametric modelling and procedural scripting are currently a dominant force within contemporary architectural discourse. The speed of form generation, coupled with the vast range of related design solutions which can be generated quickly and precisely described, creates a need for a downstream process to edit, develop and document design solutions for construction.

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

Another important factor is the rapidly increasing growth in clients' requirements for projects and, in particular, the reduction in turnaround time for submittals ranging from design options to RFI responses, as well as the breadth and precision of information required by the client during the design phase. In most cases, the type of information required, at the level of detail and the speed requested, can only be processed and provided if the project in question is built primarily on a digital platform.

ZHA has grown extremely rapidly to meet market demand, and as a result has implemented a range of technological and managerial solutions to achieve sustained growth in recent years in response to clients' project requirements. To illustrate this, the discussion of process in this chapter is loosely subdivided into upstream 'design' and downstream 'production' phases; these are of course closely connected, and it is therefore unrealistic to attempt to separate them entirely. Rather, different recent projects are used to explain the usage of different yet interconnected forms of digital technology in pre-construction and downstream tender and construction phases.

Geometry and technology

Zaha Hadid's interest in form and its geometric definition goes back more than 30 years. A central preoccupation of ZHA has therefore been the exploration of complex geometry, its representation and increasingly, over the past ten years, its translation into physical form through built projects.

The design language at ZHA has continuously evolved, but its central interest has remained focused on concepts of dynamic architectural and urban form. Architecture is understood as having a motion or movement embodied in its design, which separates it from the conventional static of traditional form language. In recent years this has been characterised by curvilinear geometry and complex, mass-customised components that are at the heart of contemporary architectural discourse today. Together, these design aspirations require considerable computational skills which are beyond the average use of CAD or 3-D visualisation modelling normally found in practice.

In keeping with the firm's ideals of research and experimentation, ZHA has chosen not advocate a dogmatic approach to software technology within the office. In other words, while the introduction and dissemination of tools and technology must necessarily be controlled in a larger firm, a number of similar tools are used in each stage of work, either because different teams have different experiences of technology, or because one type of project is more effectively tackled on one platform rather than another. In most cases multiple tools are used concurrently, whereby the effort of supporting multiple platforms is clearly outweighed by the advantage of being able to tap into the best tools and technologies each platform has to offer.

Early design phases and design exploration

In the interest of simplicity, 'early design phases' here refers to (roughly) RIBA Stages A–D, or in AIA terms from Pre-Schematic Design (Pre-SD) through Schematic Design (SD) into Design Development (DD); in other words, those project stages where early on, a range of design variants is explored in a fast and furious manner, before a guided process of sublimation and distillation occurs, allowing the project to converge onto a preferred solution. Typically, although the solution that emerges from this process is favoured as the strongest, there are many unforeseen developments downstream that require a project to be rapidly altered in response to client, government or financial requirements, with only minimum impact permissible to the project schedule (programme) and under tight control of budget.

Parametric design language

Under the leadership of Zaha Hadid and Patrik Schumacher, the firm of ZHA has developed an approach to building design which makes consistent use of the powerful computational design technologies available today. In fact, the design language of the office has evolved in tandem with technology, constantly pushing the boundaries of geometrical expression while developing the technical capability to capture and execute a design faithfully.

The integration of design intention and accurate, efficient project delivery is achieved through a digital codification of design as a series of related and interconnected geometrical operations, in which families of design solutions can be rapidly generated by controlling associative geometries and driving parameters. In other words, it can be argued that ZHA makes 'active' use of computation in its design process, namely as the driving force behind the generation of design solutions and aesthetic language, as opposed to a 'reactive' approach whereby the computer fulfils a more utilitarian function of 'describing' the geometry of a form which itself has been generated elsewhere, for example in the work of Frank O. Gehry. Downstream, design geometry can be articulated as families of self-similar components that can be produced by available CNC fabrication technologies, and rationalised to achieve constructability informed by cost, risk and aesthetics. This process-wide 'parametric language' allows ZHA to rapidly and efficiently tackle complex design problems and produce a flexible range of viable results in a short amount of time, while being able to effectively deliver building projects with confidence.

As a result, most architects within ZHA have a high degree of computational literacy and dexterity, ranging from traditional CAD skills through 3-D parametric modelling and scripting, and many are experienced in constructing projects through digital coordination. Combined with an increasing number of employees who are specialised in design computation, this level of digital fluency ensures that the firm can make the fullest use of the digital design tools available – with the ability to customise and tailor these tools to the firm's design requirements, and not vice versa.

ZHA has a widely available 'general scripting' knowledge base spread more or less uniformly around the office and the project teams. This consists in general of VB scripting in Rhino (and, more recently, Digital Project), as well as the ability to produce and replicate quite sophisticated parametric reconfigurable models using Maya, Rhino's Grasshopper and Digital Project's PowerCopy. If scripting and programming are understood as knowledge capture that can be repeatedly applied, then 'parametric modelling' can be seen as a form of 'visual programming' that in many cases accomplishes the same thing, but without the need for the user to learn extensive scripting syntax and grammar. In ZHA, this is a powerful paradigm that is widely available thanks to the firm's continued interest in postgraduate education, most notably through active involvement in the Architectural Association's MArch Design Research Laboratory or DRL, where parametric modelling and scripting techniques are universally taught to students.

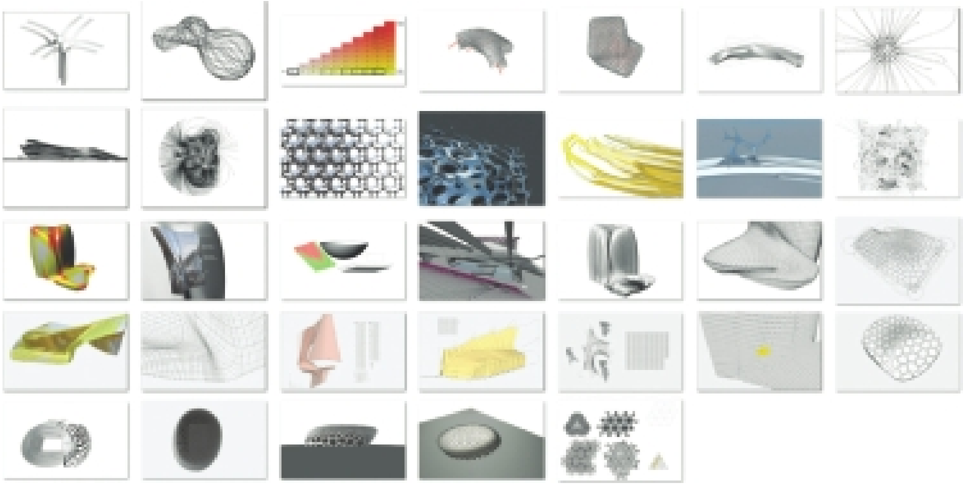


Figure 13.1 Parametric design research: Examples of algorithms and design strategies developed by ZHA using parametric modelling and scripting (programming) techniques. (Reproduced by permission of Zaha Hadid Architects.)

Design and computation research

Beyond general parametric modelling, ZHA also actively undertakes project-independent research, developing computational design tools and geometry-articulation algorithms through an in-house research team. This team is made up of architects and designers who have a particular interest and skills in formal software development. The team members divide their time into periods where they are directed to work on developing computational solutions independent of any project, and at other times are associated with, or deployed onto, specific project teams that may require a specific design-computation solution on a short- or long-term basis.

The tools developed by the research group can be considered as 'scripts' or more advanced 'plug-ins', which for the most part are developed on top of the various design platforms that ZHA uses – for example VB scripting in Rhino, and MEL or C++ in Maya. More recently, the research group has also begun to implement scripts in the form of Rhino Grasshopper parametric constructs, as well as more strategically to investigate a broader integration and interoperability of data between the various design platforms in the early design stages, as well as data transfer into the downstream production phases (Figures 13.1 and 13.2).

Design execution and integrated digital building delivery

The downstream stages of project execution can be loosely defined in AIA terms as Construction Documentation (CD), Tender Action (TA) and Construction Administration (CA). Beyond the early design phases, a mature full-services architecture practice must be able to control information through detailed design, construction documentation, tender and the construction oversight itself. In ZHA's case, rapid growth has also meant developing the capability to steadily deliver building projects through construction, if this same growth is to be sustained over the

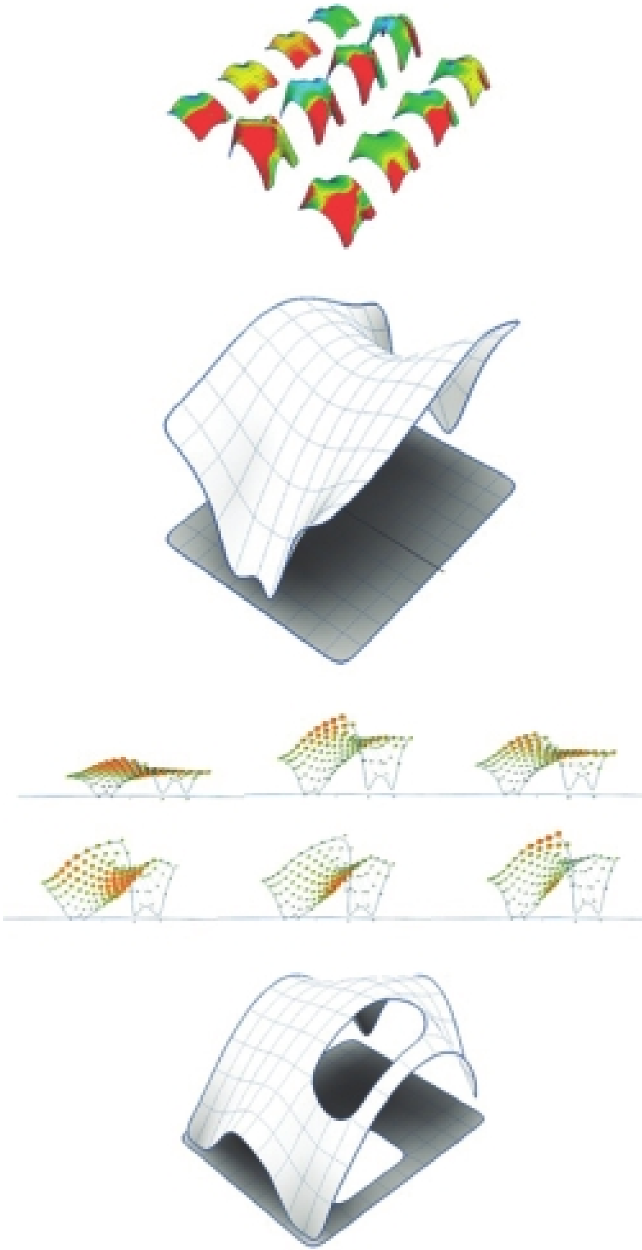


Figure 13.2 Parametric design research: Examples of algorithms and design strategies developed by ZHA using parametric modelling and scripting (programming) techniques. (Reproduced by permission of Zaha Hadid Architects.)

long term. Furthermore, this ability to execute increasingly large and complex projects must itself be attainable in a relatively short period. In many practices, steady growth means that professional project governance and documentation skills can be built up over time, in particular where a traditional paper-based process is involved.

Indeed, traditional contract forms in AEC assume 2-D paper documentation (electronic 2-D CAD files at best) to be the standard instrument of contract for executing building projects. Clearly, this is an anachronistic and archaic practice which not only proves to be a geometrically and technologically inadequate means of conveying information, but actually represents a risk to all the major parties concerned (client, architect and contractor, as well as downstream fabricating subcontractors), in that it provides a limited means of expressing complex geometry. Risk here is understood on a number of levels: financial risk, which is acute as there is an inadequate means of quantifying design geometry effectively; design risk, in that 2-D documentation does a very ineffective job of representing complex information; and project risk, in that the client has poor control over the design and the project's data and must therefore maintain a high level of confidence for the successful outcome of the project.

As well as traditional 2-D documentation, ZHA has addressed its need to develop and document complex projects comprehensively by implementing a 3-D documentation process, which can be described as building information modelling, although not always in the strictest definition of the term. The advantages and efficiencies of conventional BIM of this process are well known. In the case of ZHA's work, like many contemporary architecture practices exploring complex form language (such as Gehry Partners, Herzog & de Meuron and others), they are fundamental to capturing the project's design accurately. Certainly, accurate geometrical description, form rationalisation and componentisation take precedence in the pre-construction phase over a typical, fully fledged, ideal BIM document containing all information for project description. However, this focus on 'getting it right' in terms of comprehensive geometrical definition of the project has allowed ZHA to explore issuing 3-D geometrical model files ('digital contracts') as part of a project's contract document set, alongside the more traditional forms of documents such as 2-D paper drawings, detail books and specifications.

In practice 3-D file exchange takes place regularly on projects worldwide. However, although such 3-D models invariably play a central role in a project's development, they are normally issued 'without warranty', as 'reference files' that supplement the actual contract documents (the 2-D drawings), although those drawings have in the best case been generated from the same 3-D model and are therefore subject to a geometrical reductive process (from R^3 Space to R^2 Space); or in the worst case are not synchronised or coordinated with the 3-D geometry, resulting in potential disaster, as the contractor will invariably pick out the discrepancies in the two documentation forms and although would wish to work from the integrated 3-D model, is contractually obliged to refer back to the 2-D contract documents, which the Architect would then have to bring up to the same level of correctness as the model itself.

Digital contracting solves much of this problem, in that the 3-D model becomes an instrument of contract; in other words, the 3-D geometry that is electronically stored in the model file is officially issued to the contractor as the main geometrical definition and dimensional control vehicle for the project. Invariably this implies agreement on file formats, coordinate systems and applicable software that may be used on either side for accurate rendition of the electronic geometry, but in today's world of electronic practice this is generally easily solved, and yields a much higher level of accuracy in project description and quality of quantity surveying, a clearer understanding of project conditions and therefore – most importantly – a much higher level of project confidence by all parties concerned.

Design execution and integrated digital building delivery

The use of 3-D modelling and digital data on projects in advanced stages of development and construction at ZHA has also been steadily growing in recent years. In the earliest cases, 3-D models were only used to develop project geometry internally. In the last few years, projects have begun to employ BIM-capable 3-D tools such as Digital Project and Revit as a central geometrical coordination platform.

As noted previously, another important factor is the rapidly increasing growth in clients' requirements. In most cases, the type of information required, at the level of detail and the speed requested, can only be processed and provided if the project in question is built primarily on a digital platform that can be efficiently interrogated for information, and tracked and audited for design transactions and changes.

The latter point is particularly critical during the construction phase, as an agreed tender offer by the general contractor (often tied to a GMP, GMax or guaranteed maximum price). Any changes to the contracted geometry can readily result in expensive Change Orders, and the records that track design changes are fundamental to informing the reasons and responsibility for the change – and whether it was mandated by the design team, or by the contractor, and approved by the client. These aspects of project governance are important to ensure that confidence is maintained in the project-delivery process at all stages of work.

An initial 3-D coordination project

One of the first projects to employ 3-D digital coordination at ZHA was the Glasgow Museum of Transport. A Digital Project model was used to integrate the primary structure (steel) with the exterior and interior cladding systems, as well as the main mechanical systems ducts and plant equipment. The steel members in the model were specified by the structural engineer and subsequently detailed with Tekla XSteel to provide all connections (Figure 13.3). This detailed

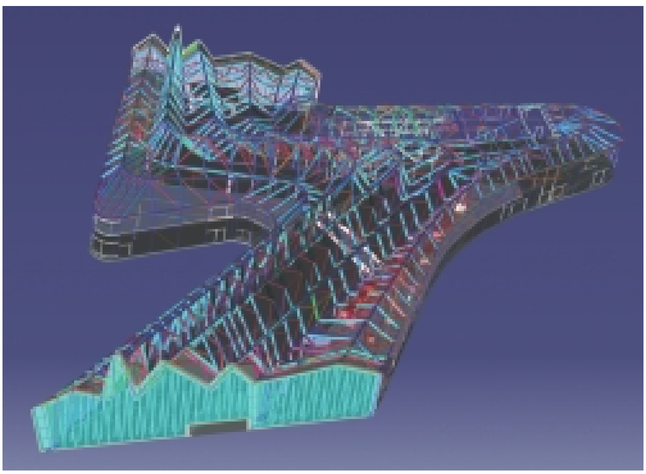


Figure 13.3 Digital coordination: 3D coordination model by ZHA for the Glasgow Transport Museum showing steel structure and cladding systems. (Reproduced by permission of Zaha Hadid Architects.)

Figure 13.4 The resulting construction for the Glasgow Transport Museum. (Reproduced by permission of Zaha Hadid Architects.)

