Sense-making across collaborating disciplines in the early stages of architectural design

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Sense-making across collaborating disciplines in the early stages of architectural design

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Dominik C.C. Holzer

25.10.09

Acknowledgements

Abstract

In my PhD thesis I raise the claim that a main ingredient to successful design collaboration in architecture and engineering is to make sense out of the information that is provided by designers and consultants as early and comprehensively as possible.

The design of buildings has become a task with such a level of complexity that a social effort is required to coordinate and integrate the various worldviews of disciplines involved. In my research I first analyse obstacles to sense-making across collaborating disciplines by investigating the worldviews and priorities of the main parties involved in the design of buildings. I then propose novel ways for exchanging knowledge and generating common understanding between design professionals during early design and I introduce the process of *optioneering* as one possible method to assist architectural and engineering work practice.

In order to address the above issues, I have embedded myself in the engineering firm Arup in their Sydney and Melbourne offices. There, I have examined methods for communicating and integrating aspects of building performance between designers and design consultants over a period of three years. As part of my research at Arup, I have gained an understanding about the everyday requirements of design professionals for sense-making in collaborative practice.

Thesis Supervisor: Mark Burry

Professor of Innovation (Spatial Information Architecture) and Director of the Spatial Information Architecture Laboratory (SIAL), RMIT University, Melbourne, Australia

Key of Interviewees:

As part of my investigations for this PhD thesis, I have interviewed 28 practitioners from 7 different professional backgrounds. Although I cannot list their names due to privacy reasons, I have put together tables that describe their professional occupation and position.

Acoustic Engineer 1	Senior Associate, Arup Sydney office, 13 years experience	Interviewed on July, 17th 2008
Acoustic Engineer 2	Senior Acoustic Engineer, Arup Melbourne office, CAD expert, 6 years experience	Interviewed on July, 25th 2008
Acoustic Engineer 3	Graduate Acoustic Engineer, Arup Melbourne office, CAD modeling expert, 4 years experience	Interviewed on Nov 12th 2008
Acoustic Engineer 4	Senior Acoustic Engineer, Arup Melbourne, 10 years experience	Interviewed on Nov, 12th 2008

Architect 1	Director, Arup London office, 25+ years experience	Interviewed on Sept, 15th 2008
Architect 2	Senior Architect, collaborating with Arup in Singapore, 12 years experience	Interviewed on Sept, 30th 2008
Architect 3	Junior Architect, collaborating with Arup in Singapore, CAD expert, 4 years	Interviewed on Sept, 30th 2008

Architect 4	Archineer, collaborating with Arup in Singapore, 5 years experience	Interviewed on Sept, 30th 2008

Environmentally Sustainable Designer 1	Senior Associate, Arup Sydney office, 12 years experience	Interviewed on October 6th 2008
Environmentally Sustainable Designer 2	Senior sustainable design consultant, Arup Singapore office	Interviewed on Sept. 29th 2008
Environmentally Sustainable Designer 3	Senior sustainable design consultant, Arup Melbourne office, 8 years experience	Interviewed on July 16th 2008
Environmentally Sustainable Designer 4	Graduate sustainable design consultant, Arup Melbourne office	Interviewed on January 15th 2009

Façade Planner 1	Senior Associate, Arup Sydney office, 20+ years experience	Interviewed on July, 23rd 2008
Façade Planner 2	Associate, Arup Sydney office, 10 years experience	Interviewed on July, 23rd 2008
Façade Planner 3	Senior Façade Planner, Amsterdam office, 8 years experience	Interviewed on Sept. 24th 2008

Façade Planner 4	Graduate Façade Planner, Melbourne office, 4 years experience	Interviewed on Nov.18th 2008

Fire Engineer 1	Senior Fire Engineer, Arup Sydney office, 25 years experience	Interviewed on July, 22nd 2008
Fire Engineer 2	Senior Fire Engineer, Arup Sydney office, CAD expert, 6 years experience	Interviewed on July, 16th 2008
Fire Engineer 3	Junior Fire Engineer, Arup Melbourne office, CAD modeling expert, 5 years experience	Interviewed on Nov, 24th 2008
Fire Engineer 4	Senior Fire Engineer, Arup Melbourne, 12 years experience	Interviewed on Nov, 24th 2008

MEP Engineer 1	MEP drafting and CAD coordinator, Arup Melbourne office, 14 years experience	Interviewed on Aug. 19th 2008
MEP Engineer 2	MEP consultant, chair of the *Design and Technical Executive*, Arup London, 18 years experience	Interviewed on Sept. 12th 2008
MEP Engineer 3	Senior MEP consultant, Arup Melbourne office, 9 years experience	Interviewed on Oct. 13th 2008

MEP Engineer 4	Senior Associate, MEP consultant, Arup Singapore Office, 11 years experience	Interviewed on Sept. 29th 2008

Structural Engineer 1	Senior structural engineer, chair of the *Buildings Practice Executive*, Arup Sydney office, 20+ years experience	Interviewed on July 24th 2008
Structural Engineer 2	Senior structural engineer, 20+ years experience, Arup Sydney office	Interviewed on July 23rd 2008
Structural Engineer 3	Structural engineer, 3D integrated design & CAD expert, Arup Amsterdam office	Interviewed on Sept. 23rd 2008
Structural Engineer 4	Senior structural engineer, chair of the *Buildings Group*, Arup Melbourne office, 20+ years experience	Interviewed on Oct 11th 2008

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"... design practice will be recognizable no longer abstractly as a cognitive search process, but as a fully embodied, institutionally located, practically constrained, politically contingent, ambiguity-resolving social process-as a social process of making sense together in practical conversation, a process in which the giving of form and the making of sense are profoundly coterminous." (Forester 1985, 20)

1. Introduction

1.1. Motivation

My personal motivation for engaging with this PhD research was arising from the dissatisfaction I experienced in everyday practice as an architect. Before commencing my PhD I had worked for five years as practicing architect on large-scale commercial projects as associate of a major European architecture firm. The often disconnected manner of day to day communication between design professionals I witnessed when working collaboratively on architectural projects made me wonder if we can actually talk about the building industry as an *industry*. As a practicing architect I have experienced gaps in the information flow between clients, architects, consultants, and contractors that seem to be rooted in different professional cultures, in the incapacity to make immediate sense of what other parties try to achieve, and in the fragmented state of the building industry. Professionals are more inclined to act from within their discipline-specific silos rather than operating in a synergetic fashion.

At the outset of my PhD thesis I asked the following two questions: Firstly, why are we seemingly working against each other rather than with each other? And secondly, why is it so difficult to grasp where design partners 'are coming from', particularly in the early design stages?

These questions triggered my decision to *dig deeper* and learn to understand the problems we are facing in order to propose better ways of interacting on building projects in the future.

1.2. Question and Hypothesis

In my PhD thesis I raise the claim that a main ingredient to successful design collaboration in architecture is to make sense out of the information that is provided by design professionals as early and comprehensively as possible.

The ongoing segregation into ever more specialised disciplines challenges traditional work-methodologies in the building industry. The design of buildings has become a task with such a level of complexity that a social effort is required to coordinate and integrate the various worldviews of disciplines involved. Parallel to practice-related transformations in the industry, the tools that designers and consultants apply have undergone drastic changes over the past two decades. So far, these changes have mainly benefited the workflow within individual professions and they have barely helped to overcome disciplinary boundaries in early design. In my research I firstly analyse obstacles to sense-making across collaborating disciplines by investigating the worldviews and priorities of the main parties involved in the design of buildings. I then propose novel ways for exchanging knowledge and generating common understanding between design professionals during early design. In this context, I introduce the notion of

optioneering [1] as a method that allows designers and consultants to engage confidently in decision-making in a multi-criteria environment.

Designers and consultants agree that it is during the early design stages[2] when integration of design-knowledge counts most as any decisions during this period have the biggest impact on the cost and performance of a building.

As an architect, I fully embedded myself in an engineering practice (Arup) for a period of three years to gain immediate access to day to day work-experience though *action research* [3]. There I examined methods for communicating and integrating aspects of building performance between designers and consultants in the early design stages. Through observation and participation in practice, I scrutinised the way architectural design is currently being communicated across disciplines during the early stages of design. My aim was to uncover how architects and consultants bring their expertise to the table and make their input understood for sense-making in teams.

The increased availability of computational means to analyse and share design-data and the increasing speed in which we do so cannot be purely seen in a technical context. Literature from Papamichael and Protzen (1993), Kvan and Kvan (1997) and Pulsifer (2008) suggest that next to technical support, social aspects of design communication need to be considered by professionals who share design information. My review of literature states that the benefits of using Information and Communication Technology (ICT) depend on the type of support required by

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[1] I discuss the meaning of *optioneering* in detail in Chapter 5.1. Little reference can currently be found about this term in encyclopaedic literature, but it is increasingly being used in engineering practice.

[2] In the context of my PhD I refer to feasibility studies, conceptual and schematic design (design development) as the *early design stages*. This refers to the Royal Institute of British Architects (RIBA) stages A-D.

[3] Action Research is a terminology coined independently by Collier and Lewin in the middle of the 20th century. *Action research is about working towards practical outcomes, and also about creating new forms of understanding, since action without reflection and understanding is blind, just as theory without action is meaningless.* (Reason and Bradbury 2006, 2, pp.39)

different types of architectural and engineering practices (Coxe, et al. 1987; Chen, Frame and Maver 1998; Eastman 1999; Chaszar 2003; Coenders and Wagemans 2005). It has effects on all aspects of design including social, organisational, and communicational concerns. Within my PhD thesis I examine the reasons for the difficulties encountered by designers in *making sense* of what other design partners bring to the table. I then focus my research efforts towards understanding the obstacles to design practice which lead to the disjointed nature of the information–flow between designers and consultants in the early design stages. I ask:

- *Why is it more often than not difficult to understand each other and (as said colloquially) "sing from the same hymn sheet" when working on a common design problem?*
- *What different types of information do individual consultants bring to the table?*
- *How is this information interpreted by others?*
- *How does it affect the work of other team-members?*
- *When is it mostly needed to support sense-making in teams? and*
- *What are the tools currently available for designers and consultants to do so and what are their benefits and deficiencies?*

As an original contribution to the field of architecture I reveal how various designers, consultants and clients apply professional judgement in the early design stages in order to deal with the information they are receiving (and the information they not receiving) from others. I do not propose a single unified process in which designers and consultants interact in the early stages; instead I argue that there can be more guidelines, frameworks and smarter interfaces that help them to streamline their work-methodologies, make sense of the information others bring to the table, and interact in a more integrated manner. To support this argument, I investigated the impact of the increased use of computational tools and interfaces in various ways. Firstly, I scrutinised the way we share information across teams. Secondly, I explored processes that allow architects and

consultants to optimise design concurrently towards integrated and sustainable solutions. In my thesis I offer potential solutions for fostering collaborative efforts between partners in the building industry that will benefit not only individual members, but the building industry as a whole.

1.3. Conceptual Framework and Methodology

During the three-year period of conducting my PhD, I drew from sources in academia and from experience in practice. Next to the acquisition of knowledge through academic research, I was embedded in an engineering firm (*Ove Arup and Partners* [4] in Sydney and Melbourne) where I engaged in qualitative and quantitative[5] research. Being embedded with engineers gave me, an architect, the possibility to contextualise better the connectivities and dependencies of architectural design within the overall planning process. I had access to day to day operations of the firm both as an observer and as a participant in design projects. At Arup, I collaborated mainly with the Building Group consisting of acoustic engineers, environmentally sustainable designers (ESD), façade planners, fire engineers, mechanical, electrical and piping (MEP) engineers, and structural engineers. During the three years of research and work, I was truly embedded in practice and I participated in the design-development of a large-scale commercial project (a stadium design). As part of this action research, I collaborated on projects and organised workshops and interviews with practitioners of the firm to learn about the information-requirements designers and consultants have during

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[4] Ove Arup and Partners is an engineering firm with a network of offices acting on a global level. The type of services provided by Arup spans from building engineering consultancy in the building and infrastructure sector to activities in project-management and planning, URL: http://www.arup.com For the purpose of simplification I will abbreviate *Ove Arup and Partners* with *Arup* in this PhD thesis.

[5] The qualitative part of the research included the day to day collaboration with practitioners in the office, the setup of workshops for design collaboration, the scanning of the knowledge-base within the organisation and in particular the analysis of information gathered from one-on-one interviews with practitioners. The quantitative part included the collection of numeric data from practitioners using a questionnaire to profile the different disciplines in the *Buildings Group* at Arup.

the early design stages. The interviews gave me valuable feedback on what various information designers bring to the table in the early stages of a project, what kind of information they would like to have at their fingertips, and what media are deemed most appropriate for them to make sense in collaboration with others.

1.4. Exegesis Layout

The chapters in my PhD thesis are structured to first introduce my research question and my environment as researcher embedded in practice to familiarise the reader with issues arising from everyday architectural and engineering practice in the early design stages. The subsequent chapters are interconnected yet autonomous components that provide the reader with insights about specific aspects of sense-making across disciplines in architectural design. Within these chapters I present the evidence gathered in practice and I use it to build up the argument that I bring forward and discuss in greater detail in the conclusions of my PhD thesis.

After this introduction I describe in the second chapter the approach I chose for writing my PhD thesis and I contextualise my contribution within the field of architectural research and practice. In doing so I provide reference to the main body of work that has informed my investigation as part of my literature review. In this chapter I give a detailed insight on the methodology that I applied to my research and I describe the research-environment both in academia as well as in practice which has helped me to gather the evidence for the argument I present in this PhD thesis. I gained most insights about the process of sense-making across disciplines in architectural design within the context of everyday practice and my own contribution to the topic has strong references to *action research* as previously described.

Chapter three is the background chapter containing my literature review. In this chapter I reflect on literature in the field of architecture, engineering and construction (AEC) to tackle the issue of sense-making from sociological, technical as well as financial and legal aspects. I explore how other authors dealt with the issue of knowledge transfer from individual professionals to others and how knowledge can be built up beyond professional boundaries both on individual, as well as on a team-level [6]. As part of this investigation, I explore how advances in Information and Communication Technology (ICT) transformed the modes of operation in early stage design collaboration across disciplines. How do we make sense of the different types of information we are dealing with on a building project? How do individual professionals communicate their specific building-performance requirements to others? At a conceptual stage of the design process, how do we prioritise those aspects of design that appear to have the strongest impact on the final outcome? As part of this exploration, I scrutinise the value of referencing design-information drawn from successful (or unsuccessful) precedence projects during the early design stages.

Chapter four is an analysis of early-stage design practices from various disciplines through quantitative and qualitative research. I present the responses gathered by me during workshops and one-on-one interviews with designers and consultants from Arup and affiliated companies. I provide insights about current problems in work-practice focussing on how knowledge is currently being generated and captured in design meetings, the type of media that are used to do so, and the mechanisms for storing knowledge to make it easily retrievable by various members of the design teams within and outside Arup. During the interviews I questioned practitioners about their perceived future requirements for work practices within their field and across a wider range of disciplines in order to be able to suggest novel ways to exchange information and build up knowledge across disciplines in early design.

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[6] I will provide a comprehensive listing of those authors in Chapter 3.2. *Sense-making in a social context.*

In Chapter five I introduce *optioneering* as one possible method to assist collaboration in architectural and engineering work practice. I describe how optioneering can inform the design-evaluation process, both in terms of knowledge-sharing, sense making as well as design decision support across distinct design domains.

I then present methodologies for quantitative and qualitative design evaluation across disciplines. As part of my investigation I scrutinise how we can find transdisciplinary synergies in collaborative design practice that go beyond the benefit of individual disciplines. I analyse how architects and engineers can develop and manage trade-offs of building performance that cut across professional boundaries, and I consider the mindsets and toolsets that are required to do so.

Concluding the chapter, I present the functionality of a computational framework that I helped to develop to assists in sense-making across design-disciplines. I point out the various capabilities of the framework including the user-interface that allows practitioners from varying background to make their information easily understandable to others.

Chapter six points the reader to possible consequences of my findings. I discuss how prevailing practice mentality in AEC can be changed to accommodate transdisciplinary ideas and systemic innovation. Further I describe how academic institutions can assist in the lowering of disciplinary boundaries and educate scholars towards an integrated manner of designing. I then scrutinise the definition of role the architect and the engineer in the context of social design regarding authorship and authority. Finally, I look beyond early-stage design to gauge what effects the methods described in my thesis can have on the consequent design process.

I give a summary of my research in Chapter seven where I conclude my PhD thesis and I offer a perspective on how my doctoral research could be extended by future discourse in the field, both in academia as well as practice.

Appendix A consists of an in depth action research case-study that reveals how I tested some of the concepts presented in my thesis on an actual project (under construction at the time of writing). Appendix B contains the transcript of an interview I conducted with André Chaszar, one of the world's leading experts on design collaboration between architects and engineers. In Appendix C, I include original transcripts of seven of the 28 interviews that I conducted with members from each of the disciplines represented in the Arup Buildings Group and collaborating architects. Appendix D contains a large-scale version of a matrix with summarised results from the interview process with the 28 practitioners.

1.5. Glossary

ABACUS   Advancing Buildings and Concepts Underpinning Sustainability

AEC   Architecture, Engineering and Construction

AIA   American Institute of Architects

APAI   Australian Postgraduate Award Industry

BDA   Building Design Advisor

BDS   Building Description System

BIM   Building Information Modeling

BREEAM   BRE Environmental Assessment Method

CAD   Computer Aided Design

CFD   Computational Fluid Dynamics

DDAA   Delivering Digital Architecture in Australia

DOM   Domain specific Object Model

ESD   Environmental Sustainable Design

FAF   Framework Application File

FDS   Fire Dynamics Simulation

FEA   Finite Element Analysis

GSA   General Services Administration (USA)

IAI   International Alliance of Interoperability

ICT   Information and Communication Technology

IFCs   Industry Foundation Classes

IPD   Integrated Project Delivery

JCT   Joint Contracts Tribunal (UK)

LEED   Leadership in Energy and Environmental Design

MADA   Multiattribute Decision Analysis

MCDA   Multi Criteria Decision Analysis

MEP   Mechanical, Electrical and Piping

MODA   Multiple Objective Decision Analysis

NIST   National Institute of Standards and Technology (US)

NURBS   Non-Uniform Rational Bezier Spline

PFI   Private Finance Initiative

PPP	Public Private Partnership
R & D	research and development
RIBA	Royal British Institute of Architects
RMIT	Royal Melbourne Institute of Technology
RUCAPS	Really Universal Computer Aided Production System
SIAL	Spatial Information Architecture Laboratory
SOM	Shared Object Model
SPC	Special Purpose Company
VSE	Virtual Studio Environment
XML	Extensible Markup Language

2. Approach and Methodology

This chapter presents my approaches towards conducting research on the topic of sense-making across disciplines in the building industry. An in-depth definition of the research problem is outlined followed by the methodologies and strategies I employ to address it. Information about the fields of enquiry related to my topic is provided, mentioning authors whose work has influenced me most. I indicate the gaps in the literature around my research enquiry and I explain the reasons for choosing to embed myself in engineering practice. The setup of my research environment and the nature of my involvement with the engineering firm Arup are also discussed.

In architecture, engineering and construction (AEC) the integration of different types of knowledge and expertise across disciplines is a complex task. Work methodologies of architects and engineers are often not streamlined beyond profession-specific thresholds and there is a lack of support for exploratory design-collaboration and knowledge-sharing during the conceptual and scheme-design stages (Moum, 2006, 410; Pulsifer 2008, n.p.). As part of this thesis I reveal that digital tools applied by individual professions in AEC (such as architecture, structural engineering, façade planning, environmentally sustainable design) are predominantly tailored to suit profession-specific needs and they are not adequate to communicate design in an integrated manner across design teams (Laiserin 2008, n.p.). My review of literature (Schön 1983, 1992; Cuff 1991; Lawson 1997, 2004, 2005; Kvan 1997, 2003, 2006) suggests that the problems resulting from this information-gap are of a social, organisational, communicational, and technical nature and they represent a severe impediment for designers to combine their efforts in the most effective way.

The fundamental underlying question in this context is whether design is actually a social activity. There appears to be a split between the way architects present themselves to the public in the design process (often in the role of the sole

designer) and reality in everyday practice. There is often little congruence between the picture architects present in public to highlight their contribution on a design project and the credit they deserve as one member of a team of professionals who were involved in realising the project. My architectural research embedded in engineering practice suggests that architects are constantly depending on input from other disciplines in order to proceed with their own work. A substantial part of the work undertaken to plan, design and construct a building is beyond the architect's reach. Any attempt to create a building can only be realised in a social context unless one refers to isolated, small scale projects. Cuff (1991, 20) highlights the espoused theory architects apply to present themselves and she argues that it is rooted in architectural education where academic programs are not set out to teach architects how to become team players. Architects are rather trained as sole designers who coordinate and command others instead of truly integrating their knowledge with the knowledge of others (Cuff 1991, 251).

I aim to ascertain how current modes of communication between different designers and consultants need to change in the future and I aim to propose a new work-methodology that takes the most advantage of the potential offered by tools sponsored by Information and Communication Technology (ICT). I base my judgement on in depth studies of professional conduct of designers and consultants during the early design stages. I scrutinise the information they are receiving from others, the way they operate in teams across disciplines, and the way they share their design with others.

In spite of manifold efforts by researchers and practitioners over the past four decades to finding solutions for the lack of common understanding between various participants in early stage design (Peters 1991; Chen and Maver 1995, 1998; Kalay 1997; Hartog, Koutamanis, and Luscuere 1998; Mahdavi 2001, Chaszar 2003; Taylor and Levitt 2004; Mueller 2006) many questions still remain. The reliance on computational processes and the use of ICT has not proven to be the remedy to overcoming social and epistemological differences between various practitioners. Some lay the blame for it on a *"lack of a comprehensive theory about*

design" (Papamichael and Protzen 1993, 2). Others argued that it is due to *"varying notation"* in the way architects and civil engineers process information (Peters 1991, 23). Others again hinted at *"differences in education"* that lead to diverging understanding of what the design process is about (Salvadori 1991, XII; Cuff 1991, 22; Gann and Salter 2001, 97). In any case, questions remain about the difficulty in bringing designers who work on the same problem together on one table to make sense of each individual's input in an easily, comprehended way. I argue that the kind of support needed varies throughout the design stages and that no one method or tool can afford comprehensive assistance to every stage.

I chose to focus my investigation at the earlier design stages because they represent the period where the fundamental ingredients for any project are being determined and where consequences of any decision-making process have the strongest impact on the quality of a project (Moum, 2006, 410; Penttilä 2007, 293). Dealing with uncertainty is one of the biggest challenges designers and consultants are faced with during the schematic and conceptual design stages. During my research in practice, I experienced that it is during those early design stages when all partners involved in a design project are most in need of support in understanding their colleague's input. Ideas are constantly being generated, assessed, weighted, discarded, and major decisions are being made. The level of communication between various partners is intense and many factors that will contribute to the final outcome of the project are unknown at the commencement of a project.

In order to embed my argument in the wider academic context of sense-making and design evaluation in architecture and engineering, I scanned prominent publications in the field of social science, ethnology, integration theory, communications, creative media, information technology, architecture and

engineering[7]. In the next section I outline literature that has been most useful to me in the conception of my thesis.

2.1.   Review of Research for Design Collaboration in Architecture, Engineering and Construction (AEC)

Before presenting my annotated literature review in greater detail in Chapter 3: *Epistemological barriers between professions in the building industry*, I will overview work that has been most influential on my own research in this section. I place the most relevant texts into prospective, both in terms of their content, as well as their historical relevance.

My review of literature suggests that communicational aspects of the design process in AEC have, until recently, been investigated mainly within the limits of the architectural profession. Prominent in this exploration are authors such as Schön (1983, 1992), Cuff (1991), Lawson (1997, 2004, 2005) and Kvan (1997, 2003, 2006) who advanced research on communicative aspects of architectural design. Their contribution to the field together presents an ongoing investigation about the designer's understanding of the manifold facets of the design process. The above authors deal with the way creative processes unfold, how designers frame and re-frame design problems and how they analyse the interdependent relationship of the process of drawing and how they interact with others while doing so. It was not until the 1990's that the first substantial contributions to the field regarding design communication across a wider range of architectural and engineering disciplines were published with work by Chen and Maver (1995,

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[7] It is not the purpose of this PhD to uncover the reasons for the differences between professions in AEC based on their development in history. I therefore did not draw from literature that addresses historical aspects of architecture and engineering professions. Furthermore, I have omitted areas of literature that deal with engineering optimisation as I have dealt with this topic extensively during my Masters *Transdisciplinary Collaboration towards Optimising Building Performance* which preceded this PhD.

1998), Papamichael (1991, 1993), Kalay (1993, 2004) and Hartog, Koutamanis, and Luscuere (1998), to name a few.

Chen and Maver (1995, 1998), Papamichael (1991, 1993), Kalay (1993, 2004), Hartog, Koutamanis, and Luscuere (1998) and Mahdavi (2001) assess the changes in architectural practice and process as part of their observation. Cultural boundary conditions, the consideration of environmental impacts in building design and advances in Information and Communication Technology (ICT) act as constant drivers of design and building practice. One major underlying question in this context is the impact of digital tools on the conception and construction of buildings and the way they contribute to create shared (or sometimes even segregate) knowledge amongst members of design teams. Questions raised within the literature of Chen and Maver (1995, 1998), Papamichael (1991, 1993), Kalay (1993, 2004) and Hartog, Koutamanis, and Luscuere (1998) scrutinise fundamental issues inherent to design collaboration ranging from the social activities of individuals during the process of designing, to issues such as the link between Computer Aided Design (CAD) and creativity.

Similar to the change in direction seen in literature in design communication from domain-internal to more multi-disciplinary investigations, there has been a shift in literature in social sciences and organisational theory (Valkenburg 1998; Cook and Brown 1999; Barnett 2000; Orlikowski 2002; Pulsifer 2008) towards understanding epistemological processes of the individual to processes that involve the sharing of knowledge in groups and teams on both intra-as well as interdisciplinary level. The focus of writers in social philosophy like Popper (1963, 1972) and Polanyi (1958, 1967) lay in the definition of objective knowledge, personal knowledge, and the way individuals transform information to knowledge in a wider epistemological context. Literature (Simon 1991; Nonaka 1994; Cook and Brown 1999; Orlikowski 2002) has since increasingly addressed issues of bridging epistemologies in organisation knowledge-creation and team decision-making. Authors like Simon (1991) and Nonaka (1994) first discussed the practice of team-management and organisational science, and they opened up the

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discourse about the transfer of knowledge from the individual, to group-work in the early 1990s.

My readings on this subject are thematically linked to the relationship between creative design processes and epistemological support to those processes. The debate about the transferability of knowledge is ongoing. Cook and Brown (1999) and Orlikowski (2002) distinguish knowledge that can be created by individuals and knowledge that is created in teams. The basis for this discourse is the move away from understanding knowledge as a static asset that can be stored and transferred to the activity of knowing – situated in the process of interaction.

One observation that I made during my research is that the focus on most of the material on knowledge transfer seems to lie within the field of business management and coordination (Simon 1991; Cook and Brown 1999; Barnett 2000; Parker 2002 ; Orlikowski 2002). There are comparably few exceptions to this where knowledge transfer in a design environment is dealt with. In my PhD research I therefore seek to address this gap in more detail and I provide an in-depth review of literature dealing with knowledge transfer in a design environment in Chapter 3.2.2.

At the start of the twenty-first century there has been a general shift in literature towards describing the importance of building performance and methods for designers to communicate performance aspects from one discipline to another. Kolarevic (2003, 2004), Chaszar (2003, 2006) and Littlefield (2008) all edited publications where they invite mainly practitioners to report on their findings and they present different types of approaches for resolving design and communication issues with a high level of technical know-how on cutting-edge buildings and structures. One common feature emerging from the literature is the report on the increasing use of rule-based design methods that assist architects and engineers to maintain a high degree of flexibility during their design explorations from the early stages to construction.

Applied research on the use of computers in communicating design has a long history. Eastman (1975, 1998, 1999, 2006) has investigated building representations in a holistic manner from a computer scientist and a cognitive perspective since the 1970s. Eastman's research focuses on object oriented design with the attempt to inform design components with additional attributes that carry behavioural and situational information. Eastman's (1975, 1998, 1999, 2006) efforts focussed on interoperability assisted by virtual representations of building components with an attempt to standardise and automate design-processes. The approaches presented by Eastman give lesser attention to the social aspect of building-design communication. Many of the findings arising from his research have strongly influenced the *Building Smart* [8] movement, an organisation that currently promotes the use of *Building Information Modeling* [9] (BIM) in academia and practice.

The topic of knowledge-transfer in multi-disciplinary design collaboration has not only been addressed in theory. The *Building Systems Integration Handbook* (AIA 1986) by the American Institute of Architects (AIA) is a work of reference that has set the standards for systems integration across multiple disciplines. The AIA handbook has been written with the involvement of a group of experienced design professionals who not only present detailed technical solution for system integration, but also provide procedural assistance and advice for social etiquette in communicating design across multiple disciplines. Many architect bodies publish guidelines to help regulate design interaction between practitioners of varying background. The *Plan of Work* (2008) for multi-disciplinary services by the Royal Institute of British Architects RIBA comprehensively lists services that need to be provided by individual professionals according to varying contractual frameworks. As helpful as these guidelines are, they often focus on legal requirements and organisational structures and they give little insight on how the

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[8] http://www.iai-international.org/IndustrySolutions/BuildingSmart.html

[9] I will describe BIM in greater detail in Chapter 3.3.4: *The potential and the limitations of Building Information Modeling*

interaction takes place and how information is handed over in everyday practice. This thus leaves a gap to be addressed.

As much as national institutions and industry bodies like the AIA or RIBA make efforts to educate members of the building professions in matters regarding design collaboration, I did not find evidence of research about design-collaboration across disciplines occurring within practice in the preparatory research to undertaking my doctoral studies. Some commentators (Addis 1994; Otto and Rausch 1995; Holgate 1997; Brown 2001; Sasaki 2005; Balmond and Yoshida 2006) on the architecture and the engineering side report on successful collaboration on building projects, but so far I have not been able to locate a single account of shared research efforts between companies who search to improve their collaborative methods[10]. As much as the project-based investigations mentioned above provide me with a comprehensive synopsis of past and present research activities in the field, such research is not entirely sufficient to address challenges in everyday practice.

In awareness of these limitations of available material in design-literature I searched for an approach that would provide me with access to experience from building practice. Consequently I decided to pursue a path in my research that gives me the opportunity to explore the issue of sense-making as it occurs in every-day architect-engineer work environments. I introduce the research setting in practice and I point out the methods applied by me to approach the topic of *sense-making* through *action research*, assisted by everyday interaction in a firm with expert designers from multiple domains.

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[10] Such research may well exist, but the lack of public exposure may be due to intellectual property (IP) issues and the wish of those involved to use research outcomes for gaining market advantage.

2.2. Research embedded in practice

I conducted my PhD research based on a theoretical investigation of an academic body of knowledge and empirical methods through observation, interrogation and participation in practice. I argue that practice requires input from academia to advance working-methods as much as academia depends on intervention from practice to advance discourse and critical investigation. I will make a case for this claim in my PhD thesis. I realised upon completion of my Masters degree prior to commencing my PhD that issues regarding the collaboration between different disciplines in architectural and engineering design can best be addressed with strong support from within practice. The *Embedded Practice* experience with the PhD stream at RMIT University in Melbourne, Australia has given me this support.

2.2.1. Definition of the DDAA *Embedded Practice* research

 At the outset of conducting research for my PhD, I agreed to position myself within a company in order to experience design-interaction as it occurs in day to day practice. A major part of the research I present in my PhD thesis has been made possible through an Australian Federal Government funded *Linkage Project* [11] that I participated in as beneficiary of a postgraduate scholarship from the Australian Postgraduate Award Industry (APAI). The linkage project titled: Delivering Digital Architecture in Australia (DDAA) – is based on a collaborative research agreement between an academic institution and an industry partner. The Delivering Digital Architecture in Australia (DDAA) project was set up as collaboration between the Spatial Information Architecture Laboratory (SIAL) at RMIT University in Melbourne, together with the engineering firm Arup in Sydney and Melbourne as industry partner. This hybrid environment between academia and practice (as shown in Figure 1) has offered me a fertile ground for

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[11] The Linkage Projects scheme supports collaborative research and development projects between higher education organisations and other organisations, including within industry, to enable the application of advanced knowledge to problems. Source: http://www.arc.gov.au/ncgp/lp/lp_default.htm

research embedded in practice for a duration of three years between early 2006 and early 2009.
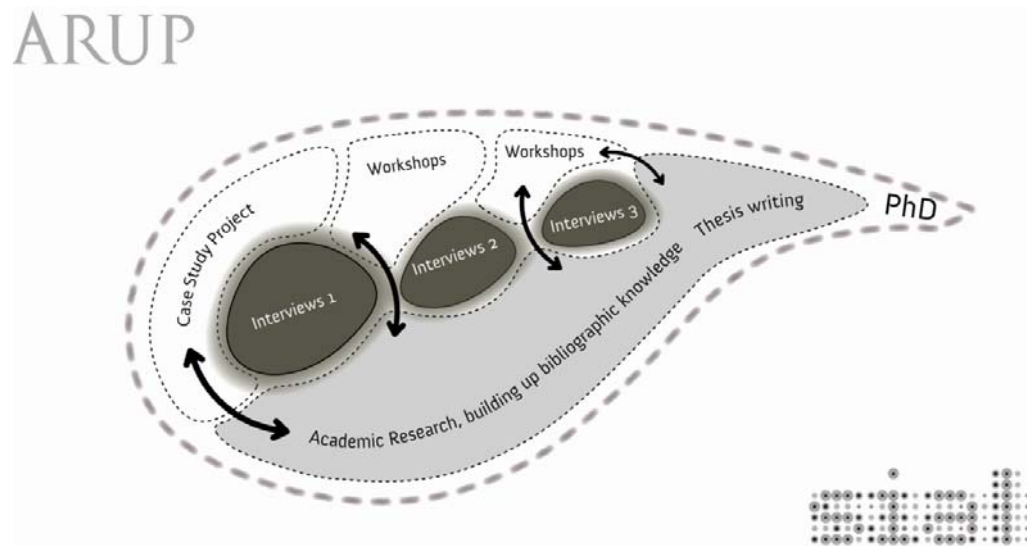
Figure 1: Diagram explaining the research setting between Arup and Sial, Source: Author

SIAL is a trans-disciplinary laboratory with its members engaging in academic research, teaching and work-activities across various fields ranging from architecture, engineering, arts, computer science, sociology, design-theory and others. One common interest of the various members of the lab is the quest for a better understanding of the impact of digital technology and digitally-sponsored methodologies in a design context. During my PhD research, I profited from the lab's trans-disciplinary character through the ongoing academic discourse about design ontology, design theory, social aspects of design communication, and tooling for design; just to name a few. Before conducting my PhD studies as Australian Postgraduate Award Industry (APAI) scholar, I had conducted my Masters degree research at SIAL and I developed a particular interest in rule-based architectural design methodologies such as parametric design in relation to design optimisation processes in civil engineering.

Thematically speaking, my participation in the *Delivering Digital Architecture in Australia (DDAA)* project can be seen as continued investigation of some of the research topics arising from my Masters thesis. Apart from the different purpose of elevating my research to a PhD level, one major distinction of being an APAI

scholar has been my status as *Embedded Practitioner* with an industry partner. The way the DDAA linkage project is conducted signifies a switch from the conventional focus on the research being undertaken within the university at a distance from the end user. Rather, both the research site and the postgraduate researcher are embedded within the practice itself (Maher, Nelson and Burry 2006, n.p.). The project differs from a *professional doctorate* in that I was not an employee of the engineering firm Arup, but I spent up to forty hours weekly in their office for a period of two and a half years with sufficient freedom to withdraw from day to day project work at times to reflect on the process rather than outcome.

Figure 2: Examples of Arup high-rise buildings from around the world juxtaposed on a harbour-setting, Source: Arup

Figure 2 shows a photo-montage of some examples of projects that Arup has been involved with. One of Arup's goals in the building sector is to offer clients comprehensive and integrated assistance in multiple engineering disciplines. These disciplines include: Acoustic Engineering, Environmentally Sustainable Design (ESD), Façades, Fire, Mechanical, Electrical & Piping Services (MEP), and Structural engineering. They are consolidated at Arup under the umbrella of the *Buildings Group*. Over the past six decades, Arup has provided engineering consultancy for an impressive portfolio of benchmark-projects both on the building as well as infrastructure level, collaborating with world-leading architects and planners (Arup 2009). Common to the office-philosophy is a quest for *shaping a better world* with a strong emphasis on finding environmentally friendly and technologically innovative solutions. Arup's main business in the building sector

lies within the construction of commercial office space, the design of major infrastructure projects and the design of large-scale sporting venues[12].

What distinguishes Arup from many of its competitors in this context is the company's willingness to engage in daring designs that more often than not challenge existing design-methodologies and concepts for construction. Being able to rely on a strong task-force of experienced, service oriented engineers with many years of expertise; the firm constantly breaks new ground in the application of new techniques, new tools and new modes of operation (Bailey, et al. 2008, n.p.). This attitude combined with the inventiveness and rigor Arup applies to achieve their goals, have made the firm one of the world's leading consulting group in design, engineering and construction of cutting edge buildings. The company participates in small-scale projects to experiment with new techniques, toolsets and design-methods, and it does not shy away from applying new, untested ideas on large-scale developments, sometimes on the fly while the project is still being developed (Green, et al. 2005, n.p.)

Within the global Arup community, the Sydney and Melbourne offices hold a position of leadership in research, development and the implementation of 3D virtual design. Publications on work undertaken by the Melbourne and Sydney offices highlight this status (Bailey, et al. 2008, n.p.). Some of the projects that originated there, such as the Beijing Olympic Swimming Stadium, the Marina Bay Pedestrian Bridge in Singapore, and the Rectangular Stadium in Melbourne received national and international awards of the highest level[13].

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[12] A comprehensive listing of projects Arup has participated in can be found at the following URL: http://www.arup.com/arup/projects.cfm

[13] The Beijing Olympic Swimming stadium was the winner of the *Project of the year* award from the Association of Consulting Engineers in Australian (ACEA) in 2008, the Melbourne Rectangular Stadium project was given the Bentley Award of Excellence in the *Innovation in Commercial or Residential Building* category in 2008.

The Melbourne and Sydney offices hosted me during the three years of my period as embedded practitioner to research everyday work-practice using 3D CAD technology across architecture and engineering disciplines. As part of the DDAA project, I collaborated closely with two experienced colleagues, one from an engineering IT background and a computer scientist from RMIT. They are both experienced in working on innovative projects in the building sector at a global level.
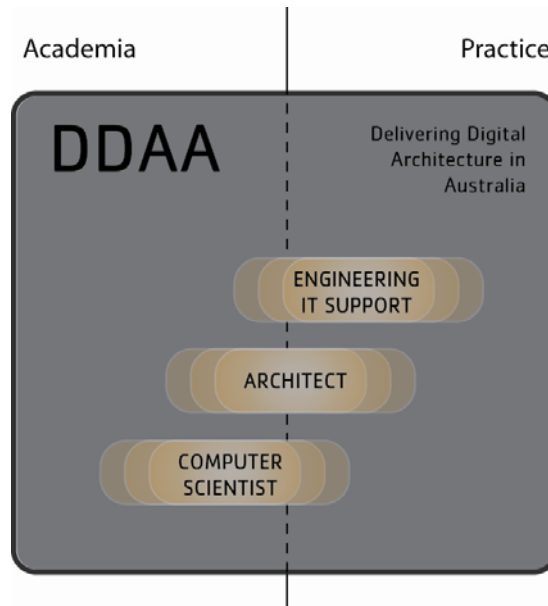
Figure 3: Structure of the Delivering Digital Architecture in Australia team, Source: Author

The DDAA research agenda includes the study of cross-discipline communication methods to understand better the richness of information on the computer monitor, either as CAD or analysis output

The DDAA collaboration has been conceived as a means of consolidating and extending both Arup's knowledge base and the expertise of members from SIAL on early digitally mediated design projects, where engineering input requires significant ad hoc feedback from design optimisation. Prior to the specific collaboration mentioned in my PhD thesis, SIAL and Arup had engaged in research together and had worked on live projects where synergies could be found in the collaboration between practitioners and academic researchers, supported by computational means (Burry and Maher 2003; Nicholas 2008). The experiences referred to above served to underline the need for deeper investigations into knowledge transfer between architects and engineers and the exploration of a more generalised software tool to serve as interface between geometry and

building performance in an iterative design process, with a robust but flexible schema for bi-directional transport of data between proprietary packages.

The opportunity to collaborate with a team of professionals and researchers from architectural, IT-engineering and computer science background has proved of great benefit to the research of this PhD thesis. By working in a collaborative environment in everyday practice, I was able to conduct applied research in order to bridge the gap between experimental academic discourse and requirements from everyday practice.

Two goals were defined by the collaborative team DDAA team: The first was to provide designers with close-to-real-time structural feedback in the design process for decision support. The second was to integrate engineering intelligence in the morphological generation of geometry in a concurrent, transdisciplinary fashion rather than using it to facilitate the construction of a pre-given idea. This integration was achieved by investigating heuristic strategies for both professions to examine the interconnectedness of their design methods and the exchange of data in a concurrent design process. As part of the research group I used ready-made applications for parametric design and engineering analysis in combination with a custom-developed optimisation and code-checking software to foster the collaborative process. By doing so I analysed the challenges and potentialities to the modus operandi of architects and engineers that arise in everyday practice at Arup, and I scrutinised current models of interaction between the two professions. As I demonstrate in part one of this chapter, I undertook an in-depth literature review of the effect of computational sponsorship of the architectural and structural design process with a particular focus on knowledge exchange using parametrically defined geometry models. At the beginning of the involvement in the project, I was already well advanced in the use of parametric software tools, which I had previously applied successfully on several projects in research such as my Masters study (Holzer 2006) and practice (Holzer et al. 2005).

In order to capture the work and the ongoing investigation on the DDAA collaboration, and in order for all DDAA members[14] to access easily the information produced by the research team, I set up an interactive intranet page together with my colleagues where all project-related information has been stored. This repository contained mostly text-based material about news and events such as upcoming conferences, symposia, and workshop dates; it further contained focussed essays on interoperability, team notes of all individual participants, and publications produced by the team members. The intranet served as platform to store information about architect/engineer communication, notes on parallel industry studies, meeting minutes and it contained references to external and (Arup/Sial) internal links to sites of interest to the DDAA team.
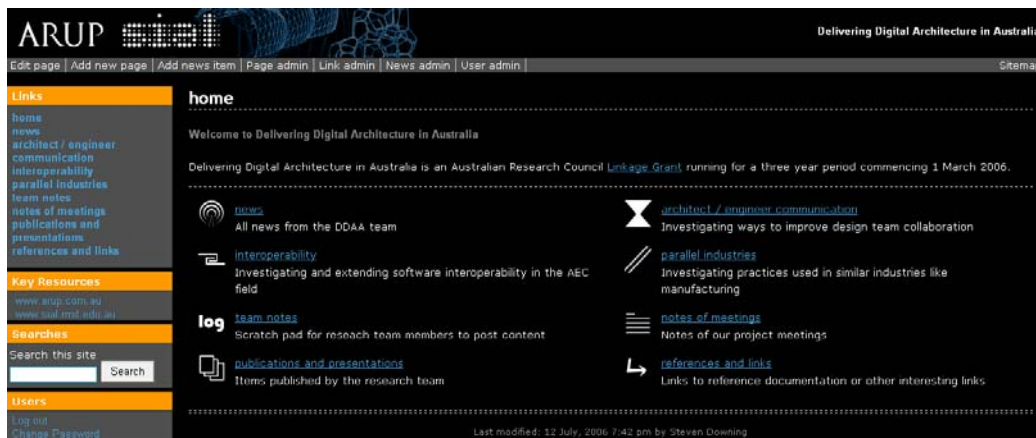
Figure 4: Snapshot of the Arup DDAA intranet-site, Source: Author and DDAA team

2.3.   Quantitative and qualitative techniques applied as research methodology

I chose to use both qualitative as well as quantitative analysis to encode the information I gathered during interviews, workshops and day to day observation in practice. Chapter 0 *Observing early stage design collaboration* contains the results and a critical analysis of a series of *semi-structured* (Barriball and While 1994, 328) interviews that I conducted within Arup employees and with affiliated designers.

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[14] The DDAA team consisted of: Steven Downing (IT/Engineering support), Yamin Tengono (Computer Science) and I.

In preparation for the interviews I had scanned a plurality of sources of knowledge available to practitioners at Arup[15] to put together ten common questions relevant to each interviewee. The interviewees were chosen according to purposive (synonymous to theoretical) sampling using the *maximum variation [16]* method (Lincoln and Guba 1985, 201).   The maximum variation sampling method has allowed me to focus on the differences between various professions as I always questioned an equal number of members from each profession. At the end of each interview, I asked the interviewee to rate 36 pre-defined aspects of building design according to the priority to their work using a one-page questionnaire.

I present and discuss the responses from the questionnaire using quantitative analysis in Chapter 4.4 *Observations describing discipline-profiles individually,* and the answers from the interviews using *qualitative analysis* in Chapter 4.5. This method of inductive analysis of sense-making across disciplines and the consequent critical reflection on the material has assisted me to build up the argument I present in Chapters 5 *New modes of early-stage design collaboration* and 6. *Critical analysis and discussion.*

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[15] Arup has a strong knowledge-support system in place that is accessible to each employee through a plurality of intranet-sites with databases, project-reference libraries, forums, special- skill networks, online handbooks, lessons learned pages and more. In addition to this knowledge support, there are office librarians working in each team who act as a centrepoint of information sources of information from within and outside of the company.

[16] The maximum variation sampling method is used when the purpose is to document unique variations that have emerged in adapting to different conditions (Lincoln and Guba 1985, 201)

Summary Chapter 2:

In this chapter I have presented the approach and methodology of my PhD research. After discussing my research area and the problem I am addressing, I outlined a summary of relevant literature from the field I cover as part of my PhD thesis in regard to its content and its historical context. Next, I described the academic and practice-based environment that hosted me during the period of researching for my PhD.

My position as *embedded practitioner* at Arup has allowed me to tap into the knowledge professionals apply in everyday practice and to interact with them as action researcher on a day to day basis. I presented the aims of the ARC funded *Delivering Digital Architecture in Australia* project and I described its relevance to the process of conducting my PhD research. In the conclusion of this chapter I discussed the specific approach I chose to encode and evaluate the information gathered in practice through qualitative and quantitative analysis.

In the following chapter, I focus on literature by colleagues who have investigated the interaction between design professionals collaborating on building projects. I scan literature that addresses social, technical, as well as legal and financial aspects influencing sense-making between collaborating disciplines

3. Epistemological barriers between professions in the building industry

"...we can see (her) designing as a cumulative process of discovery whose output is not only an elaborated intention but an enriched understanding of relationships among moves, consequences and qualities across multiple domains." (Schön and Wigginis 1992, 144)

This chapter outlines the core background information that positions my work in the wider context of academic research. In my hypothesis I argue that sense-making is an important process for designers and consultants to interact socially on common projects.

In Chapter 3.1 *Professional specificity in current building practice*, I firstly examine obstacles to the sense-making process and I analyse methods that assist professionals to derive common understanding during the early stages of architectural design. In Chapter 3.2 *Sense-making in a social context*, I demonstrate research about knowledge-sharing across teams and disciplines outside and with design domains during the conceptual stages. In Chapter 3.3 *ICT in support of design-collaboration across disciplines,* I present literature that tackles the role of Information and Communication Technology ICT in support of design-collaboration and I give insights on the potential and the limitations of Building Information Modelling BIM - a method that shows great promise to afford substantial benefits to linking of design information across disciplines in the near future. In Chapter 3.4. *Legal and financial aspects affecting knowledge transfer across disciplines in AEC,* I conclude my background research with a view outside the architectural and engineering domains by addressing legal and financial impediments to knowledge transfer in AEC

As part of my investigation in this chapter I ask the following questions:

- *How do architectural and engineering designers process information differently?*

- *What type of information is adequate in the early design stages to communicate design intent amongst a set of practitioners from varying disciplines and backgrounds?*
- *What types of media are appropriate to foster common understanding between different professions?*
- *How can knowledge be best shared amongst a team of dislocated experts, and how do we build up inter-organisational knowledge beyond project specific boundaries?*

I provide evidence of how other researchers and practitioners have explored these topics and I scrutinise how the issue of knowledge-acquisition and knowledge sharing in distributed teams has been dealt with by previous researchers inside and outside the architectural domain.

I discuss literature in which authors have addressed the difficulties faced by architects and engineers in finding a common basis for sharing knowledge and building up understanding in everyday practice. The approaches I explored range from research of communicational aspects of human-human interaction in ethnology and social sciences to more technically oriented approaches focusing on human-machine interaction, artificial intelligence, building sciences and information and communication technology. My aim is to summarise these previous approaches to position my own research in the field of existing literature. This contextualisation further clarifies the motivation behind my choice of analysis. As part of this summary I scrutinise the reason for the apparent information-gap between various participants in the architectural design process

I provide a historiography of investigations by other researchers into sharing information in teams. I analyse how they dealt with the integration of computational tools for knowledge-transfer and decision support in multi-disciplinary design-teams during early stage design. I look outside the AEC domain to understand what other factors might influence the way we communicate aspects design in teams. I do so by scrutinising various types of current contractual arrangements for the distribution of responsibilities and

liabilities on building projects. Related to this issue, I position my research in regard to current efforts undertaken by a large number of practitioners and researchers who are investigating the role of Building Information modelling (BIM) in current practice.

3.1. Professional specificity in current building practice

Literature concerned with contemporary building practice provides us with evidence that the state of common building practice is far from being integrated (Kalay 1997; Gann and Salter 2001; Levitt and Taylor 2004; Maher and Burry 2006).

As described in the 2006 Report on integrated practice by the American Institute of Architects (AIA), feedback from specialists to the designers in the AEC industry only occurs at *"discrete points with varying frequency"* (Bedrick and Rinella 2006, 4). The disjointed manner, in which parties in the building industry interact, causes delays and discontinuities in the workflow and it is consequently responsible for coordination errors and the necessity for rework. Kalay (1997, 192) points to an additional problem in this context when noting that partners collaborating on design projects establish links with each other when the need arises, but sever them when their task is completed. The asynchronous rhythm of design communication across disciplines as stated by Bedrick and Rinella (2006) is a contributing factor to the difficulty of gaining a common understanding amongst practitioners from architecture and engineering disciplines, but there might be more reasons to uncover.

The discrete encounters between practitioners from varying backgrounds often occur in design-meetings where the various members bring their concerns to the table for discussion and thereby try and make their standpoints explicit to others. One common problem in these meetings is that individual practitioners need to make their point of view explicit to others in a short period of time to arrive at a common consensus or at least at a direction that should be taken by all. (Simpson and Viller 2004). The increasing number of specialists involved in the building

industry poses challenges to the collaborative effort and adds layers of complexity to the task of coordinating large-scale design projects.

3.1.1. The problem of progressing specialisation in the building industry

Specialisation is a response to complexity (Gray and Hughes 2001, 74)

Concerns of design professionals from various backgrounds affect cultural relevance, aesthetic aspirations, physical constraints, environmental requirements or cost constraints; to name the principle. If architects traditionally only dealt with a handful of other professions during design, planning and construction, there has been an increase in specialist trades and professions over the past decades that made it difficult to coordinate large scale design projects. (Kalay 2004, 103). Figure 5 illustrates the diversification of professions who form part of the building industry in a historical context. The diagram also shows an example of an architect linking between a façade-planner and an environmental engineer.
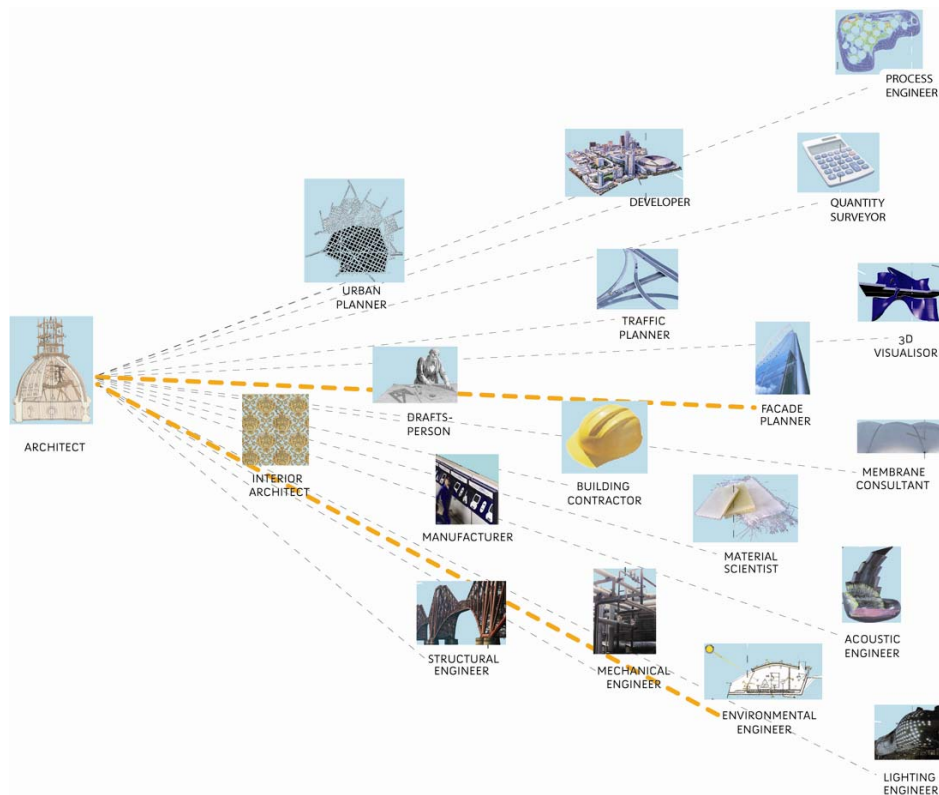
Figure 5: The architect as integrator in an increasingly more specialised industry, Source: Author

Seen from a historical perspective the building industry has undergone major changes over the past fifty to sixty years (Cuff 1991, 31-39; Gray and Hughes 2001, 12) and drastic developments have altered its structure and appearance over the past two decades (Kieran and Timberlake 2004, 12).

> *"Historically, the discipline of 'architecture' has been seen as a 'creative' discipline. Excellence in 'design' is usually equated to the excellence in the artistic and functional qualities of the design. However, the pace of industrialization and the advancement in the technology of the built environment are forcing architects nowadays to consider the technological feasibility of their 'design' at a much earlier stage of the design process."* (Banerjee and De Graaff 1996, 196)

One result of this change in design culture is the ongoing diversification in the building industry into ever more specialised professions. Gray and Hughes (2001, 12) point out one result of the oingoing specialisation as they claim:

> *"A particular effect of specialzation has been the relentless erosion of what used to be a single role in the management of construction projects, that of the architect/engineer (A/E). Some of these changes have been brought about because of the demands of clients, some because of technological complexity and some because of institutional defensiveness."*

Aish highlights the discipline specialization and organisational fragmentation in the building industry and he criticizes the current inadequacy of the state of information exchange in the building industry where the generation and the storage of information occur in profession-specific silos (Aish, 2000, n.p.). The insular nature of specialised building professions is not simply due to a historic development; it is a deliberate state that some professions wish to maintain. Turkle et al. explain one reason for this segregate thinking:

> *"Professional identity and authority derives from the ability to translate specialized knowledge and skills into a market monopoly."* (Turkle, et al. 2005, 26)

With an increase of size and complexity of architectural projects and concurrent pressure to deliver building projects on budget and on time, we are dealing with an increasing number of specialised consultants. These practitioners are trained to bring in-depth knowledge about their particular field to the table, but they often lack broader knowledge about the effect of their design input on other fields across disciplines (Taylor and Levitt 2004, 3; Hensel 2006, 61).

> *"As new specialisms emerge there is a concomitant increase of skills required for coordinating and balancing divergent interests. Interdisciplinary skills therefore complement the emerging pattern of specialisation assisted by complementary technologies."* (Gann and Salter, 2001, 96)

Gann and Salter assess that the amount of mechanical, electrical and electronic equipment installed within buildings grew as a proportion of the total value of the construction from 7% in 1970 to 20% in 1990. Gann and Salter further encourage architects to acquire the necessary skills for coordinating the work of various professions into the design process or else face the danger of leaving an important factor for driving design to others like project managers, the client and cost consultants.

The progressing subdivision of responsibility and accountability by time and professional discipline is seen by Rush as the main reason for buildings to perform poorly (Rush 1986, 265). In this context, he defines *"operational islands"* when juxtaposing the functional gaps that emerge due to varying responsibilities of individual professions and trades with the management discontinuities apparent between various design stages in the building process. Figure 6 illustrates the creation of operational islands when overlaying professional specificity with management phases of building design stages.
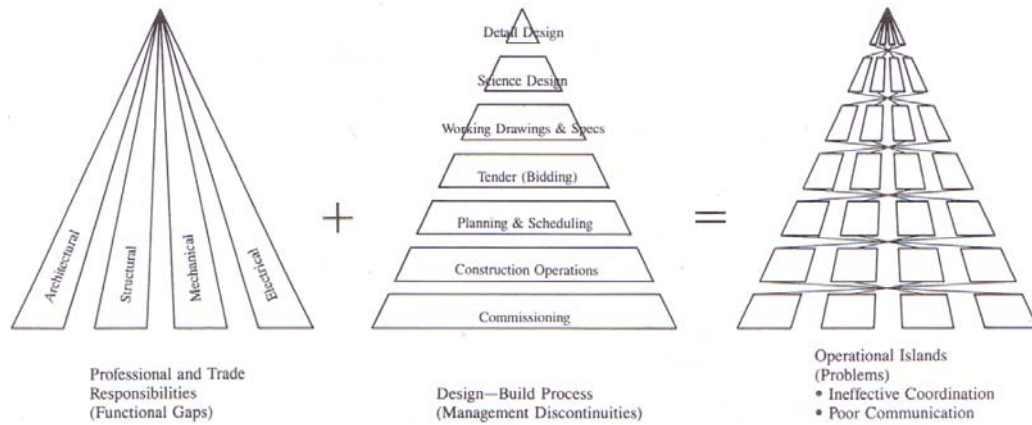
Figure 6: Operational Islands in AEC, Source: AIA (Rush) Building systems integration handbook p.266

Rush (1991) points to an important aspect in searching for the reasons behind the information gap occurring between professionals during the design, planning and construction process: According to Rush, the different nature of information-exchange during the various stages of a design project. The kind of feedback and support that is required amongst practitioners in the early stages is different from the kind of information that is being required by the various members during the subsequent stages, during construction or even during operation of a building. There is neither continuous transition from one design-stage to another, nor a simple increase in detail that needs to be considered by architects, engineers and others.

The coordination of work undertaken by a team of expert from various disciplines is a challenging task. As illustrated in this section, one major difficulty in design collaboration is dealing with the quantity of parties and managing the complexity of the information that they bring to the table. Another difficulty arises from different theories of specialists based on their educational and professional culture that has lead to epistemological silos where the transfer of knowledge between collaborators is difficult to achieve. In the next section I therefore address the influence of education on professional conduct in the AEC industry in greater detail.

3.1.2.   Distinct professional theories, education and disciplinary silos

"When you go from the engineering school to the architecture school, you clearly enter a completely different world" (Billington 1991, 50)

Architects and various engineering disciplines share different world-views and theories based on strong differences in educational background and professional identity. They are faced with different concerns on building projects and they use different notations to describe design issues and framing design problems (Peters 1991, 23). I scrutinise educational and theoretical differences between various professionals in this section to explain their impact on the sense-making process.

"Architects are educated to be responsible for the allocation of spaces and for specifying the materials of the building; structural engineers are educated to be responsible for making it resistant to gravity and lateral forces; mechanical engineers are educated to be responsible for heating, cooling, and ventilating the building, and so on. Their specialisations are reinforced by educational practices and socioeconomic trends that promote and reward excellence in ever narrowing fields." (Kalay 2004, 106)

Peters (1991, 24) argues that a division in the way engineers and architects process information has occurred over the past two centuries. He points out that this division has led to substantive differences between the two professions and it has helped in creating a gap in the information-flow between architects and engineers. Whereas architects apply visual language to synthesise spatial, functional and aesthetic properties of a design idea, engineers are more inclined to use abstract notation of mathematics to analyse design problems. Peters (1991, 28) reminds us that architects and engineers follow different goals when working on the same project: whilst architects are interested in a finished product, engineers appear to focus more on system and process.

Ward, Horton and Brown (1992, 428) Maver (1997, 155), and Roberts and Marsh (2001, 345) argue that architectural education focuses too much on teaching

architects about aesthetics of design with too little attention given to gaining an understanding of a variety of issues related to building performance and system-integration

> *"The lack of integration between technology and the remainder of architectural education is a concern of many architectural educators."* (Roberts and Marsh 2001, 345)

Salvadori (1991, XIII) points out a main factor leading to the schism between architectural and engineering thinking. He states that young engineers are too inclined to rely on results they derive from science and mathematics as the provider of truth whereas architects are more inclined to critical thinking and deriving inspiration from their surroundings (Salvadori 1991, XIV). In many countries architecture and engineering education occurs entirely separately with members from both professions not interacting with each other before they enter their professional careers. Saxon (2001, 7-13) assess that there are few truly interdisciplinary programs for architectural and engineering education that encourage collaboration across disciplines already during design education.

Maver (1997, 155) stresses the importance of educating architecture students not only towards the formal appearance of buildings, but also to focussing their attention on functional behaviour of buildings and on the performance aspects. Advocating interdisciplinary concerns in the architectural education agenda is a difficult endeavour. Cuff (1991, 22) suggests that one reason for this difficulty lies in an espoused theory that encourages a distorted view of the image of the architect. Young architects get inculcated with the idea of being the sole author of a building project during their academic career (Cuff 1991, 22). Cuff reveals the discrepancy between the way that architects work collaboratively in practice and the way that they portray themselves to others as sole designer who is supported by others. Ward, Horton and Brown (1992, 427) point out that the amount of information dealt with in architectural education is continually increasing. In order to assist their argument, they outline the difficulties faced by even

experienced architects to accommodate environmental assessment in their design process early on as the representation of results is often mechanical and little inspirational for the conceptual and schematic design stages. Banerjee and De Graaff (1996, 185) describe how architectural education fails to accommodate the integration of building-performance or technology–based topics in their curricula.

> *"Although most architecture courses around the world do have components of the 'technology of the built environment' as a part of their curricula, the perennial problem is the lack of integration of these 'technological' subjects within the architectural design process. Usually, the subjects are taught in isolation from the studio design projects in an incoherent and unrelated way, resulting in alienation of the student body and in ineffective knowledge transfer."* (Banerjee and De Graaff 1996, 185)

The limited access to the working-methods of their partners' provided by educational programs from architecture and engineering fosters the silo-mentality of design professionals in practice (Salvadori 1991, XII). Gann and Salter (2001, 95) state that the lack of engagement between designers and consultants during education contributes to the use of different languages and a lack of understanding in practice.

3.1.3. Semantic idiosyncrasies, problems of language and notations

> *"As each field has become more specialized, they have developed their own technical language and understanding. They have also guarded entry against what they perceive to be 'external' interests. Demarcation lines have therefore been maintained. This has hindered communication and the transfer of knowledge across disciplinary boundaries"*. (Gann and Salter 2001, 100)

Gann and Salter (2001, 99) agree that designers require better knowledge of different scientific and engineering fields to understand the way interdisciplinary problems are being solved from an engineering, social science, and humanities

perspective. By stating the above, Gann and Salter highlight that performance-oriented collaborative design requires a holistic approach to compensate for the lack of adequate communication across disciplines. Designers who solely focus on the performative augmentation of their work are doomed to fail as improvement in one part is of limited significance without simultaneous improvement in others (Hensel and Menges 2006, 64).

The type of measurement for any successful solution to a design problem can vary substantially between professions. Thammavijitdej and Horayangkura (2006, 52) point out the reasons for this problem. The problem stems from the different languages and notations that get applied within individual professions and the different aspects of the building that are of concern at any given moment. Thammavijitdej and Horayangkura (2006, 52) outline three factors that lead to communication conflicts between architects and engineers:

1. *Terminology misinterpretation*
2. *Inattentiveness, and*
3. *Inadequate information supply*

After interviewing 62 architects and 98 engineers, Thammavijitdej and Horayangkura (2006, 53) argue that misinterpreting terminologies in either verbal communication or drawings is a main contributor for conflicts between the two professions. According to Thammavijitdej and Horayangkura (2006, 54), detailed clarifications are required even during design meetings where knowledge gets exchanged rapidly. They further suggest that architects and engineers communicate with *unfamiliar language* which can lead to ambiguity and the loss of attention during meetings. They assert:

> *"To get the message across, the speaker probably needs to put more effort on seeking to establish a common ground of understanding, which involves assisting the other to overcome such a barrier"* (Thammavijitdej and Horayangkura 2006, 54)

This comment by Thammavijitdej and Horayangkura highlights the social interdependency between design professionals who wish to create common understanging. In the following section I scrutinise the *social* aspects linked to the architectural design process.

3.1.4.   Acknowledging the social nature of design

"In order to have a successful collaboration, each participant should understand, to a certain extent, the social construction of their counterpart collaborator…" (Hamid, et al. 2006, 92)

In most cases in building practice architectural design is a social effort rather than the stroke of genius of an individual, depending on the size of a project (Cuff 1991, 108; Kvan and Kvan 1997, 1). Figure 7 illustrates the interdependence of building systems (Envelope, Structure, Interior and Mechanical) that require coordinated planning by those responsible for their realisation.

"The importance of collaboration is growing, as globalization and increasingly complex technology and products require more teamwork. The complexity of the problem becomes unmanageable for one individual." (Moum, 2006, p.414)

Kvan and Kvan (1997, 2) state that given the fact that design collaborators are often separated by distance and discipline, it is essential for them to find common ground by drawing upon a "*network of knowledge*". As much as architectural design often originates from one individual, it nevertheless cannot be seen as an isolated activity because of its connectivity to, and dependency from a manifold of participants who carry the design forward to becoming a built
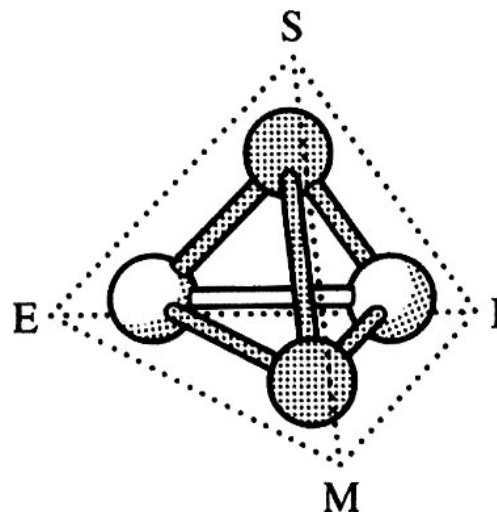
Figure 7: Main building systems, Source: Building systems integration handbook, p.11

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project. Each of the participants plays a specific role that demands social interaction, mutual acquaintance and accountability. Kvan and Kvan define three distinct implications of the term *social* for collaborative practice: The first implication acknowledges the emergence of a collective body of knowledge – social knowledge, the second refers to common procedural interaction in the form of social roles, and the third implication explains the process of identifying and subscribing to common work models and terms: An activity that the Kvan and Kvan describe as *"socialization".* (1997, 3)

Some have contemplated architects in their former role as *Master Builders* – the omniscient centre of all knowledge on a building project. (Snoonian 2002, 289; Kolarevic 2003, 57; Ambrose 2006, 26-33) and they question if the *digital age* will allow architects to reclaim this position.

In the previous two sections I acknowledged the professional specificity in current building practice by highlighting the reason for the progressive specialisation. I presented the variety of notations in use which depict various professional world-views and I pointed out social aspects in design collaboration. Based on the notion of the *social* context of design practice, I focus on the manner in which sense-making can occur among designers and consultants in the next chapter.

3.2. Sense-making in a social context

"Where the formal process of searching a solution space calls for the logical predefinition of all alternatives, the models of conversation, dialogue, and question-response interactions allow for the native, historically rooted competences of participants to create new meanings together, regarding both means and ends." (Forester 1985, 17)

In order to research the social context for sense-making across collaborating disciplines, I investigated the principles that allow professionals to gather and share knowledge. In this section I firstly describe basic cognitive processes that are present in collaborations between professionals both on an individual level and in teams. As part of this investigation I report on problem-framing and

solution-finding that lead to the build up of knowledge across professions. Next, I scrutinise knowledge exchange in the early stages of architectural design. As illustrated in the previous section, variations in the use of language and profession-specific conduct impede the *sense-making* process between disciplines.

3.2.1.   Sharing knowledge in conceptual work.

"The kind of problems that planners deal with – societal problems – are inherently different from the problems that scientists and perhaps some classes of engineers deal with. Planning problems are inherently wicked" (Rittel and Webber 1972, 160)

Rittel and Webber (1972, 155) first noted the fundamental shift in the way we address societal problems and the definition of professionalism that has occurred in the second half of the twentieth century. After decades of clear professional distinctions with hierarchical structures that are rooted in theories emerging during the industrial age, societies in the western world now learn to embrace the process of planning[17] and problem solving in a more network-oriented way. Rittel and Webber (1972, 159) state:

"We are now sensitized to the waves of repercussions generated by a problem-solving action directed to any one node in the network, and we are no longer surprised to find it inducing problems of greater severity at some other node."

Rittel and Webber distinguish between wicked and tame problems and they argue that planners are likely to face ill-defined, wicked problems in times of increasing social, technological, and professional differentiation and increased network thoughtways. Whereas tame problems can clearly be defined in terms of an objective e.g. a solution, social problems are wicked and cannot be solved as such.

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[17] Webber and Rittel describe planning as a goal-finding activity (1972, 157). In the context of my PhD thesis I see the activities of design and planning as closely linked. Design is understood as a creative effort for solution finding (Lawson 2006, 48; Maasen 2009, n.p.), planning is an activity that provides a procedural framework to produce order among object s or concepts (Guilford 1967, 55) Lawson points out that the activities of designing and planning are at time overlapping. He states: *Even planning and organising our time can be seen as a kind of design activity* (Lawson 2006, 234)

One can find good or less good paths to addressing them. Rittel and Webber list several characteristics of wicked problems: they state that wicked problems are impossible to be defined, as problem finding and problem solving occurs concurrently by situating it in its context. In this sense they concur with Popper (1972, 44) who argues that the activity of understanding a problem is equal with that of solving the problem. Wicked problems have no stopping rule, there is no best possible solution but an unlimited array of potentially satisfying or as Simon (1975, 290) - calls them *satisficing* solutions. One cannot immediately or ultimately test the solution of a wicked problem, every implemented solution is consequential and unique.

These observations lead Rittel and Webber to the following comment about the increasing heterogeneity of western societies:

> *"As the sheer volume of information and knowledge increases, as technological development further expand the range of options, and as awareness of the liberty to deviate and differentiate spreads, more variations are possible."* (1972, 159)

In response to the above observation I wonder: What are the consequences emerging from the expanded range of options and variations in solving problems in the context of my PhD topic? And, acknowledging the wicked nature of design and planning, how do we best collaborate in our increasingly networked society?

Rittel and Webber explain why professional identity defined through a mentality of thinking and operating in silos of knowledge is inadequate to help resolve the challenges faced by modern western societies[18] and they argue that the purpose of professionalism needs to be explored in the context of networked societies. Do we associate professional conduct with clearly defined objective knowledge in a certain field?

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[18] I refer to these as the predominant societal context of post WWII western civilisation.

Opinions about the *objectivity of knowledge* are split. There are those writers like Popper (1963; 1972) who emphasise the *objectivity* of knowledge that can be clearly written down and that is unmistakeably transferable. Others like Nonaka (1994) or Orlikowski (2002) put emphasis on the usefulness of applying *knowing in action* that occurs in the process of interaction between individuals and teams. The discourse about how to best address wicked problems in design and planning is ongoing.

The distinct focus on either objective knowledge, or knowledge applied in action is of great importance for my PhD thesis as it affects *sense-making* in architectural design. I discuss the effects of situated knowing in design collaboration in Chapter 5.3.3. *Making sense in architectural design collaboration.*

At this point of my PhD thesis I investigate two aspects of knowledge-exchange in design collaboration: Firstly, how can we address the complexity that is inherent in sharing information in collaborative practice across teams and disciplines? And secondly: How do we pass on knowledge between individuals and between members of teams?

In his theory about *bounded rationality* Simon (1991, 17) postulates that the human mind is not capable of dealing with complexity beyond a certain level. Simon brings forward the argument that learning only occurs in individual human's heads. He adds that an organization learns only by the learning of its members, or by ingesting new members who have knowledge the organization did not previously have. This seems to conflict with the notion raised by researchers since (Cook and Brown 1999; Orlikowski 2002). They stress the difference between the traditional view of *knowledge* and the process of *knowing* in action. This distinction allows them to differentiate between knowledge created by groups of people from knowledge created by individuals.

Simon (1991, 18) acknowledges that individual learning in organizations is a social and not a solitary phenomenon and he states that the generation of long-term organizational memory is jeopardized by fast turnover of personnel. In this

context he stresses the importance of experts (whom he refers to as "*indexed encyclopaedia in the formation of organizational knowledge*"). Simon (1991, 23) raises a point about respecting knowledge of other parties and acknowledging its relevance for one self. These two characteristics are essential in collaborative processes where professionals transgress their own domain to engage with their partner's problems. The concept of engaging with knowledge beyond one's own domain is also reflected in Nonaka's (1994, 18) research in the context of *redundancy*.

> *".. communication between individuals may be seen as an analogue process that aims to share tacit knowledge to build mutual understanding." (Nonaka, 1994)*

Debating the learning process between individuals and groups, Nonaka (1994, 20) describes the use of metaphors (symbols rather than common attributes) and analogies as an essential trigger to induce shifts between modes of knowledge creation. They cut across different contexts and allow imaginative perceptions to combine with literal levels of cognitive activities. In the context of inter-organisational collaboration Nonaka notes the evolution of communities of practice where shared narrations, continuous dialogue and the build-up of trust amongst members are more important than formal job descriptions.

Nonaka (1994, 15) adds to this point by proposing a conceptual framework for mapping the differences and similarities in individual, group and organisational learning. Next to the rather static process of problem solving, he acknowledges that organisations are creating new knowledge dynamically in the process. Nonaka points out the social component of knowledge creation through "*communities of interaction*" (1994, 22) on various levels. Individual knowledge gets amplified organizationally. Such knowledge according to Nonaka is often

developed in action involving parallel processing of complexities and it differs from knowledge that is discrete and that can be captured explicitly in records[19].

This fundamental distinction between two types of knowledge, one explicit in the form of intelligible, the other one implicit and developed in action, prompts three questions. Firstly, can we evaluate these two types of knowledge in the same way? Secondly, is knowledge gained in action objective? And thirdly, does knowledge in action stand the test of scientific scrutiny?

Popper (1972, 33) acknowledges that humans require a commonsense notion of certainty to face the challenges of everyday life and that the notion about the intensity of certainty is only questioned by the expectation of possible consequences with a particular matter.   At the same time he does not agree to the theory that humans cannot do without subjective procedures and he states that: "*the activity of understanding consists, essentially, in operating with third-world objects*" (Popper 1972, 164)

The third world objects in Popper's constructs are the contents of books, libraries, computer memories, and suchlike; in other words they are transformations of information into a form that can be made explicit and examined by others in a uniform, clear language and that be tested by all in terms of its verisimilitude. Other commentators such as Polanyi (1967) do not agree to the rigorous attribution of the process of understanding based on explicit information.

Polanyi (1967, 3-25) distinguishes between the terms *tacit* and *explicit* knowledge. Whereas tacit understanding is based on a process of knowing that is partly inexplicable and internalised though personal involvement with a subject matter,

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[19] Popper Defines World I as the physical world, World II as the world of our mental experiences and world III as the intelligible contents of books, libraries, computer memories, and suchlike. In *"Objective Knowledge"* Popper describes World II as the mediator between World I and World III (1972, 154).

explicit knowledge is something that can easily be expressed and shared with others through various types of media (e.g. third world objects as noted by Popper) (Polanyi 1967, 9)

Building on Polanyi's theory, Nonaka (1994, 19) presents the spiral of knowledge which brings together the ontological and epistemological dimension of knowledge creation, moving between declarative and procedural; as part of the spiral, four modes of knowledge conversion occur (Figures 8a): tacit to tacit - *socialization* → creating tacit knowledge through shared experience, explicit to explicit – *combination* → reconfiguration of existing information between individuals or in groups, tacit to explicit - *externalization* and explicit to tacit - *internalization* → such as learning.
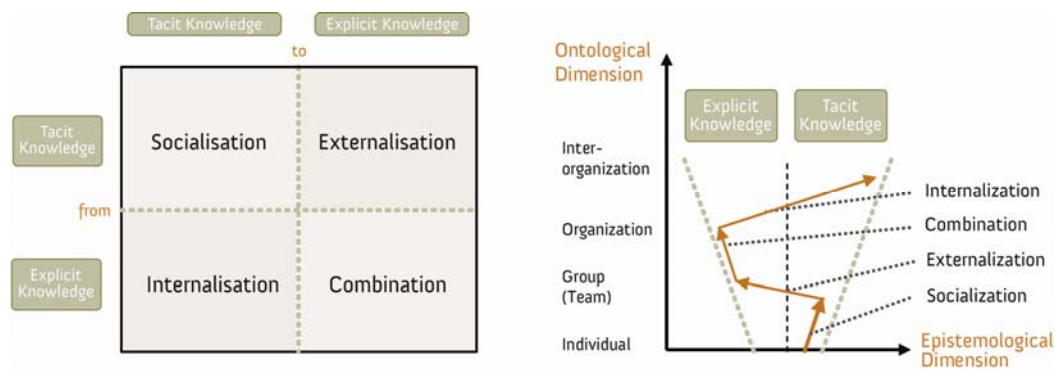
Figures 8 and 9: Components of the spiral of knowledge creation according to Nonaka Source: Taylor and Levitt

Cook and Brown quote Sir Geoffrey Vickers' definition of *"knowing' as the actual act of apprehending, of making sense, of putting together"* (Vickers 1976, 2) and they consequently call for a distinction between the definition of knowledge and knowing. They make extensive reference to Nonaka's knowledge spiral and they introduce the activity of knowing as bridging element between the tacit and explicit by individuals and groups (Cook and Brown 1999, 55). As opposed to previously assumptions stated in literature about the relation between tacit and explicit knowledge, Cook and Brown argue that each of them are distinct categories of knowledge and they add that new knowledge gets created by both individuals and groups by applying knowledge as a tool of *"knowing within situated*

interaction" (Cook and Brown 1999, 54). They extend this argument by pointing out the importance of understanding tacit and explicit knowing as individual processes. One type of knowing cannot simply be seen as an aid in acquiring the other. Tacit knowledge cannot be converted into explicit and the other way around.

Barnett addresses changes in the definition of knowledge with particular references to *working knowledge* which is gained not through academic or theoretical discourse, but through the world of work.

> *"Considerations of truth are influenced by considerations of effectiveness in the practical domain"* (Barnett 2000, 29)

In this context Barnett sees an epistemological transition occurring – a shift from knowledge understood as a matter of what one knows, to knowledge understood as a matter of what one can do - knowledge generated in action. Barnett states that knowledge understood in this context can be apparent at the level of groups, systems, organisations as well as individuals. (Barnett 2000, 16)

Orlikowski (2002, 249) defines the activity of knowing as an ongoing social accomplishment where actors engage in the world of practice. By doing so she offers a distinction between the notion of organizational knowledge as something static that sits within the mind of a group of people to the common activity of knowing which is emerging from ongoing and situated acting. Orlikowski (2002, 250) understands knowledge and practice as reciprocally constitutive and she argues that *"tacit knowledge"* as described by Polanyi (1967, 9) is a form of *"knowing"*.