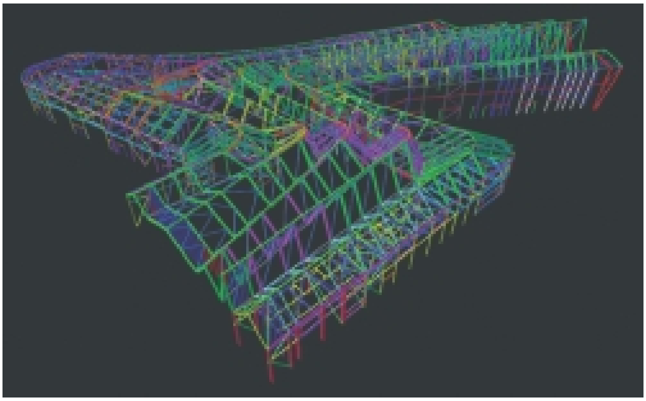


Figure 13.5 Steel coordination: 3-D steel shop drawing model used for coordination and fabrication. (Reproduced by permission of Zaha Hadid Architects.)

steel model – essentially a 3-D shop drawing – was used for the fabrication of the steel components (Figure 13.4). Its high level of detail (including nuts and bolts) made it highly valuable for the coordination of interior finishes and ceiling geometry to the steel. While the 3-D coordination played only a partial role on the Glasgow project, it clearly has opened the way for ZHA to expand its use of 3-D BIM across the firm, in different roles as project needs dictate (Figures 13.5).

Digital form definition and mock-up construction

A similar 3-D coordination process is currently being used for SOHO Galaxy, a large commercial mixed-use project now under construction in Beijing. The project can be considered representative of the digital design and documentation techniques currently being developed and employed by ZHA. During the early concept phase, the project was originally designed using 'subdivision surface' technology within Maya to produce the underlying master surface 'parametric driver' geometry that would define the design intention for the project – in this case, a set of four egg-shaped volumes that are fluidly interconnected to create a single building mass. This 'driver' geometry forms the basis for a 3-D digital coordination process using Digital Project and defines all downstream project geometry, such as slab profiles, façade contours and cladding surfaces. For example, the façade of the SOHO Galaxy project is generated by slicing the 'driver' surface horizontally at each floor, producing horizontal bands of inset glazing divided by rings or 'fascias' of white surface geometry that provide a reference to the original underlying shape (Figure 13.6).

As part of the design development process, ZHA and the client elected to build a series of façade mock-ups in different materials to assess geometrical complexity, contractor capability in China as well as material performance, constructability and aesthetics (Figure 13.7). An area of the project was chosen which allowed the team to test the broadest possible set of geometrical conditions. A tender package for the mock-up was issued to fabricators as a combined 3-D model and 2-D drawing documentation set. The same identical area of façade geometry was executed in sheet metal, steel plate, fibre-reinforced plastic (FRP) and glass-reinforced concrete (GRC) panels respectively.

The mock-up process led to the façade material choice for the project, in this case aluminium sheet metal panels. The geometry of sheet metal ensures that the manufacturing process minimises the use of expensive forming techniques such as moulds or pressing, thus keeping the cost down and expediting execution. Using such single-curved surfaces to implement sections of originally double-curved geometry (the 'driver' surface) of course implies approximation or rationalisation of the original shape. However, at the scale of the panels and fascia width, the visual difference per fascia band is negligible and, with the exception of highly curved areas, allows about 95 per cent of the building façade to be implemented in sheet metal geometry, with considerable savings to the project.

Intercontinental building integration

Digital coordination and execution processes also benefit a fast-track project being designed remotely. The Seoul Dongdaemun project is a large cultural facility currently under construction in Korea. The building's detailed design was conducted between ZHA in London and the executive architect team in Seoul, using 3-D Digital Project models to integrate project geometry created simultaneously in London and Seoul. This allowed the project to be designed and detailed faster and in part with greater independence, as the building systems were developed in parallel on both continents rather than sequentially. This was achieved by establishing a common envelope surface (a 'parametric driver', described previously) which served both as the definition geometry for the external cladding systems as well as the interior boundary for the structural and mechanical systems inside the building.

The ZHA team in London led the overall definition of the project's parametric infrastructure, and worked in collaboration with the Viennese geometry consulting firm Evolute to develop a geometric tessellation of the envelope surface that resulted in a family of self-similar cladding panels. These were optimised to control cost by minimising the amount of single- and double-curved panels while retaining a visible aesthetic of surface continuity. The team in Seoul concurrently used the same envelope surface, with specific offsets and subdivisions, to generate the internal steel skeleton, the external envelope sub-structure and a model of the building's MEP

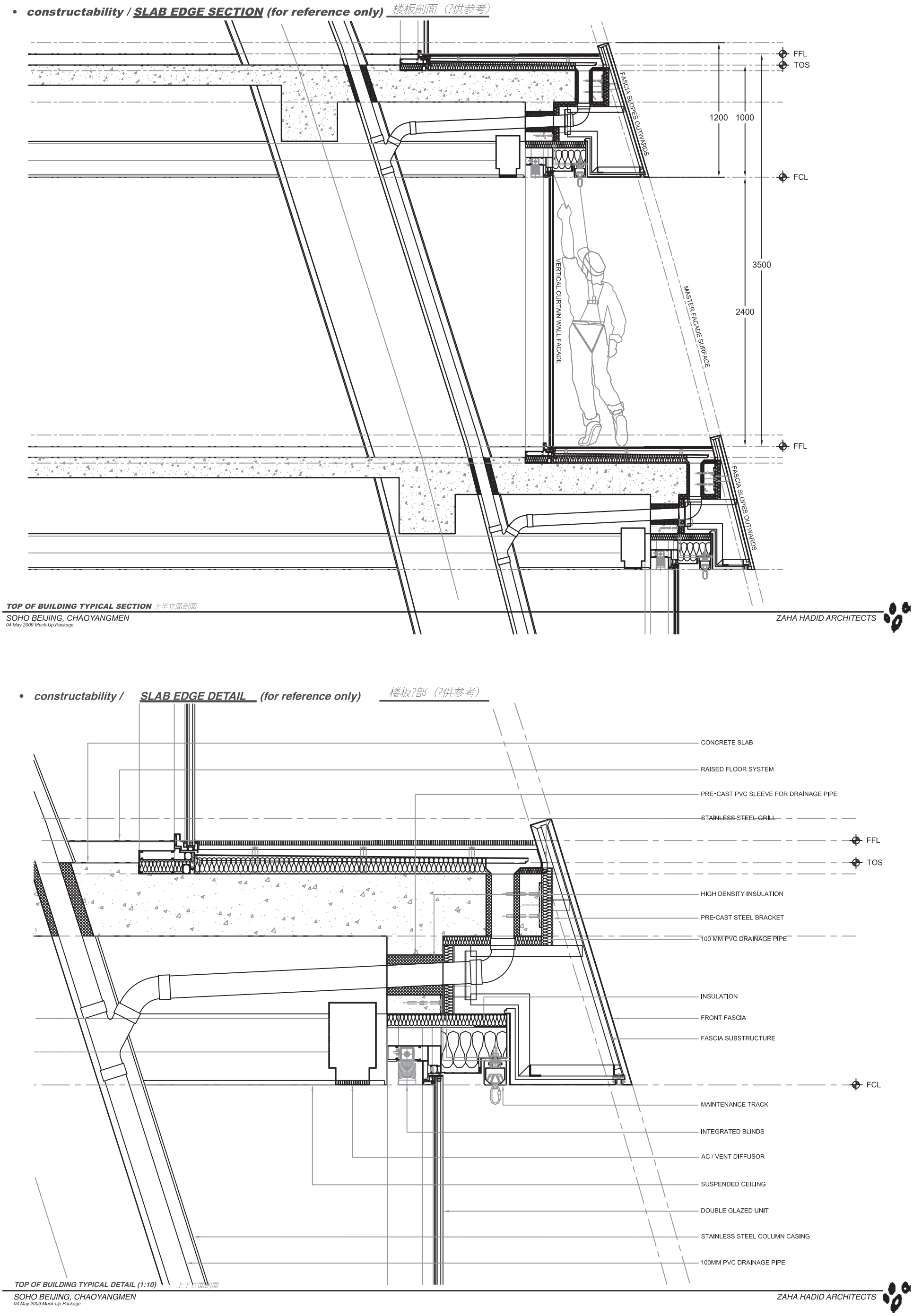


Figure 13.6 Façade construction: Detail section through the façade of the SOHO Galaxy project in Beijing showing fascia and glazing system with concrete structure. (Reproduced by permission of Zaha Hadid Architects.)

Figure 13.7 Façade mock-up: Sheet metal facade 1:1 test mock-up built in Beijing for SOHO Galaxy project, October 2009. (Reproduced by permission of Zaha Hadid Architects.)

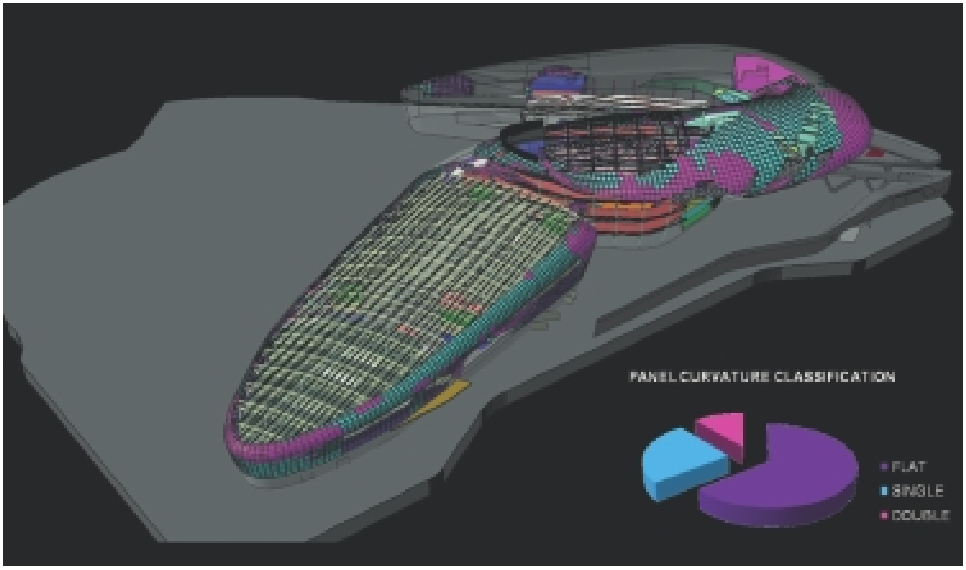


Figure 13.8 Distributed digital coordination: Integrated 3-D model showing cladding and structural systems developed simultaneously in London and Seoul. (Reproduced by permission of Zaha Hadid Architects.)

systems to achieve a full building integration model to enhance project coordination and construction (Figure 13.8). The external envelope geometry and internal structure and systems models were subsequently integrated into a single model in Seoul, which is currently being used for construction coordination on site.

Ongoing development and knowledge capture

The rapid expansion undergone by ZHA in recent years is increasingly being superseded by a process of consolidation of the long-term commercial sustainability of the firm. Specifically, this refers to 'knowledge capture' and streamlining of project delivery methods within the firm, such that new projects can be effectively taken on while ongoing jobs are efficiently delivered. Knowledge capture is accomplished in a number of different ways, each contributing to the ongoing development of the firm and complementing the others' scope of knowledge.

At ZHA, management best practices, technical construction knowledge and digital design knowledge are being actively captured through various in-house online media and databases. The information and knowledge recorded range from descriptive techniques to parametric knowledge capture (scripts, parametric features and power copies) using a technical 'Wikipedia' and other digital repositories to ensure that the firm has a sustainable and growing knowledge base that can meet ZHA's continuing growth need, and effectively counter the professional information loss ('brain drain') that inevitably happens when skilled employees move on in the mobile contemporary job market.

14 Algorithmic modelling, parametric thinking

Neil Katz

There are several keywords associated with design methodologies and software tools associated with them, which include, generally, 'computational design' and 'building information modelling' (these terms somewhat replaced 'computer-aided design') and, more specifically, 'parametric design' and 'algorithmic design'. I suggest that these latter two terms describe an approach to design as much as (or more than) a type of software tool created to enable this approach. In fact, special software tools (or even computers) are not necessary to design this way.

Computers and software tools, however, can substantially enable the designer to design and explore 'design spaces' to levels and to depths that would be a challenge without them. In my experience, at the office and also working in collaboration with artists and independently, I have found that the simplest software tools can also be the most powerful, that generic tools with the ability to be programmed or scripted can be more flexible and less encumbering than more powerful tools designed to be used in a particular way.

In this chapter, I will describe some of the innovative contributions to the field of computational design made by Skidmore, Owings & Merrill, as well as my own education and interest in geometrical modelling and algorithmic methods. The intersection of these two things has provided the opportunity for me to participate in many different ways on many projects at SOM – different ways in one aspect, which is a great variety of types of problems to work on; but usually participating with methods and an overall philosophy that is shared from project to project. A variety of examples of this will be presented.

Developing software tools for architects

Skidmore, Owings & Merrill is an interdisciplinary design firm, well known for designing very large and complex projects. Founded in 1936, SOM is internationally recognised as a leader in the design of skyscrapers and other building types, and for the development of technological innovations in structural design, building systems, curtain walls, as well as design software, all of which are integral to the buildings we design. In the 1970s and 1980s SOM developed its own software tools specifically to meet the needs of its practice: to enable it to model (design, analyse,

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

Figure 14.1 The earlier 'green-screens' used by SOM. (Image © SOM.)

document) large and complex projects (e.g. skyscrapers, hospitals, airports) and to enable large interdisciplinary teams to collaborate on these projects, sharing the same set of data. Initially called 'DRAFT' (an unfortunate name, I think, because it was much more than a drafting tool, but a full three-dimensional modelling tool, with some interesting features even lacking in today's more sophisticated software), it was eventually further developed in collaboration with IBM to become a commercially available tool for the building industry called 'AES' (Architecture and Engineering Series).

When I began working at SOM, while I was still a student of architecture at Pratt Institute, Draft was being used by a handful of (maybe a dozen) people in the New York office. I was hired as a 'plotter operator'. Our computer system consisted of a mainframe computer and terminals distributed throughout the office. All processing was done on the central computer; the terminals basically consisted of just a screen and a keyboard. When more people wanted to use Draft than the one mainframe computer could handle, we had to get another mainframe computer – if too many 'users' were connected to a single computer, it slowed down everyone. Architects would generally work on their models and/or drawings during the day, and if they wanted printed documents of their work, they would fill out a form as they left the office in the evening and pick up their completed 'plots' the next morning. Printing was done overnight, otherwise it would slow everyone down during the day. It was my job to collect the forms and plot the drawings. When I wasn't busy running the plotters, I was able to learn how to use the software (and when I started working full-time after graduating, was able to teach it to others).

The equipment we were using at that time seems pretty dated today (Figure 14.1). We affectionately referred to them as 'green-screens'. They created images on the screen in an analogue way; there were no pixels, the image was much like that you might see on an old oscilloscope. Figure 14.2 shows the mainframe computer and all its accessories. Technically it was a minicomputer, not quite as powerful as a mainframe. It needed its own huge air-conditioned room,

Figure 14.2 The 'mini-computer': The mainframe computer and all its accessories. (Image © SOM.)

with a raised floor for cables, disk drives for data storage, tape drives for back-ups, a terminal with a keyboard and screen and a dot-matrix printer. Instead of a mouse, the cursor was controlled by two thumbwheels (to the right of the keyboard) – one thumbwheel moved the cursor left and right, and the other up and down. These became as fast and intuitive to use as today's mouse.

We had two types of plotters: electrostatic plotters for black-and-white drawings, and a pen-plotter for colour drawings. Colour plots were done sparingly – it could take all night for a single plot of a complex drawing. In addition to placing different colour pens in the four-pen cartridge, we experimented with placing model-making tools (such as a hard-tipped stylus) to create parts for physical models. Eventually (in the late 1980s) we acquired a laser-cutter in our model shop.

In 1980, SOM published a booklet called 'Computer Capability'. It was a brochure highlighting some of the features of Draft and how it was being used at the office. Intended as a marketing tool, it addressed how our projects were benefiting from using these tools that we had developed – how we were able to create better designs, and analyse and document them, more thoroughly and efficiently than could be done without such tools. In the booklet we referred to a relatively unique approach: 'Information from a single data base is used to draw a variety of graphic illustrations.' The same data was used for far more than to draw a variety of graphic illustrations – it was also used to perform many analyses, including structural analysis, environmental (particularly shadows) analysis, work schedules (e.g. doors, furniture, equipment) and so on. With our collaboration with IBM, AES became available on workstations that could be at someone's desk instead of in a computer room. At first these were very powerful (and expensive) UNIX workstations, but eventually AES became available on standard PCs.

One aspect that made Draft so successful was that at the time it was developed and used, sharing of electronic information was an issue only internally; SOM had just about all the disciplines required to design and engineer the projects that we work on in-house. Anyone outside of the office we needed to share our information with (consultants, clients) could not use the electronic information (because they were not using computers), so they required paper documents, which we were easily able to provide, either as backgrounds or as final documents. When other entities began requiring from us electronic data in a different format than it was created, we began dealing with issues that were frustrating and had little to do with our design process. We

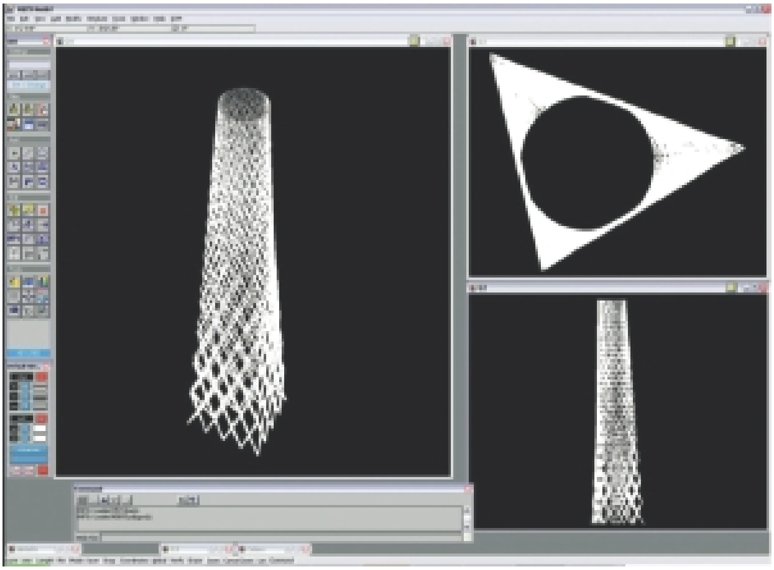


Figure 14.3 An early model developed for the World Trade Center, created with AES. (Image © SOM.)

did build translators into our software, but they are never perfect and rarely even acceptable (and that has not improved much, even today).

There are a couple of features of Draft and AES that were particularly attractive to me, which did one or both of the following: allowed me to work in a way which was consistent with how I was beginning to think about the design process – that the result of the process was a system or a process itself rather than a particular design or form or product (and this thinking was directly related to my research in geometry and form) – or encouraged me to work that way.

One aspect of the software which did this was that the tool was extremely simple. This isn't to diminish at all the incredible effort that went into designing and building the tool – in fact, to say that the tool was simple is meant to be an extremely positive statement, and to create the tool to be simple probably required more effort than to create a complex tool. The basic set of primitives that the software used to create a model were points, lines and polygons. There weren't even curved objects (e.g. arcs, circles, splines), which needed to be approximated with lines and straight-edged polygons.

Another aspect of the software was the ability to create simple 'programs' to create models. Today we would probably call this 'scripting'. The interface to the application was command driven; this was one complaint that many people had, that there was too much typing, but this also made learning scripting much easier. As AES developed, new primitives were introduced, including arcs and circles, and eventually even architectural objects like wall and doors and windows. My favourite AES primitive was something called a 'cell', which was a collection of commands (a script) that could be placed as an object in the model. Like other objects (such as points), a cell's attributes included its location in space, and that could be used as a parameter in the set of instructions embedded in the cell.

Figure 14.3 shows the last model that I created with AES, in late 2001 and early 2002. This is an early model of a scheme we were developing for the World Trade Center after

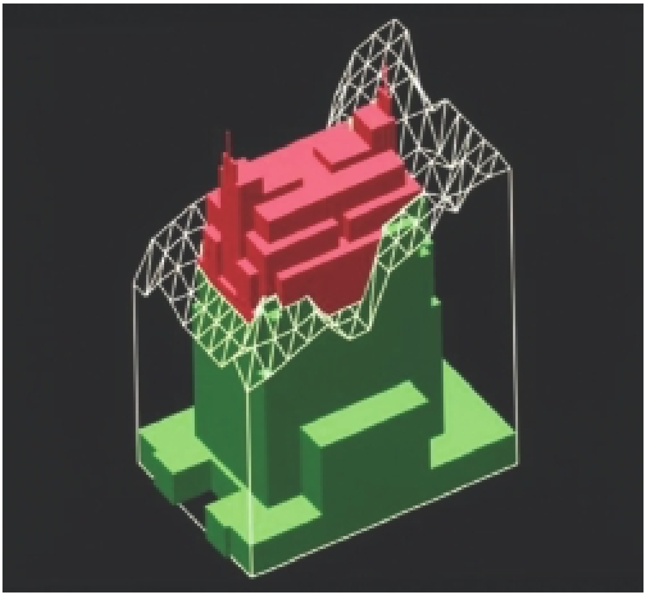


Figure 14.4 The 'no-shadow' envelope for a project in Boston. (Image © SOM.)

11 September 2001. This is one of many models experimenting with variations of a structural system, which featured a diagrid at the exterior of the tower. These variations were created with a script.

SOM had a team of programmers that were responsible for writing the code for Draft and AES. In addition to creating the main modules of these systems (which included the basic graphics-creation module, a rendering module, a plotting module and various analysis modules), they also created special smaller applications to meet particular office or project requirements (usually when scripting was not powerful enough). We have implemented this in an analysis for a project in Boston (Figure 14.4). We were in the process of designing a building while a new law was being proposed that would prevent new buildings from casting shadows onto the Boston Commons. We were concerned that this law would be affect our project (it did). The law prevented a building from casting a shadow in addition to shadows which were already being cast by existing buildings, and within some reasonable time range (not too close to sunrise and sunset). We created an application that considered the following: the building site (its shape and location within the analysis context as well as its geographical location on earth), the park (shape and location), surrounding context buildings in three dimensions (which were already casting shadows onto the park) and a set of dates and times (for example the 21st day of each month, and from one hour past sunrise to one hour before sunset on these dates). The program generated a 'no-shadow envelope', which is seen in white in the image. We compared the building we had already been working on to this envelope: the part of the building shown in red, which penetrates the no-shadow envelope, would at some point – even maybe for an instant – cast a shadow onto the park.

For projects in New York City, we go through an extensive zoning analysis process. The city has restrictions on the massing of new buildings, intended primarily to let daylight onto

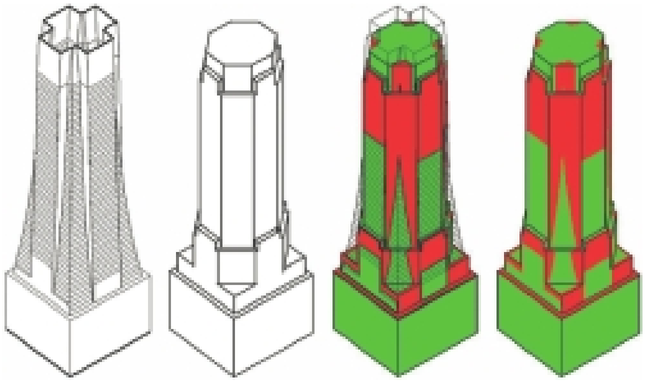


Figure 14.5 The encroachment and recess of a building in relation to the zoning envelope for its site. (Image © SOM.)

sidewalks and streets surrounding buildings. The zoning code for buildings in midtown Manhattan gives us a choice between two methods. The first is 'encroachment and compensating recess', which prescribes a zoning envelope, with setbacks increasing as height increases (encroachments of this envelope are allowed but each encroachment must have a compensating recess, and there are rules and limitations). Figure 14.5 shows a proposed building and its encroachment and recess in relation to the zoning envelope for its site. The other method is 'daylight evaluation', which defines a 'skygrid' and viewpoints, and a method of projecting the proposed building from these viewpoints (the projection is called 'Waldram') and deducting points for each cell in the skygrid that the projection of the building touches. The first method can be done quite easily with simple modelling tools, but the second method is much more difficult. SOM's team of programmers created an application for this analysis, which read a 3-D model of the building, a site polygon, and asked questions about street widths (which are used in setting views). In minutes we had a score for the building, as well as a graphical representation of the analysis (the city requires both of these to be submitted). This graphical representation is shown in Figure 14.6 (this is the same building shown in Figure 14.5). The speed at which we could do this analysis made it as useful as a design tool. We could immediately respond to the results and modify the building to get a passing score. How does one decide which method of zoning analysis to use, if we have this choice? It's very tempting to choose the easier method, but each analysis method favours a slightly different massing, and a model that might fail one of the analysis methods might pass the other one.

Both of these custom applications were written to work with Draft format graphics files, and to run on our old UNIX workstations. We don't have either of these any more and, because these applications are not typical and used consistently, they were never updated. We still do these analyses, but instead of depending on a dedicated application, they are performed, one might say, 'manually'. For the Waldram zoning analysis, what took just a few minutes in the 1980s now takes a full day of computing projections and scores.

For most projects we perform some sort of shadow analysis. It is unusual to be as restricted in terms of shadows as we are near the Boston Commons, but we often want to know what

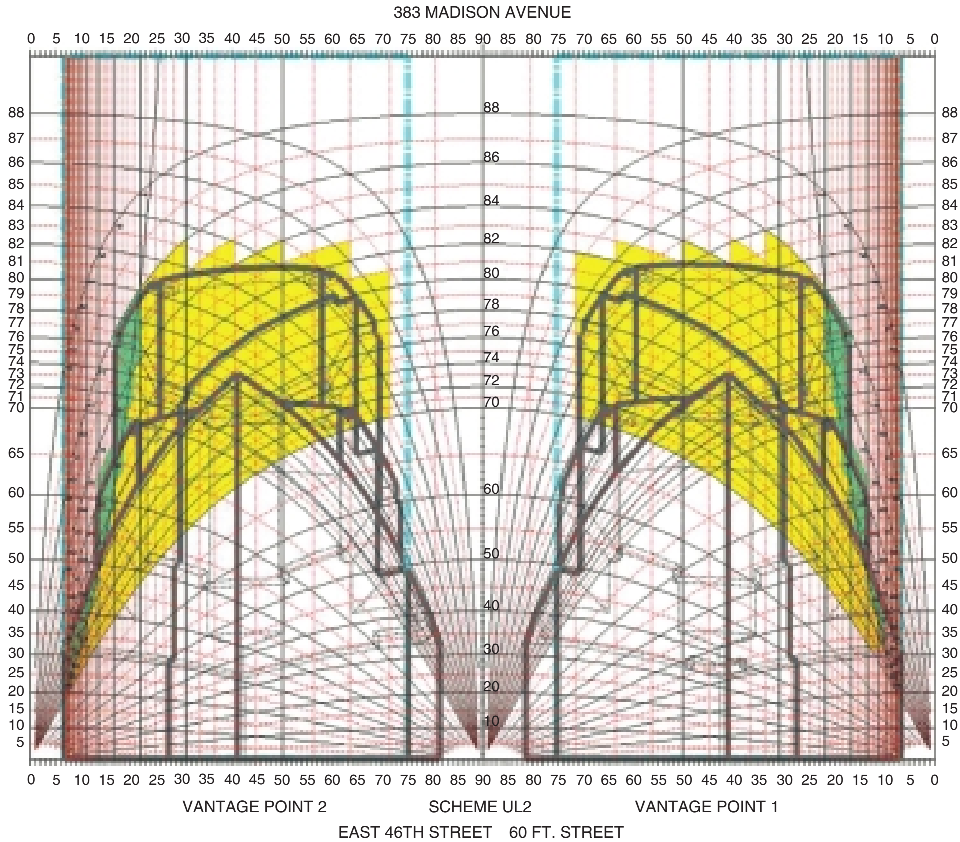


Figure 14.6 A 'waldram' zoning analysis for a building in midtown Manhattan (same building as shown in Figure 14.5). (Image © SOM.)

effect the shadows of our proposed projects will have on their surrounding context (particularly open spaces), and also how shadows of surrounding buildings will affect our project. We often want to graphically distinguish our project's shadows from the context shadows, and also often want to present a matrix of dates and times, giving on one sheet an overall picture, spanning times and dates, of the shadows changing as the sun's position is changing (Figure 14.7).

SOM project work

In each case discussed in the following sections, a particular aspect of the project is presented, each with a unique problem to be solved or design issue to be addressed. Due to the fact that our projects are usually large and complex, our project teams are also quite large. The organisation of the team, and how I fit into the team, varies from project to project.

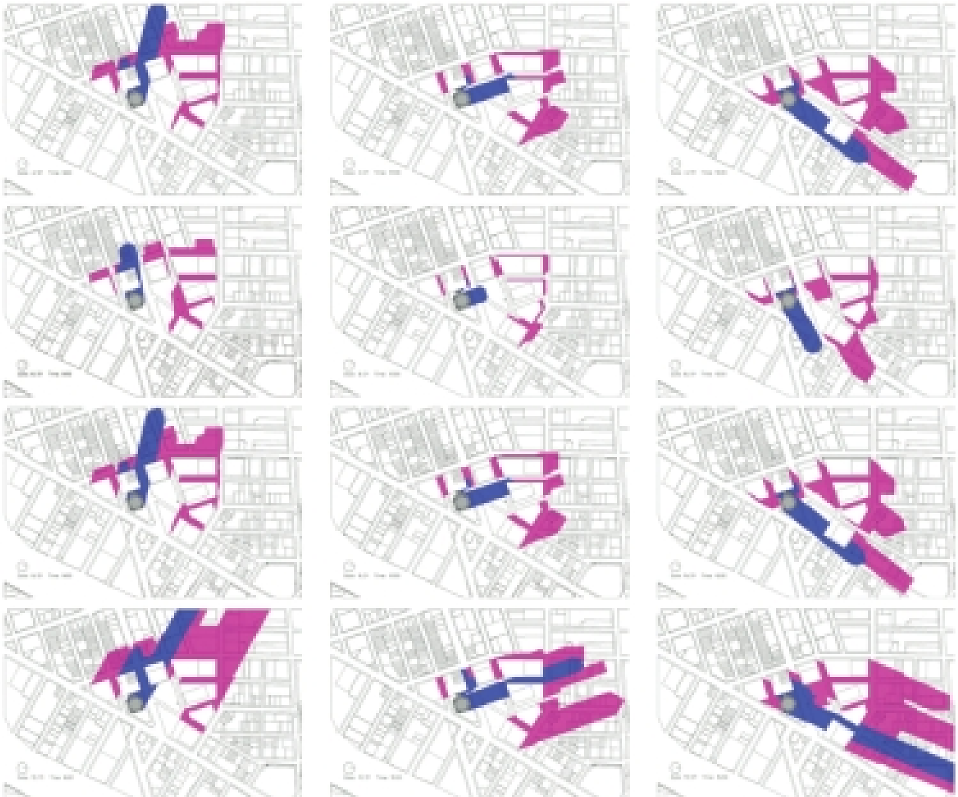


Figure 14.7 A shadow matrix for a project in Long Island City, New York. (Image © SOM.)

Project example: World Trade Center Tower One, New York – spire

Larry Silverstein had asked SOM to look at options for the site shortly after the World Trade Center towers were destroyed. We developed a masterplan for the site, and preliminary design ideas for the tall tower that was part of that masterplan (Figure 14.8). The tower featured a diagrid structure defining a massing which transformed from a triangle at the base to a circle at the top. Several of the diagrid experiments we looked at used a pure cylinder as the form, making the process of modelling the diagrid a bit easier, and allowing us to focus on certain aspects without the distraction of the transforming shape. These models were initially created with AES.

It was about this time that SOM was experiencing a transition from AES to AutoCAD. I should mention a few words about this transition in the office, and my own transition from one modelling tool to another. It is never easy to make a switch like that. (It is often not easy even to upgrade to a new version of the same software.) Our New York office had a clear distinction between people who worked on the design of projects (from conceptual and schematic design through to design development) and those who worked on documentation or 'production' (people belonged to either the 'design' department or the 'technical' department). (That distinction is becoming more and more obscured, partly due to the tools we are using and the changing way in which projects progress.) Our technical group was able to

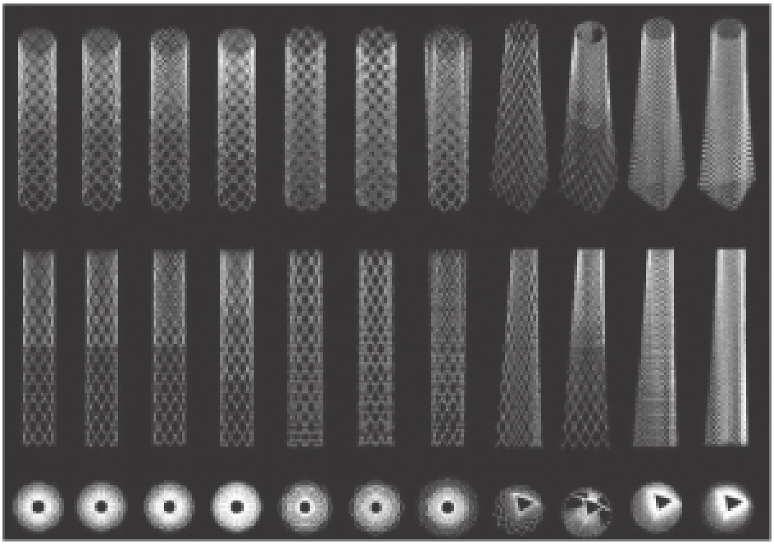


Figure 14.8 Preliminary structural diagrid design ideas for the World Trade Center Tower. (Image © SOM.)

make the switch from AES to AutoCAD more quickly and easily than our design group. But in order to facilitate this, we spent much time and effort customising AutoCAD to make it behave, at least conceptually, like AES. AutoCAD's early versions were not designed for large, multidisciplinary and very collaborative projects and methods of working, so we created a set of tools to help people load and save the data that they needed to work on, and in fact to allow people to update a database of the building information rather than work on one drawing or file at a time.

My own introduction to AutoCAD was earlier than our transition at SOM: I was asked to teach it. I believe one needs to learn something differently when the goal is to teach it as opposed to when the goal is to use it to get something done, and this undoubtedly affected the way I began to use AutoCAD at SOM when we did make that switch.