Orlikowski (2002, 251) is not entirely in agreement with the notion presented by Simon (1991, 17) that learning occurs only in individual human's heads, when she argues that knowledgeability across context and over time occurs through the reproduction of knowing generated in social practices. In this context, she argues that it is impossible to transfer competence from one situation or group to

another and she argues for the build-up of competence through *useful* and in that sense situated as opposed to generalised *best* practices. (Orlikowski 2002, 254)

Nonaka's spiral of knowledge and the consequent theories presented by Cook and Brown, Barnett and Orlikowski play a pivotal role in the understanding of how knowledge is generated and how it is possibly even shared between individuals and teams. By associating the acquisition of knowledge to a specific procedural and social context, the above authors offer important clues about how wicked problems in collaborative environments can be addressed.

In consideration of the principles of knowledge-sharing in action between individuals and teems I now elaborate on this topic in the context of architectural design in the following section.

3.2.2. Knowledge management in architectural design

In the previous section I have focused my investigation on basic epistemological principles of the generation of knowledge and the sharing of knowledge in teams. In order to understand the relevance of these findings in the context of the AEC industries, I ask the following three questions. Firstly, is it possible to achieve smart transfer of best practices between teams in project-based industries (like the AEC industries)? Secondly, how do arguments about knowledge exchange currently aired in social sciences translate to collaborative processes in design environments? And thirdly, is there a schism between knowledge-support in design that favours the acquisition of procedural knowledge and the kind of support derived from guidelines, handbooks or other grounded sources?

The above questions are pivotal to my research and I refer to them throughout my thesis in search for answers regarding sense-making in collaborating teams.

Requirements for knowledge-exchange in the design environment are undergoing transformations in relation to shifts in design practice (Pulsifer 2008, n.p.). One reason for this transformation is the increasing specialisation of professions involved in the building process as described previously. Another reason for the

transformation is the recent move from prescriptive project-briefs in favour of more performance-orientated design (Kolarevic 2005, 29-62). The description of a building through its performative qualities has become a key aspect in enabling a tight control over issues of project cost and sustainability. Over the past two decades clients have become increasingly sensitised to the *value for money* aspects of design to the point where project briefs are handed out with specific building performance-targets that need to be met[20] (U.S. Green Building Council 2003, 45). The public domain and the authorities are mostly responsible for including building sustainability as key drivers in architectural design. Environmentally sustainable design (ESD) is becoming a requirement to reduce global carbon emissions and for the production of *cleaner* buildings in general (Ward, Horton and Brown 1992).

Due to the nature of the AEC industry, where teams reconfigure on a project-basis, few systems are in place to help transfer knowledge gained on projects across disciplines to foster *systemic innovations.* (Taylor and Levitt 2004). The point made by Taylor and Levitt (2004, 89) is one indicator of the segregated nature of the building industry: teams constantly configure, dissolve and reconfigure in periods of a few years as a matter of course in the building industry. Acha, Gann and Salter (2005, 255) state that professional organisations often face difficulties in developing procedural as well as organisational memory from the projects they carry out for building-up knowledge in practice.

> *"The challenge faced by project-based firms is to manage the dialogue between temporary actions and imperatives and the range of ongoing and repetitive business practices – including innovation and technical support – that provide the framework in which projects can thrive".* (Acha, Gann and Salter 2005, 256)

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[20] The LEED Green Building Rating System (U.S. Green Building Council 2003, i) states that:
Projects earn one or more points toward certification by meeting or exceeding each credit's technical requirements. All prerequisites must be achieved in order to qualify for certification. Points add up to a final score that relates to one of four possible levels of certification.

In the above context Lawson (1997, 264) argues that the design team has become such an obvious organisational structure that most design offices put nearly all their human resources into these teams. According to Lawson's research, prioritising the temporary design team leaves little energy for the conscious reflective thinking that might more easily enable knowledge to be transferred beyond project- and team-specific boundaries. This problem not only occurs intra-organisationally but is apparent on projects involving teams across organisations as well. It points to challenges in the way design professionals build up knowledge in teams, how they find common ground, and how they make sense of each other's input. In the following paragraphs I analyse literature that deals with the ways experts apply their knowledge during the process of designing as individuals and in groups.

Schön and Wiggins (1992, 135-156) describe the interplay between seeing and reacting to what is being seen by designers in their conceptual work. By analysing various case-studies from designers with different levels of experience, they have explored the basic dialogue that occurs when a designers juggles between an idea and its representation on paper. The case-studies were aimed inter alia at discovering implications for epistemology, education and computation in design. Schön and Wiggins (1992, 135) define three kinds of seeing in design:

1. *literal visual apprehension*
2. *appreciative judgment of quality, and*
3. *apprehension of spatial Gestalt.*

Schön and Wiggins argue that the basic driver for these kinds of seeing apart from a visual registration of information (Alexander 1964)is the construction of meaning. By quoting Alexander (1964, 58) they point out that our ability to recognize qualities of spatial configuration has to be seen independently to our ability to symbolically describe the underlying rules we apply to recognise them – hence allowing us to make judgements tacitly. Schön and Wiggins (1992, 155) conclude that it may be important for designers to elicit conscious reflection when building up knowledge of design domains, when improving the development of

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appreciative systems and when creating new understanding of design problems as the process of designing itself assists in all of the above.

Kvan (2006, 28) asserts that expert designers work using meta-strategies such as reframing (see also at Schön 1983, 94) thereby displaying the ability for tacit reasoning.

> *"The implication of this position is that design depends upon the acquisition of a substantial and significant body of knowledge, that this knowledge acts upon a body of data and that the process of acting is contingent on a ability to engage in tacit reasoning that derives from a lengthy engagement with the field."*

Valkenburg (1998, 12) offers a detailed analysis of team-design interaction based on the transcript of a video recording with experienced architectural designers who are given a particular design task. She argues that little research has been done to date of design methodology in team design, and her initial observation points towards an occurrence of a high level of incomprehension about the design content in a team. Valkenburg asserts that each designer in a team first has to harmonise his/her own interpretation of the task at hand with the interpretation of others in the team to build up a shared understanding. This process is made possible by the team generating alternatives and collectively awarding values to these alternatives through arguments to finally come to an agreement through an explicit choice.

> *"Shared understanding is a mutual view amongst the team members on relevant design topics and design activities."* (Valkenburg, 1998, 113)

Lawson (1997, 259) points out that the idea of a unified strategy that leads to a shared view of the design process is more myth than reality. After closely observing how designers work in practice for more than three decades Lawson argues that there is not one route through the design process but many. Parts of one design usually serve for more than one purpose: Lawson (1997, 297) claims that integrated solutions are the best way forward in order to address the plethora of requirements design teams face on projects. He adds that methods of science

are unhelpful to the designer in such a context. Design problems are multi-dimensional and interactive – scientific rigor and sub-optimising specific design tasks do not encompass the complexity inherent to building projects.

> *"Creative designers often are able to work with multiple or parallel lines of thought, each of which involves its own design features."* (Lawson 2002, 330)

Lawson (2002, 328) assesses that a plethora of design-aspects are communicated not only visually, but through verbal conversation. He draws a distinction between design as an ad-hoc problem-solving activity and as an act where designers apply semantic and episodic knowledge to develop solutions through experiential memory. In this sense, designers combine *slow reflection* with the necessity to keep many things in mind at the same time for rapid decision making (Lawson 2005, 388).

Whitehead and Peters (2008, 22) agree with Lawson when they describe design as an evolutionary process that is solution-oriented rather than problem-oriented. They concede that the design process needs to be combined with procedural activities that allow for a project to move from ideation to construction.

> *"..at a conceptual level the development of form is all process, while at a material level it is all procedure."* (Whitehead and Peters 2008, 22)

Papamichael and Protzen (1993, 1) present a theory describing the design as "*thinking and feeling while acting*" and they concur with Webber and Rittel's (1972, 160) argument that design problems present in many ways ill-defined, wicked problems. Papamichael and Protzen (1993, 3) divide the design process into four activities:

1. formulation and specification of the *as-is*,
2. formulation and specification of the *ought-to-be*,
3. generation of a plan leading from a current situation to a desired one, and
4. checking for undesired side- and after-effects.

"Designers do not 'know' the relative importance of design criteria. They feel it continuously throughout the design process, reformulating it as they compromise between what is desired and what is possible." (Papamicheal and Protzen 1993, 9)

Addressing reasons for the complexity of common design problems, Kalay (1997, 191) points out that projects undertaken in the building industry differ from those in other industries such as car-manufacture and aerospace due to the fact that each project is unique. Architectural design often deals with the unknown where problems are defined and solved concurrently while designing and during construction. In this context Kalay (1997, 193) argues that collaboration between architects, engineers, construction managers and owners is difficult as each group has different world views and he describes two modes of practice that are incompatible with each other. The one applied by specialists such as engineers is dependent on precise problem and goal definitions before they can start to search for solutions, whereas architects – who apply a mode of practice through discovery - are often not capable of "*defining desired effects until the design process is well on the way.*" (Kalay 1997, 195)

In reference to early stage design, Moum (2006, n.p.) agrees to comments made by Schön and Wiggins (1991, 137) about the necessity to deal with design issues on a level of detail that allows for a flexible creative process that does not get hindered by disturbing accuracy. At the same time Moum concurs with Lawson (2006, 260) that a holistic view of the design process is required if various performance attributes of a building are being investigated.

The perspective of a holistic design-view as propagated by Moum prompts the question of how we can work with feedback from building performance analysis during early design. Is it possible to analyse design with a level of precision high enough to yield correct trends, but not too precise to hinder creative design processes?

In response to the above question, Moum sees an increasing importance in the interaction between the individual and the group to fine-tune the level of detail of

information that can be dealt with as a group as well as the definition of common design goals and priorities. (Moum, 2006, n.p.)

> *"The rate and value of innovations in the Architecture and Engineering Industry continue to rise. Most businesses compete on knowledge."* (Pulsifer, 2008, n.p.)

Achten argues that the increasing requirements for sharing knowledge across disciplines needs to be addressed by them early on (2002, 2). He particularly stresses the importance for design partners to apply engineering knowledge in the early stages of design to enable consultants to engage more pro-actively in architectural design. In design collaboration, as Achten explains (2002, 4), mutual goals need to be set, the goals of others need to be understood and a communication environment to support collaborative processes is required. Such an environment would be able to provide functionality for: "*information retrieval, sharing, and handling, recording of design processes and managing design histories*" (Achten 2002, 5).

Based on experience as the leader of a knowledge management department in a large globally operating design firm, Pulsifer (2008, n.p.) stresses the importance for architecture and engineering firms to capture and disseminate knowledge with a systematic approach throughout their organization and beyond. Pulsifer explains how advances in business process re-engineering and organisational management during the 1970's have become common topics in the building industry since the mid 1980's. If technological aspects of knowledge management were predominantly investigated in those days, there is now an emphasis in the industry on more social and network-oriented exploration of how knowledge gets shared between individuals and teams.

Pulsifer argues that knowledge management needs to be rooted in a deep understanding of architecture and engineering practice, the interdependencies of disciplines, and organisational business goals (2008, n.p.). She lists four components that need to be identified, understood, and monitored by an organisation to implement knowledge management:

1. *Key activities or tasks within the project lifecycle that represent knowledge creation or knowledge collection points.*
2. *Repeatable business processes and activities that require and benefit from knowledge consumption.*
3. *Existing or potential groups that assess, validate, and promote best practices and standards within the organization.*
4. *Existing or potential information systems and technologies that hold and promote the capturing, categorization, translation, and dissemination of knowledge.*
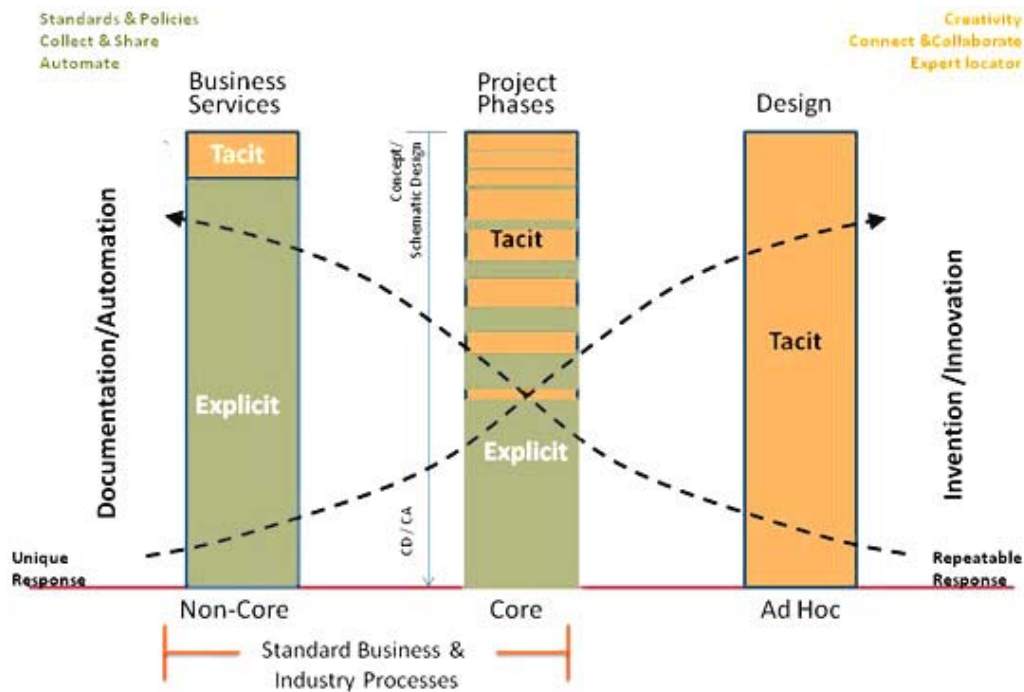
Figure 10: Knowledge Management requirements in various building phases, Source: Pulsifer

Using Polanyi's distinction between tacit and explicit knowledge, Pulsifer explains that various activities of designers and consultants during the design phases require a different type of knowledge support. She states:

> *"In general, process automation, on-line documentation, and standards tend to be more appropriate mechanisms for supporting explicit-based activities, on the other hand, social networks, non-linear relationship systems, and collaborative environments tend to facilitate tacit-based activities."* (Pulsifer 2008, n.p.)

Pulsifer points out the difficulties in converting tacit based activities to explicit processes and she argues that a "*culture of knowledge*" is crucial to achieve this goal. She adds that the culture of knowledge needs to be complemented by a framework to facilitate the flow of knowledge in organizations, with the individual as the key point of communication.

The diagram in Figure 10 shows the level of tacit and explicit reasoning applied during *Ad Hoc*, *Core* and *Non-Core* design activities. While repeatable responses are low during tacit reasoning in conceptual, innovative design, they increase when the design process deals with automation and documentation.

> *"Proximity to colleagues provides security, generates atmosphere and fosters collaboration and discussion."* (Simpson and Viller 2004, 18)

The discourse regarding knowledge sharing in architectural practice has been enriched by those authors who consider the role of information and communication technology in the collaborative design context. Simpson and Viller (2004, 12-20) conducted an ethnographic study of human behaviour in an architectural studio-based design environment. In this study they analyse the nature of *physical collaboration* of designers to then aim at proposing factors that could be beneficial for adoption in virtual collaborative design environments.

Simpson and Viller observe a separation between the function of design architect and the function of the person producing computer-drawings. In meetings, the predominant means of information exchange is through sketching and verbal communication assisted by gestures and eye-contact as well as reacting on either physical or virtual computer models.

In Figure 11, Simpson and Viller illustrate the relationships they observed in current design practice between individual sketching, group discussions, and the generation of CAD.

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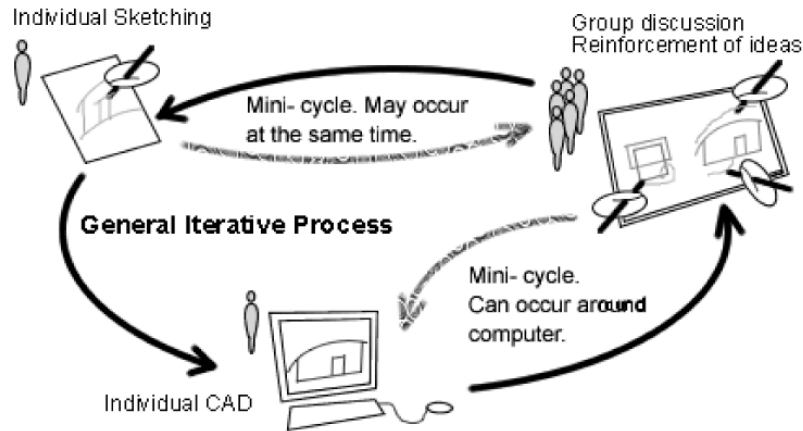
Figure 11: Sketch illustrating interaction between an individual and a group during the design process, Source: Simpson and Viller

Simpson and Viller (2004, 13) classify interaction during collaboration in three categories, namely:

1. *interaction in and through the physical environment,*
2. *recruitment/interaction by circumstances, and*
3. *interaction through gestures and external artefacts.*

They point out how meetings in an office environment help the formation of *"mini societies"* that are connected through a unique atmosphere, therefore helping to create strong working relationships, an ambiance of trust and commitment (Simpson and Viller 2004, 15).

Simpson and Viller highlight the challenges for translating qualities of the physical office environment from the architectural studio to a virtual, computationally augmented environment. What support for collaboration can we expect from virtual design environments and how can they either augment or substitute the traditional setting in the architectural studio?

Efforts undertaken to assist creative design and planning processes through information and communication technology ICT have been manifold since the early days of CAD. Some efforts have yielded promising results enabling designers to collaborate in an unprecedented manner; others have not yet managed to support the design process in the way envisioned by their

propagators. In the following section I critically review selected literature discussing previous attempts in the development of ICT systems that sponsor collaboration in the architectural design context.

3.3. ICT in support of design-collaboration across disciplines

> *"Over the past two decades, numerous digital tools, both software and hardware, have emerged to help designers formulate, express, visualize and test design ideas"* (Laiserin 2008, 235)

Up to this point in this chapter I emphasised my review of literature on sociological and epistemological aspects of design collaboration. I now direct my enquiry towards technological support for information exchange and the build-up of knowledge in creative design teams.

I focus on the *changes to the design process through ICT* in Chapter 3.3.1. In Chapter 3.3.2, *previous efforts in the development for collaborative decision support systems for architects and engineers* are reviewed. Chapter 3.3.3 describes the *current state of ICT support for collaborative design.* I discuss the *potential and the limitations of Building Information Modeling (BIM)* in Chapter 3.3.4.

3.3.1. Changes to the design process through ICT

> *"Simulations and simulators promise new possibilities for knowledge, prediction, interaction, and innovation. At the same time, they present novel media for experimentation and new means to exercise experiential knowledge and expert judgment."* (Turkle, et al. 2005, 100)

Sense-making in design collaboration is supported by information and communication technology (ICT) in manifold ways. A multitude of researchers have dealt with the impact of ICT and CAD on the architectural design process (Negroponte 1975, Mitchell 1977, Aish 1979, Frazer 1980, Eastman 1986, Gero

1993, Lynn 1999, Kalay 2004, Kvan 2006, Laiserin 2008 [21]) and it would exceed the scope of this thesis to try and summarise all of tier efforts. Instead, I will focus my investigation on the collaborative aspects in the context of a transition from traditional (paper-based) representation of architectural design to the sharing of design information using digital CAD models.

Paper-based representations of design projects are still prominent as a medium for exchange of design information at the start of the twenty-first century (Gallaher, et al. 2004, ES-3), but digital representations of design information have increasingly become common in architectural practice since the 1990's (Papamichael et.al 1996). The adaptation of information technology has been fostered by the availability of electronic mail and other forms of digital communication-exchange such as the Internet and it has helped to speed up the design and documentation process across the AEC industry (Kalay 2004, 34-81; Hamid, et al. 2006, 91). Increasingly shareable media for the exchange of design-data and faster interfacing capabilities between design-partners in the building industry pose new opportunities and challenges in the way collaborating partners communicate. In this section I analyse the impact of ICT on the process of sense-making between collaborating disciplines in architecture and engineering.

In pre-digital times, design-development has often occurred in a sequential process where architects handed over their designs to engineers to check if and how a given solution could be built. Hamid et al. (2006, 92) argue that increasing efficiency and growing bandwidth of communication is shortening intervals for designers to produce design iterations and at the same time it has increased the amount of information available. Furthermore Hamid et al. note the problems arising from increased yet compressed social interaction facilitated by improved communication. They believe non-technical aspects such as lack of common understanding, conflict resolution and motivation of participants are topics that

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[21] This list is far from being comprehensive, but it names some of the major contributors who have continuously reflected on the architectural design process sponsored by digital media and computational processes over the past three to four decades.

have not been sufficiently dealt with by researchers and practitioners in the AEC field alike. I am addressing this imbalance in my PhD research in Chapter 4.5: *Qualitative analysis of interview responses*. There I present research interviews with practitioners who provide insights about common understanding, trade-offs and personal motivation.

In engineering domains, ICT has revolutionised the way professionals analyse, evaluate and present outcomes from their field through possibilities of computational analysis and simulation (Rosenman and Gero 1997, 387-403; Chaszar 2003, 112-118; Kolarevic 2005, 33). Engineers have become confident with the validity of results derived by digital processes to analyse and test specific aspects of building performance (Coenders and Wagemans 2005, 86).

> *"The combination of both the modeling techniques and innovative, visual information design has led to better cooperation between engineers and architects early in the design process, and ultimately to more efficient buildings as a result of this collaboration."*
> (White, et al. 2008, 186)

One major obstacle for concurrent work methods between architects and engineers is that traditionally any major change to a design project results in cumbersome alterations for architects and, in particular, for the consultants downstream (Mora, Bedard and Rivard 2008, 254). Direct involvement of consultants in the early stage design process (as opposed to the checking and evaluation of prescribed design targets) beyond basic advice about configurations is difficult to achieve.

> *"Technological capabilities are hybridised with traditional media, pre-established habits and desired team dynamics to achieve evolutionary progress, rather than an all-or-nothing adoption of the radically new."* (Mueller 2006, 45)

As much as advances in the uptake of ICT in the design, planning and construction of buildings have brought benefits to designers and their consultants to augment their capabilities, my literature review also reveals critical comments that hint at potential dangers and challenges inherent in the uptake of ICT in the

building industry. I present some of those critical arguments in the following paragraphs. The research that has been undertaken about the link between ICT and design has assisted me to propose new methods for design-negotiation in Chapter 5.1.*Optioneering.*

Back in the early 1970s Negroponte first described the use of computational tools in the arts and he noted that the creative thinking of a designer can get affected by the *machine* and he explored how human-machine interaction can assist in a plethora of decision making processes in a design environment (Negroponte 1975, 194). As a consequence of his observations Negroponte urged designers to draw a distinction between heuristics of form and heuristics of method and to find ways of taking advantage of digital technology to pursue both of these. Whilst heuristics of form relates more to an investigation of space, geometry and structural systems, heuristics of method implies a far deeper investigation on how creative design processes unfold, how they can be made explicit, and how they can be shared with others (Negroponte 1975, 177). In this *digital age* architects rather seem to investigate *heuristics of form* than *heuristics of method* through digital means to assist their drawing. Some investigations of the use of digital processes as form-generators have had positive side-effects for the development of the architectural profession. A summary and a historical overview of computer applications as form generating tools can be found at El Shafie, (El Shafie 2008, n.d.)

Whilst information technology enables the rapid exchange of design-data as a matter of course in everyday architectural practice, we cannot assume that the same can be said for the support of creative processes or the exchange of knowledge.

> *"... there has still been no major systematic investigation of the impact of CAD on contemporary design creativity."* (Lawson, 2002, 329)

In the more than thirty years of observing designers in action Lawson has been mostly critical about the use of CAD in architectural design processes. One point made by Lawson is that CAD is too often not used as support during the design

process, and that it is potentially jeopardising creative processes. CAD software developers focus on drafting and design-documentation capabilities of their tools that are only useful once the design process is already finished (Lawson, 2002, p.327). He states:

> *"Having to work with a computer tool that does not represent knowledge the way you do may cause considerable interference in your thinking."* (Lawson 2004, 71)

Lawson assesses that the reciprocal feedback processes which occur between pencil and brain while designing have not been mirrored with parallel CAD tools. Tools currently available do not allow designers to keep various design-options open simultaneously for evaluation. When analysing the shortcomings of CAD, Lawson points out the dichotomy between the unlimited possibilities of representation compared with the limitations of materiality and space in our physical environment (Lawson, 2002, 329)

In retrospect, Lawson (2005, 380-387) refers to the early days of CAD as a period where the computer was used as an *oracle* to produce primitive design solutions that consequently had to be adapted by humans. The limited range of answers was not sufficient to tackle multi-objective problems. In this context Lawson (2005, 386) argues that: *"..the human design process in architecture is not a process of sub-optimisation! In architecture, then, solutions and problems map onto each other in messy ways."*

In accordance to his previous statements Lawson (2005, 394) defines the current situation of CAD as the period where computers have become *draughtsmen* stating that the type of CAD, that serves for checking consistency and reliability of drawings, has limited impact on design. Lawson therefore calls for software that would easily allow for encompassing a plurality of building-related aspects and that would give access to ad hoc or integrated information across the AEC field.

Lawson (2005) calls for the establishment of information-frameworks that allow users to gather and access information about design-decisions. He suggest including information in those information-frameworks that is usually not made explicit in the process of designing. This idea is taken up by Cerulli et al. (2001, 429) who list six points that are dealt with in such an information framework:

1. *The handling of ownership, rights and responsibilities,*
2. *Versioning of information,*
3. *Schema evolution,*
4. *Recording of intent behind decisions leading to information,*
5. *Tracking of dependencies between pieces of information, and*
6. *Notification and propagation of changes*

There has been a series of attempts by academics to develop computational support that tried to incorporate one or several of the aspects listed above to address creative, social as well as technical aspects of design collaboration across disciplines.

In the following section I review five frameworks that stand at the vanguard of efforts in the creation of collaborative design tools for the early design stages. Even though, at times, they follow different goals, their commonality lies within the principle of providing designers with decision support rather than automating the design process.

3.3.2. Previous efforts in the development for collaborative decision support systems for architects and engineers.

> *"Improving the overall quality of buildings is the main motivation behind the development of computer aided technologies in the Architecture-Engineering-Construction (AEC) industry. A seamless design and evaluation environment has been envisioned by researchers since the early days of computational design but the integrated design system has been elusive for the last 30 years."* (İLAL 2007, 149)

In this section I highlight efforts undertaken by researchers to develop computational tools that support architectural design as a holistic process. I then present literature describing five systems (RUCAPS, P3, BDA, VSE, and SEMPER) in more detail in the chronological order of their development. I scrutinise the reasons for the successes, but also the drawbacks in applying the tools, in order to illustrate their ability to provide answers to questions I am asking about early-stage design.

In the previous section I highlighted some of the manifold possibilities for ICT to assist the sense-making process in architectural design collaboration. My review of literature revealed positive comments about the use of ICT by some (Turkle, et al. 2005; White, et al. 2008), but also critical voices by others (Negroponte 1975; Lawson 2002, 2005) who remind us that designers have to be alert about the process, and method-related implications of the use of ICT. Comments such as those made by Negroponte and Lawson remind us that, as much as computers help us to design more efficiently and to streamline communication with others, computers also have an effect on creative and social aspects of the process of designing.

During the literature research for my PhD thesis I have become aware of the fact that despite the availability of numerous applications for design generation, simulation and analysis, there are currently only few tools available to support collaborative design efforts across disciplines in a holistic fashion. This insight has triggered my curiosity to learn about the reasons for the apparent lack of collaborative tools as I see such tools as essential support for sense-making in early design stages.

By considering software developments for the 1980s and 1990's a more differentiated perspective from my initial instinctive assumptions began to emerge in my research. In the process of investigating the above topic in greater detail, I learned that computational platforms that help to share design information and to build up common understanding across disciplines had been developed since the 1970's. Driven mostly from within the academic context in the US and Europe,

researchers such as Augenbroe and Winkelmann (1991) Kalay (1997), Papamichael (1996), Chen, Frame and Maver (1998) and Mahdavi, Suter and Ries (2002) have succeeded partially to set up computational frameworks in support of design collaboration.[22]

The literature I present in this section illustrates that the research of the above authors has made a strong impact on current efforts for the development of design collaboration systems. The research I describe in Chapter 5.4: *DesignLink – A proposal for a collaborative design framework,* is based to a large extent on the work of scholars I outline in the next paragraphs.

Kalay (2004, 67) defines tools such as BDS[23] and OXSYS[24] as "*first generation CAD systems*"[25]. He argues that, even though graphically poor, they were nevertheless better suited as multi-user "*building design systems*" than the second generation tools that focused on drafting and modelling. Kalay states (2004, 70):

> "*Architects thus gained computer-assisted drafting and rendering capabilities but lost the analytical capabilities that formed the basis for the introduction of computing into the profession in the first place.*" he adds:
> "*This "dumbing down" of architectural CAD happened while other disciplines – most notably the electronics industry – were making their own CAD software more intelligent.*"(Kalay 2004, 71)

Two questions emerge from this overview: what are the reasons for the shift in focus between first and second generation CAD systems? And: was the change in focus driven by designers, by software developers or by others?

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[22] A comprehensive listing of tools for design collaboration can be found at İlal (2007): *The quest for integrated design systems: A brief survey of past and current efforts*

[23] BDS stands for *Building Description System*, it was developed by Charles M. Eastman and his colleagues at Carnegie Mellon University in 1974

[24] The OXSYS system was developed at Cambridge University in the early 1970s for the Oxford Regional Health Authority

[25] A comprehensive listing of first and second generation systems can be found at: Phiri, M. *Information Technology in Construction Design* Thomas Telford Publishers , 1999

In response to the above, Aish (2000, n.p.) alludes to the fact that the move from enterprise computing to personal computing is responsible for the different focus of CAD tools between the first and second generation. As member of a team of researchers who investigated the enterprise platform RUCAPS[26] in the 1980's he states:

> *"..much of the construction industry is trapped within the desktop/document metaphor, which we could argue is wholly inappropriate to multi-user collaborative workflows found in the construction sector"* (Aish, 2000, n.p.)

Aish points out that multi-user enterprise models using 3D geometrical and parametrically alterable data were in use in the pre-PC era in the 80s. Even though these systems (BDS and Rucaps) were commercially successful, it was difficult to find contractual arrangements that would compensate for extra efforts undertaken by those team members whose work offered advantages for others. Aish claims that personal computing can be seen contributing to the disaggregation of design information by abstracting it into *incomplete 2D representations* such as drawings. Design intent cannot be comprehensively captured by one model or system and he proposes a new model of collaboration (Aish, 2000, n.p.). This new model requires the re-engineering of the design process where analysis on a project can be carried out by multiple users, using different tools and merging results back into a single (model) environment to assess compatibility and conflicts (Aish, 2000, n.p.).

Aish acknowledges the necessity for such an environment to produce multiple design-iterations and to allow for interdisciplinary negotiations and interpretation of performance results in order to arrive to a consensus. He proposes that such a system be set up as an open source environment for all partners in the AEC industry to add to and profit from. Aish sets out the following five issues that

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[26] The *Really Universal Computer Aided Production System* (RUCAPS) was developed in the late 1970's by Davison and Watts. It was later applied on large scale building projects containing both 2D and 3D information. (Day 2002)

would potentially deliver the strategic planning of an enterprise-centred environment (Aish, 2000, n.p.):

1. *Semantic completeness*
2. *Data integrity*
3. *Data longevity*
4. *Parallelisation of design*
5. *Expressibility (or 'extensibility'- adding project-specific functionality)*

In his analysis of the RUCAPS platform, Aish has documented from firsthand experience how some of the problems we are currently facing were apparent already 30 years ago. Why do designers prefer the non-integrated individual work methodology we see today? Is there an advantage for designers to maintain their own design space without having to share their every move with others or being locked into a system of multiple dependencies and constraints from others? I will respond to these questions in section 4.5.6: *What is the ratio between multidisciplinary interaction and sole investigation?*

It was not feasible to transfer multi-user enterprise systems such as BDS, OXSYS, or RUCAPS to become PC applications for use in everyday architectural or engineering practice, but their development has served as a stepping stone for further investigations in the field.

Since the early 1990s a series of researchers have investigated the development of multi-disciplinary CAD platforms in academia. Some of these developments were driven by the wish to include environmental data in the design process, some researchers focused on CAD support for spatial layout, and others again aimed at including reference information from precedence projects in their CAD environments. One aspect that these efforts by distinct research groups have in common is the search for tools that support social aspects of collaborative design next to their quest for automation and technological advances.

Kalay (1997, 191) proposes *P3*, an integrated computational environment in support for multi-disciplinary design collaboration that encompasses three main modules:

1. *a product model*
2. *a performance model and*
3. *a process model.*

Kalay argues that sequential communication as it currently occurs among participants in building practice is inefficient as it rather promotes optimisation of individual sub-parts of a building at the expense of the overall project (1997, 191). He identifies two main drivers for the need to collaborate in a more integrated way. The first emphasis lies on accountability and sustainability and the second lies on the expansion of theoretical, technological, and organizational knowledge and practices used by each of the various professions in the AEC industry. In addition to noting these two drivers, Kalay stresses the importance for designers to develop awareness of how decisions made by one effect the other (1997, 193).

A summary of common data-exchange formats then available can be found within the writings of Kalay (1997, 195). Although agreeing to their usefulness, he criticises the focus of research efforts on data-exchange in favour of the development of computational tools that assist in collaboration aspects of the early-stage design process while design ideas are still being formed. (1997, 196)

Kalay notes that the development of an integrated collaborative design process model has been hampered by difficulties in sharing semantic content of information in addition to syntactical content and the difficulties in providing timely and appropriate feedback on design proposals made by each professional (1997, 196). One particular problem in this context is the lack of tools for clarifying the reasoning behind decisions made by one practitioner in a language easily understandable to the others. According to Kalay, building performance modelling is one way to compensate for low level of semantic information inherent to design data by embedding more semantics in the disciplinary-specific

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tools that process the data. He notes the positive aspects for this process but warns: *"This evaluation-based representation made it possible to develop the current host of design and evaluation tools used by the building industry. It came, however, at the expense of collaboration."* (Kalay, 1997, 198)

One problem with the integrated environment P3 as presented by Kalay is the idea that practitioners would set up process models that they adhere to in the conceptual stage. Although Kalay acknowledges that designers develop their process as they design, he believes that priorities for trade-offs can be agreed on a-priori: *".. a complete model of collaborative design must also represent the dynamics of the transactions and tradeoffs that occur while design ideas are developed, for that is where the design intent is represented, negotiated, modified and tested."* (Kalay 1997, 198)

The tools described by Kalay to enable this process have since been outdated by multi-criteria optimisation algorithms such as Pareto[27] and others. Kalay describes the P3 system as an environment that hosts building-object oriented data. This description suggests that P3 leaves little scope for designers to interact intuitively in the early design stages.

Parallel to the research undertaken by Kalay and his colleagues, Papamichael and his research team have been working on the development of an object oriented computational environment at the Lawrence Berkeley National Laboratory at the University of California. The *Building Design Advisor* (BDA) (Papamichael, et al. 1996) links design analysis from multiple disciplines and visualises results from the analysis in a common software environment, the BDA *Decision Desktop*.

The merit of this framework stems from the connection of various tools brought together in one environment to assist designers from multiple backgrounds to evaluate architectural, daylight and thermal performance. In addition to this synthesis, the system includes a reference library of prototypical values, building

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[27] Vilfredo Pareto (1848-1923) was an Italian economist who investigated probability distribution for multi-objective or multidisciplinary optimisation problems.
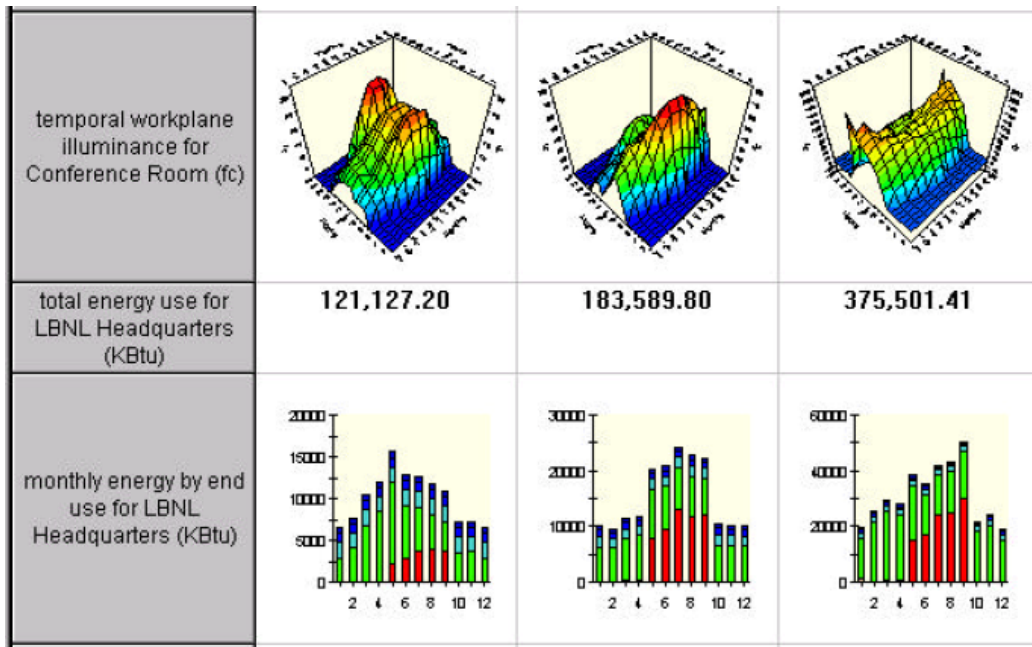
case studies and a generic product catalogue to allow users to compare results of their current model with precedence data (Papamichael, et al. 1996, 87). During the 1980's systems for evaluating environmental design, such as DOE-2™, SUPERLITE™, RADIANCE™ and COMIS™ have become available for use on desktop computers, but Papamichael et al. (1996, 85) argue that results provided by these systems are difficult to review and interpret as they had been designed for research scientists rather than building designers.

> *"A major drawback of existing building simulation tools is that they were not designed for use by building designers"* (Papamichael, et al. 1996, 86)

Papamichael and Protzen (1993, 2-5) critique contemporary efforts in the field of computational design support such as AI techniques or expert/knowledge based systems which focus too much on automation in the search for optimum design solution. They argue that previous attempts for automating aspects of design have failed to provide a comprehensive theory about design. In response to this drawback, Papamichael et al. propose the BDA as single graphical user-interface that supports multi-criterion decision-making throughout all design stages (Figure 12).

According to Papamichael et al.(1996, 88-94), the BDA consists of an application core for control of processes and data management, an integrated data model for building representation, an application programming interface that allows linking external applications to the BDA framework, and a graphical user interface. The BDA itself is a design decision-support environment that controls linkages to various analytical tools, graphic editors and databases; it is not aimed at automating the design process, but at providing users with multi-media support for comparing multiple design options with each other and with precedence case study projects.

temporal workplane illuminance for Conference Room (fc)			
total energy use for LBNL Headquarters (KBtu)	121,127.20	183,589.80	375,501.41
monthly energy by end use for LBNL Headquarters (KBtu)			

Figure 12: Screenshot detail of the BDA *Decision Desktop*, Source: Papamichael et al. [28]

Papamichael et al. concede that the BDA has not been implemented in the industry and it has remained within the realm of academic experimentation. As much as the system allowed for variation in the definition of properties of various building components, it did not consider alterations in the geometrical setup which occur continuously in everyday practice. The shortcomings of the system raise questions if its development might have profited from strong exposure to design practice to foster its user-friendliness and adaptability for everyday tasks. Practice based research may therefore offer opportunities to effectively develop software according to actual needs.

The abacUS[29] research team at Strathclyde University in Scotland, headed by Tom Maver has researched computational design systems to integrate environmental sustainable design aspects since the late 1970's. During the 90's the group had been working on a virtual design studio representation, based on research from

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[28] The screenshot of the BDA Decision Desktop from 1996 illustrates the level of progress that had been made by researchers more than ten years before the conception of this PhD thesis. 3D graph analysis is combined with text and 2D chart information to allow users to compare three design options.