How should people who are 'computational designers', or specialists in computational techniques such as parametric modelling or building information modelling, be implemented on projects at offices such as mine? Of course there is no single or correct answer, and I have been 'implemented' in a variety of ways, each of which has pros and cons for me, for the teams that I work with and for the office. I could generally work in one of two ways: as a resource for the office, not assigned to a particular project or team, but with several teams at once; or as a dedicated project team member. For the World Trade Center project, I was a full member of the team. One advantage of this way of working is that I become intimately familiar with the project and all its aspects, including team members and leaders and their capabilities and expectations.

The design of the World Trade Center went through several iterations. After a competition for the master plan of the site (SOM did not become the master planners), SOM was awarded the design of One World Trade Center, the tallest of five towers on the site. The current design, under construction, is a square at the base, whose corners are chamfered as we go up the tower,

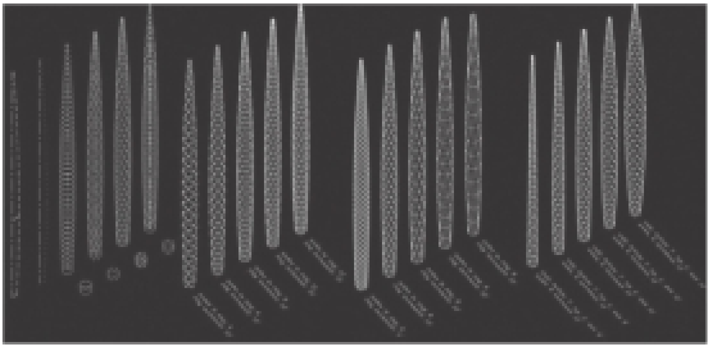


Figure 14.9 Examples of the variable parameters in the model of the spire of the World Trade Center Tower. (Image © SOM.)

to become an inscribed rotated square at the top, at 1368 feet to match the height of the original towers. Above that is a spire, containing broadcasting equipment, bringing the tower to an ultimate height of 1776 feet (as prescribed in the master plan). As a team member, I was involved in all aspects of the design, analysis, modelling, and documentation of the project. Most particularly and extensively, however, I was involved with the design, analysis and documentation of the spire. Initially the spire was conceived as a lattice structure, enclosing the broadcasting equipment, each piece or set of equipment with its own protective casing. The shape of the spire needed to satisfy several conditions, including being large enough to contain the enclosed equipment and to span the vertical distance from the top of the roof to the prescribed height, satisfy the structural stiffness requirements (the stiffness requirements of the broadcasters were more severe than we otherwise needed to follow; they didn't want their equipment to move very much at all) and architecturally to work well as an icon for this monumental site and also be an architecturally integral part of the building. While we can consider the entire structure, including the broadcasting equipment, as the 'spire', we referred to the enclosing element itself as the 'shroud'. Factors which were incorporated as parameters into the script that built the model include critical dimensions of the shroud, vertical spacing between lattice nodes and rings, number of nodes in each ring and thicknesses of the members (which could either be consistent throughout the structure or vary).

As mentioned earlier, with scripts we can loop through many values of a parameter and create a new model for each value, even create a set of models within a model, which can be extremely useful for comparative analysis (Figure 14.9). Rendered images or even diagrammatical representations of a model are often useful for evaluating the effects of changing values of one or more parameters. We can create representations which most clearly identify these effects and differences (by selecting appropriate views, for example, or colour-coding particular aspects of a model). Sometimes a more tangible representation is desired or required, as in the form of a 3-D printed physical model, or to compare different experimentations with different parameters. Figure 14.10 shows the effect of varying the thickness parameter of the members. While our structural engineers had a lot to say about this aspect, there were architectural reasons for making the members thicker than required in order to make the spire more visible from a distance. If the members were too small, we were concerned the spire would become invisible. Ultimately, the spire was designed not as a lattice but as composed of solid panels, as shown in Figure 14.11.

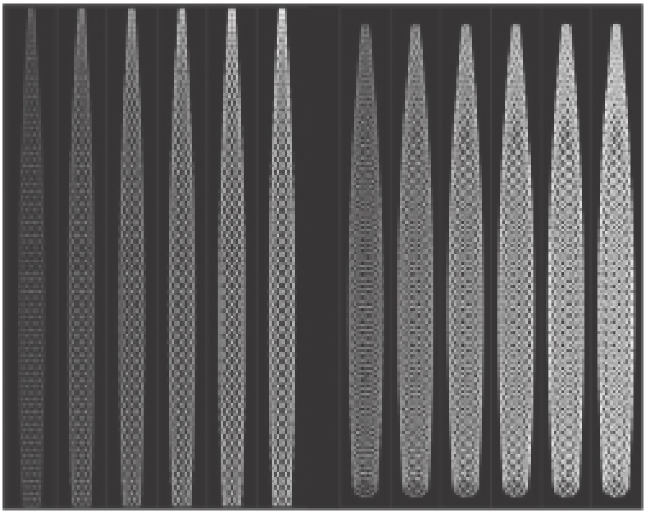


Figure 14.10 The effect of varying the thickness parameter of the members. (Image © SOM.)

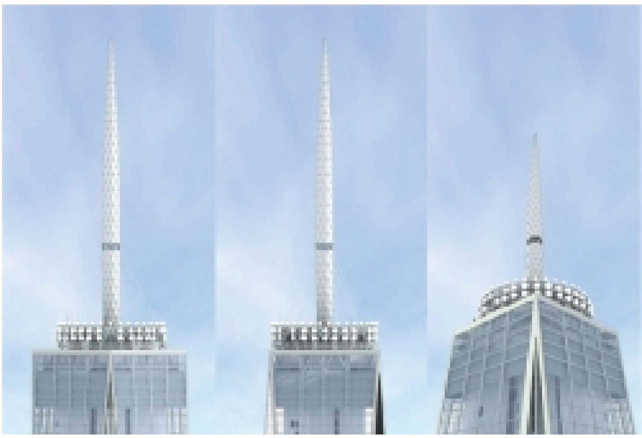
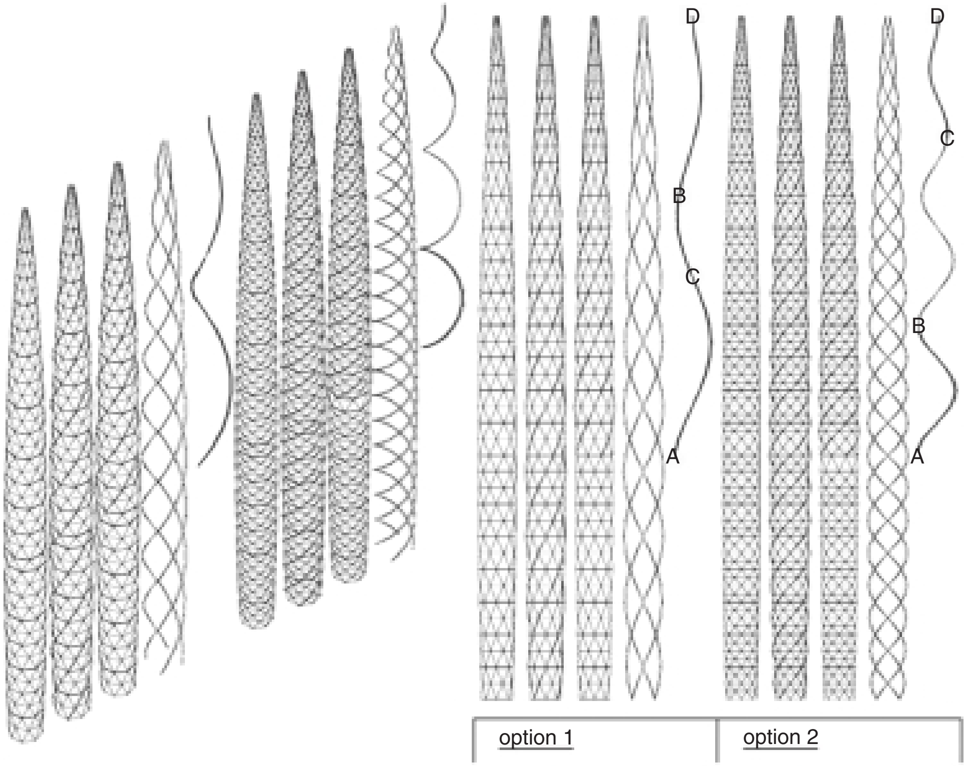


Figure 14.11 The final design of the spire (rendering Ajmal Aqtash). (Image © SOM.)

Fairly early in the design process we met with potential fabricators of the spire, to help us determine constraints from the points of view of manufacturing and fabrication (and even delivery and installation). We talked about how large individual panels can be, how they can be grouped together, how beneficial (and cost-saving) minimising the number of different panels is and so on. Within each 'ring' there are two types of panels (up facing and down facing) and in our model there are eight of each of these in a ring, but each ring is different from every other ring. We also created a horizontal symmetry plane, so that panels equally spaced above and below this plane can be identical. This had an insignificant effect on the visual appearance of the spire, but reduced the cost. One (very strong) reason for switching to a solid panel spire from a lattice spire



helix/diameter ratio calculation:

	option 1	option 2
one helix revolution, from A to B		
spire radius at A:	139.66	139.66
spire radius at B:	102.81	130.58
average diameter (A + B):	242.47	270.24
length of inner helix from A to B:	2046.98	1270.19
length / average diameter:	8.44	4.70
one helix revolution, from C to D		
spire radius at C:	122.90	85.53
spire radius at D:	18.00	18.00
average diameter (C + D):	140.9	103.53
length of inner helix from C to D:	1966.08	949.54
length / average diameter:	13.95	9.17

Figure 14.12 The depth of the fin becomes smaller as the diameter of the spire decreases. (Image © SOM.)

is structural – the solid panel spire is stiffer in the wind than the lattice spire – but subsequent analysis showed that it was still not stiff enough. Our engineers gave us a couple of options to address this. One option was perforating some of the panels; they suggested a perforation pattern for the panel itself, and we looked at options for which panels were perforated (to create an interesting and desired architectural effect). The second option was to add 'helical strakes' to the spire, vertical 'fins' which follow the spiralling edges between the panels. The depth of these fins varies with the thickness of the spire, so at its widest point these fins are very deep, and when the diameter of the spire becomes smaller, the depth of the fin decreases as well (Figure 14.12). The design

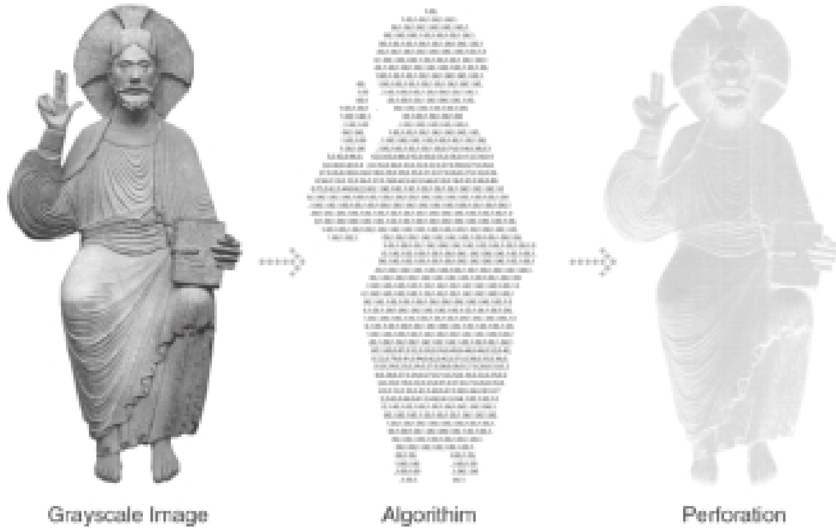


Figure 14.13 The process of transforming the original image to the perforation pattern of dots. (Image © SOM.)

team preferred this option. The visual effect of these helical strakes, particularly as the sun's position changes during the day and throughout the year, becomes very interesting.

Project example: Cathedral of Christ the Light, Oakland, CA – Omega Wall

> When the bishop voiced his desire to include a strong representational image of Christ in the building, [design partner Craig] Hartman wanted to make it integral to the architecture. As a guide, the church supplied a digital image of a carved stone relief at Chartres Cathedral. A team of architects, environmental graphic designers, and members of SOM's digital design group worked together to create an algorithm that sorted the pixels according to brightness. The image was tweaked to enhance its legibility before then being mapped onto the 3-D surface. In finished form, the backlit image will rise more than 50 feet high, composed of more than 90 000 holes, ranging in size from 4mm to 24mm, laser cut into the anodized aluminum panels. (*Architect Magazine*, 2008)

This part of the Cathedral project was done in close collaboration with the graphics department in our San Francisco office. It is always interesting to work with a new group of people, who usually have different points of view, sets of priorities and ways of working. They created the 'explanation' of the process of transforming the original image to the perforation pattern of dots, as shown in Figure 14.13. The 'wall' is made of large, flat triangular panels which are arranged to create a three-dimensional surface, with a vertical ridge at the front face. The image is projected onto the panels on the wall, and then each panel must be rotated or 'unfolded', so

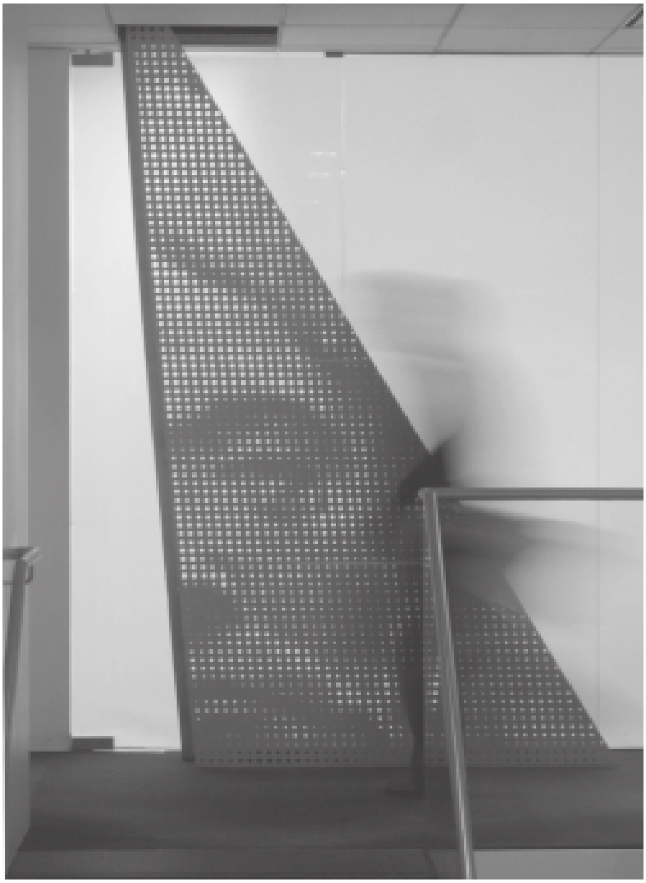


Figure 14.14 The projected image on the panels on the wall, one mock-up panel. (Image © SOM.)

that all panels can be sent to the fabricator as a true shape and not a projection, as shown in Figure 14.14.

The fabricator asked us to identify each perforation on each panel with a number and a diameter and circumference. This information was documented graphically as well as in a spreadsheet (one page for each panel, with each hole identified by its number, location on the panel – *x* and *y* location from a reference point on the panel – and diameter and circumference). Figure 14.15 show the completed Omega Wall.

Project example: Koch Center/Science Math Technology Building, Deerfield Academy, Deerfield, MA – skylight

For several of our school projects, we have collaborated with artists. For the Koch Center/Science Math Technology Building at Deerfield Academy in Deerfield, Massachusetts, we collaborated with James Turrell, an artist who works with light and space. We had collaborated with Mr Turrell before and his work seemed particularly appropriate for this building. Because of the nature of

Figure 14.15 The completed Omega Wall. (Image © César Rubio/courtesy of SOM.)

his art, Mr Turrell worked closely with an astronomer, Dick Walker. An interesting aspect of the project designed in collaboration with James Turrell and Dick Walker is the 'analemma skylight'.

Just outside the auditorium is a common space in the building. Part of the space is three storeys tall. On the ceiling of this space is a hole, six inches in diameter, which is open to the sky (covered with a glass dome). Sunlight comes through this hole and projects a spot on the curved brick wall. On the brick wall there is a curve, etched in metal, in the shape of a tall, thin figure. This curve is called an 'analemma'. Every day at precisely noon, the spot of light which is projected through the opening will align with this analemma. The original intention was as follows: in the morning the spot will appear on one side of the wall, and as the sun moves during the day the spot will move as well. At exactly noon the spot will coincide with the etched analemma. The spot will continue moving through the afternoon until it disappears. During the summer months, when the sun is high in the sky, the spot of light will appear low on the wall. During the winter months, when the sun is low in the sky, the spot of light will appear high on the wall. During most of the year, the spot will move between the two extremes.

In order to allow the spot of light to come through the small opening in the ceiling surface, the opening in the roof surface must be much larger. To allow the 'sun-spot' to appear from

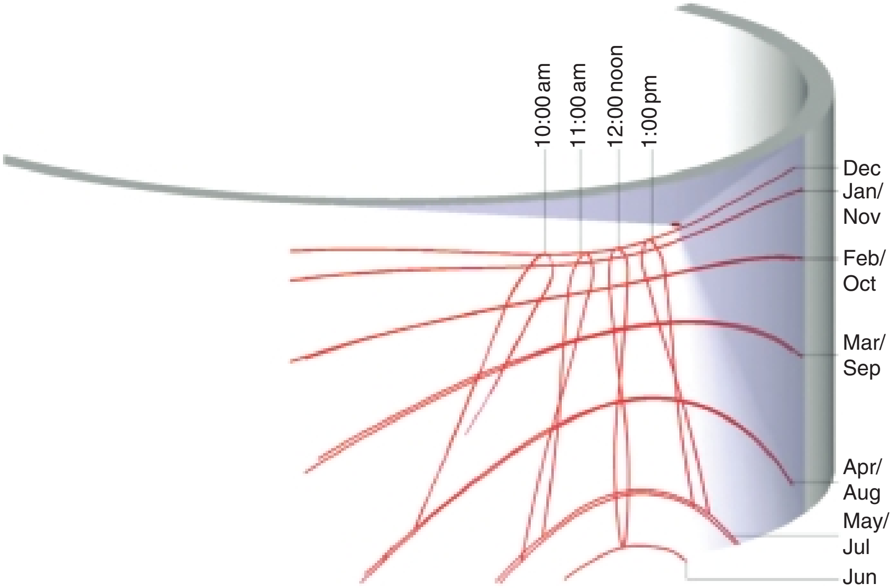


Figure 14.16 The projection of the path of the spot of light through the hole in the ceiling. (Image © SOM.)

sunrise to sunset, or early morning to late afternoon, the opening on the roof surface would need to be impossibly large, which would present too many structural and roofing system challenges. So we limited the time period during which light would be permitted to come through the skylight to create the spot. This became a parameter in the procedure which generated the opening, and we experimented with several different values. We determined that the opening resulting from allowing the sunlight to enter from one hour before noon until one hour after noon was acceptable, and that that time period during which the spot was visible was also acceptable.

Figure 14.16 demonstrates the projection of the path of the spot of light through the hole in the ceiling. The lines labeled with month names are the path of the spot (if allowed to come through the hole all day) on the 21st day of the month indicated. The line for December is high on the wall, and the line for June is low on the wall, as described above. Lines for the other months seem to almost coincide, for example February and October are almost identical. The dates 21 October and 21 February are symmetrical around 21 December (and 21 June). There are the same number of days between 21 October and 21 December as there are between 21 December and 21 February. If, on 21 October, we were to mark with a piece of chalk the centre of the sunspot every *x* minutes (5 minutes, 15 minutes, 60 minutes) and then connect these marks, we would create that same line. If, every day of the year at noon, we were to mark with a piece of chalk the centre of the sunspot, we would create the noon analemma. If we were to mark the centre of the spot at 11 a.m. or 1 p.m. instead of noon, we would create different analemmas. In fact, when the building was completed, the noon analemma was not in fact etched in the wall, but the intention was that for one year, the students of the school would do just that – mark the location of the sun every day at noon, and at the end of a full year they would have created the analemma, and then it would be permanently marked in metal.

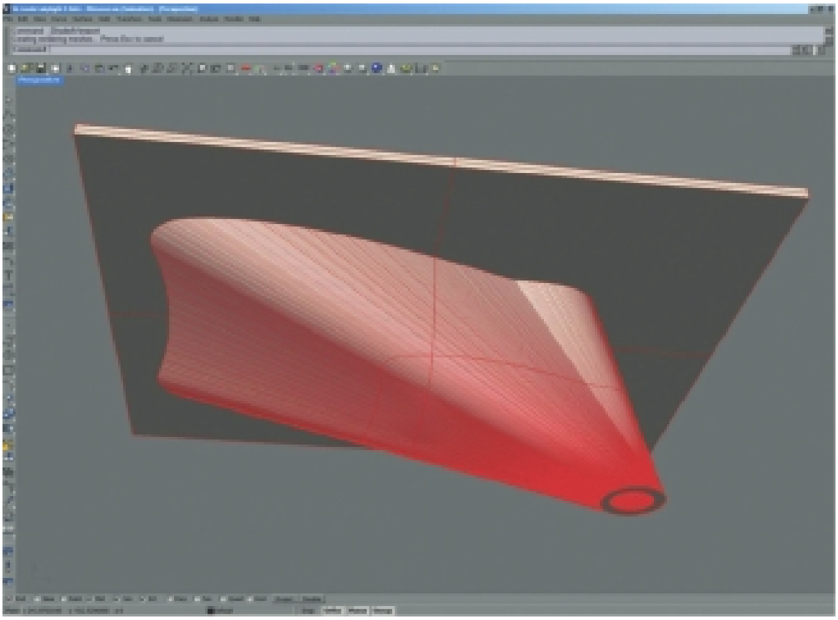


Figure 14.17 STL file needed for the 3-D printing was creating from a Rhino model. (Image © SOM.)

In order to fabricate the skylight, which only admitted the sunspot of light into the space between 11 a.m. and 1 p.m., we had to define the form to be sent to the fabricator, which was computed algorithmically. The function of the skylight was to allow light into the interior space, through the small opening at the base of the skylight, which is in the plane of the ceiling, only within a two-hour time period – from one hour before noon until one hour after noon, throughout the year. The computation of this form used the following parameters: the geographical location on earth of the project (latitude and longitude), the distance between the ceiling and roof planes, the extreme times (11 a.m. and 1 p.m.) and the extreme dates (21 June and 21 December). Changing any of these parameters would result in a different skylight shape. Since the depth of the skylight is fixed, exactly 37 inches (about one metre), the size of the skylight is determined: it is about 3 feet wide by about 8 feet long (about 1 metre by 2.5 metres). It was fabricated in fibreglass.

Because the fabrication of this skylight was expensive, we wanted to be able to test it somehow before it was built. During the time this project was being designed the office acquired a 3-D printer, a rapid-prototyping machine. Our skylight was a perfect application of this technology. We created an STL file for 3-D printing (using Rhino instead of AutoCAD, since people in the office had more experience with STL files in Rhino), as shown in Figure 14.17. Due to the size restraint of the 3-D printer, the model was printed in two parts and then glued together. We also created a model of the space in which the skylight is located, including the floor, ceiling and curved wall. We brought the model to the sight in Deerfield on a sunny June day for the test. Initially we thought we had a problem – the light was first admitted through the opening at 12 noon instead of 11 a.m. – which seemed to be off by exactly one hour. The system is, of course, 'calibrated' for Standard Time and the 'error' was due to Daylight Saving Time. Knowing this, it worked perfectly.

Concluding remarks

The examples presented are a very small subset of the projects that I have been involved with at SOM, but are representative of a philosophy of working on architectural projects which I began developing in school, and which has been supported by my firm. That philosophy – perhaps 'methodology' is a better term – is difficult for me to articulate clearly (hopefully my examples have done a good-enough job), but is more concerned with investigating methods and processes of solving design problems, and addressing these processes in a very systematic way, than with the specific forms that can result. These methods and processes are greatly enabled by computational power (but sometimes more by simple generic tools than more sophisticated but specific ones) and I believe are most enabled by the algorithmic and procedural thinking process of the investigator.

Because of the nature of our field our studies are three dimensional in form, but this methodology can work for any creative endeavour, including two-dimensional form. In our practice, each project has its own fascinating set of issues to be addressed; articulating (and sometimes inventing) these issues is a fascinating task in itself. We deal with structural issues, sustainability and environmental concerns, economical fabrication and the desire to create iconic and architecturally interesting, exciting, innovative, functional and efficient buildings. We create ways of form-finding, analysis (as an integral part of the design process) and documenting our work. Parametric and algorithmic thinking and modelling have been excellent tools in this work.

The processes that went into the examples shown and many others are shared and distributed in several ways and at several levels. The overall method of working and philosophy is applied to each project that I work on. The hope is, of course, that the approach and method of exploring a design space are the reason I am asked to participate in these projects, but that the result of my participation is often a solution space of choices which meets the design criteria, which is often more important to many than how they were derived.

Some of us in the office are using tools such as Digital Project, Generative Components and Grasshopper. Some tools are better at addressing some design tasks than others, but the biggest factor in deciding which tool to use is usually the comfort level with a tool of the individual who will be performing the task. If the tool is flexible enough, and the person has reached a certain skill level, then any task can be done. And another very important aspect of our work process is possibly that skills and concepts developed in solving one problem are usually re-used to solve similar problems (scripts can be partially or completely re-used as well), even on a different project, by different people or teams and with different software.

Acknowledgements

All images in this chapter are copyright of SOM. The author would like to acknowledge the following people who took part in the projects described:

World Trade Center Tower One: SOM partners David Childs, design; T. J. Gottesdiener, management; Carl Galioto, technical; William Baker, structures. Senior designers Ross Wimer (first phase), Jeffrey Holmes; project manager Kenneth Lewis.

Cathedral of Christ the Light: SOM partners Craig Hartmann, design; Gene Schnair, management; Mark Sarkisian, structures; Keith Boswell, technical. Senior designers Patrick Daly; Omega Wall Lonny Israel, Alan Sinclair; project manager Raymond Kuca.

Deerfield Academy: SOM partner Roger Duffy, design; project manager Chris McCready. Consultants for analemma skylight James Turrell, artist; Richard Walker, astronomer.

Reference

Architect Magazine (2008). 'Building the modern cathedral'. February.

15 Interview with the Specialist Modelling Group (SMG): The dynamic coordination of distributed intelligence at Foster and Partners

Hugh Whitehead, Xavier de Kestelier, Irene Gallou and Tuba Kocatürk

The Specialist Modelling Group (SMG) is an in-house consultancy at Foster and Partners, which has introduced a highly advanced three-dimensional computer modelling capability that allows the design teams both to explore design solutions rapidly and to communicate data to consultants and contractors. The Specialist Modelling Group was formed in 1997 and is led by Hugh Whitehead, a Partner at Foster and Partners. Some of the over 100 projects that the SMG has made a contribution to include the Swiss Re Headquarters, the Sage Gateshead Music Centre, London City Hall, Albion Riverside residences, the Chesa Futura apartment building, the new Beijing International Airport (Figures 15.1 to 15.5) and Queen Alia Airport (Figures 15.6 to 15.10).

The Specialist Modelling Group has expertise in complex geometry, environmental simulation, parametric design, computer programming and rapid prototyping. The SMG brief is to carry out project-driven research and development in the intense design environment of the Foster and Partners office. One of the primary goals of the Specialist Modelling Group is to develop control mechanisms that drive geometry in response to relationships. These control mechanisms can be parametric models or custom programmed scripts. The CAD geometry that these mechanisms are driving responds to the constraints acting on the architectural design. The group consults in the areas of project work flow, digital techniques and the creation of custom CAD tools. These specialists work with project teams on either a short- or long-term basis and are involved with projects from concept design through to fabrication.

The following text is an excerpt from an interview conducted with three members of SMG (Hugh Whitehead, Irene Gallou and Xavier De Kestelier). The discussion focuses on the role of SMG at Foster's, changes in the deployment and contribution of new tools and technologies in the creative design process and design coordination, emerging roles and directions in education and changing practices in the architectural profession in general.

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

Figure 15.1 Bejing Airport (Image Credit Nigel Young/Foster + Partners, copyright Foster + Partners.)

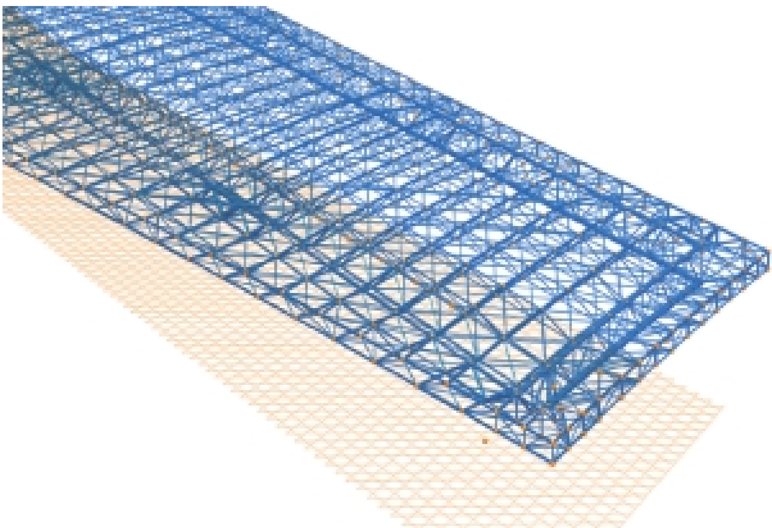


Figure 15.2 Bejing Airport, 3-D model of spaceframe roof structure of terminal 3A. (Image credit and copyright Foster + Partners.)

Figure 15.3 Bejing Airport, parametric model of cantilevered edge detail. (Image credit and copyright Foster + Partners.)

Figure 15.4 Bejing Airport, spaceframe structure under construction. (Image credit and copyright Foster + Partners.)

Figure 15.5 Terminal 3B of Beijing Airport. (Image credit Nigel Young/Foster + Partners, copyright Foster + Partners.)

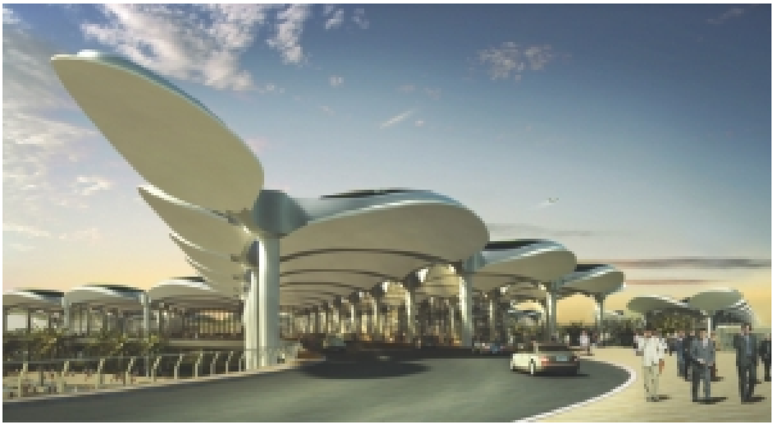


Figure 15.6 Rendering of Queen Alia Airport roof structure. (Image credit and copyright Foster + Partners.)

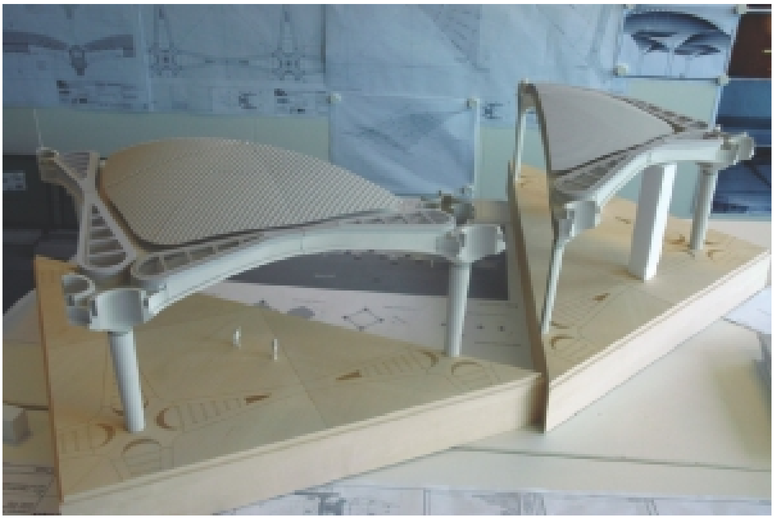


Figure 15.7 Queen Alia Airport, 3-D print of roof structure build as kit of parts. (Image credit and copyright Foster + Partners.)

The interview

TUBA KOCATÜRK: **How would you define the role of SMG at Foster and Partners in the design project lifecycle?**

HUGH WHITEHEAD: We think of ourselves as in-house consultants. That is quite a difficult triangular relationship. Because on the one hand we are a part of the design team, but on the other hand we have a continual dialogue with the external consultants. The external consultants are chosen by the design team. So, to work our way into that role, we tend to

Figure 15.8 Queen Alia Airport, prefab concrete parts and formwork: Column head, beam and roof shell. (Image credit and copyright Foster + Partners.)

Figure 15.9 Queen Alia Airport, prefab concrete column heads installed on site. (Image credit Nigel Young/Foster + Partners, copyright Foster + Partners.)

focus initially on helping data transfer because a lot of the studies we do are cyclic, so you go around the loop once and if you do it well in a structured way and you agree procedures and what kind of data exchange formats people would like, then you can go around the loop faster next time. In a way, our role is split between strategic design consultancy and then supporting analysis and these two really go in hand in hand. But having set up this

Figure 15.10 Queen Alia Airport, prefab shell structure. (Image credit Nigel Young/Foster + Partners, copyright Foster + Partners.)

model it was quite easy in a way to integrate with the sustainability group who are more on the strategy side. The urban design group is a new one for us. But we are doing a rapidly increasing number of urban design projects and looking for proper tools and techniques to help inform the processes, so there is a kind of synthesis going on. We did a presentation a while ago to the design board. And at the start of the presentation we felt we had to try to lay out the story board and describe what we do. Because it's very critical how long you've got. And I think we realise it's what we call a 'breadth and depth problem'. All the time, we are trying to increase the breadth but at the same time increasing the depth. If somebody comes to us and they want something quite specific, you know they will have to navigate across the breadth and then go down into the right level of depth. That is a lot of what our consultancy does, it tries to map that out for you and help with the kind of advice the teams need.