[29] Advancing Buildings and Concepts Underpinning Sustainability abacUS (University of Strathclyde 2009)

the design studio in the real world. Their proposed *virtual studio environment VSE* (Chen, Frame and Maver 1998, 787) contains two main components:

1. *A fixed part that regulates the multi-user input (VSE base system), and*
2. *A loosely coupled part that regulates the individual input from various disciplines (domain resources)*

The two parts correspond with each other through the use of resource agents that act as wrappers to individual applications. Chen, Frame and Maver (1998, 788) point out that next to the technical dimension apparent when using CAD, the social dimension, and with this, human-human interaction needs to be considered in the development of tools that support interdisciplinary design collaboration. They propose a virtual studio environment based VSE on a metaphorical representation of real studio environments where designers from various backgrounds can interact with each other both synchronously as well as asynchronously to evaluate design options.

According to Chen, Frame and Maver (1998), a focus on data interoperability is insufficient to integrate successfully design aspects from various professions and they urge us to extend the meaning of design integration from tool interoperation to collaborative use of tools by human designers. Chen, Frame and Maver (1998, 794) describe three scenarios for design integration across multiple users:

1. *Directly sharing artefacts,*
2. *indirectly sharing artefacts, and*
3. *accessing different but interoperable artefacts*

The research undertaken by abacUS on VSE in 1997, pointed in the direction of tools that support *social* aspects of design collaboration rather than tools that provide a sole focus on the technical aspects for information-transfer. The basic idea behind the VSE system is aligned with many other efforts, past and present such as the BDA or P3. It was assumed by its authors that a transfer of the real to the virtual design studio was possible. This was a challenging hypothesis at a time

when the state of information and communication technology did not yet allow for high-speed audio and video streams over the world wide web.

As demonstrated by Simpson and Viller in their comparison between the physical and the virtual design studio (2004, 12-20), there is more to interaction around a table than sharing space and resources. Human to human interaction cannot be easily simulated on a screen.

In describing a case of how the VSE would be used, Chen, Frame & Maver (1998, 797) postulate that practitioners would work on one solution that gets moved around until everybody is satisfied with the results. However as Lawson points out in his assessment about the design process that designers intend to juggle several design options in their mind simultaneously to make their decisions (2005, 387).

Another attempt to develop a platform for information-sharing across disciplines has been proposed by Mahdavi and his colleagues at the Carnegie Mellon University, Pittsburgh and the Technical University Vienna. Mahdavi presents a scheme for integrated building performance called SEMPER (1996). SEMPER enables users to connect domain specific[30] object models (DOMs) to an overall shared object model (SOM). As part of this multi-year project Mahdavi, Suter and Ries sought to connect building performance information drawn from energy, life-cycle analysis, lighting, acoustic, and thermal comfort domains. Similar to previously described systems (VSE, the BDA and P3), Mahdavi, Suter and Ries (2002, 301) highlighted the lack of computational support for sharing information across domains to provide timely performance evaluation feedback to building designers and engineers in the early design stages and beyond. They point at three main features on which SEMPER is based (Mahdavi, Suter and Ries 2002, 302):

1. *Coherent performance modeling throughout the entire building design process*
2. *Seamless communication between simulation models in a general building representation*

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[30] *domain* in this context refers to a specific engineering discipline

3. Comprehensive multi-disciplinary performance modeling capability

The object based setup modelling structure allows users to include various semantic representations of spatiality in the shared object model that can be filtered and linked to domain object models according to domain-specific needs. These spatial representations range from site-specific information to boundary elements and connectivities of spaces within the building down to material, mechanical and interior properties such as furniture. (Mahdavi, Suter and Ries 2002, 306)

> *"For each disciplinary domain, the simulation application's representation or DOM, must be generated upon filtration and modification of information in the shared model according to the specific view of the building in that domain."* (Mahdavi, Suter and Ries 2002, 305)

At the same time, the conceptual strength of this approach is at the same time its Achilles heel. Due to the quest for balancing trade-offs between intelligibility, coherence and consistency of shared representations, and in order to allow for automated translation between DOMs and the SOM, Mahdavi et al. created their own domain-specific tools that link to the integrated environment SEMPER (Mahdavi, Suter and Ries 2002, 313). Mahdavi et al acknowledge limitations in their approach and they concede that a commercially viable realisation has not emerged out of their research efforts due to a mismatch between design information representation in commercial CAAD and SEMPER. They state:

> *"As long as CAD design documents do not meet the criteria of non-ambiguity integrity, completeness, and consistency, one cannot do without the corrective, interpretative, and complementary role of an (naturally or artificially) intelligent agent."* (Mahdavi, Suter and Ries 2002, 315).

My review of previous efforts for the development of collaborative design systems highlighted the challenges and difficulties researchers were facing since the 1980's.

All of the approaches presented illustrate the vigorous ambitions by researchers who, at times in parallel, had aimed to set up a support systems that would allow users to address architectural design in a holistic, socially responsive, and environmentally responsible way. In awareness of the effort that had been put into the development of the systems explored by me (RUCAPS, P3, BDA, VSE, and SEMPER) the question emerges why seemingly none of them has been taken further by major commercial software-houses to propagate their use in commercial practice. Is the reason for this related to Maver's (1995, 21) description of : *"Macro-myopia"* - the *"phenomenon of overestimating the short term impact but under-estimating the longer term impacts"*? Has the research described above lead to tools that worked properly in a highly controlled academic context, but failed to deliver in the chaotic environment of common architecture practice? Or, were the tools conceptually ahead of their time, but lacked the right technological support to make them become effective at the time of their development.

Comments of those who participated in the development of the frameworks identified either an imbalance in compensation for extra efforts undertaken for appropriating information and the failure of a single model approach (Aish 2000 - RUCAP); or they reported on rigid procedural models and the use of object libraries that hinder intuitive design during the early stages (Kalay 1997 - P3; Papamichael 1996 - BDA); others again failed in their attempt to recreate the design studio in a virtual version to evaluate results of single optimisation processes (Chen, Frame & Maver 1998 - VSE). Comments (Mahdavi, Suter and Ries 2002) regarding the SEMPER framework explained it was not set up to interact with current commercial software used in practice at the time.

Researchers such as Hartog, Koutamanis and Luscuere (1998) have continued to investigate ICT support for collaboration in early design stages. Changes in the methods by which architects and engineers interact with computational tools have opened up new pathways for collaboration. One important contribution to the ongoing quest for collaborative tools in early design stems from research at TU Delft in the Netherlands where Koutamanis and his colleagues have been

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researching the integration of environmentally sustainable performance aspects in the early-stage design process. One suggestion stemming from their research is to consider the level of detail in design analysis necessary to support decision-making in the early design stages:*"…certain design criteria need not be determined in five digits."* (Hartog, Koutamanis and Luscuere 1998, 10)

Hartog, Koutamanis, and Luscuere (1998, 3) pointed out that commonly used rule-based systems for environmental performance evaluation were not sufficient to serve as design guidance during the early design stages. They searched for a more indicative method that facilitates conducting comprehensive environmental analysis on a design proposal, even if it is not crystallised yet. Koutamanis (1997, 247) alluded to the fact that communication between designers and specialists is based on the exchange of abstract descriptions of a design and he stated:

> *"Abstraction should occur in a bottom-up fashion that supports new strategies which match the complexity and priorities of today's design problems. The main characteristic of the new forms of analysis is that they follow an approach we may term* **descriptive***. They evaluate a design indirectly by generating a description of a particular aspect comprising detailed measurable information on the projected behaviour and performance of the design."*

Koutamanis presents the *descriptive* approach as one of three approaches for integrating analysis in design:

1. *Proscriptive*
2. *Prescriptive and*
3. *Descriptive*

In contrast to the descriptive approach for integrating analysis in design which is indicative in nature, the proscriptive and prescriptive approaches are based on deontic principles. Koutamanis describes *proscriptive* as: *"formal or functional rules that determine the acceptability of a design on the basis of non-violation of certain constraints"* and *prescriptive* as: *"systems that suggest that a predefined sequence of actions has to be followed in order to achieve acceptable results."* (Koutamanis 1997, 247-248)

Each of those three approaches have their specific counterparts in analysis and evaluation: *normative analyses* derive from proscriptive design approaches to match rules and regulations; *knowledge-based analyses* are best suited for solving design problems following prescriptive sequences; and *descriptive analyses* projects a design's behaviour and performance to provide experts with feedback for decision making (Hartog, Koutamanis, and Luscuere 1998, 3). Hartog, Koutamanis, and Luscuere asserted that normative systems do not lead designers to fruitful outcomes as they are too restricted. Knowledge-based systems fail to give more than useful guidance as design performance varies strongly from project to project where immediate feedback from a variety of building performance analyses is required.

> *"Users must be able to switch between design representations, information on precedents, visualisations of simulations, spreadsheet with the results of analysis, etc."* (1998, 11)

An ideal framework as described by Hartog, Koutamanis, and Luscuere would be a computational environment that combines knowledge-capture from previous projects with performance results of the actual project in question to visually compare design alternatives. Important in this context is the ability of designers to link their design thinking with appropriate implementation mechanisms such as linking design form to functional and performative analysis and requirements (1998, 12). The findings and proposals by Hartog, Koutamanis, and Luscuere remain important today.

The distinction between proscriptive, prescriptive and descriptive modes is particularly relevant in the context of my PhD thesis. I see a strong relation between the way we address complexity when resolving wicked design problems, and the means we use to drive architectural analysis and design. I refer back to the distinction between *descriptive* and *prescriptive* approaches in Chapter 5.3.2 *From Inter- to Transdisciplinarity*, where I discuss the development of a transdisciplinary design environment.

In the following section I discuss the most recent development in ICT support for early-stage design. I focus on tools that allow for flexible set up of geometry and intuitive interaction with 3D geometry modeling tools.

3.3.3.   The current state of ICT support for collaborative design

During the 1990s architects and design-researchers have increasingly become involved in thinking in processes and the exploration of dynamic, responsive systems (Lynn 1999). This procedural way of thinking has led to a diverse design-culture which adopts techniques and methods of form-finding from fields outside the architecture domain such as movie animation through the support of digital processing and simulation.

> *"Rather than as a frame through which time and space pass, architecture can be modeled as a participant immersed within dynamic flows."* (Lynn 1999, 11)

Experimentations using computational tools animation for morphogenesis by Lynn and others allowed them to embrace virtual design and to learn how to 'let go' of total control over their design process. By doing so the computer became a design partner in the process of exploration with the capability to surprise designers with unexpected results. The more playful use of design software enabled architects and consultants to generate a plethora of design variations for comparison and selection. Lynn later scrutinised this approach and he states:

> *"I started to learn the software by experimenting, but after a happy accident it only makes sense that you practice, master and integrate the unanticipated result into a technique"* (Rocker 2006, 90)

Burry (1999, 78) had earlier described parametric design through associative geometry as one possible "*anti-accident methodology* ". Using such as methodology, design is set up on the basis of rules and references that govern geometry and thereby provide the designer with syntax for creating an unlimited number of morphologically different versions of the same design-template (Burry 1999, 79). The designer's perception about the end-result of his or her investigation has

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shifted. Applying parametric and other rule-based design methodologies, we are no longer limited to producing *one perfect design*, but we are now able with little extra effort to produce a series of possible solutions to choose from.

At the start of the twenty-first century, rule-based design has become increasingly debated in architecture and engineering design. Aish (2005, 10-14) discusses the intimate connection between composition, algorithmic thought, composition and geometry. In this context he describes how rule-based modeling can assist designers to progress their ideas *from intuition to precision*. (Aish 2005, 10).

Whitehead and Peters (2008, 20-33) rely on rule-based automation processes in the opitmisation of geometrical entities in the architecture practice of *Foster + Partners* [31]. They apply rule-based modeling techniques such as programming and parametric design to cope with the complexity inherent in projects where manual processes would have taken too long. Defining rules that drive design-components has allowed them to generate a plethora of design options to work with. Using parametric design methods as well as scripting/computer programming, designers at *Foster + Partners* are able to "*sketch with code*" to communicate design intent with others (Whitehead and Peters 2008, 29). They are thereby setting up a flexible and fast approach that is used by the design team to easily manipulate geometry. Whitehead and Peters note that computer programming proves to be more effective than parametric design methods depending on the complexity of the task. Long chain dependencies of associative models are avoided if fast and simple modification of the design-model is required (Whitehead and Peters 2008, 33). Whitehead and Peters describe the different qualities of rule based design through scripting and parametrics as follows:

> *"Scripting disengages one design problem from another, allowing the design to be developed in many areas simultaneously. Parametric models can be swapped, input*

[31] **Foster + Partners** is a globally operating design firm with their main office in London., UK. www.fosterandpartners.com

geometry can be modified, inserted or removed without having a large impact on other parts of the process." (Whitehead and Peters 2008, 29)

Silver (Silver 2006, 5-11) argues that the acceptance of programming and scripting in the AEC industry has undergone changes in the past decade. These changes are due to the increasing availability of tools that allow users to interact intuitively with code in the generation of architectural design. Silver believes that programming has become the new drawing for many architects, and he makes the following prediction:

> *"The ability to craft tools that address both the practical challenges of building design and the human capacity to imagine new forms is a fairly recent development. As specific programming languages become less mysterious and easier to master, 'home-made' software will most likely become a familiar part of design culture"* (Silver 2006, 11)

The uptake of rule-based modeling techniques in design practice is on commented by Turkle et al. in a survey of *Information Technologies and Professional Identity* (2005). With reference to parametric design they argue:

> *"The belief among architects is that this* [author: rule based] *modeling technique enables designers to externalize, share and enables them to manipulate the logic of their designs. More than one researcher has asserted that this enables digital models to be seen as a type of communication device for design intent."* (Turkle, et al. 2005, 19)

Chaszar (2003, 112) speaks in favour of parametric design when arguing that the high-end design tools such as CATIA™ and CADDS5™ are some of the few support environments with *collaborative capabilities.* He acknowledges that they are costly and their use requires extensive training. Chaszar adds that achieving integration of various tools is more likely than finding a single software solution that encompasses various types of design analysis. An integrated workflow is dependent on data exchange formats and capabilities of communicating design intelligence in a clearly understandable fashion across teams for feedback and evaluation purposes. (Chaszar 2003, 112)

> *"At certain times in the evolution of the design, it would be desirable for (all of these) parties to be looking at the same information (digital model and alphanumeric data) simultaneously, and moreover to be subsequently watching and commenting on the results of the various design modifications being made even as they happen."* (Chaszar 2003, 114)

Software developers are responding to comments such as those made by Chaszar about the lack of available low-cost tools that require little expert training to operate. Since the early twenty-first century computational modeling tools have been developed that focus on providing intuitive support to 3D architectural modeling. One prominent example is the tool SKETCHUP™ that has been developed by Google. A study about conceptual design tools used by architects undertaken by Parthenios (2005, 78) illustrates that SKTECHUP™ was rated as the most appropriate tool in conceptual design after the use of paper and pencil and physical 3D models. In Parthenios' study 49% of interviewed designers were using SKTECHUP™ at some point during conceptual design[32]. The potential for SKTECHUP™ to become a tool for design collaboration is highlighted by Ellis, Torcellini and Crawley (2008, 239). In their account of linking EnergyPlus™ as plugin to the SKTECHUP™ environment, they report benefits for designers "*to integrate energy simulation into the earliest phases of the design process*" complemented by an easy-to use 3D modeling user interface (Ellis, Torcellini and Crawley 2008, 241)

Examples of custom plugins such the abovementioned plugin for SKTECHUP™ illustrate the potential for more performance-evaluation software to be linked to existing 3D computational modeling tools. The *Project Chicago: Green Building Research Team* associated with the CAD software provider AUTODESK has developed a custom environment for green building research. Results from this research have first been presented in 2007 with the aim to investigate: "*how modeling, analysis, and sustainable validation could converge into an improved design process.*

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[32] The same study show that only 9-11% of interviewees responded using BIM tools such as REVIT™ in conceptual design. Contrary to claims raised by BIM advocates, Parthenios points out that REVIT™ was used by nobody at the outset of design.

See how an instant and interactive means to evaluate innovation, water, energy, indoor environmental quality, and carbon footprint elements could give designers an immediate sense of the results of different design scenarios" (Autodesk, Inc. 2007)

The researchers at Autodesk have developed a platform where building-performance specific information as well as outside reference data is connected to the geometry model. Users can select a variety of topics to investigate through the live model (as seen in figures 13 a-d).
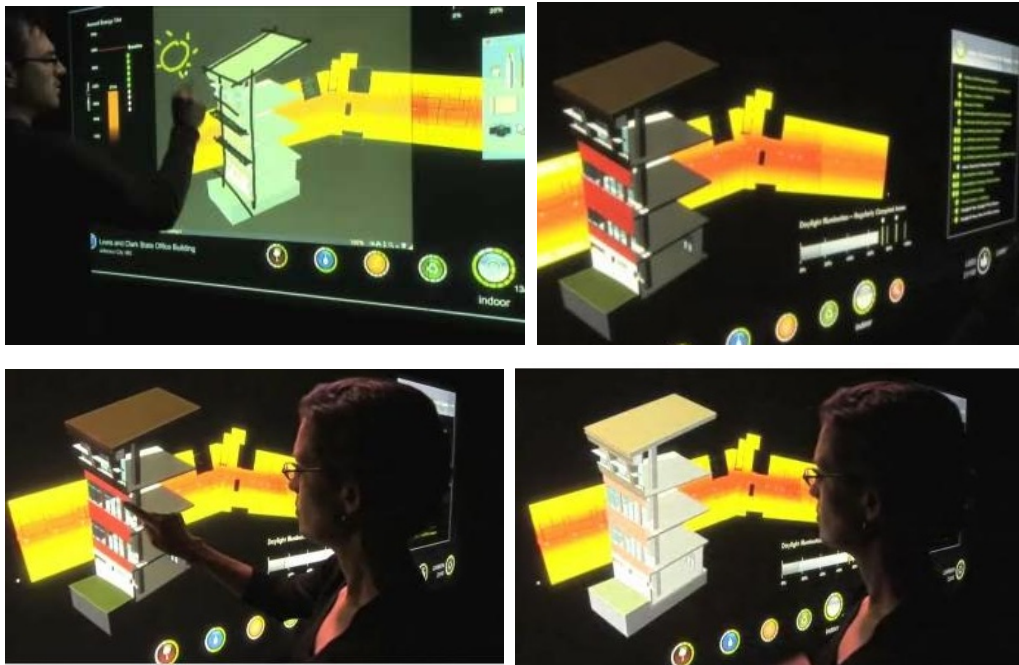
Figures 13a-d: Project Chicago – interactive environmental design evaluation with interactive user participation, Source: Autodesk

The user interface as presented by *Project Chicago* is highly intuitive allowing users to interact with a 3D digital model on a large touch-screen. Users can interact with the model, either by selecting building elements, executing commands, or calling up text-based information through touch. Such systems promise highly interactive, multi-disciplinary interaction between designers, consultants and the client. Changes to the model can be made in real-time and results from analysis get updated in an instant (Autodesk, Inc. 2007). This interface by the *Project Chicago* member is currently only used for research purposes within Autodesk and it is not yet available for common use in the industry.

While I focused my investigation on ICT assisting social aspects of design collaboration in the past two sections, I will analyse the method of *Building Information Modeling* BIM and its implications for design practice in the following section. As I highlight in the next chapter, BIM methods emphasise data interoperability and an integrated flow of information between designers from early stage design to construction and operation of buildings.

3.3.4.   The potential and the limitations of Building Information Modeling (BIM)

Over the past 35 years numerous researchers have investigated methods and tools for computationally sponsored exchange of building-specific information and design interoperability across disciplines. I described some of these efforts in the previous section of this chapter.   Research into the application of building information modeling (BIM) differs from these investigations. In this section, I point out the particular approach that has been taken by researchers and software developers in the deployment of BIM. I reveal the reasons why BIM has gained wide-spread acceptance by some key members of the AEC industry.

Methods propagated as part of BIM have been preceded by decades of research and development that were closely linked to the development of CAAD. The roots of BIM stem from research in the field of Building Science and it has gradually been progressed to become what we know as BIM in current building practice.

Champion to this research has been Eastman (1975, 1998, 1999, 2006) who aims at providing computational support for all phases in a building lifecycle through one holistic process and a unified data format. Starting from a pre-design phase of feasibility studies, design, and construction planning, Eastman (1999) proposes an object-oriented framework for linking geometrical data of building components to semantic information, relevant during construction, facility management and operation. The predominant goal of this quest is to find ways to organise *Building Product Models* (Eastman, 1999) which allow for a automating the computational integration of all building components during the building lifecycle. Khemlani et al. (1998, 50) provide an overview of different tools, representations and formats in use since the 1970s to achieve the abovementioned goal such as OXSYS, IBDE, STEP, COMBINE and KAAD. They state that: *"Augmentation of the data with computer-readable 'knowledge' is difficult, given that inference of meaning is one of the most difficult abilities to impart to computers."* (Khemlani 1998, 49)

Activities for streamlining different software applications in AEC industries were pursued by the International Alliance of Interoperability (IAI- now *buildingSmart*) since its foundation in 1994, with the introduction of a common format for data exchange – the *Industry Foundation Classes* (IFCs) following in 1997[33]. Since that time, the format has increasingly been adopted by a plurality of CAD software developers, making it broadly accepted in architecture, engineering and construction firms.

The term BIM was increasingly used by the software company Autodesk based on Eastman's previous work on the *Building Product Model* and it got ultimately coined as the standard descriptions of such models by Jerry Laiserin in 2004. In recent years BIM has become a key work in the AEC industry due to a strong push from software developers to promote products such as REVIT™, TRIFORMA™, DIGITAL PROJECT™ and ARCHICAD™. Advantages offered by the BIM approach have been acknowledged by developers and building owners alike and in 2005 representatives of the AEC and the facilities management industry formed the *buildingSmart* organisation with the goal to*: "identify, test, review, recommend and implement smart ways to deliver quality buildings and services to the facility owner'"* (buildingSmart, 2009, n.p.)

BIM offers a way out of the current Babylonian plurality of non-compatible design representations in order to push software developers and users to convert towards one common industry standard for design-data exchange. As the application of BIM becomes more accepted and widespread throughout the industry, we do find ourselves in the paradoxical situation that nobody seems to agree on how to define BIM (Davies 2007, n.p.). Depending on the sources one finds definitions describing it as method for managing project information where non-geometry attributes get associated with geometrical entities (Khemlani 1998, 49; Moum 2006, 414; Penttilä 2007, 292), or definitions which mostly point out its

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[33] http://www.iai-international.org/About/History.html

capabilities for cost-control and to facilities management (National Institute of Building Sciences 2007, n.p.).

Davies (2007, n.p.) expresses his concerns about the confusing image which is currently being propagated of BIM in the AEC industry from the perspective of a long-time user. .

According to Davies (2007, n.p.), BIM-like methodology has been in use for several decades. It is not to be limited to providing 3D digital information; neither can it be seen as synonymous with one tool (e.g. Autodesk's REVIT™). Davies further questions the notion that BIM ought to use one single database or building model and he criticizes those who see it necessarily linked to a building-lifecycle or facilities-management perspective. Although BIM might offer possibilities to integrate those elements, it is a far more open platform where individual contributors can share information in a standardised format to manage project information. On the topic of interoperability and the build-up of inter-organisational knowledge Davies argues that it is necessary for individual users or user groups to first develop their own working method for a project before entering a wider BIM dialogue with others, and to take a simple step at a time (2007, n.p.) [34].

Eastman (2006, 3) has been leading the development of building information models and he provides a description of BIM capabilities as a platform for exchanging design information parametrically for various types of building systems, the definition of spatial layouts and interior arrangements. Using the example of a wall system, Eastman (2006, 4) describes how parametric features can organize a plurality of parameters. At the same time Eastman hints at current limitations of BIM enabled parametric representation of buildings when designers attempt to set up BIM models using non-rectilinear geometry and problems arise in an attempt to create curved walls or custom objects. Eastman (2006, 5)

[34] This distinction was later repeated by Jernigan (2007) to differentiate between *little bim* and *BIG BIM,* as well as Tocci (Van, J. 2008, n.p.) who distinguishes between *lonely BIM* and *social BIM.*

criticizes the lack of support for exchanging parametric objects across multiple BIM platforms:

> *"Teams wishing to work on multiple BIM platforms cannot exchange their designs in en editable format. A major long-term research objective will be the development of sharable parametric objects."* (Eastman 2006, 5)

Eastman sees potential for pre-engineering building components before they get on site, thereby offering major advantages for clients, consultants, contractors, and subcontractors. The work undertaken by Eastman and his colleagues at the IAI for the implementation of BIM has been promoted by the National Institute of Building Sciences in the US. They issued a vision statement about the implementation of BIM defining it in the following manner:

> *"An improved planning, design, construction, operation and maintenance process by using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format useable throughout its life-cycle by all."* (IAI, 2004)

Apart from this vision and the argument about an open data-exchange standard which allows for free flow of information, the charter names interfaces to *Business Process* through business rules as core elements of the standard. The *National Building Information Model Standard* (NBIMS 2007, 12) suggests that any relationship dealing with information flows within the BIM scope can be standardised and those standards will then be available to all involved. The *US National BIM Standard* (NBIMS 2007, 11) defines business rules that address the issue of changes which occur when dealing with integrated practice. These changes refer to intellectual property rights and to business processes in practice.

With this level of formalisation promoted through the US *National BIM Standard* in mind, I raise the following two questions: Firstly, is it possible to find computationally definable standards for integrating building components? And secondly, can or should one try to address creative design issues using business rules in early design?

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Pentillä (2007, 291) offers a critical view on the possibility of applying BIM methodology in the early design phases. In the context of major changes caused by the adaption of ICT in the building industry, BIM capabilities are unquestioned by Penttilä (2007, 293) in terms of their usefulness in the advanced design stages, but he scrutinises whether object oriented methodology assists architects in managing design information during the early stages where the most important design ideas are created.

In contrast to the later stages, when design intent is already clearly defined, information during the early stages is poorly structured and vague. The information management context needs to be versatile and flexible to address this lack of precision. Penttilä illustrates (2007, 297) how BIM-like design methodologies work in other industries such as automotive design and naval architecture and he sees the necessity to apply more managerial approaches to architectural design in the future, in particular when working on larger scale projects

> *"The slow but indispensable evolution from document-oriented design towards model-oriented design still requires much rethinking and adjustments in regard to most parts of the building project chain."* (Penttilä 2007, 298)

Laiserin (2007, n.p.) sees owners and contractors as the main beneficiaries of BIM implementation, with architects lagging behind. He understands the use of BIM predominantly as *managing* information with the potential to automate parts of the professional workflow in the AEC industry. In the eyes of Laiserin, the successful use of BIM is not about acquiring the right software, but about adopting manifold processes in everyday work to tap more effectively into the potential BIM technology has to offer; this can occur without any guarantees that the necessary investments in those new processes instantly pay off for everybody involved (2007, n.p.). Laiserin criticises software developers for not adequately adjusting their tools for requirements of real life interoperability. According to Laiserin, engineers find it easier to adopt new BIM technology than architects, because they are trained to combine geometry with data (2007, n.p.).

Despite current shortcomings in the capabilities of BIM tools, one potential scope for BIM remains the seamless integration of information through standardized formats across the whole building lifecycle (buildingSmart 2009). This implies that BIM assists to bridge the interoperability-gap that exists between distinct software tools during conceptual design, design documentation, virtual pre-assembly, cost control, construction sequencing and facilities management – just to name a few.

The point is being made within the IAI and *buildingSmart* that designers can get a better understanding of complex design-issues and resolve them quicker – which – in return – gives them more time to focus on design (Eastman 1999). Three questions remain:

Firstly, how far down the track in the design process should we start using BIM? Secondly, can one single BIM model assist in the design process from the early stages to operation and demolition? And thirdly, can we maintain parametric flexibility while increasing the quantity of information inherent to the BIM model?

As addressed by Davies (2007, n.p.), it is difficult to get a distinct picture about the usefulness of BIM during the various stages in the life of a building (from conception to operation). Some software providers want to make end users such as architects and engineers believe that all aspects of design from early stages to detailed design, construction and operation can be solved using their specific BIM tool (Autodesk 2009, Bentley 2009). In my review of current literature about BIM, I was not able to find a proof that this notion is correct. Davies argues the notion presented by some providers that BIM has to use 3D building components and that it necessarily encompasses the whole building-lifecycle is not correct (Davies 2007, n.p.). Parthenios (2006, 64) concurs with this argument and he states that the claim made by those propagating BIM about its usefulness during all design stages is unjustified. His comment is based on the responses from more than 240 architects about their design methods and tools in the early design stages.

In a quest for finding the right stage of project development for the implementation of BIM on a building project Davies (2009, n.p.) points at difficulties for design partner to work concurrently to find integrated solutions:

"In order for all disciplines to release their coordinated information at the same time, it is imperative that a design freeze is agreed ahead of an issue. To avoid unnecessary re-design and additional hours, that often means waiting, providing only minimal input at the earlier stages of design, hand calcs and 'finger in the air' estimates of performance, until certain key issues have been resolved."

Following Davies' comment, the usefulness of BIM models can rather be found at a point in the development of a project where key design issues have been agreed on by multiple stakeholders and the project is ready for tender. Figure 14 lists some of the activities supported by BIM that occur in the stages where the design is resolved to a large extent and it is unlikely that major changes are required.
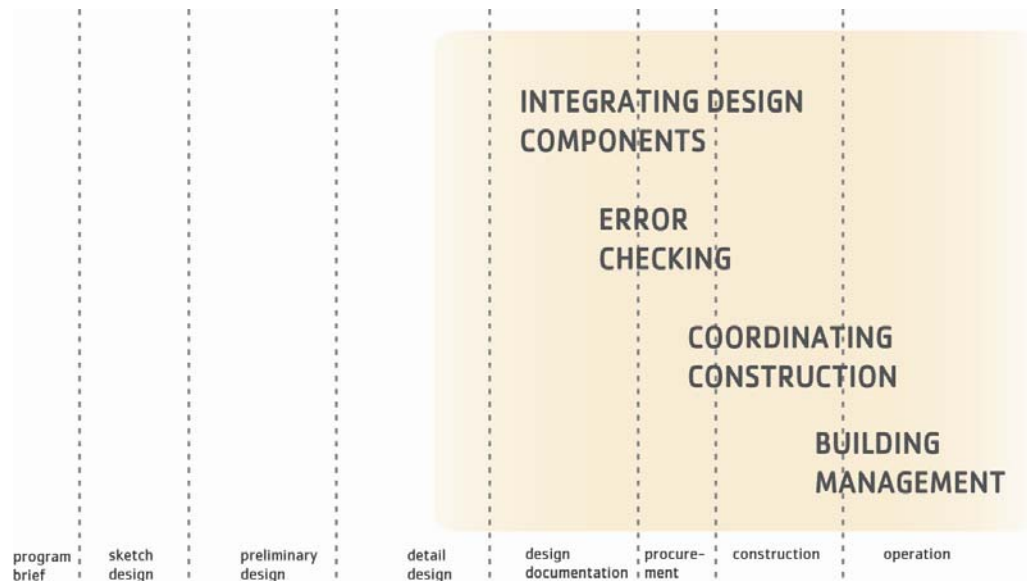
Figure 14: **BIM capabilities – strength in documentation, construction and operation, Source: Author**

An example of such capabilities is the *One Island East* project as shown in Figure 15.
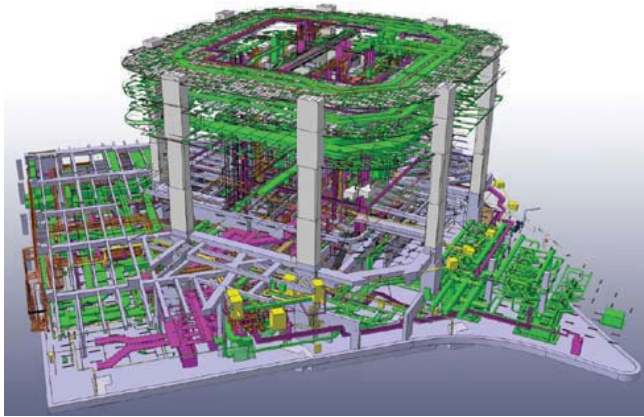
The One Island East project in Hong Kong developed by Swire is one of the first office buildings that has been pre-designed virtually in the parametric BIM software Digital Project (DP). Shelden and Rose (2008) explain how detailed 3D information was used to procure the project in a traditional tender process. They state:

> *"The BIM model provided an enhanced quantity take-off capability that improved the speed and accuracy of the management of quantities before and after tender. Lower, more accurate tender pricing resulted from better identification and management of the contractors' unknowns early on."*

> *"The One Island East model included all major MEP elements. Clash detection was used extensively and continuously both to identify interferences associated with these items and to manage the construction of correct openings in structure and architecture. This process enabled the design team to identify and resolve over 2000 conflicts before tendering. Later, during construction, the contractor used the same technology and working methods to identify and manage hundreds of clash and coordination issues."*

The project has won the 2008 BIM Awards by the American Institute of Architects (AIA) Technology in the Architectural Practice Knowledge Community (TAP) for "Design/Delivery Process Innovation" (AIA 2008, n.p.). A parametric setup of major building components for the One Island East tower was not allowed for by the design team. Instead, the generation of the 3D model focused on the assembly and coordination of all building components and the linkage to construction schedules and erection sequences.

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My review of literature seems to suggest that the more information contained by an integrated 3D model, the more difficult it is for the design team to remain flexible in the creation of design alternatives. This observation accords with Deiman and Plat's findings about cost aspects of a building project from early to more advanced stages of design.

Deiman and Plat (1993) argue that referencing information about cost-consequences to design decisions is a key factor for evaluating their importance in succeeding stages. The earlier decisions are made in the design process, the more significant is their impact on the final outcome (Deiman and Plat 1993, 327). A more integrated approach to building design and construction than seen in the traditional design process can lead to better informed decisions amongst participating design partners during the early stages of collaboration where alterations to the design have the biggest effect on the overall outcome and cost of a project (CURT 2004, 6). At the same time changes become more difficult and costly to accommodate later in the design stages.

As shown in Figure 16, MacLeamy has created a two dimensional graph to map design effort to impact cost and functional capabilities and the effect of design changes on the cost of a project. He maps them against the various design stages to illustrate how this curve can eventually be moved to the left.
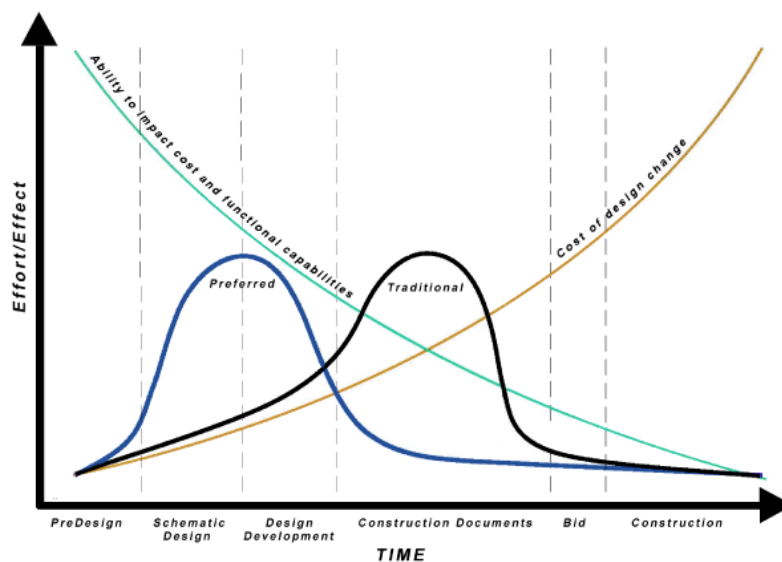
Figure 16: Curves traditional and preferred effort/effect vs. Time, Source: MacLeamy

The benefits for more integrated virtual representations of a building project in the early stages is acknowledged by clients globally. It has become a legal requirement in the US and Denmark to produce comprehensive 3D computational representations of building projects as testing-ground for various aspects of their performance. As shown in Figure 17, the US General Services Administration (GSA) issued a BIM-guideline in late 2006 which introduces their roadmap for a stronger integration of the use of BIM in the US AEC sector in general and the *Public Building Service* in particular (GSA 2006, 12). The point is made by the *Program Office* of the Chief Architect *Public Buildings Service* in the US that the GSA has instantiated a requirement in 2007 which forces all planners to produce BIM models for spatial program validation as an open standard if they apply for funding for their projects (GSA 2006, 14). This specification is a significant shift for a public client to push proactively the industry to use a specific standard.

The delicate issues of ownership and rights to design data is touched upon in the GSA (2006, 26) guide, but it fails to offer any significant proposal other than that in the case of *Public Building Service* being the client, they hold all rights depending on the agreements in the A/E (architecture / engineering) contract.

Spatial Validation

The National 3d-4D-BIM Program has chosen to focus first on using BIM for spatial validation because spatial validation is a universal problem on all projects. For all projects receiving design funding in Fiscal Year 2007 and beyond, a spatial program BIM will be the minimum requirement for all major (new and modernization) projects that will be submitted to the Commissioner of the Public Buildings Service for Final Concept approvals. In preparation for this requirement, OCA is working with a wide array of stakeholders (e.g., software vendors, A/E teams, and spatial data management professionals). See *BIM Guide Series 02- Spatial Program Validation.*

Figure 17: Standardised CAD information using BIM for spatial validation, Source: GSA National BIM guideline, p.8

In order to link the technical advantages of the BIM approach to legal and contractual frameworks, a rethinking of traditional ways of collaboration and project procurement is required. Figure 18 displays the differences between the traditional design stages and a new approach presented by the American Institute of Architects (AIA) California Council. This new approach identifies a highly collaborative first design stage as *"Conceptualization"*. The AIA then proposes strong communication of design intent across participating disciplines to aim at integrated project delivery (IPD) built on trust between design partners and to structure design, planning, and construction activities more effectively.
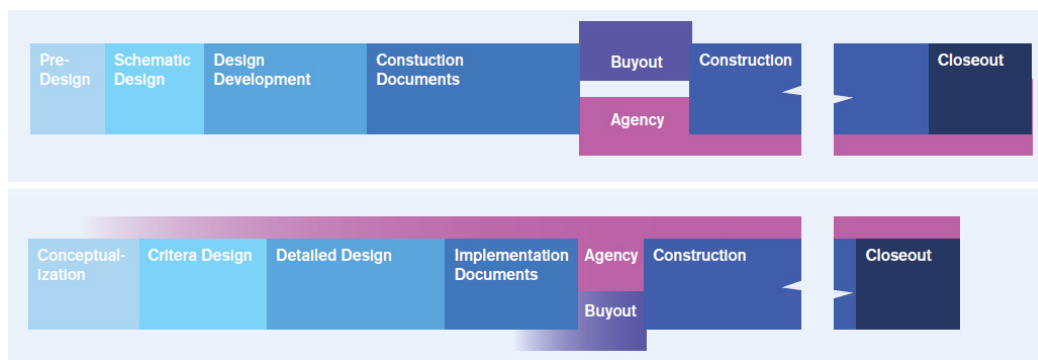
Figure 18: Differences in traditional and integrated project delivery, Source: AIA California Council, p.4

IPD associates project procurement and collaborative work with the appropriation of design data through BIM (AIA California Council 2007, 5). The IPD guide offers a new description of the period that is currently associated with schematic design and early design development: "*Criteria design*". According to the AIA guide, it is during this phase that "*different options are evaluated and tested. In a project using Building Information Modeling, the model can be used to test 'what if' scenarios and determine what the team will accomplish.*" The IPD guide lists the following tasks during *Criteria design* (AIA California Council 2007, 5):

- o *Design decisions are made on a 'best for project' basis.*
- o *Visualization of building model is tied to cost model.*
- o *Scope is fixed, price is fixed, owner signs off on what will be built allowing the team to evolve and optimize the design.*
- o *Further develop preliminary schedule – schedule is better informed due to collaborative approach and commitments to schedule are more firm.*

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- *Earlier recognition of inadequate building performance, but assessing responsibility is more difficult because of the number of participants and overlap of roles.*
- *Leadership remains with traditional participants*

CONCEPTUALIZATION

The project team comes together at the earliest stage, improving accuracy of decisions. The rest of the process becomes more predictable, thus avoiding costly redesign work.

DESIGN

Collaboration between the architect, contractor, and engineers allows for better decision making, helping to improve quality and mitigate risk.