Xavier De Kestelier: Referring to our role in the design project lifecycle, the ideal situation is always that we are there from the first moment, first sketches and ideas. That is the most comfortable way of us being involved with the design team, all the way through to the construction of the building. We've done quite a few projects like that and that is when we look back and see that it was quite successful. Some of us, for example, are involved in the beginning, then we don't talk to the design team for a few months and then we step in again. Sometimes we are only involved for quick design iterations, or it can be during the detailed design process when something doesn't quite work out geometrically. We've also helped with projects where we've not been involved during the early design stages. So it happens at different stages, for different projects and for different lengths of time. The shortest I've been involved in was two hours, and the longest was about a year continuously. It really depends on what kind of assistance is required.

Tuba Kocatürk: **As I understand, there is a very strong research element in what you do and the way you input knowledge into the overall design. Additionally, you seem to**

provide strong computational support as well as the translation of geometry into a buildable format. Is there anything else that would characterise your contribution as SMG?

Irene Gallou: We add value to the project on a project-specific basis. Actually, none of the work we do is repetitive and we try to do it better every time. We do not only conduct the analysis but we also bring in new tools and new parameters. We also provide post-occupancy evaluation, which actually helps us to close the loop. Therefore, our contribution varies considerably, at the beginning of the design process, during and after completion.

Hugh Whitehead: Irene Gallou's work is probably a faster turnaround than ours, shorter cycles and probably a little easier to plan. Irene Gallou gets a specific request for a specific input in a specific time. Having said that, she is always overloaded, whereas we tend to come in on a fairly loose brief and have no idea where it's going to lead and how long it's going to take. In terms of contribution, I think we help to cross-fertilise the six design groups. Each of the six design groups is the size of a fairly large office. And it's a very heavy multiplier, one SMG person for about 100 others. So it's fairly difficult for us to make a significant impact in more than a handful of projects, but because we dip in and out of a lot of projects, we work with a lot of different design teams and we help cross-fertilise ideas, techniques and approaches. That I think is an increasingly important part of our role.

Tuba Kocatürk: **Why can't SMG's input into those design teams be provided from within the teams?**

Hugh Whitehead: If it can, then we move to the next project. Actually, in the past we put a lot of effort into training and education to raise the level of skills in the design teams. I would say that it's reaching a new level of plateau at the moment where the skills are much more comprehensive than they used to be, and that frees us to do more of a research role, so when we see the level of skills rising in a team, we are happy about it.

Tuba Kocatürk: **How would you characterise someone who is applying for a job at SMG? How would you profile this person?**

Hugh Whitehead: We think of ourselves as 'Architects plus' because we are all trained as architects originally and then we grafted the other skills on top, so I think that is the first requirement. The second thing is that we usually like people to spend some time in the design team before they join SMG and I think that is always essential, because we have to be able to carry out an interpretive role and a lot of what we do is down to interpretation, so we really have to understand the mindset of the design team and how they are coming to terms with the requirements of the brief and anything else. The other thing is that, because we are a small group, we are always under pressure. We resist the temptation to just grow the group because then it loses its focus. And so when we take on new people we tend to not add more of the *same*. We don't take a particular skill set and say we need more of this type of person. We almost do the reverse and look for a diverse skills set. Last year we had a very good PhD student from Bath University who actually trained in architecture and engineering and he was also a very good programmer as well. He was an expert in form-finding, and he was really a perfect addition to the group. It's really not easy to take someone fresh minded because they have to spend some time absorbing the culture, understanding the way different design teams work as well as building up the skills set. When someone joins, it takes about a year to build up that fluency of all the skills and techniques, and then it takes a further year before they can really take on a design brief and interpret it properly. To be a fully engaged SMG member takes about a two-year induction process. This is a lot of investment, which is why we need to be very careful about it.

Tuba Kocatürk: **How did the deployment of parametric and computational design techniques and technologies transform the following at your practice: the design process, the design coordination and the management of multidisciplinary knowledge throughout design?**

Hugh Whitehead: I think this is a change the whole industry is going through, not just us. It does change the design process, but you have to be careful that it does not change it too much. We always try to avoid formula solutions, so everything we do is very much project driven, directed by the mindset of the team. And since every project is different, and every team is different, the technology we underpin projects with needs to be very flexible. It needs to be almost custom built per project and it has to evolve with the project. At the same time, you cannot have a system where it's just provided for the team; it has to be grown with the team and we always look for ways to help them engage in the process and ideally take it over from us. We just want people to understand it, grab it and run it themselves. This is important, because ultimately they are responsible for the delivery of their project. We cannot have them just throw it over the wall and say: 'It's SMG's fault that it doesn't work.' I think the changes are more about attitudes than about technology and that comes with experience. One of the shifts that we have seen happening recently is that when we started we used to spend a lot of time developing tools and then exploring different techniques. Now finally, we have got to the point where we could actually put this together in a workflow. Having spent so many years doing that, we can now do it in the other direction where we can look at a team, look at their skills, their capabilities and look at what their deliverables have to be for them to secure a project, and then sit down with them and say: 'What would be your ideal work flow?' And we actually get them to engage in the specification of what they need. So it's quite challenging and surprising for many teams to be asked: 'Just stop a minute and stand back from what you are doing and look at it from a process point of view. How are you going to get from where you are to where you need to be?' And that actually works much better for us because we can do the work-flow consultancy first, then, with the teams, we evolve the techniques that they need, and while that's going on, people who have the scripting and programming capabilities start putting these tools in place. And ideally, we would always use the kind of tools which can be taken apart and re-customised and re-used for other projects. I think one of the biggest challenges for us at the moment is how to create an environment where people can actually share scripts or share code, so that ultimately you get the benefits from some code re-use. But also, people are very good at learning by themselves and educating themselves, so somehow you could find a way to create a resource which people would actually want to plug into. Then they learn, develop and grow through that resource, which would be wonderful.

Tuba Kocatürk: **Do you have a central knowledge base or database where people can add in or share new scripts, codes or programs?**

Hugh Whitehead: Currently not, but it's something we talk a lot about. And it's something we are trying to work towards. I am not sure if a database is a solution to it, because we also have to support several different scripting languages and people write those codes at different levels. If you have a toolkit with a function library, people who have that level of scripting can benefit from that. But we would also like to be able to support people on design teams doing much more end-user programming, not just one-off quick solutions, based on: 'If you show me a script that works, I'll hack it, so it does what I want it to do.' There is a lot of potential there which is untapped because nobody has worked out how to make that easy.

Xavier De Kestelier: We do have a system where we expose all the scripts that are written in different ways. We can write scripts specific to a project or specific to a person.

Tuba Kocatürk: What distinguishes the teams which makes you design customised work flows for each team?

Hugh Whitehead: There is one central problem with any project: 'How do you manage change propagation?' Because whatever the idea is, we try to capture it in a model-driven process. But that model is not a single model. It is much more of a 'federation of models', for which we have to supply the links to get them to work together.

Tuba Kocatürk: How they are going to coordinate it is another challenge, I suppose.

Hugh Whitehead: If you commit to a model-driven process and it is not a single model, then a lot of model composition goes on, and model referencing and data exchange between different modelling processes, some of which are analytical, some geometrical and some of which are visual, contextual or environmental. All these have to provide feedback to the design team, which then helps them to make better-informed decisions. Once those decisions are made, they have to be implemented in the model and generate a whole new set of responses. So if you look at it, the central problem really is: 'How do you manage that change propagation?' Once you've got the change propagation working through your modelling process, that is not the end of the story, because what the teams mainly do is produce drawings, which become a part of the contract and are used to communicate with consultants and contractors. So in addition, there is a whole drawing-extraction process to be set up and managed. Now we have model composition, then drawing extraction and then drawing composition, which engages with the system and links to other distribution systems. So it really is a systems problem. And most design teams do not have time to think about it in these terms. They are just focused on the task in hand, saying: 'How do I get this model built or this drawing done by the end of the day?' When you look at it from the point of view of effective communication between all the other team members and the consultants, in-house or out-of-house, you have to propagate those changes in a controlled way.

Tuba Kocatürk: Do you have any projects which exemplify how you customise work-flows according to different projects or teams and so on?

Hugh Whitehead: We have some interesting examples where we apply this work-flow consultancy. The first one is a group of tower projects (vertical ones) and the second a horizontal one, a transport exchange. The horizontal one has lots of repetition, it's very modular, where we think 'this is going to be really easy', whereas the tower was complex, with no repetition anywhere, so you would think that the change propagation would be much harder. But it turns out that the team in the tower projects accepted the work flow much more easily and we got successful results far more quickly than expected. About the transport interchange, the jury is still out on that. I think that is partly because we stressed the technology to a point where nobody had expected it would have to carry that level of detail. This is, I think, a very important point to raise. A lot of it is due to managing the details properly and doing things efficiently, because otherwise your drawing-extraction system is not going to cope with it. There is always the problem that design teams will just model and model and draw and draw obsessively high levels of detail. They need to get their heads around the fact that the problem does not necessarily have to be in the propagation system. So the trick is having a file structure where you can help people take responsibility for their own piece of work and only publish what other people need to see. We have done quite a lot of experiments in different types of file structure which help people do this.

Tuba Kocatürk: **How do you see the future of the architectural design practice, in terms of profiles, skills and any other views on the necessary changes to be implemented in architectural education?**

Hugh Whitehead: There used to be a real problem with architectural education. Even a bit of scripting and parametrics was exceptional, but now they are everywhere, almost to such a high level that people who are graduating from architectural schools are becoming disappointed to find that there are not always enough opportunities to use those skills.

Xavier De Kestelier: If I can compare now with five years ago, back then the only scripting or parametric design within the office would be done within SMG. But nowadays, architectural students graduate with the knowledge of how to use scripting, parametrics and so on. Today, it's almost second nature to them. I think there is a complete shift happening here. However, the problem we often perceive is that although the new graduates come with computational capabilities, there is also a certain skill which is not there yet, which is the application of these skills within the built environment and construction context. So my role is changing from setting up the parametric models to giving advice on how to do the modelling and scripting from a built environment or geometrical point of view, in such a way that the building will be able to stand up, and will be built on time, with the right materials, what to watch out for and where problems could emerge. Part of our role is not only guiding the teams on how to make the tools but actually how to apply them in real contexts. That is a real shift, I think. In my teaching at architectural schools, I tend to give them 3-D skills pretty early. I've been teaching parametric design to second-year students. I teach them generative components, digital fabrication and scripting as well. Some people think that this is far too early in their architectural education. I really don't think it is, because if you leave it too late then the complete focus will be on the parametrics and descriptive aspects of the geometry. But if you embed these techniques early on, the focus of attention shifts from the tool to the design. In other words, the parametrics or scripting becomes only one of the other tools and gets used mainly to solve a design problem rather than being used just for the sake of using it.

Tuba Kocatürk: **Is there a huge variation among the teams at Foster and Partners according to the extent to which they embed digital tools in the design process?**

Hugh Whitehead: Each of the six design groups has a group leader and deputy group leader. In a way, each group leader characterises the design approach of that particular group. But within the group there is so much variation of different projects led by different partners, with different design teams. It's a very rich mix really and it's very fluid. At Foster's we tend to run very large teams and the reason for that is that we like to have a wide range of skill sets. People who have the ability to be a good team player help to engage all those different skill sets, which then adds up to something more evolved and radically different. I think that is something that characterises all the groups who are looking for a diversity of approaches. There is always a big demand and high aspirations to achieve something that is radically different. So your starting point is never going to be: 'Oh, let's do something like, such and such a building.' It almost has to be the opposite to that.

Tuba Kocatürk: **In terms of the role of technology and its contribution to design teams, would you agree with the statement that technology provides the mechanism by which designers can integrate many different types of information? As long as one knows how the mechanism works, it will be easy to integrate any new information.**

Hugh Whitehead: I do, yes, very much so. And that is why we are trying to look at it from more of a platform point of view than just a choice of applications. We broaden that enormously with the number of applications that we run in the office. It used to be tightly policed and constrained, but it's very much open now. So that brings us new challenges of how we pass ideas and data from one application to another.

Tuba Kocatürk: **This actually brings us to our next topic: What do you think about commercial design software? As I understand it, you are developing your own tools in addition to using a combination of various commercial software programs. Do you think using as many applications as possible enhances and/or supports creativity, or does it somehow impede creativity?**

Irene Gallou: We use quite a number of off-the shelf applications. But most of the time, we try to customise and combine them, because there is not one single application which gives you exactly what you are trying to achieve. The perfect software that can do everything does not exist yet. How the software contributes to design creativity probably depends on what you are trying to achieve with the software. We try to combine and customise as many as possible to achieve what we are trying to do and we think this enhances creativity.

Xavier De Kestelier: I think the trick and the necessary skill is to know what to use when. And it is a richness, really.

Hugh Whitehead: I actually wouldn't like to have one single software program which does it all. If there was such software, then everybody would buy it and everybody would be on the same level of playing field. And what we have always been interested in is to create a special and different kind of playing field where we can invite particular people to play and help us to get into new territory. Recently we had a large team putting together a big design submission. Walk into the conference room and you see this amazing wall full of drawings and illustrations, renderings and everything else, and the whole table was full of 3-D print models. Yet this was still at a sketch design stage, even conceptual. I think that it's miraculous that all this can happen so quickly. That is a reflection on a very rapid improvement in the software and a very rapid uptake of the skills; there is absolutely no doubt about it. Educators and software providers have gone up the curve very quickly and much faster than we ever expected. But looking at it, I've got a feeling that the time from a quick sketch to a 3-D print on the table is getting shorter and shorter. And something occurred to me: we are almost getting to a point where the 3-D print will rise on the table even before there is a sketch, because the teams are working at such a rate that they now have developed well-engineered processes which get that kind of speed and productivity. When you talk about creativity and all those other things, it throws the emphasis not on the production techniques but on how you direct the process, how and at what stage you get the strategy into defining the objectives, which then allow you to specify the tools and techniques which accelerate other processes.

Xavier De Kestelier: I think this discussion brings us back a little bit back to the first question, the role of SMG within the practice. Besides acting as consultants, one of the other aspects of our role is looking into new technologies and researching how we can implement these within a design process. This is often at a software level, but in quite a few cases this is also hardware led. We beta-test quite a few technologies and investigate if they have the possibility to enrich, supplement or speed up the design process. I think 3-D printing is the archetypal example. We bought our first 3-D printer four or five years ago and tried it out for a few months within SMG. We thought that this was just going to be for very specific or geometrically complex projects, but we have managed to push that technology through to our whole office now. There is now a dedicated rapid prototyping department where we build around 5000 models a year. This department is run on a daily basis by our modelling shop, although we continuously consult the modelling shop for future developments. Besides initiating the in-house rapid prototyping, we have also set up and refined the work flows between modelling and rapid prototyping.

Hugh Whitehead: It also changes the dynamics of the design review process. When one of the senior partners walks into this room, the design team starts showing a walkthrough of the design and you get greatly accelerated decision making, there is no question about it. Everybody in the room feels directly involved and you know that you've all got the same focus and the same experience, so you take those conversations away with you and it becomes the context for your next cycle and determines the work you are going to do. All these things have helped us get more towards the model-driven process, because just to get it up on the screen, just to get it ready for the 3-D print, you have to produce clean models.

Xavier De Kestelier: The way 3-D printing works has really changed the way people model. We used to model mainly for the rendering, but now they have to model it to a certain accuracy even at the beginning stages or otherwise you cannot print it.

Hugh Whitehead: But you have to model for the analysis as well. The analysis has different kind of requirements. The whole model-driven process is a story in itself. I never, ever thought it would take this long. I mean, 10 or 20 years ago the technology seemed to be already there, but it has taken an incredibly long time to mature. Having said that, we are at a point right now where I never expected it to happen this quickly. We bumped along the bottom for a long time and suddenly started going up very quickly, and as a result of that all sorts of attitudes and approaches in design and construction started to change together very fast.

Tuba Kocatürk: Is the architectural representation shifting from 2-D abstraction and more towards 3-D simulation?

Hugh Whitehead: There is actually quite a strong lobby against that, because abstraction is important and 2-D drawings are a very elegant form of shorthand which still has a very important role to play. I think parts of the process are much better as a drawing-driven process and other parts as a model-driven process. It's important to recognise it as parts of a whole process and to represent ideas whatever way is most efficient. And some parts of the projects are best as a database-driven process. So in a sense, we've got the freedom of choice and it's not about one or the other but more about how well we manage to combine them.

Xavier De Kestelier: It's very easy to put too much detail in too early in the process. You now have the ability to do that. But we've got to be careful, because if we put too much detail in too quickly and too early on, it looks like a finished project while it's not.