Figure 19: Integrated Project Delivery with BIM, Source: Autodesk

The AIA BIM protocol (E202) helps addresses legal aspects of collaboration with the use of BIM (AIA 2008). It is a declared goal of the AIA to promote IPD for sharing responsibilities and mitigating risks of those involved in a project to avoid costly audit trails and litigation between collaborators. Van (2008) discusses the E202 protocol that regulates how multiple stakeholders contribute to the assembly of a virtual master-model. The information flow is regulated though a matrix that associates the *Level of Development* (LOD) and the *Model Element Author* (MEA). Van explains:

> *"Quite simply, the Model Element Authors (MEA's) are the parties responsible for developing the model content as specified in the Model Element Table. The Levels of Development are paired with an assigned MEA for each major building assembly."* *(VAN 2008)*

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So far in this chapter, I have highlighted the social and technical aspects that influence sense-making and the generation of common understanding between designers and consultants in the early design stages. As demonstrated on the example of IPDs, aspects of design collaboration cannot be seen in isolation from legal frameworks that regulate responsibilities for various activities of all design partners during the whole building lifecycle from ideation to demolition. In addition to social, technical and legal aspects, financial considerations are often key drivers in any design-decision making and they have a strong impact on the way partners in AEC collaborate and share their knowledge. In the following section I highlight some legal and financial considerations that influence the way designers and consultants interact on building projects and the way knowledge is being shared across disciplines.

3.4. Legal and financial aspects affecting knowledge transfer across disciplines in AEC

I reported on the interconnectedness of social and technical constraints to collaborative design in the previous sections and I hinted at obstacles for open exchange of information due to contractual constraints. In this section I highlight the impact of procurement methods and management-strategies on the sense-making process between disciplines.

A US report on the *National BIM Standard* lists 29 possible beneficiaries of increased interoperability and the sharing of design information across disciplines in an integrated manner using BIM. These beneficiaries include clients, architects, engineers, estimators, specifiers, contractors, lawyers, sub-contractors, fabricators, code officials and operators (National Building Information Modeling Standard NBIMS 2007).

As listed in the RIBA Outline Plan of Work, the distribution of roles between the client, the architect, the consultants and the contractors on design projects is dependent on the type of procurement method that regulates responsibilities though contractual frameworks (Phillips 2008, 4). Contractual frameworks also regulate the distribution of tasks and workloads between individual professions.

By way of an example, architects and engineers are not the only party who might profit from the creation of a comprehensive 3D computer-model of their project and it may raise questions as to how far it would be their job to produce work which is used for building information management rather than modelling. The generation of computational 3D models is done by the upstream parties, but it currently mainly favours the downstream parties – notably the client, the sub-contractors and the operators (Holzer 2007, n.p.).

In order to understand better how the flow of information in building projects is regulated through different legal frameworks, I investigate the predominant types of project procurement in the following section.

3.4.1. Types of procurement methods and their impact on design collaboration

The construction of building projects are legally bound to be carried out on the basis of clearly defined contractual arrangements that regulate legal responsibilities of all parties involved. These legal guidelines are often defined by independent organisations such as the Joint Contracts Tribunal (JCT) in the UK to regulate project procurement, financial liabilities as well as the interaction between the client, project managers, consultants (including architects and engineers), contractors and sub-contractors. There are manifold procurement methods that can be chosen to coordinate multi-disciplinary services throughout the various work stages of a project. The RIBA *Outline Plan of Work* (Phillips 2008, 4) lists five distinctive procurement methods that each divide responsibilities differently across various team members during work stages that range from *Appraisal* to *Post Practical Completion* and beyond:

- o *Fully designed project (either single stage tender or with design by contractor or specialist)*
- o *Design and build project (single stage tender or all designed by the contractor)*
- o *Partnering contract*
- o *Management Contract/Construction Management*
- o *Public Private Partnerships (PPPs) / Private Finance Initiative (PFIs)*

One decisive factor to the way knowledge gets shared between partners in the building industry depends on the client's choice of one the above mentioned contractual methods to set up their project. The RIBA Outline Plan of Work illustrates that each procurement method differently regulates how designers interact with consultants, contractors and sub-contractors (Phillips 2008, 4). The choice of procurement method in return influences the communication streams between the client, designers, and consultants. Information-feedback between manufacturing or constructability constraints and design is sometimes not possible between designers and contractors in the pre-tender phases.

As I explain in this section, some types of contracts hand over a large proportion of responsibilities regarding the team-structure, risk-aversion and the smooth integration of all work-processes to the architect; others employ managers who direct a job in a top-down manner focussing on financial aspects. Other contracts again give the contractor most control and responsibility over how a project is carried out. Only few of the above mentioned procurement methods encourage team-building with shared responsibilities that are built up from mutual aims, trust and project teams interacting with the perspective of long-term collaboration.

A comprehensive description of the RIBA procurement methods can be found at Cooke and Williams (2004, 23-46).

Each of the previously described procurement methods has different implications on how information is shared amongst project partners not only in regard to the commencement of services provided, but also in regard to dependencies between team members. Procurement methods regulate how design professionals are supposed to interact during the various work stages. In *traditional procurement methods* the architect is the representative of the client and therefore leads the design team including the consulting engineers and the quantity surveyor. The design is complete before the tendering stage at the point of which major variations are avoided and contractors are chosen through competitive tendering. While giving the client certainty about cost this method is not well suited to include construction-knowledge from the contractor in the early design stages (Cooke and Williams 2004, 27).

Design and build contracts allow the client to chose various options between two extremes: either to be fully involved in influencing the design and the fees with the architect or a project manager as lead consultant, or to hand over all responsibilities to the contractor. In this case the contractor appoints the design team and guarantees the quality and cost (Cooke and Williams 2004, 31). In *Design and build* agreements it is therefore possible that the design process is driven by price at the expense of quality to allow the contractor to avoid risk and maximise profit.

Cooke and Williams also describe *Management Contracting* where the client invites contractors to bid for managing a project and to subsequently chose among bidders for work package subcontracts. This approach is highly business-oriented with little emphasis given to the design team. The project manager may interact with the package subcontractor through a design team coordinator and there is little direct interaction between the designers, the consultants and the subcontractors.

Public Private Partnerships (PPPs) are arrangements where public sector sponsors advertise large scale projects to attract pre-qualified bidders who collaboratively compete with others as a *Special Purpose Company* (SPC) of contractors or contractors with design consultants (Cooke and Williams 2004, 38). Advantages for the public sector client in such an approach include the potential for high returns, continuity of work, involvement in the design and buildability and strong control over the programme. The bundling of services through the SPC provide value for money that contracting services separately cannot and maintenance agreements can be included in the PPP contract to ensure that longer-term interests of the public sector client are considered in the SPC's proposal (Webb 2002, n.p.). A report of the UK National Audit Office states that one necessary ingredient for successful PPPs is for authorities and contractors to seek to understand each other's businesses and to have a common vision of how they will work together to achieve a mutually successful outcome to the project in a spirit of partnership. (UK National Audit Office 2001)

> *"the extensive use of subcontracting has brought contractual relations to the fore and prevented the continuity of teams that is essential to efficient working."* (Egan, 1998, p.8)

The use of subcontracting and competitive tendering on design projects has a significant impact on the argument presented in this thesis. Sense-making between parties in collaborative design has not only been influenced by the speed of developments and of specialisation, but also by procurement methods that favour subcontracting and competitive tendering. We can follow from Egan's statement

that procurement methods that favour competitive tendering make it difficult for designers and consultants to establish a social terrain of design negotiation if it is compromised by cost too early in the design process. Another aspect related to competitive tendering is the loss of design-intelligence that may occur if subcontractors re-interpret design information according to their own specifications. Figure 20 illustrates the information-gap that can occur when subcontractors generate their construction drawings[35] independently from the previously elaborated design documentation by the design team.
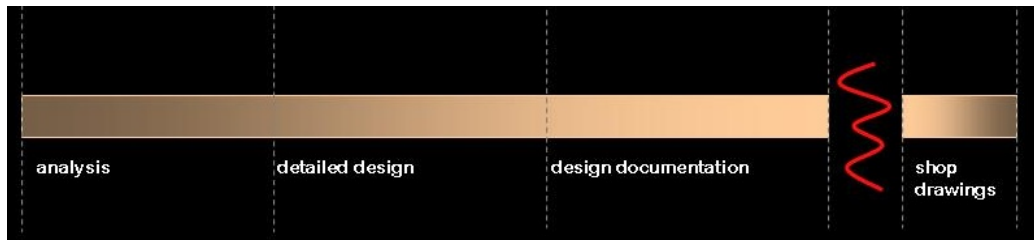
Figure 20: Information gap due to business constraints, contractors re-interpreting geometry according to their preferences and needs, Source: Author

In the *Rethinking Construction* report Egan (1998, 4) described the state of the UK construction industry at the end of the twentieth century In response to a low and unreliable rate of profitability, they argue that radical changes to the processes through which jobs are delivered will be required to achieve improvements in the industry. One of the proposals brought forward in the Egan report is the need to: "*replace competitive tendering with long term relationships based on clear measurement of performance and sustained improvements in quality and efficiency*" (1998, 5)

Egan (1998, 4) encouraged the build-up of long-term relationships between various companies involved on construction projects to increase learning capabilities across organisations for achieving incremental improvements in the industry. In the *"Rethinking Construction"* report Egan (1998, 31) proposed the following:

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[35] In Australia construction drawings are also referred to as "shop drawings".

o new selection criteria for partners on building projects, with
o more transparent sharing of responsibilities and successes,
o clear performance targets, and
o an end to the reliance on contracts.

He states: (Egan 1998, 30)

> "*Contracts can add significantly to the cost of a project and often add no value for the client. If the relationship between a constructor and employer is soundly based and the parties recognize their mutual interdependence, then formal contract documents should gradually become obsolete*".
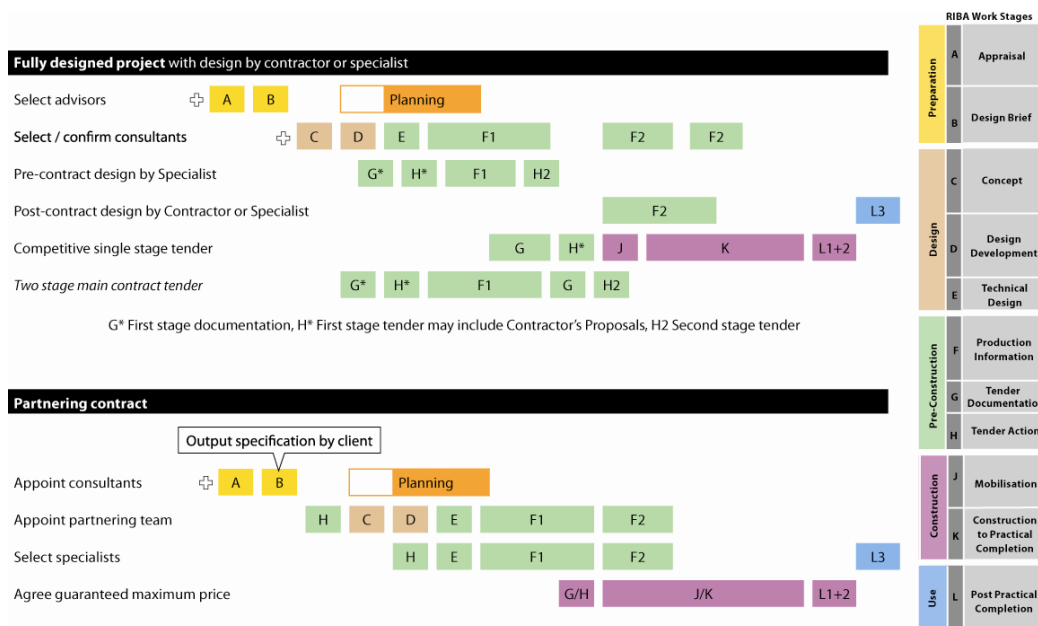
Figure 21: Work Stages and comparison between Fully designed project and Partnering contract procurement method, Source: RIBA Plan of Work Multidisciplinary Services

Partnering Contracts are used for projects where partners mutually agree on a more even distribution of responsibilities and remuneration built on trust as well as an option to increase long-term relationships between businesses and the overall aim to work more efficiently. (Cook and Williams 2004, 42)

> *"The great advantage of partnering is that all the parties are expected to work together to solve any design issues that may come up."* (Birkby, 2006, n.p.)

Birkby presents the method of *Partnering* as procurement method on building projects where partners agree on a *'fair dealing and teamworking'* (Birkby, 2006, n.p.) clause at the outset of a project as a way to avoid disputes later on in the design and construction process. In *Partnering* mutual co-operation, the exact definition of responsibilities and trust between client and contractor is crucial as at times the boundaries between the work of different designers might be blurred. Birkby acknowledges the difficulties in defining precise liabilities in a partnership in building practice. He (Birkby 2006, n.p.) points out that different types of partnering agreements allow participants to choose from a variety of options with more or less prescriptive associations of responsibilities

Smyth (1999, 2) addresses the reasons why partnering may not be the obvious choice of procurement-method by clients. In regard to client-relations with designers, consultants, and contractors she offers an explanation why companies in the AEC industry operate predominantly on a project-to-project basis instead of searching for longer-lasting collaboration:

> *"There are few economic incentives for a client to remain loyal to a contractor, even where the client may have been very satisfied with prior services."* (Smyth 1999, 6)

Smyth points out that *Partnering* needs to be set up with a valid strategy to increase repeat business. She urges caution for its use. Smyth (1999, 5) argues that *Partnering* is currently mainly driven by interests of the client and she lists three different types that favour parties differently:

1. *Strategic partnering,*

2. *Project partnering, and*

3. *Framework agreements (a hybrid between the two)*

Problems may arise for contractors who engage in *Project Partnering* due to switching cost when clients choose to engage different contractors after a short period of time. Smyth (1999, 5) states that repeat business is highly significant for contractors who should therefore search to engage in longer-lasting *Strategic*

Partnering.   In order to achieve mutual objectives, problem resolution and continuous improvement of relationships, Smyth urges (1999, 6) clients to move towards strategic partnering in spite of potential higher initiation cost, and she argues that changes to current partnering practice can only come about from substantial restructuring of procurement methods in the building industry.

> *"It is understandable why many contractors may end up paying "lip service" to partnering as a means simply to secure work, and then, failing to carry through their promises or deliver the improvements."* (Smyth 1999, 4)

An equally critical point of view is reflected by Bringham (2008, n.p.) who reports on JCT Frameworks which were launched in the UK in 2007. Similar to *Partnering* these frameworks allow professionals in the building industry to determine contractually interrelations and responsibilities with their partners with a long-term perspective.

As described by Bringham as *call-off* deals (2008, n.p.) JCT frameworks seek to avoid one-off work relations that might have been won at the lowest bid and with short-term goals in mind. Instead they allow partners to develop longer-lasting relationships to move "*teamlike from project to project*". Bringham (2008, n.p.) scrutinises the uptake of JCT frameworks in building practice as partners may get alienated by mistakes in the cost-estimation of contractually bound services. Services regulated through JCT frameworks cannot be altered over a period of years. He argues that litigation among parties in the construction industry are likely to happen and he adds: *"we in construction are fond of fighting"* (2008, n.p.)

The choice for any of the procurement methods mentioned so far is strongly dependant on client preference, on mutual agreements between work-parties and on the type of project to be carried out. From a business perspective, it is important for design firms to position themselves appropriately in the market and to come up with management strategies that best reflect their work-philosophy

and organisational strength. Different types of design-services require different types of expertise and knowledge-base.

Coxe et al. (1987, 6) distinguish three main types of architecture and engineering firms, in order to propose a *best fit* management model on how their practice should be organised. The distinction and superposition of the firms is based on the experience of Coxe et.al as management consultants. The *Superpositioning* model (Coxe et al. 1987, 16) distinguishes three key methods that firms apply in conducting their work:

1. *Ideas*: expertise or innovation on unique projects involving one or few stars – the technology is highly innovative and work is often done for fame.
2. *Service*: experience and reliability, especially on complex assignments – the technology is providing extensive services to clients who want to be involved.
3. *Delivery*: highly efficient for similar or routing assignments, clients want more a product than a service; this is achieved by repeating previous solutions with highly reliable cost and technology compliance.

Coxe et al. (1987, 32) point out that the classification into these three types is not judgemental in terms of qualitative differences, but it provides a better understanding of the operational differences that any of the three methods represents. They state that not one type is superior to the other, but that it is important for the firms to understand where their emphasis lies in order to be successful as a business. Building upon the *Superpositioning* categories, Coxe et al. (1987, 35) explore some of the issues related to the management and the information-flow for each type that include the choice of project process, project decision-making, staffing, and the identification of the firm's best markets. Whereas *ideas* oriented firms search to collaborate with others to innovate and explore new, and unique paths for each project, *service* oriented firms depend strongly on the expertise and long-lasting commitment of their employees to push the boundaries of what is possible, backed up by a proven track record of

previously successful approaches, and *delivery* oriented firms aim at specialising in a particular building-sector where issues from project to project are highly repetitive and budgetary constraints are of highest importance.

In conjunction with the types of technology, Coxe et al. (1987, 33) state that specific values are the second main characteristic that help define business strategies for architecture and engineering firms. They distinguish between:

- o *Practice* (carrying on or exercise of a profession or occupation) – centered professionals (way of life), and
- o *Business* (commercial or merchant activity customarily engaged in as a means of livelihood) – centered professionals

These comments illustrate the effects on the choice of strategy of how architectural and engineering firms should be run in order to be successful in a specific segment of the AEC industry. By looking at firms in architecture, engineering and construction from a management perspective, Coxe et al. (1987) demonstrate that not one type, but different types of support are needed to make them successful in their specific market. This has strong implications on the design ideology, staff recruitment, and knowledge-exchange between designers, consultants and contractors as well as the technical and organisational support.

Barnett (2000, 28) points out that sharing working knowledge inter-organisationally is difficult as competitiveness between various organisations is a major issue in maintaining a market edge, and companies are afraid to give away their knowledge to the opposition. Barnett (2000, 23) argues that a focus on intra-organisational prosperity makes it difficult to overcome IP issues, to agree on ownership rights and to share working knowledge collaboratively. While these conflicts are hindering the establishment of a strong sense of interoperability across firms, Barnett believes that making working knowledge explicit to others is the only sensible way forward to tap into synergies in our current work-practice.

Inadequate interoperability in the building industry results in major financial losses across the whole building sector. Upon comparison of the way the building industry in the US presents itself to other project based industries (see Figure 22) such as car-manufacturing, aerospace and ship-building, researchers have proven that productivity in the building industry has substantially lagged behind (NIST 2004).
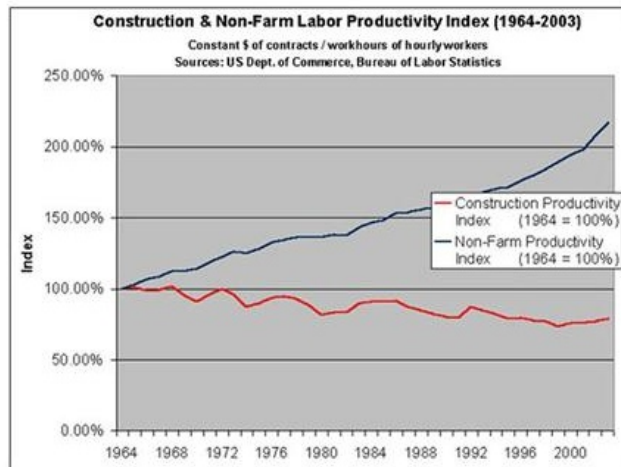
Figure 22: Graph comparing the construction productivity index with the non-farm productivity index in the US 1964-2004, Source: NIST report 2004

A report issued by the National Institute of Standards and Technology from the U.S. department of commerce (NIST 2004) gives a sound overview for the reasons of the high cost incurred due to inadequate interoperability among stakeholders in the U.S. building industry in 2004. At the outset of the report it is stated by the authors that the building industry has not profited from innovation in IT and communication as other industries such as automobile and aircraft manufacturers. It is agued by the authors of the report that:

> *"interoperability costs do not simply result from a failure to take advantage of emerging technologies, but rather, stem from a series of disconnects and thus a lack of incentives to improve interoperability, both within and among organizations, that contribute to redundant and inefficient activities."* (NIST 2004, ES-8)

The NIST report presents results from interviews with 105 firms from the building industry, mostly owners and operators as well as architects, engineers and general contractors. The evidence presented in the report points to an annual cost of US $ 15.8B for inadequate interoperability.

> *"Different stakeholders are involved in the multiple phases of the facility life-cycle, and they typically have limited contractual incentive to communicate. ...opportunities for improvement are lost due to the fact that these parties rarely communicate about their related responsibilities. One issue is that there are minimal incentives for architects to give continuously-updated information to other players beyond what is necessary given liability concerns."* (NIST 2004, 7-2)

The report lists the following eight reasons for the insufficient information management in the building industry (NIST 2004, 3-2):

> *1) Collaboration software is not integrated,*
>
> *2) life-cycle management processes are fragmented,*
>
> *3) Inefficiencies and communication problems using software in various parts of the life-cycle,*
>
> *4) CAD interoperability issues due to different platforms in use,*
>
> *5) Lack of data standards,*
>
> *6) Internal business processes are fragmented and inhibit interfirm and intrafirm interoperability,*
>
> *7) Remaining use of paper-based systems, and*
>
> *8) Lack of access to or lack of enjoyment of the use of new technology*

Gallaher et al. define interoperability cost in three categories: avoidance cost, mitigation cost and delay cost with the first two sharing the major part (6.6 & 7.7.B) and delay cost playing a minor role. They also list the cost for inadequate interoperability per stakeholder. Figure 23 shows that US $ 2,7 billion loss occur during planning, engineering & construction, compared to US $ 4.1 billion occurring during construction and the largest sum – 9.1 billion are occurring

during operation and maintenance. This provides clear evidence that the yearly US $ 15.8 billion loss in the US building sector due to inadequate interoperability is arising from the planning, engineering, and design phase by 17%, the construction phase by 26% and an overwhelming 57% from the operations and maintenance phase.   One quote from the abovementioned NIST report states that: "… *every dollar saved connecting the design to construction would generate savings in an amount 10 times more when connecting the operations and maintenance controls to the original CAD and engineering analysis design".*

Table 6-1. Costs of Inadequate Interoperability by Stakeholder Group, by Life-Cycle Phase (in $Millions)

Stakeholder Group	Planning, Engineering, and Design Phase	Construction Phase	Operations and Maintenance Phase	Total
Architects and Engineers	1,007.2	147.0	15.7	1,169.8
General Contractors	485.9	1,265.3	50.4	1,801.6
Specialty Fabricators and Suppliers	442.4	1,762.2	—	2,204.6
Owners and Operators	722.8	898.0	9,027.2	10,648.0
Total	2,658.3	4,072.4	9,093.3	15,824.0

Source: RTI estimates.
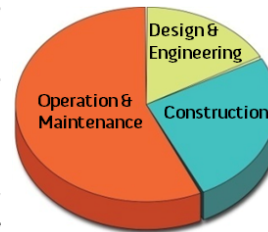
Figure 23: Comparison of inadequate Interoperability per year by stakeholder,   Source> NIST report 2004/RTI estimates

The NIST report illustrates that it is of particular importance for building owners to encourage design teams to interact in an integrated way to streamline interoperability during design, planning and construction. The report highlights the fact that efforts by designers and consultants in the design, planning and construction currently do not sufficiently feed into the operations and maintenance phase of a building.

Next to issues of interoperability there are also government regulations for sustainable building design such as the GSA and environmental rating systems such as LEED, BREEAM and GREEN STAR that encourage clients, designers and consultants to consider long-term-strategies in the design process.

What are the challenges in practice for collaborative modes that go beyond the limitations of what can be achieved on a project to project basis? I discuss new modes for collaboration in Chapter 5.3.2: *From Inter- to Transdisciplinarity.*

Summary Chapter 3:

The motivation of this chapter was to set the scene for my research by providing a context through literature from architecture, engineering social sciences, and related fields. By doing so, I address the breadth of factors that influence *sense-making* in design collaboration from social, technical, financial and legal perspectives. The chapter is structured to contextualise first professional specificity in current building practice to then discuss issues of *sense-making* and knowledge transfer in teams. I further alluded to the impact of ICT in collaborative design environments across disciplines with a focus on early stage design and a critical view on BIM. Finally I laid out legal and financial aspects related to collaborative design and the impact they have on knowledge transfer across disciplines in AEC.

In this chapter I introduced the main factors that influence the act of *sense-making* and the creation of a common understanding among various parties involved in building projects. The notion of *wicked* problems faced by planners during the complex task of designing, as illustrated by Rittel and Webber (1973) explains why there cannot be one simple path, a technical solution or even one tool to provide assistance in collaborative design. The issues related to the above topic are multi-facetted; they are rooted in the different theories and notations used by each individual profession in an ever more networked society. These particular theories, and the associated notations, are based upon the differences in education and on distinct world views that are (often falsely) maintained by practitioners to define their professional status. Our capability to transform knowledge within individuals into knowledge and *knowing* that can be shared with others in teams intra- and inter-organisationally is essential to strengthen the act of socialisation and the creation of common understanding on building projects.

Lawson (2005, 387) is critical to the role of ICT in the design process and he asserts that computational tools can only become real design partners in our profession if they link into cognitive processes that support our creative *design thinking*. Central to this is the ability of designers to juggle different ideas

simultaneously and to confidently deal with uncertainty. A key finding from my review of literature is the fact that there exists currently a lack of ICT support for interaction across disciplines who wish to explore multiple design options in early-stage collaboration.

ICT supporting designers, consultants and others within and across teams has brought benefits to the way we operate, but there are few tools available that specifically target the creation of a shared understanding between architects, engineers and others in the early design stages. There have been various attempts to create collaborative design systems since the 1980's, but due to their often *academic nature* and the insufficient state of technology at the time of their development, these systems have not found their way into everyday practice. Still, much can be learned from these previous efforts by colleagues and their work continues to influence researchers today.

Building Information Modeling (BIM) is being hailed by many in the industry as an answer to the problems professionals from architecture and engineering are facing when aiming at increased interoperability in the pursuit of a seamless transfer of information between design partners. Its rigorous definition of standardised transfer for object-oriented building elements across CAD platforms and across disciplines makes BIM well suited to manage design-data particularly for virtual pre-assembly, error checking, on-site construction coordination and facility management. For design-explorations in the earlier design stages, on the other hand, where major changes occur in short intervals, flexible data-sets and models for project-representations are often required. My review of existing literature therefore challenges the impression propagated by software vendors that the benefits of BIM automatically extend to all design stages.

Legal and financial aspects regulated by contractual agreements and procurement methods are an additional factor influencing the way information can be shared in design projects. Criteria of design quality are nowadays often challenged by criteria of affordability and financial risk-avoidance. In that sense, some

contractual arrangements rather inhibit inter-organisational collaboration than promoting it.

Competitive tendering gives both clients and consultants more security as responsibilities are shifted towards the (sub)contractor and at the same time, they promote an environment of segregation of design knowledge. In addition to this segregation, competitive tendering also leads to a design-process where early explorations often occur disconnected from issues of constructability and affordability. The way projects are set up for tendering therefore does not seem to acknowledge fully the value of long-term commitments for broad sharing of knowledge across the boundaries of projects and organisations.

In contrast to the above, the procurement method of *Partnering* is a solution that promotes trust, mutual benefits for all parties involved and the build-up of long-term relationships between teams in the building industry. Integrated Project Delivery (IPD) attempts to combine benefits derived from *Partnering* style contracts with a holistic approach to design using BIM to strengthen interoperability and a fair distribution of benefits and risks across the whole design team.

In addressing the above topics, I have drawn a comprehensive picture of the factors affecting collaboration and sense making in the early stages of architectural design. Amongst the topics identified in my summary of existing research as exerting the most influence on achieving a level of sense-making across disciplines, the different notations in use across the AEC industry appears to be the odd one out; yet it reveals itself through analysis of academic literature to be perhaps the most crucial. Thus it would appear that to gather, examine and synthesise information on discipline specific ways of seeing, knowledge exchange, and problem-solving could offer valuable insights on sense-making in design collaboration. The above activities could assist me to gain further an understanding of the many points of differences between professions. A tangible oeuvre of actual practitioner-responses seems to be a gap in current literature.

This insight has triggered me to use my embedded status in the multi-disciplinary practice at Arup to question its members about their disciplinary world-views, the notations they use to communicate their design-ideas, and the way ICT supports their collaborative design and consulting practice. I believe that the key to understanding *sense-making* in design collaboration lies in the responses to the above questions.

In the following chapter I present these responses from practitioners at Arup and collaborating architects. I conducted workshops and interviews with members from seven design and consulting professions in AEC to elicit their point of view on sense-making in early design collaboration.

4. Observing early stage design collaboration

> *"To understand design practice, we must explore how participants (such as these) make sense of their worlds, and how that sense making functions in the social construction of architecture."* (Cuff 1991, 18)

Up to this point in my thesis, I have drawn from literature by researchers in social sciences, architecture and engineering. In this chapter I report on my findings as embedded researcher within Arup. During my three year period in practice, I approached the act of *sense-making* across disciplines through first-hand observations in design collaboration between architects and engineers.

The chapter is laid out in eight sections; in Chapter 4.1: *Sources of the practice-based analysis of design collaboration,* I present the preparatory work to conceive interviews that I conducted at Arup. The questions I asked practitioners in those interviews were triggered partially by the literature I reviewed in the previous chapter; partially by my participation on a live project on which I collaborated in the first half year of my embedded research at Arup[36]; partially by day to day observations of design practice within Arup; and finally by focused workshops which I conducted in the Arup office.

Chapter 4.2: *Approaches to capturing professional identity through research interviews* illustrates the two different approaches, *quantitative analysis* and *qualitative analysis*, I took during my research-interviews in practice. For my quantitative investigations, interviewees rated 32 topics related to disciplinary design priorities in a questionnaire, and for my qualitative analysis I asked 28 practitioners to comment on a list of ten questions during one-on-one interviews.

I present responses to the questionnaire in Chapters 4.3: *Quantitative analysis – mapping results from the questionnaire* and 4.4: *Observations describing discipline-profiles individually.* By mapping results graphically and interpreting the feedback received

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[36] The Melbourne Rectangular Stadium project, as noted elsewhere in this thesis. See *Appendix A* for a full account

from different design and engineering disciplines at Arup and collaborating architects about early stage design. I first present general outcomes across all disciplines, to then discuss results per discipline.

I evaluated the responses through a qualitative analysis, the findings of which are presented in Chapter 4.5: *Qualitative analysis of interview responses*. In the interviews I scrutinised the application of skills in day to day practice settings, I questioned the main communication methods by practitioners, I asked them about the type of media they use to make sense of design-related information, and I researched the level of knowledge-exchange across disciplines that help practitioners to increase common understanding of design problems in the early stages.

Chapter 4.6: *Varying notations of geometric design-representations in architecture and engineering*, contains responses by interviewees from follow-up discussions after the one-on-one interview-sessions. There I asked them about the particular, preferred 3D computational geometry models for design and analysis related to their discipline.

Computational 3D geometry files have become a shareable medium for exchanging design information across disciplines. As I explain in Chapter 4.6, this dialogue is at times precluded by incompatible geometry-model setups and one and this same design may require several different types of models for different types of analysis. I highlight the differences between those models and I point to the reasons for maintain separate modelling styles in Chapter 4.7: *Geometry-model constraints by discipline*. In the final section, Chapter 4.8: *Disciplinary Tables*, I summarise findings from the quantitative and qualitative analysis in a series of seven tables. The tables present a compressed description of concerns in early-stage design from each of the seven disciplines that I was interviewing (acoustic engineering, architecture, environmentally sustainable design, façade planning, fire engineering, services engineering and structural engineering).

4.1. Sources of the practice-based analysis of design collaboration

As stated in the introduction to this chapter, Arup is a multidisciplinary design, engineering and consulting practice in the building sector and employees at Arup are therefore involved in a plurality of consulting activities.

The environment that I have been embedded-in, forms the *Buildings Group* in Arup's Sydney and Melbourne offices[37]. The *Buildings Group* hosts members of the following six engineering disciplines: Acoustic engineering, environmentally sustainable design (ESD), façade-planning, fire-engineering, mechanical electrical and piping (MEP), and structural engineering[38]. Within the *Buildings Group* at Arup, I found an ideal environment to study the varying world-views and notations of different disciplines that I identified as crucial in the literature review. The parameters of that group shaped my targeted range of professionals.

In this section I will illustrate how I took advantage of my *embedded* status in the *Buildings Group* to explore aspects of design collaboration through participation in a case study project, the Melbourne Rectangular stadium, through day to day investigations, and through specially targeted workshops with professionals from the above-mentioned disciplines. Access to the knowledge embodied in this group of world-leading professionals has contributed substantially to tackling the issue of sense-making between collaborating disciplines in AEC. As shown in Figure 24, as a trained architect, I collaborated initially with structural engineers in the stadium project to then extend my field of research to facade-planning, and to subsequently include acoustic engineering, ESD, fire engineering and MEP.

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[37] Arup employees engage in strong collaboration across locations globally. It is not unusual that projects are run by three or four Arup offices simultaneously across various countries and continents.

[38] For the purpose of simplification I will from now on abbreviate *environmentally sustainable design* with the acronym ESD and *mechanical electrical and piping* with the acronym MEP in my thesis document.
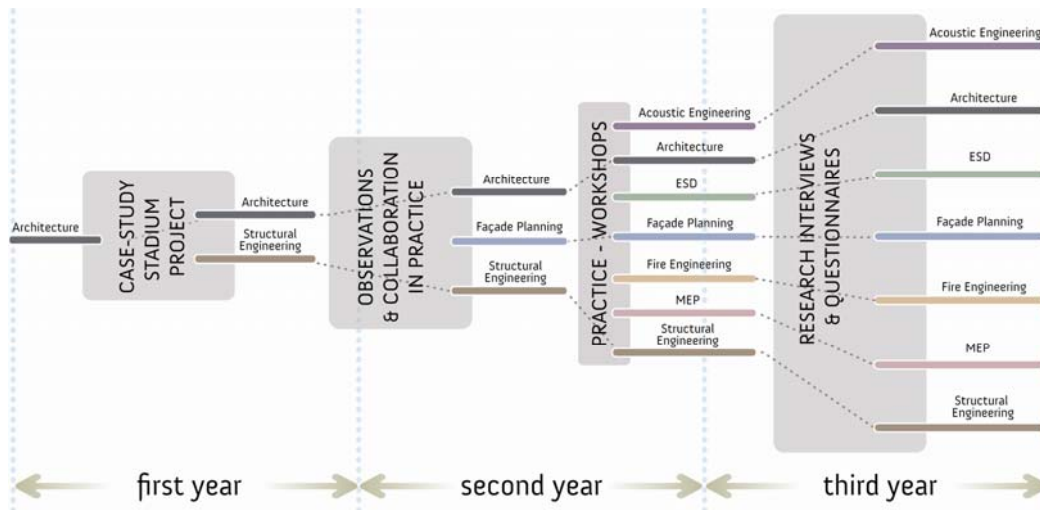
Figure 24: Timeline of the activities embedded in Arup leading to the research interviews,
Source: Author

4.1.1. Case Study Project - Melbourne Rectangular Stadium

Soon after commencing my PhD research embedded at Arup, I was asked to participate in the design development of a stadium project, the *Melbourne Rectangular Stadium*. The involvement in this project which, at that time, was mainly in collaboration with structural engineers at Arup, influenced significantly my research-approach for the remaining period of my PhD.

Such were the obstacles and information-gaps I uncovered in the design collaboration, that I decided in the course of that project to restrain myself from working on further case-study projects in order to focus my investigation instead on the sense-making process between collaborating disciplines. The stadium project made me realise the high-level of dependency between design problems across manifold disciplines. It also made me realise that advantages in design-collaboration can be gained, if designers and consultants commonly set up projects in a way that allows them to make design-decisions based on building performance analysis in close to real time.
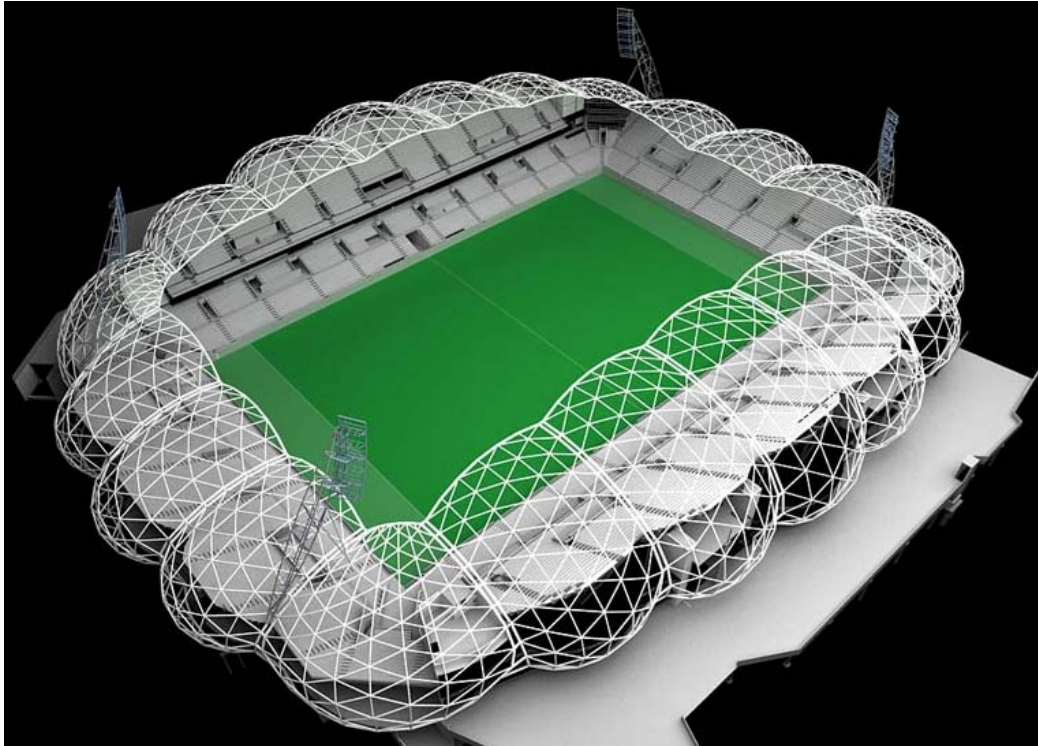
Figure 25: Melbourne Rectangular Stadium: Rendering of the concrete grandstand and the steel roof structure, Source: Arup

I will provide a detailed account of the stadium project and the lessons I learned from it in Appendix A of my PhD thesis.

4.1.2.   Observation and collaboration in practice

As a consequence of my findings in the case study project, I decided to direct my research towards understanding collaborative processes as they occur in design meetings between architects, structural engineers and façade planners. In the second year of my research embedded at Arup, I participated in design meetings of the abovementioned disciplines on a daily basis. I took notes about design-collaboration during early design meetings. I observed the flow of information from discussions during those meetings leading to the setup of 3D computational geometry models, the carrying out of design analysis, the integration of analysis results in design documentation, and the feedback of results to other consultants

and designers[39]. Towards the end of the second year in practice my observations led me to define three areas of particular interest which offered substantial insights. These three areas are:

1. *knowledge capture,*
2. *trade-offs in multidisciplinary design, and*
3. *common geometry*

4.1.3.   Focused workshops in design practice

In order to investigate the above three areas in greater detail, I conducted three workshops to explore further their relevance across collaborating design and engineering disciplines during early design. The workshops took place at the Arup office with representatives from all disciplines in the Building Group present and invited guests from collaborating architecture firms.

The list of participants in these investigations therefore included architects, structural engineers, MEP engineers, façade planners, acoustic engineers, fire engineers, and ESD consultants. During the workshops I detected a high level of curiosity from the practitioners with varying backgrounds to engage with the concerns of others and to discuss aspects of design holistically across disciplines outside their usual project-focused work environment.

In the first workshop, practitioners commented on knowledge capture during the design process and they elaborated in more detail on those tasks that require most interaction in teams with other professionals. The practitioners expressed a desire for tools that would help to compare current design options with experience on previously built projects, and that would assist in the evaluation of ideas almost as easy, comfortable and quick as sketching through coarse performance evaluation. They acknowledged the usefulness of distilling technical and cost information

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[39] Notes from my observations are not as elusive as it may appear in my PhD thesis. I entered them in a daily log, including general comments, meeting minutes, specific observations, summaries of conversations, and other forms of transcripts. Due to the confidential nature of the material, I am not able to present it in greater detail as part of this thesis document.

from a selected set of reference models sorted by building type and location to make it accessible for comparison on live projects.

The second workshop addressed trade-offs in multidisciplinary design. In discussions practitioners proposed that design meeting culture could be changed to allow earlier interaction in the design process than currently practiced. The workshop participants argued that a decision support-environment is missing in current practice to combine different sets of analyses, therefore enabling them to test design options across disciplines in a *what-if* manner. There was a consensus among workshop participants that trade-offs between various design priorities cannot be automated as they are highly dependent on arbitrary human decision and project specificity. Professionals argued that they could profit from a sensitivity study telling them what aspects of design are important to other practitioners and how that might relate to their own work.

The third workshop dealt with problems in sharing common geometrical representations of digital design data. My observations in practice revealed that each of the professions in the *Buildings Group* worked on a different set of geometry models. Members of the participating disciplines agreed that the use of a single, unified model between several disciplines involved is not achievable as various computational analysis tools require appropriation of geometry in different ways. Practitioners claimed that for an integrated approach, an expert 3D digital model coordinator would be required to help in interrelating the various modeling formats used for different types of performance analysis. Another task for the coordinator would be to compare graphically analysis models in order to highlight big bloopers, even if the geometry of the underlying models cannot automatically be reconciled. As members of the various disciplines were not aware of the formats used by colleagues in other professions, they argued for the establishment of a matrix to illustrate characteristics of the various geometrical setups in use to understand which digital models can be used across.

The information I gathered in all three workshops was pivotal for me in order to conceive questions and topics relevant for the interviews I consequently

conducted in the Arup office. In the following section I lay out in detail how I structured the interviews and what goals I had in mind when conducting them.

4.2. Approaches to capturing professional identity through research interviews

My aim for the practice-based interviews was to include insights from members of each of the six professions in the *Buildings Group* at Arup, plus comments from architects collaborating with the *Buildings Group*. Most of the interviews were conducted in the Sydney and Melbourne offices where I had been embedded over a period of three years. Some interviews were conducted in the Singapore Arup office (which forms part of the *Arup Australasia* region) where the largest projects were delivered at the time of the interviews. A selected number of interview were conducted in Arup offices in London and Amsterdam where senior high-profile experts were located who had previously worked on internationally renowned high-profile building projects and whose input was pivotal to my research.

Prior to questioning practitioners about *sense-making* across collaborating disciplines in the early stages of architectural design, I took four aspects into consideration to derive a balanced sample of responses:

1. Strategic sampling to determine a representative set of interviewees,
2. The method used to question interviewees about their experience in practice,
3. The setup of interview questions that translate across multiple professions, and
4. The method of evaluation for mapping differences and commonalities among the professions involved in the interview process.

Lincoln and Guba (1985, 201) describe the method of *maximum variation sampling* as appropriate when: "...*not to focus on the similarities that can be developed into generalizations, but to detail the many specifics that give the context its unique flavour".*

I chose *maximum variation sampling* in the selection of interviewees as I did not intend to generalise about similarities or differences between different architecture and engineering professionals, but I attempted to carve out and analyse in detail the different priorities assigned to design issues and the notations used by various disciplines who work on a common building project. I conducted a total of 32 interviews, four of which were used to pilot my questions during a start-up phase, and 28 were selected for further evaluation. Among the 28 interviewees, I interviewed four participants from each of the seven disciplines I identified above to guarantee an even spread of participants. My aim was to address senior practitioners with a substantial level of experience in their field, but at the same time I selected at least two interviewees of each discipline with advanced knowledge about ICT support in their field.

The procedure used in the interviews was complex. On one hand, I aimed to understand the varying priorities between distinct professions in their dealing with design problems, to then profile each profession using graphs that can be compared with others. On the other hand I wanted to learn about the concerns of members of the seven professions by asking them questions about their work-methodologies in the interview. To resolve this complex task, I chose to split my research interview into two sections:

1. a *quantitative analysis* section (using a questionnaire), and
2. a *qualitative analysis* section (through one-on-one interviews with 28 practitioners).

I scanned through a variety sources accessible to me at Arup to prepare for the questionnaire used to derive quantitative data from the participants. I assembled a list of 36 topics covering all disciplines involved in the interviews and, focusing on a specific building type, I asked interviewees to rate each of them according to their priority to obtain answers that translate across multiple professions[40]. I

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[40] An example of such a topic would be the *floor to floor height*. This topic has an effect on the architectural design as much as it has an impact on the structural behaviour of a building, the façade modulation, the

grouped topics according to disciplinary affiliations for each of the professions involved in the interviews, to learn how each discipline would rate them in relation to their own field. In preparation for putting together the questionnaire, I drew upon sources such as handbooks, practice guidelines, spreadsheets containing rule of thumb matrices, and database-content on the worldwide web and the Arup intranet. These sources helped me to define a set of designated topics and a questionnaire that could be answered by all practitioners alike. My particular interest lies in uncovering any specificities of the difference in responses from practitioners who approach the same problem from different angles.

Quantitative analysis for mapping differences between disciplines on its own is not sufficient to find the reasons for the impediments to sense-making across collaborating disciplines in the early stages of design. The quantitative information stemming from the questionnaire is based on numeric data that can be interpreted in various ways in charts, tables and graphs. As much as this method illustrates differences between distinct disciplines, it does not say *why* these differences are in place and what actions could help to bridge between them.

In order to complement the quantitative nature of the information taken from the questionnaire, I asked each participant in my survey to respond to a set of ten questions during the one-on-one interviews at Arup. Based on my review of literature, the lessons learned from the stadium project, the observations as embedded in practitioner and the feedback given during the workshops, I prepared interview questions to explore ten aspects through *qualitative analysis*:

1. The rules-of-thumb practitioners usually apply in everyday practice,
2. The information practitioners would you like to have at their fingertips during meetings with designers/clients/colleagues in conceptual design,
3. The summary variables practitioners use to describe performance targets in their work,

requirements for mechanical ventilation (which in return influences ESD and MEP concerns), smoke-spread in case of a fire and acoustic properties.

4. The feedback mostly required from others during the early design stages,

5. The way practitioners would like to negotiate design priorities in the future,

6. The point of considering cost-issues and the quality of feedback about cost-implications of design alterations,

7. The ratio between time needed for reflection to inform design decisions compared to time spent with other disciplines to inform decision-making,

8. The type of media most appropriate for practitioners to communicate design-intent from and to others in order to *make sense* in a meeting,

9. Ways to extract information from previously completed projects to make it accessible to them in bite size as reference on live projects, and

10. If we had a miracle toolbox during early stage design, what should be included?

All interviews were audio-taped by me to allow me to engage with the interviewee through inductive questioning, leaving a margin for slight deviations from the initial question and social exchange between myself and the interviewee.

On the basis of results taken from the priority-questionnaire and the interviews, I profile the disciplines to draw a distinct picture of varying priorities and concerns that either impede or support the process of sense-making between collaborating practitioners in early stage design.

Overall this exploration helped me to finetune my research-question, to generate my hypothesis, and to profile the argument I present in this PhD research. Reponses from the interviews feed into the discussion on novel ways of conducting professional practice which I describe to in Chapter 5: *New modes of early-stage design collaboration*.

4.3. *Quantitative Analysis* – graphical mapping of professional profiles

In this section I present and map responses from the research-questionnaire where interviewees rated the importance of 36 design topics during conceptual design on a scale from one to five. I approached the mapping with three aims in mind:

1. to create profession-specific graphs that show a distinctive profile for each discipline,
2. to understand the importance each individual discipline assigns to a topic, and
3. to compare the results across separate disciplines in order to highlight and to understand commonalities and discrepancies between them.

I asked the participants to respond to a design for a hypothetical high-rise office tower to allow them to focus on a particular building function in their assessment. The construction of commercial office towers forms part of the core business at Arup and all practitioners were familiar with the task. I do not claim that responses derived from the office-tower example can be generalised for the use of other building functions. On the contrary, I argue that the results of this questionnaire are only valid when limited to the office function I prescribed – any other building type would most likely yield completely different results[41]. In agreement with Rush's findings (1986, 30) I argue that design priorities shared by architects and engineers on building projects are highly dependent on the use and type of a building as well as socio-economic, climatic or geographic circumstances, which cannot be generalised.

My generation of the list of 36 topics was preceded months of preparation in the Arup offices in Sydney and Melbourne. There I participated in design meetings, conversed with project-engineers and I consulted the office-libraries as well as the office-internal intranet. This embedded day-to-day interaction in the first two years of my presence in the Arup office allowed me to familiarise myself with the

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[41] The weighting of priorities on a building project differs based on the type and function of the project. In this survey I profile collaborating disciplines based on the priority they assign to a particular topic related to a specific building function. Every building function requires a different set of priorities and it would result in different professional profiles.

worldviews and work-methods the engineers and planners within the *Buildings Group*. I questioned members of all disciplines within the *Buildings Group* about their basic concerns in early-stage design collaboration to inform the composition of the topic list.

My list of 36 topics is hence set out to encompass design-aspects of all of the above disciplines. In order to lend further support to my enquiries I chose topics that translate across all disciplines participating in the survey, and that have, either directly or indirectly an effect on design aspects of all professions involved. I listed the 36 topics on the questionnaire in the following order:

1. Site and climate conditions, building orientation and the building form,
2. The structural system, the core and the construction material,
3. The building enclosure such as cladding material and shading,
4. Mechanical installations, services and levels of environmental sustainability,
5. Fire compartmentation and people-movement,
6. Interior finishes and acoustic properties, and
7. Financial aspects such as cost per square meter, return on investment and facilities management.

Once all interviewees had completed the questionnaire I summarised discipline-specific data for graphical representation using either spider (radar) diagrams that contain responses to all 36 topics, line diagrams to juxtapose and compare the top 12 response from each discipline, and bar-charts to present a qualitative summary of all responses. I chose the spider diagram as preferred graphic tool to map priorities because I believe it provides the beholder with the most clearly-arranged and demonstrably striking set of information. I wanted to visualise responses to all 36 topics on the questionnaire within one graph and to overlay graphs for comparison purposes. Spider diagrams allowed for a concise representation of all these topics

Next to the responses from individual disciplines I calculated the average priority given to each topic in the questionnaire. The analyses and profiling results of each group and the *total average* are presented in the next section.

4.3.1. Profiling disciplines based on their design-priorities in the early stages
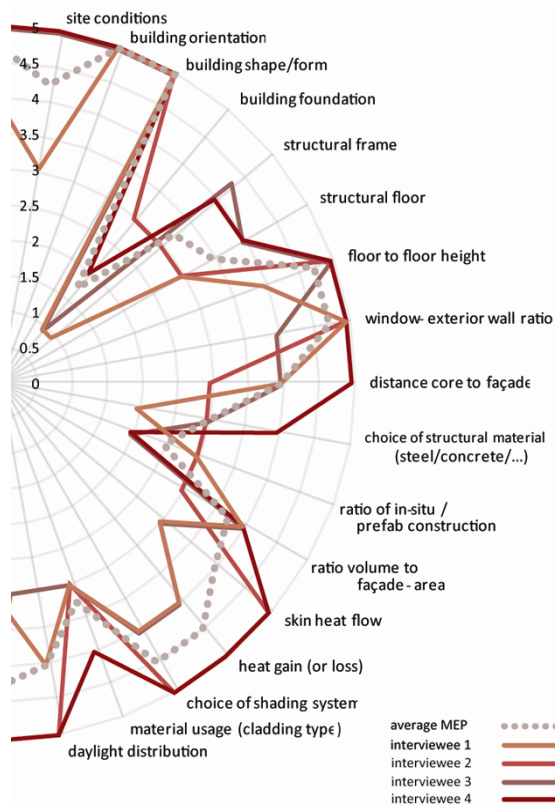
In the process of deriving a representative sample for each of the disciplines participating in the interview, I included four participants of each profession to obtain the average of their responses. I tested the validity of this method by checking the level of convergence when comparing individual responses with the *discipline average*

Figure 26: Detail of a spider diagram depicting a sample of responses from four MEP engineers and their discipline average, Source: Author

In most cases responses did consolidate with a sample of three participants and deviations between answers were in a vicinity of 10-15% at most when comparing the average of three to the average of four participants [42].

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[42] I consider this level of accuracy sufficient for my investigation because I do not aim at depicting a detailed description of a specific profession, but I aim at deriving a more general representation of profession-specific priorities limited to a pre-given design problem (an office tower) in the Australasian context. I do so to compare the responses of different *discipline averages* to understand the diverging priorities associated to different disciplines in the early design stages.

One of the key comments made by practitioners participating in the preparatory workshops was that they had insufficient feedback about those issues most relevant to their partners when trading off design-priorities. Responses from individual engineering experts (Figure 26) were generally closer to their *disciplinary average* than the responses from each of the participating architects (Figure 27). Ratings by architects did vary substantially.

Figure 27: Detail of a spider diagram depicting a sample of responses from four architects and their discipline average, Source: Author

This observation may indicate that the professional identity of architects is less coherent than the one displayed by engineers from Acoustic, ESD, Fire, Façade, MEP and Structures. Upon completion of the mapping process, I collated responses in a diagram to overlay all disciplinary graphs as seen in Figure 29.

Figure 28: Spider diagram with all *disciplinary average* responses on top of each other, Source: Author

As much as this representation by different colours does not display a clearly readable image of the varying priorities, the diagram illustrates that the topics I had selected did represent a suitable sample of concerns as there were no major gaps or any unusual concentration of responses in one particular spot. The overlay of all responses shows that nearly all topics rated high importance by at least one discipline.

In the following section I discuss the overall outcome of the topic-ratings from all disciplines.

4.3.2. Collected questionnaire results

In order to make the results from the *disciplinary average* responses explicit, I split them up in individual representations as displayed in Figure 29. I mapped the *total average* responses to provide me with additional options for comparison. After a general assessment I discuss the individual diagrams in more detail.
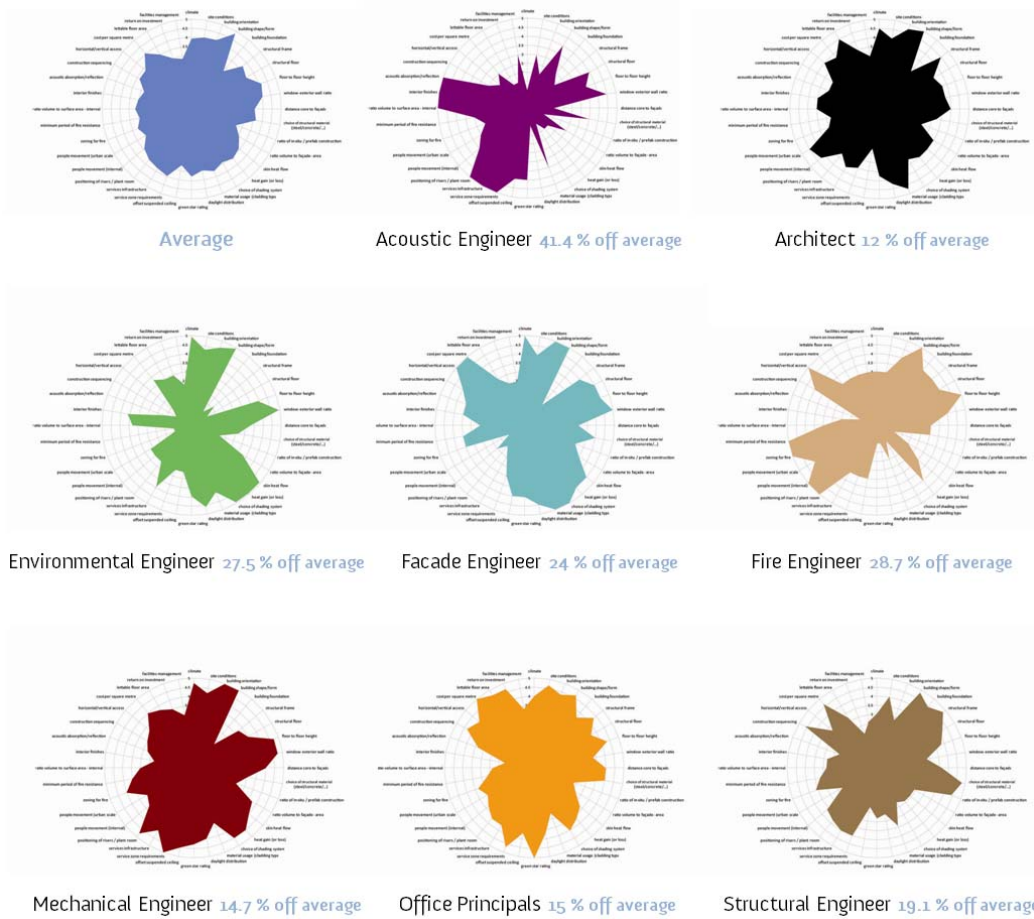
Figure 29: All disciplinary spider-diagrams juxtaposed next to each other, Source: Author

Each spider diagram in Figure 29 depicts low level of priorities as a central point with importance increasing towards the outside of the circle. The discipline profiles display distinctive characteristics that vary substantially from profession to profession. None of the discipline profiles are similar. They can be grouped in professions that are close to the overall average (Architects and Mechanical Engineers), professions that are far off the average answers (Acoustic, Environmental, Fire), and those with fair closeness to the average (Façades and

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Structural). Responses close to the average are spread in a coherent fashion around the circular diagram whereas those professions operating more in isolation display strong deviations with distinctive apexes and clusters of high or low extremes.

This graphic representation shows how some disciplines are mainly concerned with their own field and they appear to require little integration with the overall priorities of others apart from a few selected topics. I calculated and summarised the deviation from each discipline specific average from the total to be able to numerically compare the level of integration of isolation of each discipline. This calculation indicates that architects rate the closest to the average with 12% deviation and acoustic engineers rate the furthest with 41,4 % deviation from the average.
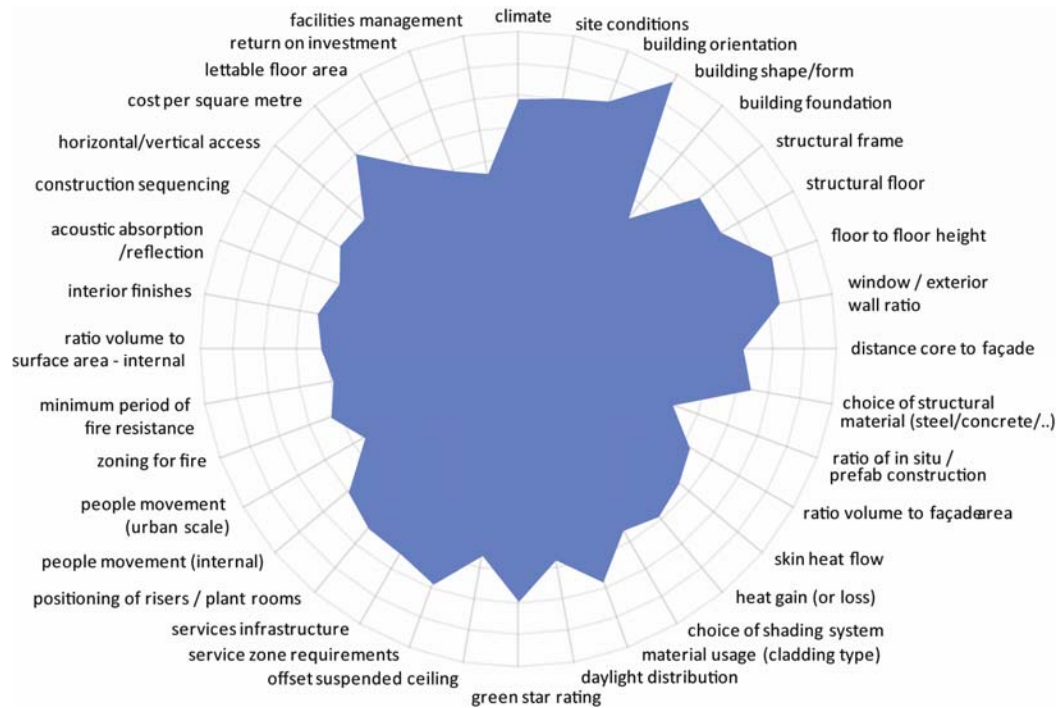
Figure 30: Bar-chart representation of the *total average* of responses from the questionnaire as a spider diagram, Source: Author

As illustrated by the *total average* graph in Figure 30, responses are distributed fairly evenly apart for considerations about acoustic particularities, the building foundation, and long-term cost to the client. The latter indicates that although

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practitioners are very concerned with cost issues that relate to their own work they have limited interest in implications of long-term planning such as *return on investment* and *facilities management.*
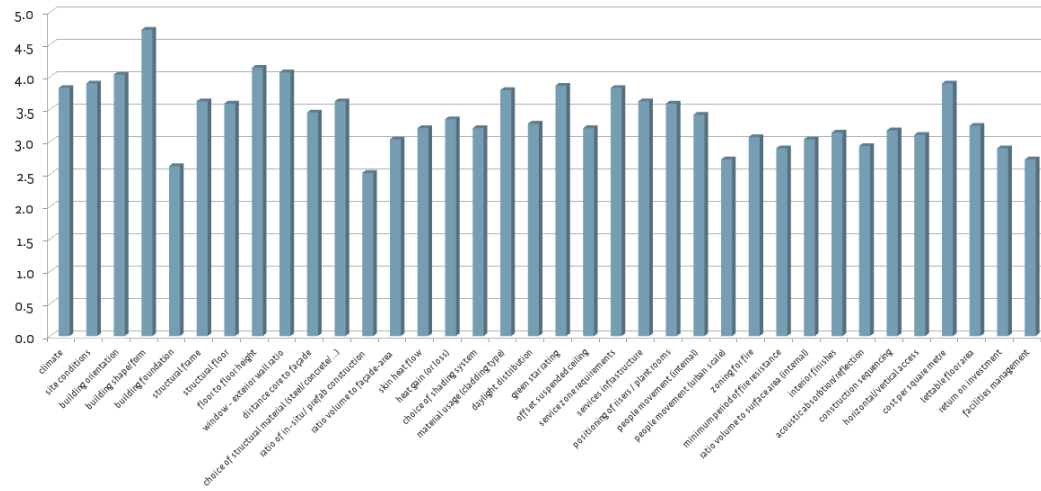
Figure 31: Bar-chart representation of the *total average* of responses from the questionnaire showing the overall spread, Source: Author

Results from the quantitative analysis undertaken with the use of the questionnaire do not only assist in profiling individual professions; by analysing the total average of responses, I am able to sort those topics that scored highest among all participants. Figure 32 illustrates the top 10 topics as chosen by the practitioners. On a level of relevance from 1-5, the topic *building shape/form* scored highest (4.7) followed by *floor to floor height* and *window – exterior wall ratio* (4.1); *building orientation* (4.0); *site conditions*, *cost per square meter* and *green star rating*[43] (3.9) and finally *service zone requirements, climate,* and *material usage* (3.8).

This result is a strong indicator that the form of a building, which is principally determined by the architect in the beginning of a project, has by far the strongest impact on on the work of all consulting engineers when considering the design of an office tower. The top 10 list illustrates that architectural considerations are not seen as the only high-priorities.

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[43] The green star rating is the Australian equivalent to the US *LEED* or the UK *BREEAM* ratings to classify the environmental friendliness of a building in regard to sustainable issues and the emission of CO2

The building envelope in its climatic and site context rates among the highest priorities including the orientation of the building, the ratio between window and wall elements on the façade and the cladding-material. This rating indicates that participants from the various disciplines acknowledge the importance of environmental performance of the building skin, including daylight transmission and thermal aspects that relate to the exposure to direct sunlight. This view is reflected in the high value for *green star rating*, which reflects the environemental sustainability level of the buildng during operation. The reasoning behind these results is not automatically obvious when interpreting the quantitative results portrayed in the top 10 list shown in Figure 33, and I present a deeper investigation when comparing these results with comments from the *Qualitative analysis of interview responses* in Chapter 4.5. In the next sub-section I examine the relevance given to individual topics by the acoustic engineers, architects, ESD planner, façade planner, fire engineers, MEP engineers, and structural engineers.
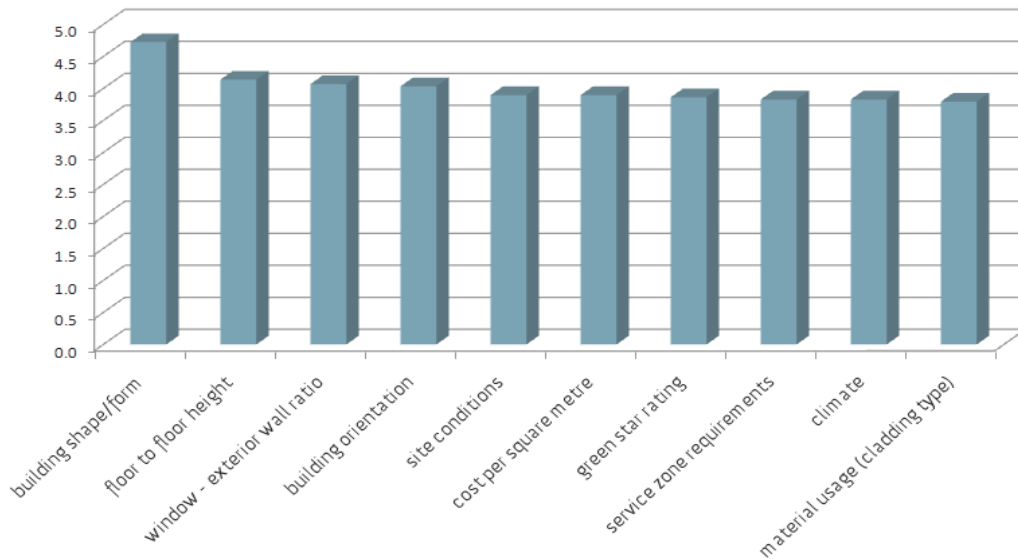
Figure 32: Chart with top ten responses from the questionnaire, Source: Author

4.3.3.   Quantitative responses by topic represented as bar-charts

In this sub-section I randomly selected six topics to graphically display the responses by the interviewees from each discipline. While the underlying data for the charts is identical to the data used for the spider-diagrams, the re-appropriation of the content in another graphic format highlights different aspects than the spider diagram. They illustrate that next to mapping professional profiles, the data from the questionnaire lends itself for analysing profession-specific sensibilities regarding particular design topics (in this case for an office tower). The rating exemplified in these bar-charts may, on first sight, display obvious results:

Whenever a topic lies within the particular field of interest of one of the groups, their ranking is particularly high. However, when analysed in more detail, the topic-specific bar-charts exhibit additional information about how other disciplines relate to the same topic. The appropriation of the interview-data highlights possible commonalities that may otherwise be overlooked by professionals from different disciplines, who are not experienced enough to judge the sensitivity a topic has to their design partners.
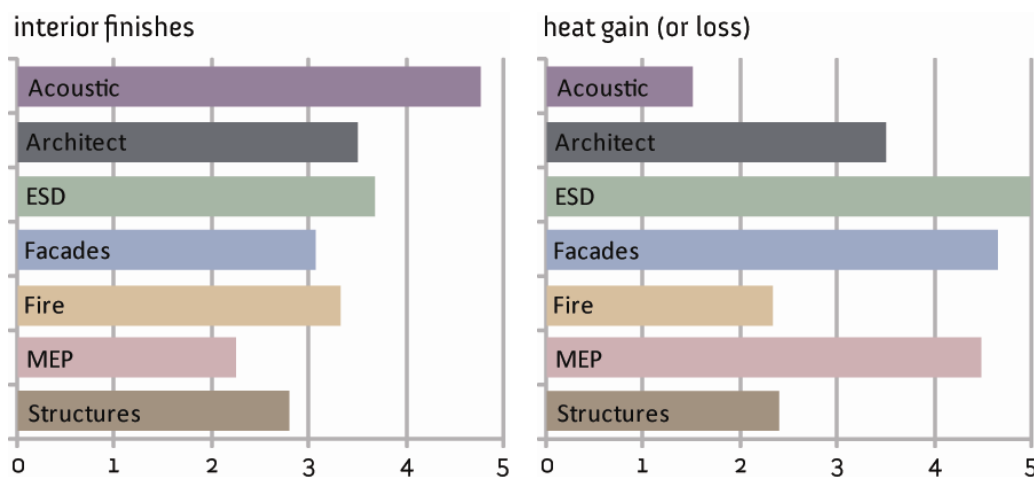
Figure 33: Bar charts with responses regarding *interior finishes* and *heat gain (or loss)*, Source: Author

As exemplified in the above diagrams, Acoustic engineers are particularly interested in the design of *interior finishes*, followed by ESD, Architects and Fire

engineers. The work of MEP engineers has little interface with the choice of interior finishes. The topic of *heat gain* in a thermal sense is of most relevance for ESD, Façades, and MEP while it has little impact on the work of Structural engineers, Fire engineers and for Acoustic engineers.
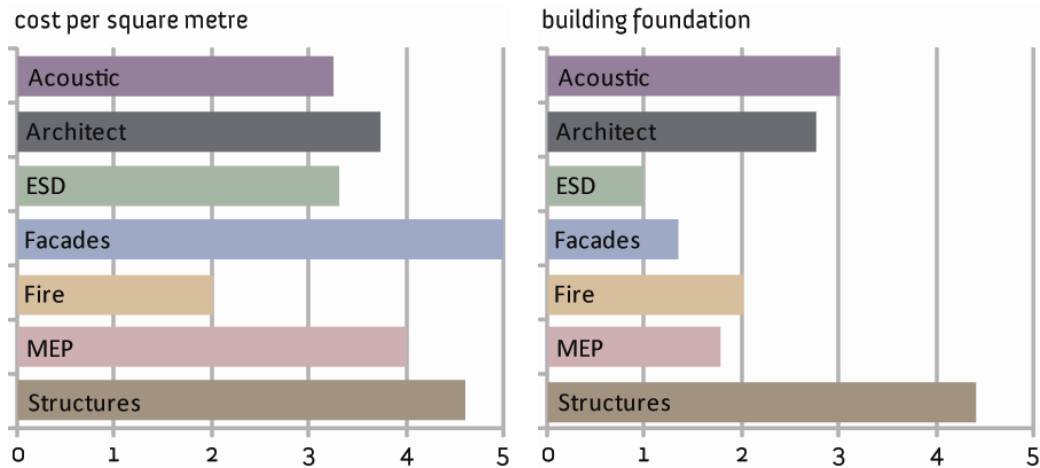
Figure 34: Bar charts with responses regarding *cost per square metre* and the *building foundation*, Source: Author

The chart generated from the *cost per square metre* responses shows that Façade-planners in particular require precise cost feedback for their work in the early design stages, whilst cost issues may be weighted-out by issues of safety in the work of fire-engineers. The graph in Figure 34 shows that the building foundation is a topic that is of high importance to the structural engineer and of little relevance to most others apart from acoustic engineers and architects.

This may lead to the assumption that acoustic engineers consider vibrations transmitted through the foundation.
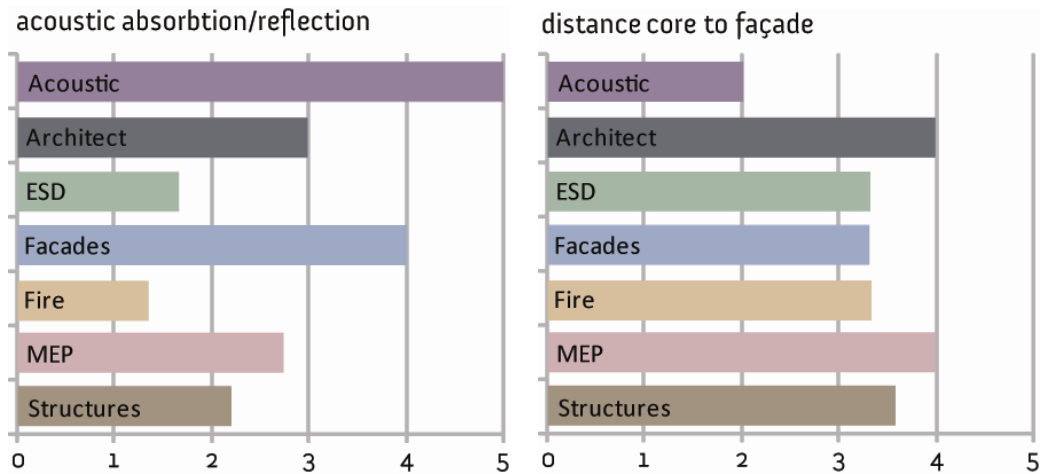
Figure 35: Bar charts with responses regarding *acoustic absorption* and the *distance from the core to the façade,* Source: Author

Similar to the previous example, Figure 35 also allows for interpretation of the interview results: acoustic absorption is central to the work of acoustic engineers and they share this concern with Façade-planners who include acoustic consideration in the design of the building envelope to avoid the transfer of street-noise into the building. The distance of the core to the façade is of high relevance for nearly all parties who participated in the interview. The reasons for this may vary and they include the layout of piping, structural depth of beams, daylight factors, distances of horizontal access, just to name a few.

4.4. Observations describing discipline-profiles individually

In this section I present and discuss the quantitative results from each of the seven individual disciplines on the basis of graphical representations through spider diagrams. I list the professions in alphabetical order starting with: Acoustic Engineering, Architecture, ESD, Façade Planning, Fire Engineering, MEP and Structural Engineering.

4.4.1. Responses from Acoustic Engineers:

As shown in Figure 36, the average responses from acoustic engineers displays a highly uneven selection of priorities with multiple apexes and two distinct areas of high ratings: The first lies within the area of building services and the service

infrastructure; the second lies within the area of interior volumes and finishes with consequences on acoustic properties inside the building. Acoustic engineers assign high importance to the structural floor, the ratio between window and exterior wall as well as the material used for the cladding. These selections reflect that acoustic engineers provide input on at least three distinct areas in a building:

1. the acoustic properties of the cladding which has an impact on the reduction on exterior noise,
2. the reduction of noise arising from building services – either piping or mechanical installations, and
3. the acoustic properties of interior finishes in relation to the surface area and particular volumes.
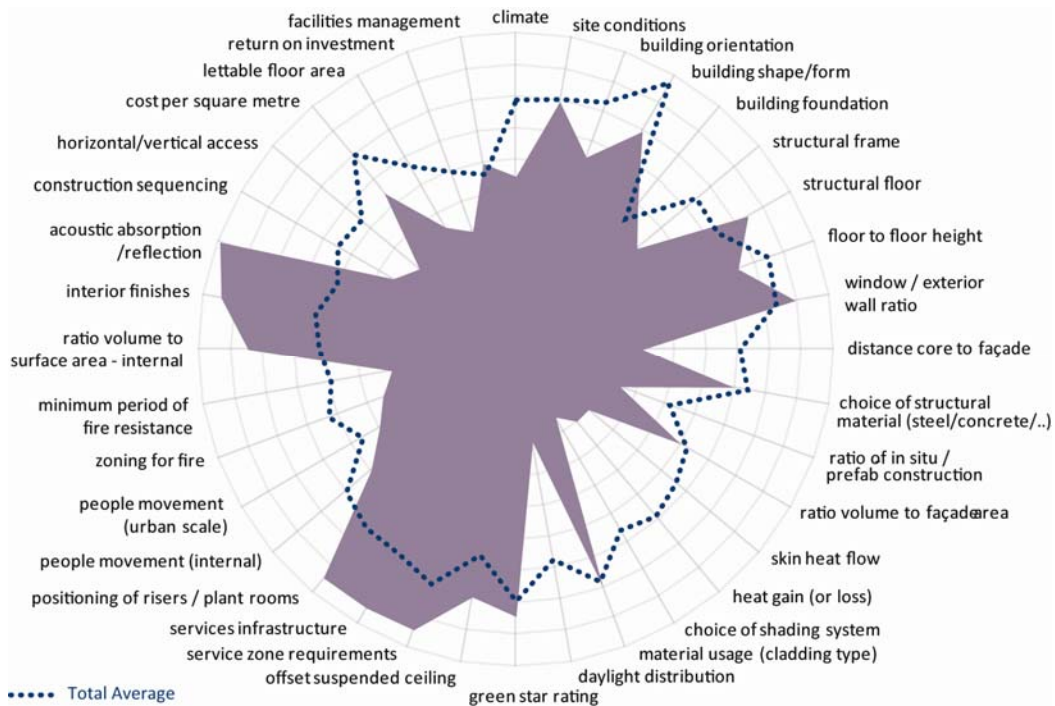
Figure 36: Spider Diagram with responses from acoustic engineers rating the priorities of 36 design-topics related to a high-rise office tower, Source: Author

Overall the selection of priorities alternates to a high degree and the responses from the individual interviewees are very close to each other. This similarity indicates a highly coherent professional profile. The results from the acoustic engineers are in strong contrast to the *total average* of all responses with 35.5% deviation.

4.4.2. Responses from Architects

Average responses of the architects illustrate fairly even distribution of priorities across various parts. Even though there are few clusters of similarly rated results, the apexes between different responses are, in most cases, moderate. Exceptions are very low priorities given to the building foundation, the construction method, the offset of the suspended ceiling and facilities management. As mentioned previously in this chapter, the individual responses from the architect interviewees vary substantially from each other and it is therefore difficult to capture architectural identity in a simple graph. In that sense, the architectural profession is quite diverse and multi-layered with individual members focusing on different aspects of building design.

The responses by the architects are 13.6% off the average, which is the closest of all professions. This can be interpreted as the architect having the best overview about all priorities combined and thus making him or her suitable as the *generalist* or the *integrator*. In contrast to most results by the engineering professions, less than a fifth of responses rate higher than 4 on the priority-scale.
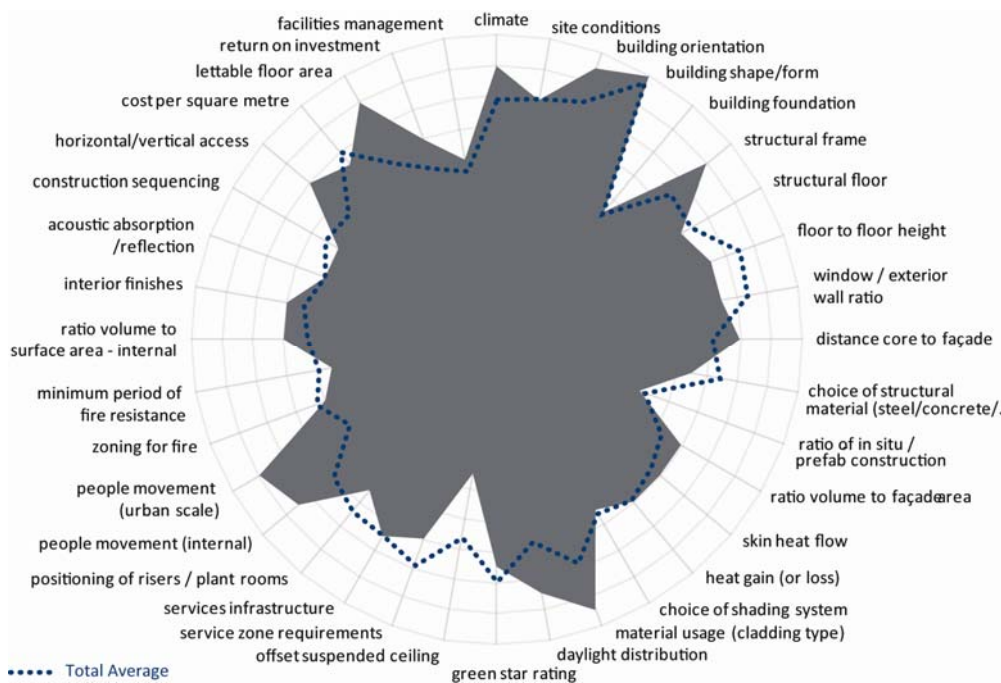
Figure 37: Spider Diagram with responses from architects rating the priorities of 36 design-topics related to a high-rise office tower, Source: Author

4.4.3.   Responses from Environmentally Sustainable Design (ESD)

Interviewees with ESD background responded to the questionnaire with strong variations of priorities assigned to the 36 topics. Responses from individual participants in ESD were very similar. As the graph in Figure 38 illustrates, there are several aspects that are of highest relevance for ESD whilst at the same time many aspects have little to no priority at all. The graph depicts sharp-angled apexes with two clusters being particularly prominent.