Hugh Whitehead: You can also use 3-D in an abstract way. 3-D print helps us to do that, because you can put abstract objects on the table which can be colour coded and they can represent quite abstract things, which then can help you to make qualitative assessments. You are getting those as well as your quantitative analysis. For example, we are doing some experiments with tools to do 'solar carving'. This is a useful approach when you want to define an external space to receive sunlight during certain periods of the year. With this method, you can actually carve out the volume where you should not be building. On the other hand, we are developing tools to help us do qualitative view analysis and that is almost the same thing in reverse. It's more a matter of what can we see from where. But once you are looking for certain components of the view, you can create an abstract form which will give you clues about where the best locations are to put certain facilities. So it's not designing the thing automatically in any sense, it's just providing a more correct type of information that then becomes a stimulus to design. But you have to resist the temptation to rely on brute-force computing, because that doesn't get you anywhere. Then you proliferate options, most of which should not even be on the table to start with. And then you have to generate an enormous amount of analyses just to eliminate them. It's very tempting to get into this sort of approach and we are working hard to resist that and to keep it more strategic.

Tuba Kocatürk: **Though it must be impressive for the client, I can imagine.**

Hugh Whitehead: Yes, but there are dangers there too, because once an object is on the table, sometimes the client will say that is exactly what he wants, when it was only put on the table to help the client understand that this is not the way to do it. Management of options is much more of an art than it sounds and sometimes you need to put up a bad option to make the others look good. At the same time, you are trying to do it in stages and continually refine the process, but also retain the ability when you reach a certain point. Where the thing is not working, you have to rewind back to some of the high-level decisions and revisit them.

Tuba Kocatürk: Let's jump from here to a more multidisciplinary discussion and another contemporary debate. What is your view of building information modelling (BIM)?

Hugh Whitehead: Before you talk about BIM, I'd like people to focus on the simple question of: 'What is a model?' For me, a model is just a representation of an idea. So what it does is it 'externalises a thought process'. This is very important, because once it's externalised it becomes a point of engagement for other people and other processes and that gives everyone a common focus. The media you choose to externalise it with can be physical, digital or both combined and the representation can be geometrical, analytical or numerical. This is where we can all get engaged in the process. If you look at BIM in terms of this definition, I think it's important for us to say as well that a sketch is also a model, but a sketch is an implicit design model, whereas BIM is an explicit construction model. I don't think BIM attempts to be a design model and it shouldn't attempt to be a design model. BIM technology provides you with a great environment in which to fine-tune construction methods, not fine-tune design. I think it's important to get this distinction clear.

For me the problem is always how you manage the change propagation. Looking at all the different teams and how they organise themselves, I came to the conclusion that information systems actually reflect management systems. So if you have chaotic management, you will have a chaotic information system and vice versa. This gives a strong incentive for design teams to actually design their delivery systems. And this is why BIM doesn't make sense in design, because it's somebody else's concept telling you what's going to be relevant to your project, saying: 'Jump into this and it will take you where you need to get.' But looking at BIM and what it is potentially good for, it aims to provide this single model which somehow combines all your 3-D geometry with any information that you may want or need and it just sounds wonderful. And it's based on the concept promoted by software vendors: 'If you put your world into my box, all will be well.' It's supposed to guarantee this synchronisation with a continual live update to all the parties involved. Well, if it could do this, yes, it would be massive cost savings for the client and the contractor. But what's the up-front cost to the design team? It has got a lot of hidden implications for designers and there are some important questions here to ask. First of all, who creates the BIM model? And once created, who owns it? And then who will manage it? And then how will it be shared? And ultimately, who is going to be liable for it? If you cannot answer those questions before you start, you shouldn't start. All those questions are industry-wide questions, they aren't just our questions, and I don't think that the technology has attempted to answer those questions yet. They just dived in and said it's a wonderful system. For me those are the important issues.

Looking at where we (SMG) are at the moment, we run software which technically is BIM enabled. So if any client asks us 'Do you do BIM?', the answers is 'Yes, of course'. But a follow-up to that question is: 'Which flavour of BIM do you like?' And most clients do not have an answer ready for that. In the meantime, if we have a design but it hasn't been designed with BIM, but somebody for the construction phase will need it, you can export to BIM and you can use industry standards to do that, but what you get out is often not usable.

Tuba Kocatürk: **Then you probably wouldn't want to update your design in the BIM software, but you would prefer to do it in another software program and export it back to BIM?**

Hugh Whitehead: Yes, exactly.

Tuba Kocatürk: **So does that mean that there is no added value for designers in BIM software?**

Hugh Whitehead: It should be a matter of choice – and not many designers would choose it as a starting point, although some would like to be able to delegate to BIM by using subcontracted services. It's really interesting that there are a lot of people emerging now who offer that service: 'We'll take any design data in any form or any format and we'll convert it to a BIM model', which is actually a construction model.

We are going to migrate to BIM, which means that we have to develop our in-house resources to do it. We are testing all those possible routes. I do not rule out any of them; for a particular project, for a particular situation, they are all worth testing. But in the meantime, most of our clients are already requesting BIM technology in their proposals. So there is a lot of debate about that going on. Clients do not often specify the actual software (as to which BIM or which design tools) unless one or the other participants got involved previously and said 'Look, this is the way to go', which may happen occasionally. Clients usually wouldn't mind which software we use, but it depends on their expectations. If they think they can get a coherent model which they can use for facility management, or they can use for planning future developments, or maintenance schedules, or all the other things, that requires a very specific kind of modelling. A construction model is not what you would want for facility management.

Xavier De Kestelier: It seems like one of the most successful ways of working with BIM is basically one architect, one computer, one design. I've seen so many examples of that and it works beautifully. But somehow it doesn't work as well if there is a team involved. Unless the brains of all the team members are synchronised, you cannot work effectively on a BIM model.

Hugh Whitehead: So how does BIM fit with Foster design? We have to have an answer to that. The problem is that we use multiple representations in multiple media for multiple options simultaneously. And while we're doing it, we are communicating with multiple organisations who work on multiple platforms. When you start talking about a single model to do all this, the conclusion is that the fit is neither obvious nor comfortable. And I think that really reinforces what you are saying, that you've talked to a lot of practices and they are actually not comfortable with it. They all have their deep, lucid reasons for that, some of which are based on experience and some of which are based on instinct. This feels too constraining or it may feel too top heavy, and the amount of time, money and effort it takes to frontload the system, you wouldn't ever get the reward for it; whereas a fully loaded system that is ready to carry construction will give you the benefit for it. And that is why at the Salford Symposium, it was really interesting to see what's happening in Hong Kong, where actually the contractors are building the BIM models for the designers, and they are really using the technology well. They are also seeing a payback for themselves, immediately. They are investing in their own training, and so their people learn what they have to do in order to build a BIM model to carry the construction process. I thoroughly applaud that. I think what's interesting for us is that, at the same time, we are trying to evolve new and different design processes and we need to understand the construction and fabrication processes we are trying to engage with. We have to do a lot of work on that side, but it's very helpful for us to know that contractors and fabricators are happy to pick up the downstream part of the modelling process. But we have to get away from the idea that was put about that you could have a single model. First of all, nobody believes that you could, and most people would agree that you shouldn't try to. We can start the BIM debate again and bring it to a better place. I think it's the single-model idea that was a complete fallacy.

16 Interview with Lars Hesselgren, Director PLP Research

Lars Hesselgren and Benachir Medjdoub

PLP is a relatively new architectural practice formed by the five former London partners of Kohn Pedersen Fox in summer 2009. It currently has 70 employees and has jobs worldwide. PLP has a strong track record in computational design and has a group dedicated to computational and parametric design. It is determined to extend computational design beyond the sphere of geometry. Accordingly, the firm engages its sustainability experts to discover ways of using computation in the area of environmental design.

The interview

Benachir Medjdoub: **Your role as head of research suggests that PLP is very keen to support applied research, which is quite rare in architectural practice. How would you define the role of a research group at PLP in the design project lifecycle?**

Lars Hesselgren: It depends very much on individual projects and the stages at which we enter a project. One big advantage of doing research within an architectural firm is that we have ready-made research material available all the time. However, practice is driven by different criteria from research, which means that often you have to deliver results very quickly; there are upsides and downsides to doing research in a practice setting.

Benachir Medjdoub: **What is your research strategy?**

Lars Hesselgren: Our research strategy is to develop better tools that allow us to do better design. One of the primary things is that we have come to the conclusion that having better tools will support better design, but also bearing in mind that we are not software developers. We consider it is very important to team up with a major software developer. This allows us to work on an effective technology which can become widely used within the broader design community. We are looking back at our involvement with Generative Components and how that came about and has evolved. It came from several users of parametric design who wanted to have something that worked better for them, but rather than individually

Distributed Intelligence in Design, edited by Tuba Kocatürk and Benachir Medjdoub

developed software, we essentially teamed up and helped Bentley to develop a particular piece of software which eventually became Generative Components, an industry tool.

BENACHIR MEDJDOUB: **You have long experience in digital design and you have played a key role in supporting the development of GC and by leading a SmartGeometry group. How did the deployment of such technologies, including GC, at PLP transform the design process and the design coordination?**

LARS HESSELGREN: We have been using and helping to develop Generative Components since its inception. We are now working to advance this with a new environmental tool which we are developing with Bentley Systems and University College London (UCL Energy Institute). With respect to GC, we have used it in a couple of projects in special situations where we had to resolve complex geometry. We have used it for a roof of a hotel in London recently and we did solar analysis to analyse sunlight falling on the roof. The long-term plan is certainly to bring these tools to everybody's desktop. Our goal has been helped by the recent announcement by Bentley that GC is now completely free, including for commercial use. We think that will mean that access to this technology and the use of it will spread very quickly and very widely so that there is a pool of talent around to use that technology.

BENACHIR MEDJDOUB: **These technologies such as GC helped you to move the boundaries offered by conventional CAD tools. Have you any specific example of a project where without these technologies you would not have achieved what you did?**

LARS HESSELGREN: Not just GC specifically but all parametric tools have the advantage to give you much greater design freedom, and I think that is the key benefit. Of course, one issue is that too much design freedom is difficult to handle. But when you build yourself a system of rules within which you get the rules to compute your solutions, it means that you can spend a great deal more time at looking at different solutions and changing a particular design concept. The canopy of the Pinnacle in London is a good example; we produced of the order of 20 to 25 design alternatives. When we modelled them 'by hand' in a conventional CAD program it took two to three days for each alternative, whereas with GC it took two and half minutes per solution. What that means is that you can tackle design issues in a fundamentally different way and that gives you much broader scope to produce successful designs.

BENACHIR MEDJDOUB: **Is there a huge variation among the teams at PLP according to the extent to which they embed digital tools in the design process?**

LARS HESSELGREN: Yes, there is a huge range, because again we are designing at different scales, from master plan to detailed building design down to details of buildings. Different teams take up the challenge at different times. At the moment I think an interesting area is going to be master planning, because it is an area where the focus on parametric, digital and conceptual tools is not yet very strong. It is an area where it will be very exciting to see the new developments.

BENACHIR MEDJDOUB: **How do you manage multidisciplinary design knowledge and its integration into a specific design projects?**

LARS HESSELGREN: Like everybody else, we rely heavily on the internet to exchange information and standard file formats. But I think the long-term issues are much more to do with the fact that once you integrate the design tools, it will mean that the decision process will increasingly move away from traditional patterns and change boundaries between professions. The manner in which you exchange information may become less onerous, because you may well decide that you have sufficient expertise in house to make decisions on certain issues, particularly at early stages, without having to involve engineers very heavily. Clearly engineers are never going to become redundant, but they may be forced to produce better and more interesting approaches to specific problems.

Benachir Medjdoub: **Have you any problem of interoperability between the different systems you use?**

Lars Hesselgren: There are certainly a great number of interoperability issues between CAD systems. We have found that Microstation is a very good system because it has import and export facilities to just about every software standard. We also use Rhino extensively for 3-D modelling and now that Microstation can reference Rhino files directly, it means that the exchange is really seamless. Microstation also has very good Autocad tools built into it. The real issue, however, is that you need to understand what interchange formats do and what they are for, and that is something where experience is really the thing that matters. There are a lot of firms who have never come across the fact that in any given project you will almost certainly have, if you include what the consultants use, five or six different design software programs, and if you don't understand the basis of how these software packages talk to each other you are going to be lost.

Benachir Medjdoub: **Does PLP have a geometry specialist team to support your design teams?**

Lars Hesselgren: We have two groups – the computation geometry group and the sustainability group – both of which are integrated with the design teams. They are embedded in the design teams which work with them at any given time.

Benachir Medjdoub: **In any firm there are experienced people who can either leave or retire. Have you put in place any strategy to capture the heuristic knowledge (mainly knowledge based on experience) when you lose staff and want to share their accumulated knowledge with other members of staff?**

Lars Hesselgren: Yes, at the moment we are setting up our own intranet that will have a depository of that type. From experience we have found that the most important thing is to have a library which tells you what expertise you actually have in the firm, so that you can go and talk directly to the people who have the expertise.

Benachir Medjdoub: **In terms of the role of technology and its contribution to design teams, would you agree with the statement: 'Technology provides the mechanism by which designers can integrate many different types of information. As long as one knows how the mechanism works, it will be easy to integrate any new information'?**

Lars Hesselgren: For the first part it is obviously true. For the second part, I think with restrictions it is certainly true: a lot of it is relative to what you mean by information and how you store information. Similarly, much has to do with the understanding of language. So when you talk about internet version 2.0, it concerns the understanding of language and the meaning of information. Information that is in a structured form such as a database is very easy to assimilate; more unstructured information is certainly difficult to understand.

Obviously the leader in this area is Google and they understand more of the area of statistical analysis. They have developed very interesting ways of looking at information which is not immediately obvious, including how they have approached the issue of translations between natural languages.

Benachir Medjdoub: **This brings us to the next question: What are your views of the commercial design software (with a specific focus on parametric tools) currently used in architectural practice and how it enhances/supports creative thinking?**

Lars Hesselgren: They are all excellent products. Rhino is certainly an easy-to-use 3-D modeller; it tends to be less exact than other modellers, partly because of the way it is used and partly because of the way it is structured. Something like Microstation is much more accurate and people who have done sketch design in Rhino will tend to return to Microstation in order to get accuracy. Digital Project is an excellent modeller based on CATIA, a very mature product. It is not, however, a lightweight, easy-to-use modeller. Due to the origins of Digital Project and CATIA, it is heavily biased towards essentially recording decisions that you have made. Then there is Generative Components, which you could compare more with Grasshopper as an add-on for Rhino. These two software programs encourage the notion that what you are designing is a system of dependency, not the object itself. I think it is extremely positive that there are two products in the same product category.

I think that parametric tools support more creative thinking than the so-called building information modellers (BIM) such as Revit or Bentley Architecture, which are mainly concerned with documenting established work flow. BIM is obviously very useful for productivity, although I think that people often exaggerate the advantage of BIM systems in terms of productivity. Good design has to do with clear thinking; simply saying that you are recording everything that you do in term of its actual modelling and information does not necessarily mean that you are thinking clearly about the design. I think that this is a real problem: leaning very heavily on software forces an established way of doing architecture.

Benachir Medjdoub: **Is the architectural representation shifting from 2-D abstraction and more towards to 3-D simulation?**

Lars Hesselgren: Yes definitely, we have a rendering group including three people that do full-time CAD modelling and rendering, and we have a physical workshop including three people. One of the issues in that context is that people have often said to me: 'If you have a computer model, why do you produce a physical model when you can see it on a computer?' The answer is that you never abandon any tool, it's like being a conductor of an orchestra and saying: 'Oh, I am going to do without the violins because I have a piano!' That is nonsense. Interestingly, the actual physical models are often built from digital models, particularly if they are complex models which are difficult to build 'by hand'. That said, sometimes it is very useful to build models 'by hand' in an assembly process, as a means of mimicking the process that you are going to use where you construct the full-size project in reality.

Benachir Medjdoub: **Have you moved to more advanced visualisation techniques such as mixed reality?**

Lars Hesselgren: At the moment we are doing 3-D straightforward rendering and animations, but not interactive real-time animations. It is certainly something we are considering seriously.

Benachir Medjdoub: **At PLP, how do you introduce and experiment with new technologies?**

Lars Hesselgren: We strongly emphasise keeping up with the latest versions of the commercial software we use and make these available throughout the office. In addition, we often act as alpha and beta testers and expect to contribute to the development of new features within the software we use.

Benachir Medjdoub: **How do you see the future of architectural design practice, in terms of profiles, skills, interdisciplinary relationships and so on?**

Lars Hesselgren: The digital design practice of today is tending towards a new golden era in design. While experts will remain useful, it is increasingly the case that various tools will give a significant advantage to those designers stretching the design envelope into all areas relevant to their design. It will be very surprising if in the long term this will not change the structure of the profession profoundly.

Benachir Medjdoub: **Do you have any views on the necessary changes to be implemented in architectural education?**

Lars Hesselgren: The new approaches to design will revolve around geometry, programming and understanding complex systems and their behaviour. These are skills that the SmartGeometry group was set up to encourage. It is encouraging that the academic world is paying increasing attention to those areas of concern, but that task is by no means complete. Certainly digital skills in the teaching realm of academia are pre-requisites that have not yet been universally achieved.

17 Geometry, topology, materiality: The structural parameters in a collaborative design approach

Manfred Grohmann and Oliver Tessmann

Collaborative design resembles a discussion or a conversation. Ideas are bounced off the different members of a design team. The engineer joins a design team, depending on the task and the point in time, with different structural parameters and contributes to an integrated solution. This chapter will present different strategies that we pursue, at Bollinger & Grohmann, involving geometry, topology and materiality. Geometry plays a major role for structural performance in large-scale structures and at the same time embodies the architectural design approach. Thus, a solution which suits different requirements has to be negotiated. Topology of surface- and vector-active systems within a predefined shape or envelope can become the objective of evolutionary design processes where structure adapts to specific needs. Materiality is embedded into a larger context of material systems that include digital work flow and fabrication.