The first cluster responds to contextual topics such as climate, site conditions, the building orientation and its form; the second (stronger) cluster reflects high importance of issues related to the building envelope such as skin heat flow, thermal heat gain, choice of shading system and daylight distribution.
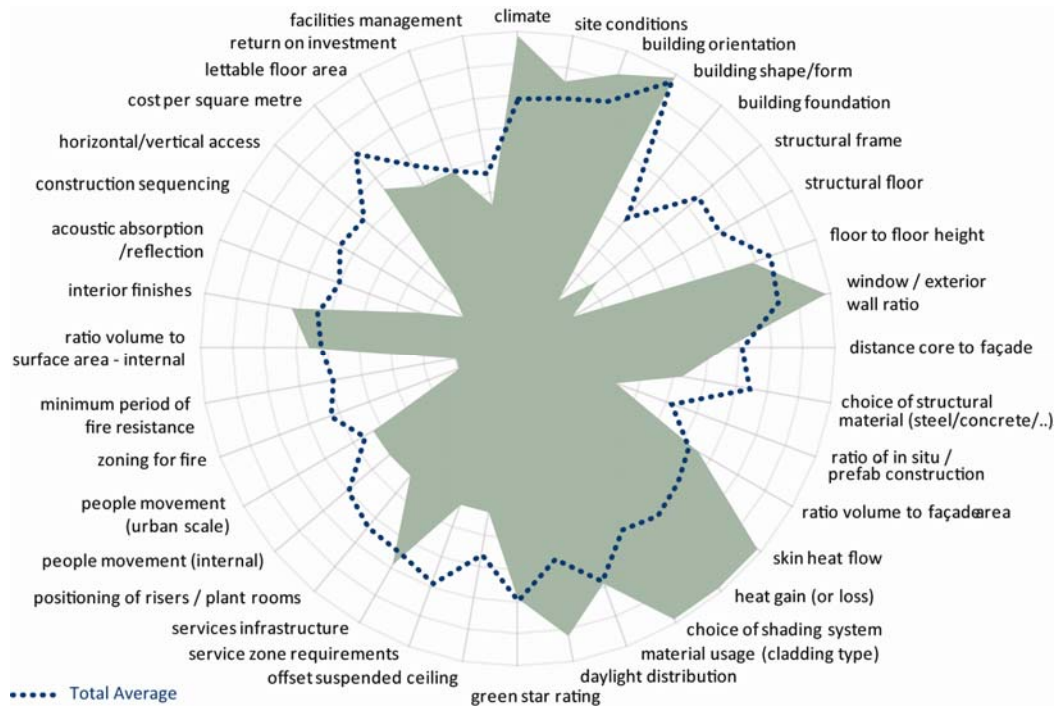
Figure 38: Spider Diagram with responses from ESD rating the priorities of 36 design-topics related to a high-rise office tower, Source: Author

In the questionnaire the participants from the ESD field show complete disregard to issues concerning the building's structure, fire safety, construction method and

sequencing as well as the type of access to the building. There is low priority assigned to the choice of structural material as well as facilities management.

Overall this result raises questions whether ideas of environmentally sustainable design are encompassing a wide enough scope of design-collaboration across disciplines. Responses are 28.7 % off the total average. This result is surprising to me as I had expected a higher level of interest across the spectrum of the 36 topics by environmental sustainable designers to contribute to the overall conception of a building.

4.4.4.   Responses from Façade Planners
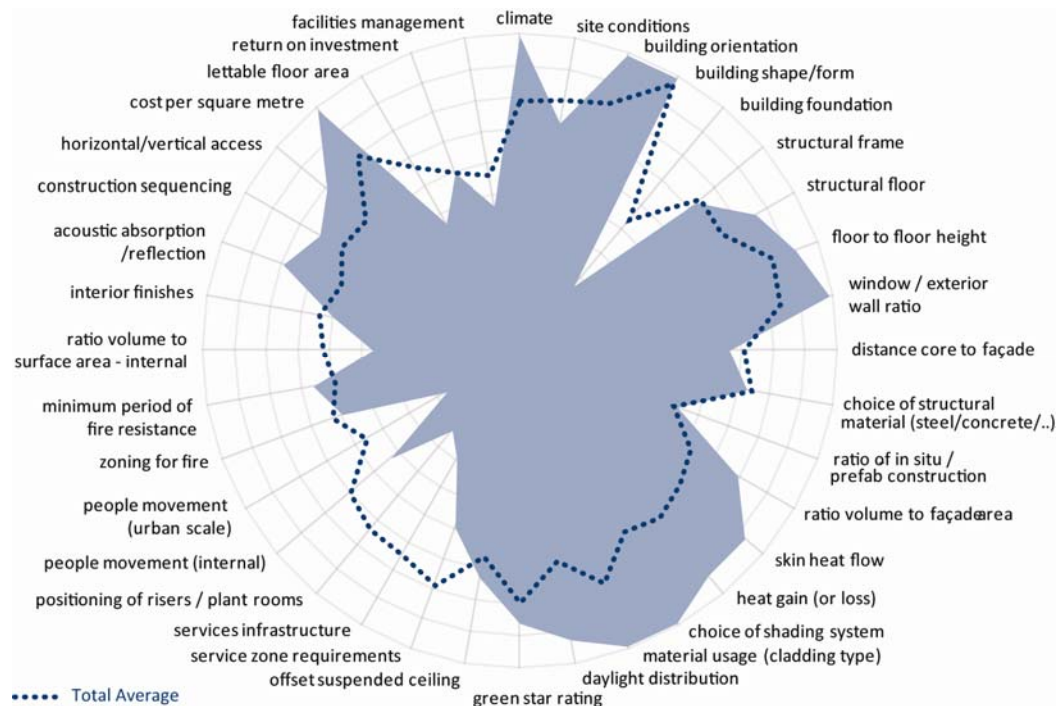
Figure 39: Spider Diagram with responses from Façade-planners rating the priorities of 36 design-topics related to a high-rise office tower, Source: Author

The graph derived from mapping responses from Façade-planners in Figure 39 presents a heterogeneous result. On the one hand there are strong differences in priorities across various topics which indicates that Façade-planners deal with those aspects in isolation, on the other hand there is a strong cluster with coherent high levels of priorities apparent in the areas regarding the building envelope, the

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building-context, the structure and cost. The graph indicates that Façade-planners have a particularly low interest in aspects of the building that deal with the interior, apart from acoustics. As much as they focus on the building envelope itself, aspects related to MEP and fire rate very low on their priority-scale. There is a marked difference in the high-ranking of the *cost per square meter* topic compared to other cost related issues such as *lettable floor area, return on investment* and *facilities management* which are all on the bottom of the priority-scale.

The responses from the Façade-planners deviated from the *total average* by 24% although the responses from individual interviewees were very similar to each other. This cohesion suggests that façade-planning has strong professional identity.
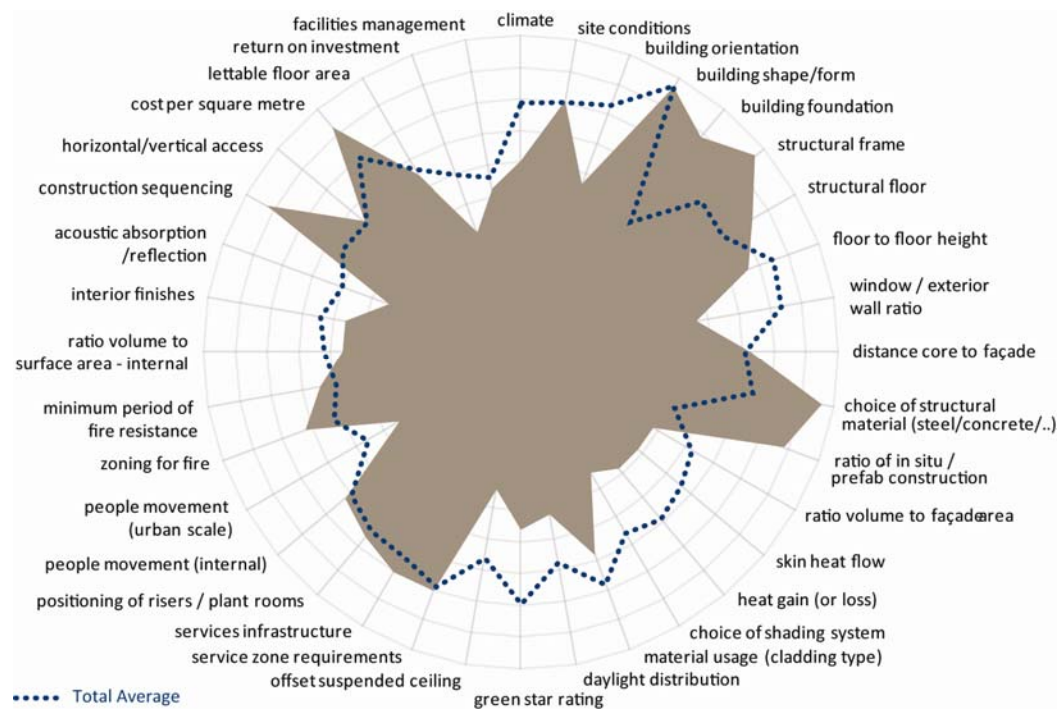
4.4.5.   Responses from Fire Engineers
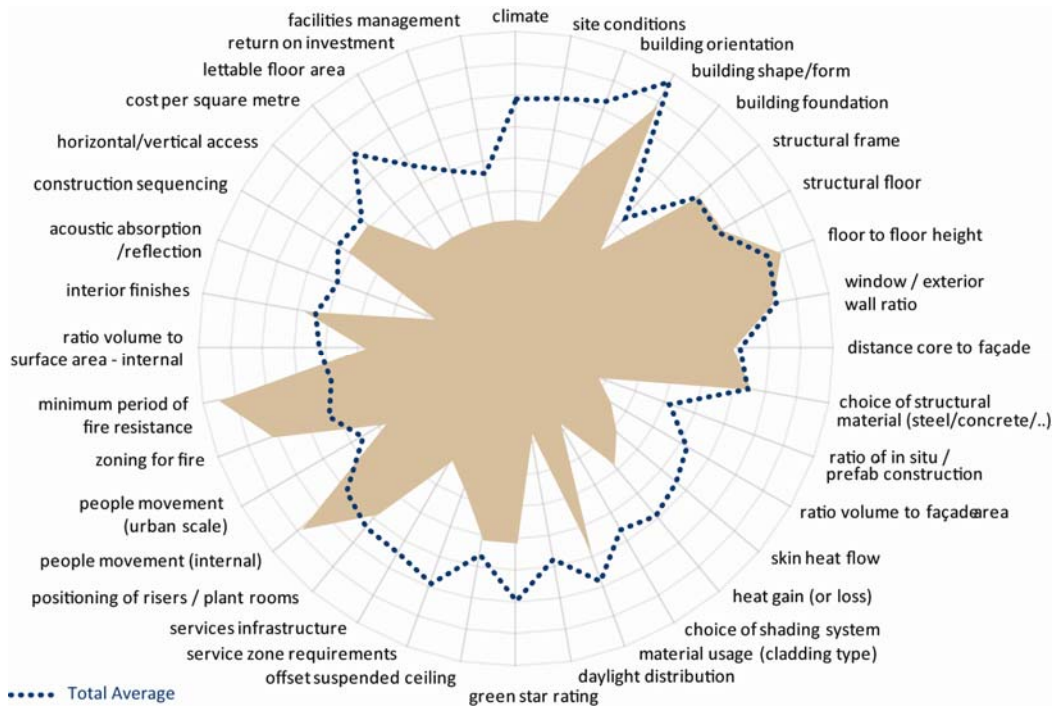
Figure 40: Spider Diagram with responses from fire engineers rating the priorities of 36 design-topics related to a high-rise office tower, Source: Author

The fire-engineering graph as shown in Figure 40 displays an atypical shape as it appears squashed diagonally. There are strong apexes indicating major alterations in the priority-rating.

The diagonal clusters of high importance-issues relate in particular to the building shape, to most structural topics, to people movement, and to issues of fire-safety. Most other topics (such as the building context, façade-related aspects, ESD, acoustic concerns and cost rate very low with minor exceptions such as the *cladding material, green star rating* and the *offset of the suspended ceiling*. These results suggest that fire engineering appears to be a discipline that operates to a large degree, detached from other disciplines except from the structural engineer, and possibly the architect.

Responses from fire engineers deviate from the *total average* by 26.2% with very strong similarities between the responses from individual practitioners. Two questions emerge: Firstly, why are the results from fire engineering so different from most of the other disciplines? And why do fire engineers put so little emphasis on cost?

It is difficult to interpret the graph without additional feedback from the qualitative analysis.[44]

4.4.6. Responses from Service Engineers (MEP)

Next to architects, MEP engineers responded closest to the *total average* with a 17.4% deviation. The graph in Figure 41 shows that in contrast to the architects, individual engineers from MEP rated very similar to their disciplinary colleagues. This indicates a strong professional coherence coupled with a good understanding about a variety of building-related aspects. There are no major apices in the graph apart from a low rating for the topic of *building foundation*.

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[44] My research about the involvement of fire-engineers in the design process suggests that their task is mainly driven by code-compliance for safety of occupants in a building. There are only few options for trading-off these severe concerns with other design aspects. Issues of comfort, cost, or aesthetics come second when serious threats to safety of occupants need to be considered.

The strong similarity of the MEP profile to the *total average* leads to the question about the reasons for the high level of integration apparent in the work undertaken by MEP experts.

One assumption I make at this point is that MEP consultants are usually introduced to the design process at an advanced stage when many of the other professionals including the architect, the structural engineer, the façade-planner, and the ESD expert have already provided their input on a project. The MEP engineer often has the responsibility to interact with all of these parties either directly or via the architect. Building services are affected by the external climate conditions as much as they are influenced by the internal spaces of a building and MEP engineers need to negotiate their space-requirements with each of the above mentioned professionals.
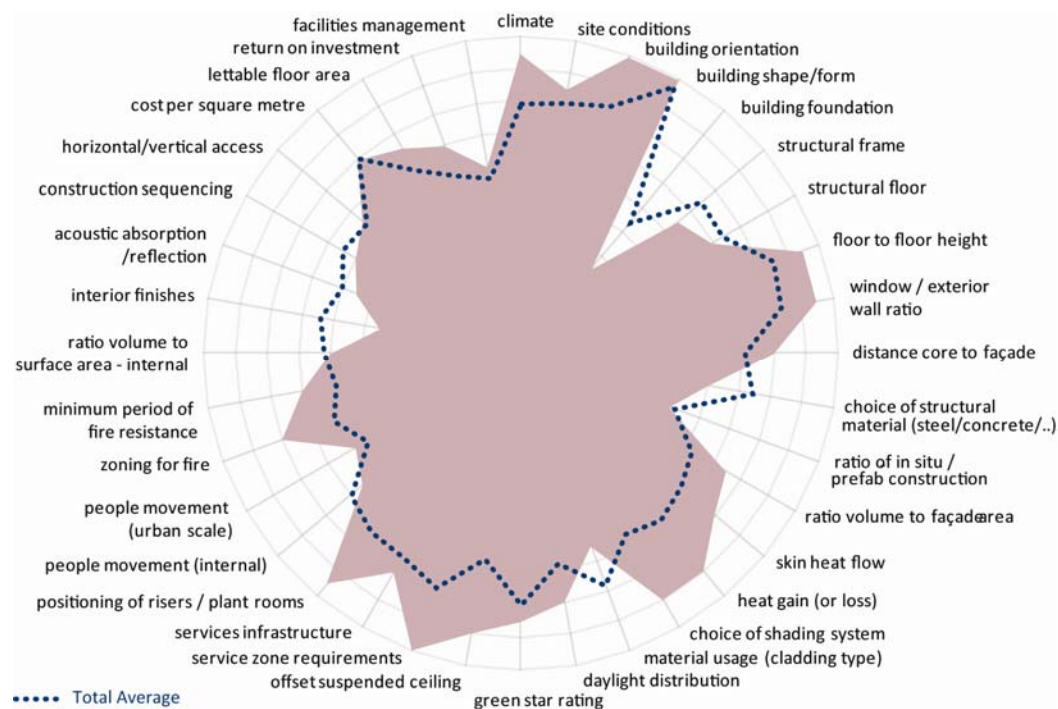
Figure 41: Spider Diagram with responses from service engineers rating the priorities of 36 design-topics related to a high-rise office tower, Source: Author

4.4.7. Responses from Structural Engineers

The graph with the results from the structural engineers in Figure 42 reflects a heterogeneous array of responses with a low 20.4% deviation from the *total average*.

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Nevertheless, responses from individual structural engineers were dissimilar to the *discipline average* indicating a low level of professional coherence. There are multiple sharp apexes to be found in the graph but at the same time there a few extreme differences between highest and lowest ratings. Structural engineers display little interest in issues related to the building envelope, the interior, acoustics and the overall context of the building. On the other hand they rate the shape of a building, its structural frame, and the structural material highest, followed by concerns about construction sequencing and cost per square meter. These observations suggest two salient questions:

The first asks if the lack of consideration structural engineers give to an array of other building related aspects is due to the fact that they are disconnected from structural concerns? The second asks: Do environmental sustainable design, MEP and acoustic engineering come secondary to structural considerations? Qualitative methods are required to respond to these questions and I address them through the interviews in the following section.

Figure 42: Spider Diagram with responses from structural engineers rating the priorities of 36 design-topics related to a high-rise office tower, Source: Author

4.4.8.   Comparing responses using line-graphs

So far I have investigated the dataset derived from the quantitative analysis to show results relating to indivdual topics or professional profiles. In this section I juxtapose and compare responses from the individual disciplines with each other by overlaying them using line-graphs. I firstly focused on the top twelve topics to illustrate how the results of different disciplines vary from the *total average*. The examples selected in Figure 43 illustrate the strong divergence in the priorities of acoustic engineers compared with the average rating and they show the comparable closeness of architectural responses to the *total average*.
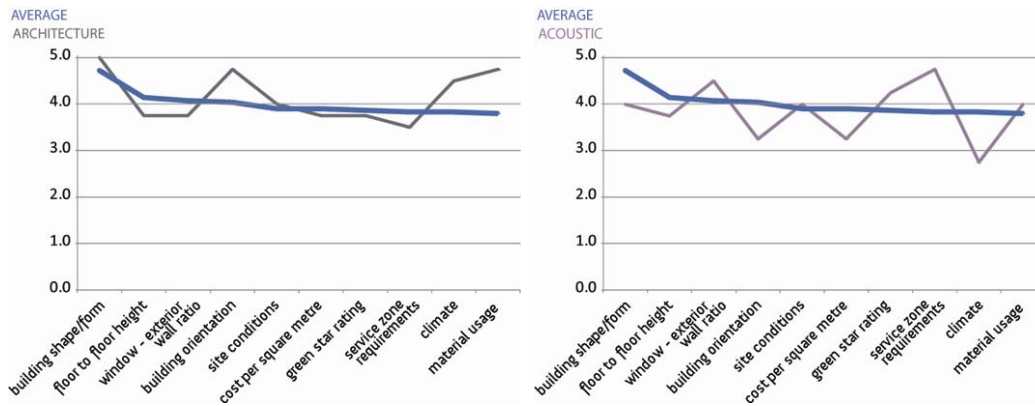
Figure 43: Overlaying the line-graph of Average responses with Architecture and Acoustic, Source: Author

A varition of this method allows me to compare disciplinary particularities by overlaying two disciplinary-graphs on top of each other as shown in Figure 44.
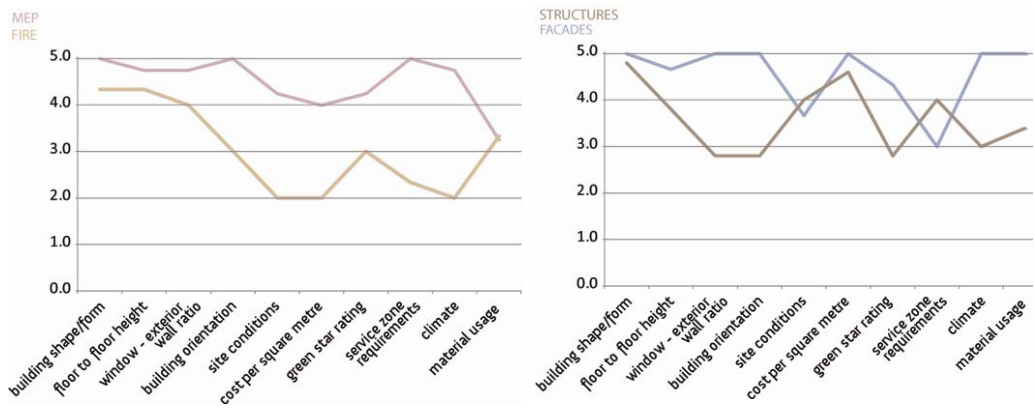
Figure 44: Overlaying the line graph of MEP and Fire, as well as Structures and Façades, Source: Author

Extracting differences from the graph shows that priorities between MEP and Fire engineers are, in almost every case, strongly diverging. On the one hand, structural engineers and Façade-planners have several points of shared priorities. These priorities include for example *cost* and *site conditions*. On the other hand, they do not share common priorities for other topics such as material usage, building orientation or the window to exterior wall ratio. The line graphs clearly depict a useful snapshot of the top 12, results but more comprehensive comparison is possible when using a spider diagram-overlay for all 36 topics.

In order to illustrate comparative analysis of all 36 topics between two disciplines, I chose two examples to compare profession specific priorities in the form of spider diagrams. In the first example I compare the results from ESD with Structures to understand which commonalities, differences and particular high priorities ('Hot Topics') they encompass. Such comparative overlays can be generated using pairs of any of the disciplines I investigated. I colour-coded areas of large discrepancies to highlight major differences between the professions. The graphs do not explain per se why members from one profession assign high priority to one topic or group of topics while it has little priority for another. This discrepancy is due to the quantitative nature of the enquiry. On the other hand the graphs illustrate differences or similarities between individual professions that may not be obvious to them.

In Chapter 0: *Coexperience contributing to collaborative understanding,* I flag the importance of comparative graphic data as presented in this chapter, to allow professionals to realise quickly commonalities and differences of their discipline-driven approach. I argue that priority-maps such as those presented in this chapter are a useful instrument to create awareness of common design issues across disciplines. Graphics depicting discipline-specific priorities could allow professionals to create a symbolic representation of their world-views in context

of a specific project type and function. They could assist in discussions across disciplines to help determine the overall building performance.
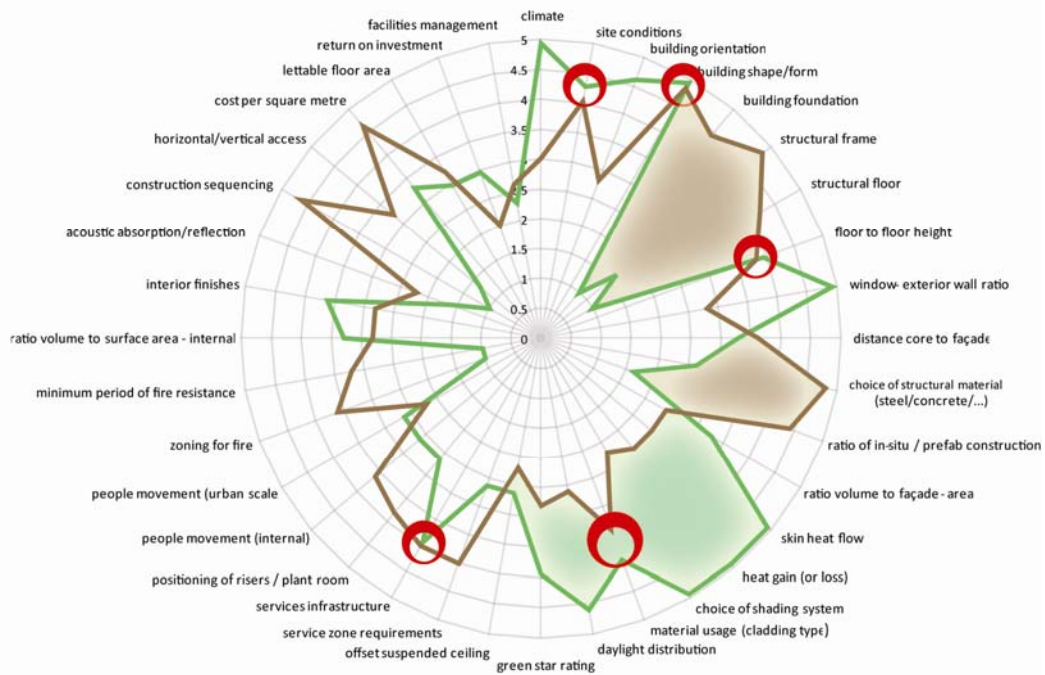
Figure 45: Spider diagram with an overlay of responses from ESD and Structures, Source: Author

Figure 45 illustrates the low level of common priorities between ESD and Structures. The two professions share five *hot topics,* three of which rated *4* or higher on the *priority-scale* of the questionnaire (site conditions, building shape, floor to floor height), and the other two rate between *3* and *4* (material usage for cladding and the services infrastructure). ESD consultants assigned low level of priority to structural concerns including the choice of structural material. This shows that the representatives from ESD do not currently consider the impact of structural systems and their material selection on our environment. Structural engineers, on the other hand, are little concerned with environmental issues apart from the cladding type, as this affects the vertical and horizontal loads on the primary structure.

The second example for comparing profession specific priorities through the use of a spider diagram presents an overlay of responses from Façade-planners and MEP engineers.

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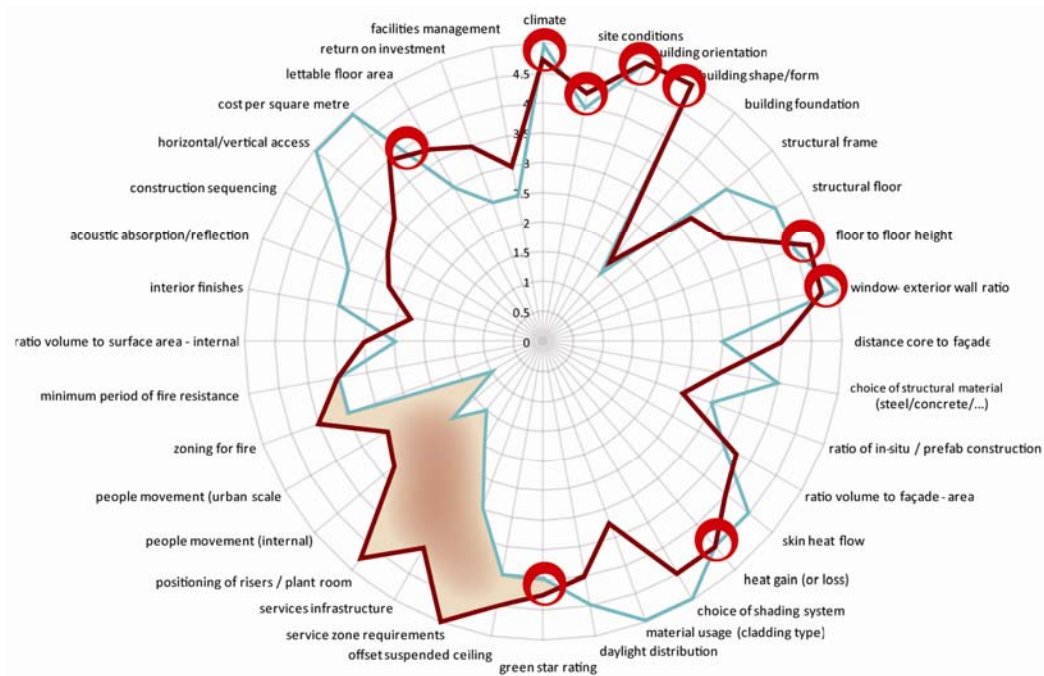
Figure 46: Spider diagram with an overlay of responses from Façades and MEP, Source: Author

The overlap of multiple similar priorities indicates a high level of interdependency between Façades and MEP. As shown in Figure 46 there are nine *hot topics* and most of them relate to the building context such as the climate, site conditions, the building orientation and form. Other shared priorities relate to issues that influence or at least describe thermal properties of an office tower such the height from floor to floor, the window to exterior wall ratio, heat gain, and green star rating. *Cost per square metre* is another topic rated equally highly by both disciplines. The biggest discrepancy between the responses from Façades and MEP stems from the area of *services infrastructure*, *service zone requirements* and the *positioning of plant rooms*. As much as these are essential topics for MEP, Façade-planners assign little priority to topics related to MEP as they do not immediately impact the building envelope. The results from Figure 46 lead to the observation that the physical performance of the façade is highly important to MEP engineers while Façade-planners do not seem to depend on MEP layouts in their judgment of priorities.

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In summary, the investigation into all seven disciplinary average responses resulted in an explicit visual representation of professional particularities. The main findings from the quantitative analysis can be outlined through the following six key insights:

1. There is a currently a distinction between professions which target the integration of design aspects from concerns of multiple participating professions (such as architects and MEP designers), and those professions which still operate in relative isolation to others by focusing on a limited set of concerns (acoustic engineers, fire engineers, and ESD planners).

2. Three of the top ten priorities as selected by all practitioners relate to basic aspects of a building such as its *shape, orientation, and site conditions*. Having these topics as part of the top ten is little surprising given their over-arching importance on building design. What did surprise me was the high rating of issues such as *floor to floor height* and the *window to exterior wall ratio* (rating second and third). My research suggests that these two aspects appear to require a high level of coordination between various professions collaborating on building projects.

3. One trend that is recognisable from the top ten results is the importance that is given to environmental sustainable issues such as the *green star rating*, the *climate*, and the *selection of the cladding material*. This seems to suggest that designers from all disciplines assign an high level of priorities to the impact of the building to the climate (and vice versa).

4. The spider diagrams revealed that architecture is (still) the one profession capable of best judging and balancing the overall priorities of a building project. Architects judged priorities closest to the *total average* from all seven disciplines represented in the survey. In that sense, the generalist nature of the architectural profession appears best suited to integrate the various engineering inputs occurring on a project such as the hypothetical

tower from the questionnaire[45].   Questions arise in how far this integrator status of the architect can be maintained with increasing complexity on building projects.

5. The overlay of pairs of disciplinary spider-graphs revealed the occurrence of *hot topics* that are shared amongst disciplines. At the same time the overlay exposed areas of large discrepancy where priorities between professions were strongly divided. Interpreting the reasons for these shared concerns and discrepancies based on quantitative analysis would require extensive speculation on my behalf and I do not see the usefulness of engaging in such venture. Instead, in the context of this thesis I propose to use these graphs as guidelines for the professions involved to understand how their work relates to the work of others. This proposal leads me to the last key insight:

6. There exists currently a lack of explicit visual information that helps designers in practice to understand how their priorities rate in relation to the priorities of other disciplines. Members of the Buildings Group welcomed the graphic depiction of priorities and they easily comprehended the results. Even further, they were highly inclined to interrogate the spreadsheet that contained all the data from the quantitative analysis, to extract information relating to their work.

The results from the questionnaire give valuable insights about different disciplinary profiles and the nature through which they engage in design collaboration. Some disciplines seem to prioritise a singular focus on specific design aspects that relate to their discipline over their capability for *sense-making* across disciplines. The reason for such attitude may well be influenced by their lack of knowledge about the effect of their work on others and the reliance on the

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[45] Engineers at Arup remarked that they saw the architect as the first and obvious candidate to coordinate their work. With all the knowledge form multiple disciplines (literally on one floor) in the *Buildings Group* at Arup, they expected a third party, the architect, to coordinate their various inputs.

architect to coordinate the various inputs from multiple professions. The highly networked interrelations intrinsic to planning and design processes as described in Chapter 3.2.1: *Sharing knowledge in conceptual work.*, may not always seem obvious to all collaborating partners. We cannot reasonably expect all team members to understand all the priorities brought to a project by others. What seems possible though for professionals, is to make the effort to understand the potential effects of their output upon the work of other professionals involved in a project. The mapping of results presented in the previous sections is one example of how this can be achieved.

4.4.9. Limitations of the quantitative analysis:

The results I have presented so far in this chapter stem from the quantitative analysis of responses taken from a questionnaire that leads to a map of priorities for the design of a high-rise office tower. The analysis of the visually processed data highlights typical profession specific profiles and I discussed the similarities and differences between the seven disciplines who participated in the interview using selected examples. In due process I repeatedly highlighted the limitations that quantitative analysis entails in the context of mapping professional particularities as the data often does not explain *why* certain topics were more important to some than to others.

In the following section of this chapter I complement the responses from the questionnaire with responses from the one-on-one semi-structured interviews with practitioners from all seven participating professions. I evaluate the results from the interviews to review critically qualitative aspects of design collaboration and to comprehend better the mechanisms that lead to common understanding and *sense-making* between disciplines in the early design stages. If quantitative analysis has provided me with answers about *what* the priorities of individual disciplines are, I use qualitative analysis to help determine *why* professionals from different disciplines assign their priorities to certain topics, I explore *how* they

bring in their knowledge in collaborative design processes and *how* they negotiate and trade off priorities to reach a common goal.

4.5.   *Qualitative Analysis* of interview responses

The model of design as sense-making in conversation may take us further, for as it requires us to specify the participants in the conversation in their institutional and historical settings, we come close to the issues of systematic exclusion and bias that are so often institutionally present. (Forester 1985, 19)

As described previously, I chose two distinctive methods for evaluating the responses derived from the interviews. In the previous sections I used the method of *quantitative analysis* to represent professional profiles. I compiled responses from the priority-rating given to the 36 topics by each interviewee in a spreadsheet to then sort the responses according to professional affiliation as numeric data. Upon completion of the spreadsheet with all quantitative data, I mapped results graphically to create a visual profile for each profession, and to juxtapose different disciplines for comparison.

In contrast to the previous sections, the method used in this section aims at a more in-depth evaluation of professional specificity using *qualitative analysis*. I first transcribed the 28 interviews fully to distil the comments that reflect special characteristics of the individual disciplines, as well as shared design issues across the seven disciplines involved in the interviews.

Prior to conceiving the interview questions I fathomed aspects of design that contribute to the sense-making process of individuals and groups.   I asked practitioners two types of questions during the semi-structured one-on-one interviews to receive feedback about their input in early stage design. The first type of question related to the manner in which they bring in their personal experience and it dealt with the deliverables that are expected from them. The focus on individual work practice allowed me to understand better each

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interviewees' point of view in regard to his or her role in the design. My five questions were the following:

1. *What rules of thumb do you apply during early design?*
2. *What performance targets are you working towards?*
3. *How can knowledge from precedent projects be captured?*
4. *What information would you like to have at your fingertips during meetings? and*
5. *Do you always have sufficient cost feedback of design alterations?*

The second set of questions related to the interaction of professionals with colleagues from other disciplines. I asked practitioners to reflect on their dependencies on others in a multi-disciplinary design environment, and I questioned them about the notations they use to communicate with others. My five questions were as follows:

1. *Would you be able to provide better estimates if you had simultaneous feedback from others and which feedback do you require most during early stage design?*
2. *When do you need to retreat from multidisciplinary design to reflect on a problem within your discipline?*
3. *What media is most appropriate for you to communicate design intent to and from others?*
4. *How could you negotiate design-priorities differently to current practice?*
5. *What would you put in your miracle toolbox?*

I present the general responses I received for each of the above questions from highly experienced practitioners from within Arup[46] and from associated architects in the following section. The semi-structured nature of the interviews

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[46] I selected the interviewees at Arup and collaborating architects on basis of either their long term experience or their outstanding contribution in their particular field. Out of the 28 interviewees, there are three office principals and eight group leaders across all disciplines. The other participants hold important positions within either as project engineers or project architects. Nearly all participants were highly-skilled in the use of CAD tools.

allowed me to deviate from the questions at times to explore inductively issues of early design collaboration and to uncover issues that I had not included at the outset of the interviews. I highlight the themes that reoccurred during the interviews and I discuss those topics where responses between the seven disciplines strongly diverge. In support of this exploration I include quotes recorded during the interviewees to stress particular points of interest that help describe a specific condition they are facing in their work practice. This inductive approach to profiling profession-specific behaviour is in accordance to the previously mentioned *"maximum variation sampling"* method by Lincoln and Guba (1985, 201). It allowed me to analyse specific aspects intrinsic to each profession to highlight its unique character. The qualitative analysis made me understand why professionals from varying backgrounds apply their judgement differently to others and where most common concerns can be found amongst them.

In Chapter 5: *New modes of early-stage design collaboration*, I refer back to the answers received from the interviews to bring them in context with the background research I presented in Chapter 3: *Epistemological barriers between professions in the building industry*. In doing so, I elicit schisms and agreements in the manner academia and practice deal with topics related to early-stage design collaboration. I aim to uncover points of interest about sense-making between design professionals for future discourse through flagging those aspects of design collaboration that are shared between various design-team members.

4.5.1. List some basic rules-of thumb you apply during early design
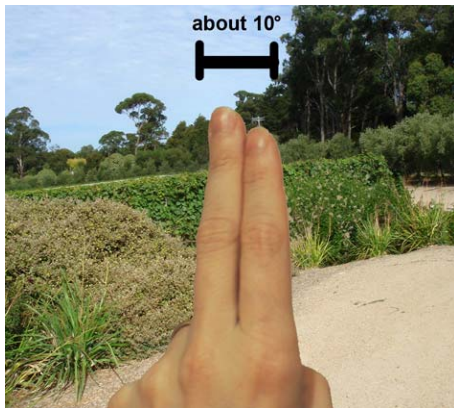
Figure 47: Illustration - Applying rules of thumb, Source: Author

Conceptual design can be characterised by processes of exploration and evaluation of ideas through estimates, second guessing and the application of rule-of thumbs to check quickly if a given design option is

feasible in accordance with the design vision (Schön 1985, 27). In the early design stages, the importance of feedback from various disciplines can never be classified *a priori*, but it becomes evident during the process of design conversations - the process of sense-making between the various parties that interact on a project (Lawson 2005, 389)[47]. As decision-making processes occur with high speed during the early stages, it is crucial that those involved provide reliable feedback in a short matter of time and with sufficient confidence that others can base their assumption on it. During the interviews I established the claim that such action is closely linked to the level of expertise of individual participants on project-teams.

One practitioner with more than 25 years of work experience stated: *"The only real guide at these early stages are your own experience and knowledge on when you are stepping over own limits"* (structural engineer 1)

Other interviewees with extensive experience agreed to this notion. They added that the rule of thumbs they apply at the outset of a project were first and foremost based on experience gained on precedent projects. A structural engineer described this in more detail: *"What we would normally do is to know from experience what size beams would be based on previous projects and spans, and use those as starting point."* (structural engineer 4)

Responses from professionals with few years of experience in practice indicated that, to them, rules of thumb were not the only guidance during conceptual design. Those junior practitioners and those with a high level of computational skill pointed to an increasing availability of computational support during conceptual design. Rules of thumb helped practitioners in the early stages to interrogate results for unexpected trends and experts of many years confirmed that they always hold a set of basic numbers in their head for the purpose of cross-checking rough design figures. The information conveyed through rules of

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[47] Both, Schön and Lawson, describe the design process as an interactive play between knowing and doing. Lawson argues *that understanding design conversation roles and selecting appropriately is part of creative and productive team working* with each team having its own style.

thumb was not aimed at giving firm evidence that a certain solution worked, but it was used to test if an idea was feasible in principle, and if it was worth pursuing.

Simon (1991, 17) argues in his theory of *"bounded rationality"* that the human mind is not capable of dealing with information beyond a certain quantity. Practitioners confirmed this notion during their interviews. As much as they relied on their memory of benchmark figures in the evaluation of performance aspects at the start of a project, they were increasingly dependant on additional support for design development during scheme design. Responses from the interviews revealed the same order in which such support was structured across all engineering disciplines. Starting from personal memory, numerical rule of thumb benchmarks were summarised in tables (either custom developed or published data) which are then transcribed into spreadsheets. These (often interactive) spreadsheets can contain formulae that link information together in a coordinated way.