The geometry

Within a structural form, the geometry defines the position of objects in space with positive characteristics in redirecting forces. When forces can be reduced to pure tension and compression, the entire cross-section of a structural element is exploited, whereas bending causes stress to occur only in the outer areas and therefore disrates the remaining material to be useless ballast. The elegant shells of architects and engineers such as Heinz Isler and Felix Candela have contributed to the vocabulary of 'slender structures' by creating forms free from bending forces. Surface structures like shells or domes resist forces through their double-curved form and integrity. The bearing mechanism is achieved by a membrane-like behaviour, like a balloon, that is not able to resist bending moments with its thin surface. Therefore shells resist external loads through tension and compression. In the case of symmetrical loads, the form will be kept in equilibrium by meridional forces and ring forces only. From an engineering perspective, homogeneous, idealised shells are elegant, as they transfer forces without incurring bending forces and thus can be constructed with minimal material thickness. However, any incision in such an 'ideal' shape, as for instance a door, leads to fundamental, problematic changes in the structural behaviour. Thus form-finding strategies that are exclusively driven by structural criteria are not suitable in collaborative design processes with architects.

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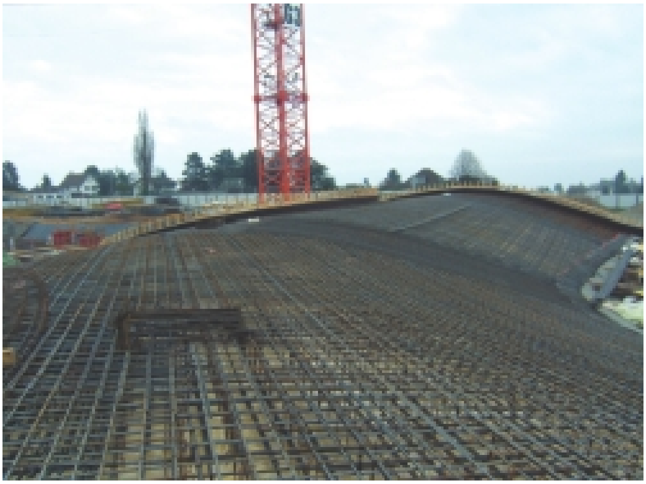

Figure 17.1 EPFL Roles Learning Centre by SANAA, central concrete shell under construction. (Reproduced by permission of Losinger Construction AG.)

The Rolex Learning Center at the EPFL Lausanne, designed by SANAA Kazuyo Sejima and Ryue Nishizawa, is a single-storey building which hosts a central library, lecture halls, study facilities and services, exhibition halls, conference halls, cafeteria and a restaurant. The building is designed with the intention to be the centre of campus life in the future. What makes this design quite unique is that instead of a planar floor slab, the Japanese architects designed an architectural landscape (a load-bearing shell) which generates a topographic separation of different zones of use. The load-bearing shell consists of two perforated free-span reinforced concrete shells, spanning up to 90 metres (Figure 17.1). SANAA's undulating landscape building includes patios, openings and various spatial qualities. Hence structural aspects were just one set of design criteria among many in the design process. The shell integrates a wide range of design criteria far beyond just structural aspects which prohibited the use of conventional structural form-finding strategies for shells and barrel vaults.

The structural design focused on analysing and identifying local areas of shell or arch behaviour, which were further developed and modified in an ongoing dialogue with the architects. The classic approach to 'form-finding' is superseded by the process of tracing performative capacities in the specific morphology. As the load-bearing characteristics vary across the landscape like an articulation, no region on the structural surface can be represented by a single structural typology. The analysis also reveals problematic areas that would necessitate a disproportionate thickness of the concrete shell. Wavy tensile force progression, high bending movements and redirected forces, combined with the lack of support points in the patio areas, were addressed by redirecting the force flow between the shell perimeters through modification to geometry, size and location of the patios. Such an iterative process of tracking performance in collaboration with the architects entails continuously iterative design and evaluation cycles (Figure 17.2).

In the BMW Welt project by Coop Himmelb(l)au, which is located right next to the Olympic quarter and adjacent to the BMW head office and plants in Munich, the complex roof geometry was designed in a collaborative process. During the competition we developed a double-layered girder grid which demarcates the upper and lower boundaries of the roof space in alignment

Figure 17.2 EPFL Roles Learning Centre concrete shell. (Reproduced by permission of Bollinger + Grohmann.)

with the architectural concept of a floating cloud. The structural design and analysis have been a generative process. Driven by the simulation of anticipated loading scenarios, the initially planar girder grid was deformed such that the upper layer assumed a cushion-like bulge. The lower layer also reacts to a number of spatial and structural criteria. For example, the roof integrates the customer lounge, a large incision that opens the views towards the famous BMW headquarters tower and channels the forces to the defined bearing points. The process merged an engineering-like form-finding approach with additional architectural criteria. The combined capacity of both girder grid layers to act as one spatial structure with locally differentiated behaviour is achieved through the insertion of diagonal struts within the interstitial space. The structural depth of the system varies between a maximum of 12 metres and just 2 metres (in areas with less force) in response to local stress concentrations. In the northern part of the building the roof merges with a double cone, a canonical shape in Coop Himmelb(l)au's works, to form a hybrid shape. Similarly, the related bending behaviour of the roof structure gradually transforms into the shell=like behaviour of the double cone (Bollinger *et al.* 2005).

The topology

Besides the geometry of a system, its topology is another crucial aspect for structural performance. The position of apertures within a surface structure or the placement of elements in vector-active systems affect structural behaviour. The distribution of forces within a massive beam is hidden from the observer's eye, as the mass-active system does not reveal its specific load transfer. However, if one visualises the isostatic force trajectories, a number of system-inherent structural types can be recognised, for example arch, truss, lenticular girder and suspension system. The predominance of such vector-active lattice systems can be traced back to a technical innovation in 1866 when Karl Culmann, a professor of engineering science at the Eidgenössischen Polytechnikum in Zurich, published his *Graphic Statics*, including his development of the most important graphic methods for calculating structural behaviour. Based on Jean Victor Poncelet's scientific work on projective geometry, these versatile graphic methods were also a response to the increasing use of cast-iron structures in the field of construction. With these novel methods being particularly suited for the calculation of lattice girders, no other structural typology signifies better the succinct impact of new calculation methods on the changing understanding and employment of structures. In the nineteenth century, cast-iron structures were predominantly used for large-scale engineering tasks like railway bridges or towers. Form and topology were exclusively developed to withstand the largest impacting force. Therefore bending moments in the structure had to be avoided to benefit from the entire element cross-section. The lattice girder represents such an optimised structural typology.

In collaboration with architects, those pure structural typologies do not necessarily support the architectural design approach. Structural elements rather become the objective of a negotiation process between structural and architectural aspects of a project. The engineer has to discard the traditional typology in favour of more project-specific and design-adapted solutions. The process to achieve this goal has fundamentally changed through the use of computational design processes. Computation, first of all, changed engineering by allowing a sheer mass of data to be tackled simultaneously and in a relatively short period. The finite-element method, for example, is based on solving partial differential equations, which was certainly a standard technique before the 1960s. Nevertheless, the computer is irreplaceable in the process of separating continuous structures into a finite but vast number of elements with various shapes and sizes to reduce the complex problem to that of a conventional structure. However, computation is more than mere calculating. Digital formalised systems are not inscribed into mechanical cogwheels and stepped reckoners, but provided as a string of symbols based on a specific syntax. Scripting and programming help to access this layer of description where the algorithm (the machine) and the data are represented with similar symbols and syntax.

An evolutionary algorithm, for example, generates and manipulates character strings which serve as genotypes – blueprints – of entire populations of structures. Those structural individuals are then generated and successively analysed and evaluated. Evaluation criteria do not necessarily originate from structural requirements, but could also be derived from the architectural aspects. The structural system is not exclusively ranked by structural performance but virtually by any quantifiable parameter. The goal is not an optimised structure but an equilibrium of multiple requirements. Every new generation of possible solutions is based on the gene pool of the best solutions of the previous iteration. The individuals are reconfigured and mutated to generate a new set of various solutions. Such a cyclical process, which takes the previous output as the new input, was applied in the design process of a pedestrian bridge in Reden, Germany designed by FloSundK Architekten (Figure 17.3).

The bridge is comprised of two hyperbolic paraboloids described by the upper and lower chords of the girders. The position of diagonals – thus the topology of the lattice girder – was not prescribed. An initial procedure propagates randomly placed elements between upper and lower chords. The structure is analysed and every single element is ranked. The ranking criteria are based on the requirement that every element in a lattice structure should be free from bending moments. Hence the quotient between the observed moment and the normal force indicates the fitness of every element. In an iterative procedure, elements with a bad bending moment/normal force ratio are assigned to new positions in the structure. The altered lattice structure is subsequently analysed once again and this process continues until a predefined number of iterations

Figure 17.3 Pedestrian bridge in Reden, Germany by FloSundK Architekten. (Reproduced by permission of FloSundK architektur + urbanistik gbr.)

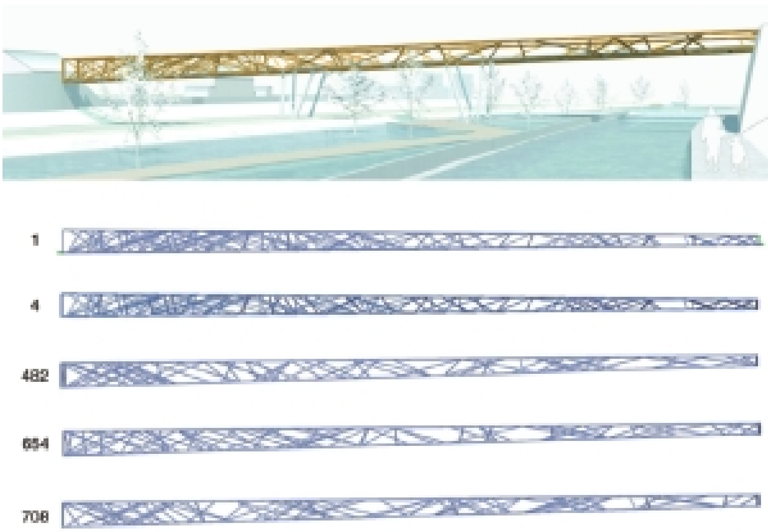

Figure 17.4 Bridge design from different generations of the evolutionary process. (Reproduced by permission of Bollinger + Grohmann.)

or a certain structural performance is achieved. The approach is of particular interest because of the observation of individual elements and their local performance. Structural capacity and topology emerge bottom-up by a self-organising procedure based on simple rules (Figure 17.4).

The design procedure yields regular lattice girders when applied to co-planar chords so that the former structural typology, based on formalised systems like the graphic statics, now becomes one possible solution among many others. This procedure does not question the validity of conventional design procedures but rather provides methods that prove to be more successful in complex environments. Those algorithms are well-defined formalised systems proceeding in a determined manner to search for the best possible solution. In such a process, the process of emergence is almost unavoidable, as the quality and adaptation increase during the development phase over several generations. Although the system is pre-determined, the outcome is not

Figure 17.5 Station Hungerburg, Hungerburgbahn by Zaha Hadid. (Reproduced by permission of Bollinger + Grohmann.)

predictable or constrained to pre-defined structural typologies. In such a process, the engineering tools cease to be merely analytical but become more generative.

The materiality

A material is always part of a broader system, which includes manufacturing and processing. It is already a well-known fact that the computational design has increased the complexity of geometry and that computer numerically controlled machines have enabled the fabrication of non-standard shapes and geometries. What still remains a less investigated domain is the ways in which the digital logic can be reflected in new material systems, which could give way to innovative design solutions. A distinctive example of such innovation can be found in the design of the new cable railway stations in Innsbruck, by Zaha Hadid Architects, where the connection of the steel structure and the double-curved glazed skin required a solution which embodied both the logic of digital design and manufacturing (Figure 17.5). Four new stations of the cable railway connect the Innsbruck city centre with the surrounding mountains. Every station is comprised of a free-formed glazed roof and solid concrete plinths. Although different in geometry, all stations create a family with a highly recognisable formal language. The architectural goal was the creation of continuous, homogeneous surfaces without obtrusive joints and fixings. Only glass proved to provide the desired surface qualities and thermal standards. The floating glass was coated from the inside with polyurethane resin, which accounts for the colour, as well as ensures a residual load-bearing strength in the event of breakage. The load-bearing structure consists of 8 mm and 12 mm vertical steel rips with a depth of up to 3 metres. The structure follows a series of cross-sections of the skin with a spacing of 60 mm between the two. The structural rips were conceived as ‘two-dimensional’ elements with a free-formed perimeter, but the

(a)

Figure 17.6a Polyethylene profile of the Hungerburgbahn. (Reproduced by permission of Bollinger and Grohmann.)

(b)

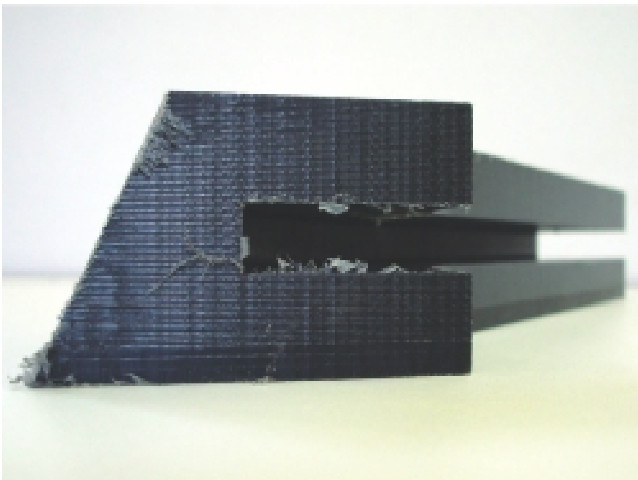

Figure 17.6b Polyethylene profile of the Hungerburgbahn. (Reproduced by permission of DesigntoProduction)

glass fitting had to follow the double curvature of the skin. The problem was at first approached with the logic of a serial production. Thus, brackets with flexible joints were initially proposed, but this solution soon proved to be unfeasible because, in this particular case, every joint had to be adjusted into a position that corresponds to a three-dimensional coordinate on the double-curved skin. Therefore, a possible advantage of 18 000 similar brackets would have turned into a time-consuming disaster on site. The solution was provided by a simple continuous polyethylene profile (Figures 17.6a and 17.6b), which acts as a linear support for the glass

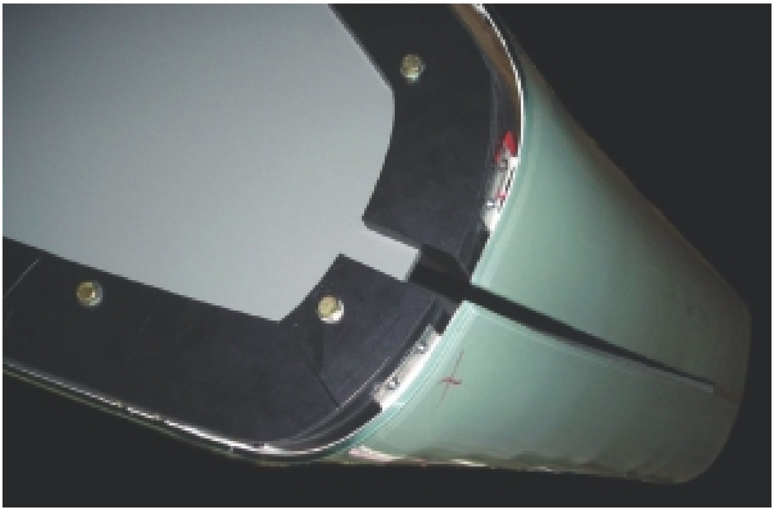

Figure 17.7 Façade mock-up showing the steel rip, the polyethylene profile, fixing and glass. (Reproduced by permission of Bollinger + Grohmann.)

panels. The profile is slotted and bolted to the steel rips. Since the upper face follows the double curvature of the glass skin, every single profile had to be milled individually. A continuous digital chain and a five-axis mill helped to cut the profile from sheet material to minimise costs. The CNC data could be automatically derived from the 3-D model through special software developed by the company, DesignToProduction. The same custom application provided the necessary information for the positioning of the bolted connections, segmentation and nesting of profiles on the sheet material. Compact T-shaped sheet-metal elements were used for fixing the glass where tight-fit screws could be placed anywhere on the polyethylene profiles, which speeded up the assembly (Figure 17.7).

The material polyethylene, in combination with digital design tools, and specific software development in connection with a CNC fabrication process, proved to be most suitable to fulfil the demands of the project. Collaborative design between architects and engineers demands multiple strategies for the development of structures. This requires, on the one hand, being reactive and trying to find solutions within a pre-defined set of boundary conditions. And on the other hand, it requires being proactive and generative within and during the definition of those boundaries. Whenever possible, we prefer the latter and join the generative team. Digital tools support this strategy by generating manifold proposals and turning analytical tools into generative ones.

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