"Everyone seems to have their own spreadsheets" (MEP engineer 1). This statement by an MEP expert highlighted the problem associated to the use of spreadsheets: Members from each discipline used a different spreadsheet and they were at times not sharable among members of the same discipline at Arup. I discuss the inadequacy of information – sharing based on numerical data in Chapter 5.3.4 where I propose a more visually explicit manner to bridge professional boundaries through the use of metaphors.

One step up from the spreadsheet in the support structure during early stage design are small scripts and custom developed interfaces that help to check performance results using *ball park figures*[48]. In recent years, practitioners use *low resolution*[49] software tools and plugins for design analysis to existing 3D CAD

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[48] I refer to ball park figures as rough or approximate numbers

[49] Low resolution tools allow users to analyse design performance based on simulation-software that references sample-data from project libraries to assimilate actual performance-analysis processes. If coarse results are sufficient for design estimates in the early stages, low resolution tools compensate for the lack of precision by the high speed in which results can be obtained.

software to evaluate quickly the performance of their proposal even in the early design stages. During my interviews I noticed a transition in office culture:

The ease and velocity of 3D digital model generation coupled with the small effort for setting up of performance analysis using those models enabled designers to become more concurrent in their evaluation. Software developers are beginning to address the request from practitioners for tools that allow them to test intuitively design options in early design without having to spend much time to model them in detail. Tools like ECOTECT™, VISIFLOW™, and SKETCHUP™ are examples of intuitively applicable digital design environments.

During the interviews it became evident to me that most rule of thumbs did not refer to causal *if - then, else* scenarios, but relate more to benchmark numbers.

Acoustic engineers hold figures in their head for comparing "*reverberation times*" (acoustic engineers 1,2 and 4) related to volumes of spaces and the distance to sound sources. Architects deal with "*net to gross ratios*" such as *floor efficiency* (architects 1, 2 and 3). ESD experts know which "*daylight factors*" (ESD planners 1,2,3 and 4) are desirable given the window-area and the depth of a floor plate. Façade-planners keep standard measurements in their head for "*façade modulation*" (Façade-planners 1 and 3). Fire engineers estimate *make-up air quantity* (fire engineers 1, 2, 3) for interior volumes and "*width of egress*" (Fire engineers 1 and 3). MEP engineers deal with percentages of "*thermal comfort and heat load per square meter*" (MEP engineers 1, 2, 3 and 4), and structural engineers refer to benchmarks for the "*tonnage*" of steel, "*span to depth ratios*", general "*sizing*" (structural engineers 1, 2, 3 and 4*)* of structural members and so forth. These types of measurements are only a few of the examples listed by the interviewees, but they illustrate the diversity of numeric formulae that architects and engineers confront in practice. The units and measurements used by practitioners for their rules of thumb are often intrinsically tied to a specific discipline and they are at times neither relevant nor entirely understood by the design partners from other disciplines.

4.5.2. What performance targets are you working towards?

In order to understand better the notation a discipline is using to describe the aspect of design their members are concerned with, I asked practitioners to list the performance targets they were working towards. The insight about the diversity of rules of thumbs extended to the performance targets of architects and engineers, and they differ substantially from discipline to disciplne as do the units for measurements. I listed a summary of important targets for each of the seven disciplines interviewed in the *disciplinary tables* at the end of this chapter.

A benchmark figure belonging to one's own disciplinary field reveals crucial information to an expert of that field, but it often does not communicate *sense* to others: An acoustic engineer explained this as follows:*"...it is not until you understand the principle behind what that number means that you understand what it is actually telling you"* (acoustic engineer 2).

One cannot expect practitioners from all fields to be familiar with all the targets that others bring to the table in early stage design. Profession specific performance aspects do have different levels of priority for the overall design. Trading-off priorities is a dynamic process that requires the input from the client, the vision of the architect, as well as the expertise of consultants and it varies from project to project.

In order to put this comment in the context of my PhD research question, I ask the following three questions: Firstly, what kind of support can enable us to make more sense of the performance targets from others? Secondly, what instruments can help us to perceive collaboration in a more holistic way? And thirdly, what metaphors cut across profession specific boundaries to assist us in understanding the principles behind numeric information of others?

I address these questions in Chapter 5.3.3 *Making sense in architectural design collaboration* where I discuss instruments that support designers and consultants to evaluate design performance in a social context.

4.5.3.   What kind of information would you like to have at your fingertips during early design?
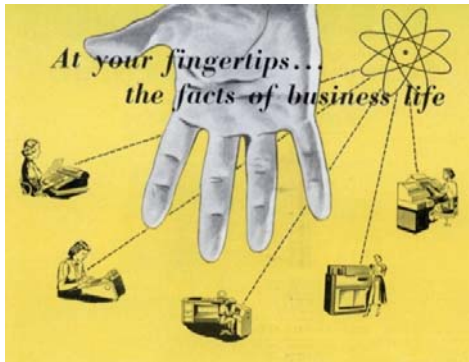
Figure 48: Illustration - Information at your fingertips, Source: Mallory

http://blog.modernmechanix.com/tag/computer-ads/page/3/

Asked about the kind of information they would like to have at their fingertips during early stage design, practitioners from all six engineering disciplines and the architects collaborating with them stressed the usefulness of image material with illustrations of successful precencent projects to bridge professional boundaries. An ESD expert brought this notion to the point by stating: "*In the early stages, it is about having access to past solutions for similar buildings using pictures and drawings*" (ESD planner 4). Interviewees stated that elements and details from precedent projects were not copied on new projects, but they served as proof of concept and as *"guidelines"* (acoustic engineer 1, architect 3, MEP engineer 1) to possible design-options.

Interviewees agreed that there is currently a lack of ICT support for capturing knowledge from precedence projects, for filtering it and for making it available real time during meetings with design partners. The problem lies not solely in the lack of a system for managing the information, but also from a lack of human resources to uncover and harvest relevant information from previously completed projects. The generation of a database containing precedence-information is a costly, time consuming effort. Practitioners emphasised the usefulness of such as database to provide them with easily accessible background information, either in the office, or remotely during meetings with other consultants and designers. Next to information that is used for comparing a proposed and yet untested solution with previously successful precedent projects, practitioners from ESD stressed the need for a: "*3D model generated quickly to interrogate combined performance impacts*" in the early design stages (MEP engineer 2).

This previous remark is motivated by the work methodology of environmental sustainable design where consultants do not deal with singular design issues, but they search for holistic solutions for the combined impact of energy use, waste production, resourcefulness and operational factors during the building lifecycle. The wish to evaluate *combined impacts* of performance indicators was echoed by all practitioners and it was stated that current ICT support is not facilitating this sufficiently in practice.

The comments brought forward by practitioners in regard to the support they require in the early stages makes a case for systems as proposed by Hartog, Koutamanis and Luscuere 1998. Such systems would allow designers to switch between prescriptive and descriptive approaches for connecting aspects of building performance with design. The concordant request by practitioners for support systems that could give them access to both prescriptive past-solutions as well as descriptive analysis results in the early stages reveals another aspect of design practice within Arup: According to Coxe's "*Superpositioning model*" (1987, 6), Arup is a firm that is highly *service* oriented. As much as Arup engineers at times engage with ideas-driven projects which require a high level of experimentation and innovation, the core business at Arup is based on providing their expertise in a service oriented fashion that builds up on a proven track record of challenging, yet feasible design.

Streamlined interaction between professionals from different backgrounds who know what to expect from each other is a precondition for high quality, service-oriented design. One comment made by an acoustic engineer exemplifies the importance of understanding not only one's own qualities and limitations but also those of other design-team members: Asked about the information he wanted at his fingertips he argued it is about: "...*gauging what experience the other people in the room have with how acoustics specifically integrates with their own disciplines. This is important to know because I do not want to cover the same ground if they know the deal.*" (acoustic engineer 2)

Understanding the appropriate way of interacting with others and learning what to expect from them is a quality a designer or consultant acquires through years of experience. Not all members of multidisciplinary[50] design teams automatically share the same level of expertise. Even experienced designers do not always get exposure to problems that do not directly relate to their own discipline.

4.5.4. Are you always aware of cost implications for design changes?

Figure 49: Illustration - Calculator, Source:
http://www.codinghorror.com/blog/archives/000440.html

The consideration of cost-considerations during design differs from discipline to discipline. In response to the above question most practitioners stated that all they required at the outset of a project was a rough estimate about the cost-aspect of their work, and that they could rely on their experience as sufficient guidance.

The reliance on rough estimates changes once the design process moves on from conceptual to schematic design. At that point a close interaction between various design-drivers becomes more important. At that stage façade-planners and MEP engineers confirmed to be sufficiently informed about the cost-implications of design changes, all other disciplines I interviewed were critical about the lack of knowledge they had regarding the impact of design choices on cost. This result is not surprising given that both façade engineers and MEP consultants work closely with manufacturers and fabricators of building components and machinery. A MEP expert explains: *"We had a meeting the other day where the client, the architect and the façade engineer all with opposing views of how much exactly the façade would cost. The QS would just say: we don't really know until we go out to the industry. This is another reason why early contractor-involvement is good on the cost front."* (MEP engineer 4)

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[50] *multidisciplinary* in this context refers to collaborating design teams with members from multiple disciplines.

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Structural and façade consultants argued that a close collaboration with contractors and manufacturers is a productive method for including cost-data early on in the design process. Such contractor-designer-consultant collaborations needed to be set up carefully to avoid giving the contractor or manufacturer too much influence to seize responsibility over the design early on. Interviewees proposed to employ contractors and manufacturers as consultants to include constructability constraints in schematic design, while not having to commit to their services too early in the process.

Design priorities are often constrained by cost factors and the interviewees agreed that they could profit from more immediate feedback regarding cost. As much as most claimed to have a good sense for rough numbers in their disciplines, they stated that they were less confident about how their work was affecting the overall cost: An acoustic engineer pointed out: *"It is important to have a gauge on how alternatives might influence the ultimate cost."* (acoustic Engineer 2)

The mention of *alternatives* in this quote is a key aspect of a design method that becomes increasingly used in current design processes. Interviewees stated that the process of *optimising* was increasingly becoming substituted by processes of *optioneering* where various design options are produced and compared to each other in reference to their implicit performance characteristics. I provide a comprehensive definition of the term *optioneering* in Chapter 5.1.

Designers required multiple design options to explore a solution (Lawson 1997, 151), but so far it has been difficult for consultants to keep up with the speed of change when conducting their analyses. The interviewees stated that the effort it takes to set up analysis models and the time it takes to run the analysis is as a major impediment to collaborate concurrently with architects. Gray and Hughes (2001, 37) confirm this by stating:

> *"The complex design process comprises contributions from many specialists. Time passes between each transfer of information while it is assimilated into the recipient's own design*

generation process... The work content within each specialization is likely to be different, affecting the resources required and the time taken to complete each section of the work."

Advances in computational simulation and analysis, as described previously, allow designers and consultants to work out a series of design alternatives in an increasingly concurrent mode. This development makes it possible for consultants to engage in the collaborative design process early on to pre-engineer a range of possible solutions. If financial characteristics can be added to such *optioneering* methods, cost-feedback can assist in the design process by providing information about the feasibility of various design options. An office principal with structural engineering background described this distinction in the following manner: *"There are two main approaches to designing: The two processes are quite telling. One is simply about taking the idea and finding a solution to a problem, the other is about pre-engineering the problem to engineer-out cost from the outset."* (structural engineer 2).

One problem in this context was highlighted by a MEP engineer who stated: *"We do not have a good feel for other people's costs"* (MEP engineer 4).

This comment illustrates that the lack of understanding *combined impacts* as previously highlighted, extends to financial aspects that influence design decisions. Interviewees from ESD and Fire pointed out that cost cannot solely be seen in the context of *"construction cost"*, but ongoing, *"recurring cost"* (façade-planner 3, fire engineer 3) during the building lifecycle plays an important role as well.

4.5.5. How can knowledge from precedent projects be captured?

Figure 50: Illustration - Learning from precedence, options for comparing existing building data with new design, Source: Deiman and Plat (1993, 332)

The issue of knowledge capture and the value of available reference data from precedent projects were strongly debated during the interviews. Responses by practitioners indicate an ambivalent relationship between the constraints of project-based work in everyday practice, and efforts that needed to be undertaken by practitioners to support them. This struggle was exemplified by the following quote: "*It is hard to know what is useful and what is not. We have tried tons of basic data collection before – like typical weights of steel for different spans, it never seems to be worth having.*" (Structural engineer 2)

As much as practitioners from all disciplines stressed the importance to encapsulate knowledge from experience in some way, they argued that it is a time-consuming and unrewarding process.

Arup is in the position to offer its employees substantial knowledge support systems through their internal office intranet. Specialist forums for a variety of design issues are accessible online. Arup employees have access to many sources of information such as scanned handbooks, (code-) libraries, a project library (Arup Projects), and pages with specialist information for individual disciplines. The support structure available at Arup is built up from years of experience in gathering information from previously realised projects. Opinions of interviewees about the usefulness of such knowledge support were divided.

Although everybody welcomed the availability of the internal office knowledge support, approximately half of the interviewees declared that they turn to colleagues for help either directly or via the specialist forums. An acoustic engineer brought this to the point: "*Our biggest resource are people and ways to tap into their knowledge. Asking people, or using the acoustics forum is very useful. There are posts every day, and there are 2-3 responses at minimum.*" (acoustic engineer 3)

One reason for the difficulties encountered by practitioners in the sharing of knowledge either through support systems or during meetings was highlighted by an office principal with structural background who stated: "*You will find within the*

issue of collaboration and knowledge exchange, that it does not automatically register that there is key information that could be useful to you." (structural engineer 3)

This comment confirms the argument about communication conflicts made by Thammavijitdej and Horayangkura (2006, 52) which I referred to previously.

Extracting the kind of information most relevant for one's work is often hindered by misinterpretation of other people's input, inattentiveness during meetings and inadequate information supply. The fact that experts from various disciplines encode and present their information in their specific language contributes to operational and cognitive gaps in the workflow across disciplines. Simpson and Viller (2004, 13) argue that it is within the studio setting that designers and their partners can overcome language barriers during group meetings. One structural engineer proposes to increase the frequency of such meetings arguing: *"You would probably try to have more regular meetings with the design team, making sure you are singing from the same hymn-sheet."* (structural engineer 4).

Increasing the frequency of meetings may be one possibility for diminishing communication conflicts. Another possibility for increasing shared sense-making across disciplines is pointed out by an office principal. He argued that it was important to consider how expertise and comparative information from precedent projects is actually shared during meetings: *"It comes down to comparative tools. Tools that enable you to show other people what you're doing, how it compares to other projects and why what your are saying is verifiable"* (structural engineer 3).

The above comment prompts the following two questions in reference to comparative tools to support in early stage design: Firstly, what content would such comparative tools host? And, secondly what is the most appropriate medium to bridge semantic and cognitive gaps between disciplines?

One of the interviewed architects responded to these questions as follows: *"In some cases numbers might be helpful as support, but usually it is a visual thing of most relevant concepts that are juxtaposed, compared, or otherwise shown"* (architect 2).

Most engineers agreed to this comment and their proposal the requirements and functions for a comparative tool can be summarised with the following four ingredients:

1. *moving towards more diagrammatic and graphic representations of our lot*
2. *filling up an library with precedence information such as CAD-data, samples from precedent projects and cost data*
3. *typical plant layouts, spatial arrangements, or even 3D details*
4. *putting information together on an easy-accessible one or two-pager*

A fire engineer pointed out an important precondition for the sort of knowledge-capture described above. It described the challenges faced in everyday practice when attempting to capture information from precedence projects: *"The challenge is getting the right people to spend the time to extract the information and put it where it needs to be. It is not something that you can delegate to someone who isn't intimately familiar with the project because then you end up getting some information out but the real useful stuff is lost."* (fire engineer 3)

4.5.6. What is the ratio between multidisciplinary interaction and sole investigation?
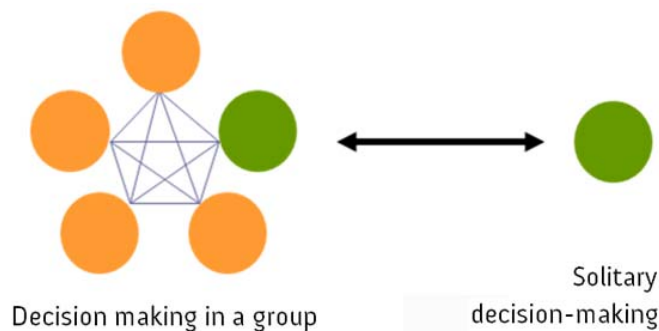
Figure 51: Illustration - Comparing the percentage of sole investigation to group interaction, Source: Author

Asked about the ratio spent for decision making during interdisciplinary meetings compared to time spent for solitary (or intra-disciplinary) reflection for decision making, practitioners responded with the following percentages. Acoustic engineers: 20/80, Architects: 25/75, ESD: 43/57, façade-planners: 40/60, fire engineers: 40/60, MEP engineers: 41/59, and structural engineers: 27/73.

These numbers only reflect time for the decision-making process and they do not include time spent on setting up geometry models and running design analyses. Four out of the seven professions that are central to my research argued that information exchange occurring during just a few hours per week in these meeting contributes to 40% or more of their decision-making. The profession specific quotas received for this question do not seem to stand in relation to the previously described percentages of deviation between *professional averages* and the total average.

All participants of the interviews argued that they needed to retreat from group-discussions to reflect on a design-problem on their own as a matter of course. Design issues are being discussed in meetings and decisions about possible design-directions are agreed on by the team. One MEP engineer acknowledged that: *"the disadvantage of round table discussions is that everything does happen so quickly."* (MEP engineer 4)

All interviewees expressed that it is in the nature of design meetings that there is little time for reflection and contemplation amongst participants. The information that is available to participants during meetings during the early design stages is at times based on expert-assumptions and rule of thumb data. One structural engineer stressed this fact by stating: *"You will be making decisions that won't necessarily be backed up by recent analytical undertakings."* (structural engineer 1)

Responses from the interviews confirmed that working with rough and incomplete design representation did not cause any concern to those professionals with years of experience in practice. At the same time even experienced practitioners admitted to requiring time for reflection and investigation to confirm that their advice was correct and/or to propose alternative solutions. The analysis required to back up decisions made during meetings is a time consuming effort depending on the type and the complexity of the analysis. A façade-planner addressed this by saying: *"After most of those meetings we have to go back and do our own research."* (façade-planner 4).

Practitioners argued that design meetings with multiple stakeholders needed to be planned carefully. It is pivotal to get all parties at one table that are of relevance in the decision-making process without obstructing discussions due to an overload of information. An environmental sustainability designer stated that it was important not to waste people's time and that topics raised by individual experts in such meetings *"... should not hold parts of the group discussion at ransom"*. (ESD planner 2)

An acoustic engineer added to this statement by clarifying: *"You want to get those coarse things out of the way at the very beginning, identifying the show stoppers."* (acoustic engineer 1)

Some interviewees observed the difficulty in defining precise goals for decision-making at the outset of meetings. All participants in the interviews agreed that design-priorities and dependencies of one profession from the other are highly project specific. An MEP engineer stated the following: *"For some types of buildings 'services' rule in other types we have to find different compromises as structural might be more important. In the end it is case by case dependant."* (MEP engineer 1)

This comment was complemented by an expression made by a fire engineer who added to the above. He clarified: *"With lots of decisions that need to be made within a project, it is not always clear who you need in order to make a decision until you start making it"*. (fire engineer 1)

Interviewees pointed out that changes in their work-methods and toolsets influence the speed and confidence in which they operated. Interviewees from all disciplines alluded to the fact that the duration for setting up design models and carrying out design analysis was decreasing. This change of process allowed them to respond quicker to questions from other disciplines regarding performance criteria in their fields, and to create several options as templates for group-discussions. A structural engineer argued:*"Our ability to assess options and to come back and present them confidently means that we've become a lot faster in doing a range of things."* (structural engineer 3)

An acoustic engineer complemented this comment by stating that it was not only important to produce options more quickly, it was also crucial to "*explain the reasons why one solution would be better than another*" (acoustic engineer 3).

4.5.7.   Would you benefit from concurrent feedback about design performance from others?
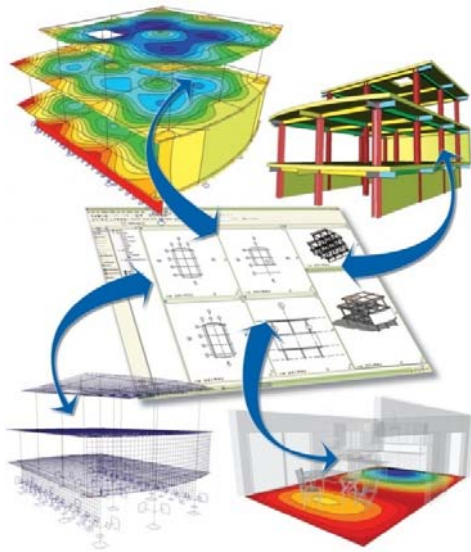
Figure 52: Illustration - Concurrent feedback from multiple design performance analysis, Source:

http://www.scia-nline.com/eNews/Images/revit.jpg

"...in conceptual design you need a decision every 15-30 minutes" (architect 2)

Although all interviewees gave a positive response to the above question, some voiced their concerns to what extent real-time feedback between designers and consultants was possible.   An office principal commented that the likeliness of real time-feedback to occur was depending on the level of experience of his collaborators.   The majority of interviewees responded that the lack of immediate feedback from others often kept them from pushing forward but they acknowledged the fact that different types of feedback had different timescales associated with them.   As a Fire engineer pointed out, a complex smoke-spread analysis using computational fluid dynamics (CFD[51]) *"could take up to 3 or 4 days to process"* for providing a single solution (Fire engineer 1). One structural engineer declared that he expected technology to change to allow designers to interact increasingly concurrent. He stated: *"I think there is going to be a need for far more interaction. If you can get instant*

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[51] CFD is a computationally intensive method for simulating and approximating the flow of fluids and gases. Carrying out CFD is a time-consuming process in engineering practice and it is assumed that the increase of computing power and the development of new algorithms for fluid-dynamic modeling will speed up the CFD process in the future.

feedback on everything, the holy grail is not to have to take a whole week to do your CFD but to do it on the spot. And therefore CFD analysis is not a proving tool, it becomes a design tool" (structural engineer 2). The above example illustrates the strong effect technology can have on the design process.

Another structural engineer made the comment that receiving simultaneous feedback from others was not as crucial for collaboration as *"getting collective awareness and experience about the key issues and to then know whom to go and talk to, to get more detailed knowledge"* (structural engineer 3).

A façade designer added to the above argument by saying *"... getting the 3D models done is not time-consuming, it is the disjointedness between us and the others"* (façade-planner 1). With this comment the façade designer highlighted the role of the 3D geometry model as interface between various types of performance analysis and design representation.

Even though 3D geometry models are not difficult to produce, a model created by one discipline was at times not useable by another. This occurs even if professionals work on the same project. I support this argument in Chapter 4.7 *Geometry-model constraints by discipline*, where I discuss the constraints of exchanging geometry models from profession to profession.

An office principal with structural background pointed out *"There is not a lot of time to actually explore your fellow discipline's expertise."* (structural engineer 3) Another structural engineer provided the following recipe to get the design negotiation process on the way: *"it is possibly best to develop what you believe to be the optimum for your own scheme at the beginning anyway and then start negotiating."* (structural engineer 1)

A fire engineer shared the work-ethic described above, which he then justifies: *"...often it is not until I see much more detail that I can pick up the problems that arise."* (fire engineer 3)

These comments, given by various engineering practitioners, explain why early-design collaboration is a difficult task. Design decisions are made under time-

pressure during project-meetings. Exploring commonalities between professions is difficult as practitioners are not aware of problems that may arise during collaboration until the project is well on the way. Responses from the engineering professionals during the interviews point at a change in design culture that has occurred over the past two decades. Traditionally they were consulted to confirm *if* a design solution proposed by the architects was feasible. In contemporary architectural design, engineers are expected to address and negotiate manifold design requirements to check *how well* they perform. I conclude that it therefore becomes even more crucial to the success of a project that team-members from different backgrounds interact as early on as possible.

4.5.8.   What media is most appropriate for you to communicate design intent to and from others ?

In asking this question, I wanted to explore if there is one common medium preferred by members from the seven disciplines who participated in the interviews. I have asked interviewees to consider verbal, textual, as well as graphical mediation. The responses from interviewees surprised me twofold. Firstly, with the exception of the acoustic engineers, hand-sketching was the only type of media that was used by all interviewees in the early design stages. Other than sketching, there was little to no overlap in the description of media in use by the practitioners from different backgrounds. The second unexpected insight resulting from the answers to the above question was as follows: Most interviewees stated that the type of media useful to them to understand design intent *from* was different to the media used by themselves to make their input explicit *to* others.

I have listed all responses to this question in the *Disciplinary Tables* in Section 4.8.

4.5.9. How would you like to negotiate design priorities in the future?

Figure 53: Illustration - Negotiation of design priorities, Source: http://www.pnd.co.nz/images/negotiate.jpg

Most interviewees expressed their discontent about the lack of computational support for negotiating design-priorities with professionals from other disciplines. The manner in which design priorities are currently being traded-off in practice was not criticized, but rather the point at which individual practitioners would enter jobs. Mechanical engineers, fire engineers and, in particular, environmental sustainability designers called for earlier involvement with the rest of the design team. The increasing pressure from clients on the whole design team to deliver projects on time and on cost advocates for interacting *"earlier in workshop settings"* and to create *"common evaluation criteria, being it money, energy targets, functionality or whatever the key performance criteria for the building are",* as stated by a MEP engineer. (MEP engineer 3)

One of the interviewed office principals with structural background addressed the issue of the common medium for interaction in early design: *"I can see no conceptual reason why you should not in the future start with a 3D model"* (structural engineer 2)

As a consequence of the previously mentioned move towards earlier involvement, practitioners of the engineering disciplines stated that they required 3D modelling tools that can better deal with rough representations of building geometry such as surface-areas and volumes. Current tools were seen as too precise. An acoustic engineer expressed her opinion that tools are required to *"automate the process of simplifying geometry"* for easy-access to rough geometry models for analysis (acoustic engineer 2).

Practitioners across all engineering and design domains demanded that the tools available to them in early stage design should be intuitive to use. Architects took

this argument further during the interview by envisaging tools where design priorities could be fine-tuned by moving sliders up and down on a performance-scale.

There existed a consensus across all interviewees that a future tool for design negotiation should allow them to generate, visualise and evaluate multiple design options. Those options should be based on common performance criteria, be it cost, energy, information from manufacturers, or whatever the key drivers for the building performance are.

An environmental engineer argued in reference to the above statement: "*You would need to have a system to be able to quickly see and evaluate the effects and outcomes of your different decisions in terms of the overall building performance.*" (ESD planner 1)

Practitioners from all disciplines agreed that computational support for design negotiation and decision-making should not replace, but complement existing strategies. The use of the simple hand sketch was still the preferred medium to quickly share an idea with other team members across disciplines.

A façade planner summed this insight up: "*You want to be able to pass a piece of paper around the table in a meeting where people put down their sketches and sometimes people draw over each other's sketches. That way you get a good understanding of what people are talking about.*" (façade-planner 3)

4.5.10. What would you like to have in your miracle toolbox for early design?

Figure 54: Illustration - Miracle toolbox, Source: http://www.wahmbreakcafe.com/tag/toolbox

The purpose of this question was to allow interviewees to let go of current restrictions in practice and to query them

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about *ideal* tools that best assists their work in early design.

One office principal with structural background proclaimed *"We should be able to explore more options, explore them across a broader range of issues, and bring them to a more optimised solution"* (structural engineer 3). An MEP engineer responded more restrictively: *"It would be useful if you had 10 different MEP solutions with advantages and disadvantages that you could somehow quite easily marry into the drivers behind the project"* (MEP engineer 4). Another structural engineer added that his miracle tool *"would be an environment where all offline analyses that we do now to justify design are actually available in real time online as you design."* (structural engineer 2)

All three answers make a case for support that provides increasingly concurrent feedback from performance analysis from various disciplines. The support environment should display qualitative properties of multiple design options to choose from and the reasoning behind them. The comments above affirm Chaszar's argument as presented previously. According to Chaszar (2006, 159) collaborative tools in the present sense should offer the following three properties:

1. *"Rapid feedback on the consequences of design, production or installation decisions, whether to a single user, a single-discipline group, or a multidisciplinary group;"*
2. *"Readily interpretable results, achieved, for example, through carefully selected classes of information and good graphical and alphanumeric display of these;"* and
3. *"Facilitation of substantive real-time design exploration and discussion of results among relevant parties."*

Comments from practitioners indicated that they were willing to sacrifice precision in favour of speed in the early stages. A fire engineer expressed this the following way: *"There has to be a point where you want results – even if they are very vague – within minutes."* (fire engineer 1)

During the interview there was an unanimous call by participants for a real-time support environment to encourage lateral thinking and to foster good imagination.

Members from each profession added aspects that the environment could address, including:

- *"It would be great to have a tool that allows you to analyse and update models quickly to consequently get results out quickly"* (Structural engineer 4)

- *"It would be good to have some visualisation about combined impacts"* (ESD planner 2)

- *"Reference information of either existing buildings or specific types, ...you would need an updated cost-database connected to that"* (MEP engineer 2)

- *"a rough 3D environment where you place sound sources and get instant feedback."* (acoustic engineer 1)

One of the environmentally sustainable designers (ESD planner 1) had envisaged an ideal system prior to the interview. He described the qualities and components for such a support environment in the following seven points:

1. *"be set up in a parametric way"*
2. *"easily manipulated"*
3. *"lots of defaults set on the model (pre input by experts)"*
4. *"be able to export quickly to all the underlying analysis packages"*
5. *"input – output filters"*
6. *"common feedback form to see what the impacts were,* and
7. *"a history log that shows you: during this design meeting we made these 12 changes and this is how it influenced what we did."*

One response about a miracle toolbox by a façade planner explained that collaborative support does not automatically depend on computational systems or other sorts of environments. The façade planner addressed cognitive barriers in the communication with other professionals as a main problem she wanted to overcome by stating: *"A miracle tool should help me to transfer the intent of the architects directly to my brain and make me understand what they want!"* (façade-planner 3)

In this section I canvassed expert input from design professionals structured around 9 basic questions that deal with professional habits in design collaboration.

The interviewees shared with me their ideas, concerns, proposals and frustrations regarding design-collaboration and sense-making in the early stages of design.

Some of the expert-feedback suggests that better tools are needed to strengthen collaboration between the different stakeholders in early design. Other comments hint at the lack of an adequate dialogue that brings different professions closer together.

I bring the answers from this qualitative analysis in context with my literature review in Chapter 5 to explore the above issues in more depth.

In the next section I discuss the role of computational building geometry models as interfaces in the workflow between various disciplines in AEC.

4.6. Varying notations of geometric design representations in architecture and engineering

During my three year period embedded within the *Buildings Group* at Arup I observed how the six major engineering disciplines (Structures, ESD, MEP, Façades, Fire and Acoustic) changed their methodology from working on the basis of 2D information (either analogue or digital) to carrying out performance analysis using three dimensional digital models. In this section, I summarise responses from interviewees at Arup regarding the type of the 3D geometry model in use by their discipline.

If calculations were carried out traditionally by engineering consultants on the basis of reference data from spreadsheets, tables, codes, standards and measurements of previously completed projects, the application of computational software has now transformed most aspects of engineering performance analysis (Coenders and Wagemans 2005, 86). I questioned members of each major engineering discipline in the *Buildings Group* at Arup about the types of computational geometry models that provide them with performance-indications of design aspects associated with their domain. My investigation in practice revealed that each profession depends on specific theoretical and technical constraints to make their analysis function in its given context. Linked to these constraints is the necessity for setting up computational 3D geometry models in a particular manner. During my interviews I observed, that each profession puts substantial effort into the generation of digital 3D-geometry models that form the basis for their discipline-specific performance analysis.

My research at Arup suggests that, using traditional[52] work-methods, designers and consultants interacted on the basis of abstracted representations of their work

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[52] My observations in practice suggest that in spite of the availability of 3D CAD modeling software at Arup and collaborating architects, few practitioners were using 3D CAD models for the exchange of

in two dimensional plans and sections. Over the past decade this method has gradually changed with the increased availability and take-up of 3D digital geometry models. The drivers for the transition from 2D to 3D are manifold; whereas architects embraced them first as a means to visualise their designs in the most realistic way, engineering consultants at Arup further embraced 3D geometry to carry out different types of analysis, design documentation and even construction and facilities management.

Within Arup, structural engineers led the way in the transition from 2D plans and sections to 3D model use, followed by ESD, MEP, acoustic engineers, fire engineers and façade-planners. Design geometry continuously gets reinterpreted by all of the above parties during the design process. As a building project progresses, the reinterpretation of the design occurs through constant input by a variety of designers and consultants, driven by the level of detail required at any given stage. I observed that, even when collaborating on the same project, the various parties interpret the underlying building geometry differently for testing the specific performance within their domain.

With all on board the 3D train, there still seems to be a lack of coordination and synthesis between the different parties who are not as yet tapping into the full potential of integrated 3D work-environments. The 3D geometry model provided by the architects often does not contain the right information to enable engineers to carry out their performance analysis. Chaszar describes this problem as follows:

> *"The different disciplines tend to work with sub-sets of the architects' information. Then they have to contribute significant quantities of information to those sub-sets in order to make them workable for their own purposes."* (2008, n.p.)

design information at the commencement of my research three years ago. In most cases design discussions evolved around 2D printouts that represented particular aspects of a project.

Interviewees stated that engineering analysis results can often not be automatically integrated in design documentation, and it requires manual input by drafters to do so. In addition to this problem, there are varying requirements for geometrical information from the different engineering disciplines, and sometimes even intra-disciplinary, when using different tools. Some interviewees suggested during the interviews and subsequent follow-up meetings, that coordinating 3D geometrical models might require a person acting as *centrepoint of information*. Interviewees proposed that the role of *centrepoint of information* should be given to somebody who is able to understand, integrate and manage architecture and engineering design data. Next to the above quality, this position should include the task of filtering and appropriating geometric representations in the models to fit the purpose of individual disciplines.

New industry standards such as IFCs for Building Information Modeling (BIM) address the issue of model interoperability, but they fail to offer solutions for the earlier design stages when smooth information exchange between different partners has the strongest impact on the final result. Laiserin raises the argument that the fragmented state of model and file-format incompatibility is the biggest shortcoming of BIM today as linkages between models from different disciplines cannot be taken for granted (Laiserin 2008, n.p.).

4.6.1. Constraints for Geometrical Interoperability

At the outset of my investigation about constraints for geometrical interoperability I asked the following five questions:

1. *Why is it so difficult to bridge semantic gaps and find smooth translators for geometry models from various design- and engineering disciplines?*
2. *Why do we constantly need to re-interpret the same design information?*
3. *What are the particularities in the setup of geometry models that each type of representation, performance analysis, and simulation require?*

4. Will it ever be possible to automate the exchange from a geometry model for a specific analysis to the other during early stage design?

5. Is the object-oriented approach presented by many researchers in line with the work-methodology of designers in the early stages?

A building's geometry embodies an unlimited set of requirements about (inter alia) programmatic, functional, aesthetic, technical and environmental aspects (Whitehead and Peters 2008). Building geometry serves as a testing ground for exploring the above design aspects and for weighting solutions that are representative for aesthetic, functional, and building performance constraints. In more general terms, Turkle et.al. explain:

> *"The dominant metaphor in geometric modeling is that design is exploration and that designers set out to discover images. Geometric modeling systems allow users to explore a "solution space" of possible designs by giving them a set of starter elements that can be composed into a finite set of configurations."* (2005, 78)

In the previous section I presented comments from design and engineering professionals who wish to share their geometry models from the early design stages onwards to test building performance across disciplines. In my research I uncovered at least three principal obstacles to the sharing of 3D geometry information between architects and consultants. Firstly, 3D geometry files can be understood as legal design-documents. They represent detailed information of how a structure should be built. Errors in the 3D geometry files can therefore lead to liability disputes if the geometry information does not match the design-intent that was agreed on by the design team, or if information stemming from various models produced by consultants and designers is inconsistent[53]. The author of any geometry file cannot be held responsible for the correctness of data contained

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[53] One example of such a dispute is the cost-overrun on Frank Gehry's Walt Disney Concert Hall: A lawsuit was filed less than month after the opening. The main contractor claimed that it and many other contractors were owed about $43 million because of changes to the design and a defective construction plan that caused delays and boosted the cost. http://www.cbc.ca/arts/story/2006/07/30/disneyhall-lawsuit-settled.html

in his or her model beyond the immediate purpose assigned by the author. As 3D geometry models are used for testing different aspects of the building's design, information has to be checked and possibly reworked by others to ensure the validity of the information for their own purpose. The issue of liability is strongly linked to the method of procurement and the team-structure as described previously. The second obstacle is the problem of translation between different software packages. Custom import capabilities of design and analysis software are particularly limited (Nicholas and Burry 2007). Information gets lost in translation which, in return, results in errors during import and export of geometry files between proprietary software tools. Geometric entities are defined in different ways. The third obstacle relates to the selection requirements of consultants for addressing the exact type of geometry needed to analyse the part of the design they are responsible for. (Johnson, von Buelow and Tripeny 2004)

| exterior surface | centreline/ centersurface | solid model | interior surface |
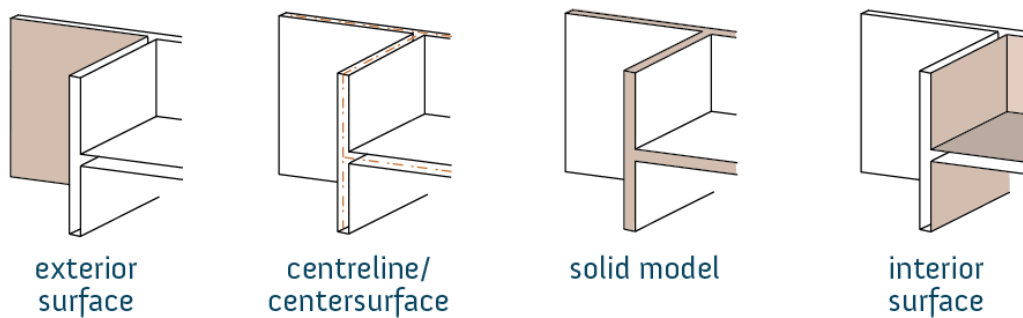
Figure 55: Different types of representation for the same geometric entity, Source: Author

A 3D computational geometry model can represent a geometric entity through a variety of methods. Interviewees listed four different methods for abstracting geometrical objects. As shown in Figure 55, a building component can be abstracted geometrically by modeling its interior surface, its exterior surface, or its centre-surface, or centreline. In addition to these modeling options, geometric entities can be abstracted to a solid model.

Addressing the semantic differences between design-notations by varying professions in the context of performance analysis and geometry modelling, Nicholas and Burry argue (2007, 256):

"..analysis often involves modelling the problem rather than the building"

Nicholas and Burry acknowledge the insufficiency of traditional methods for design-information transfer through plans, section and 3D models. At the same time they point out the shortcomings of current computational tools for modeling building geometry and for conducting building performance analysis. Information intrinsic to domain-specific analysis outcomes is often not explicit to design partners from other domains due to a lack of adequate representation and integration in the overall workflow. This semantic gap slows down the speed of information flow that would otherwise enable a quick iterative design process.

As much as CAD tools and analytical software alike have possibilities to export information in specific formats, there exist no such options when importing information (in contrast to tools like MS Excel™). Nicholas and Burry agree with Luebkeman (1992) in stating that integration of design information is an issue of *interpretation rather than precision.*

> *"..smooth integration of analyses with architecturally oriented models has remained difficult to achieve."* (Johnson, von Buelow and Tripeny 2004, 241)

Johnson, von Buelow and Tripeny (2004) offer a detailed explanation for the reasons 3D computational geometry models of the same design objects can only be shared with great difficulty amongst members from different professions in the building industry. They list SEMPER, BDA and P3 as previous approaches for linking engineering analysis data to architectural models (2004, 231). For the example of a comparison between architectural models and engineering models Johnson, von Buelow and Tripeny (2004, 233-238) illustrate the differences in the setup of such models and the reason why automated algorithmic translators fail to provide smooth transitions from one model to the other.

Figure 56 shows a process-chart by Johnson, von Buelow and Tripeny that explains the difficulty of abstracting architectural design-elements and adding engineering properties to define a structual beam or column.
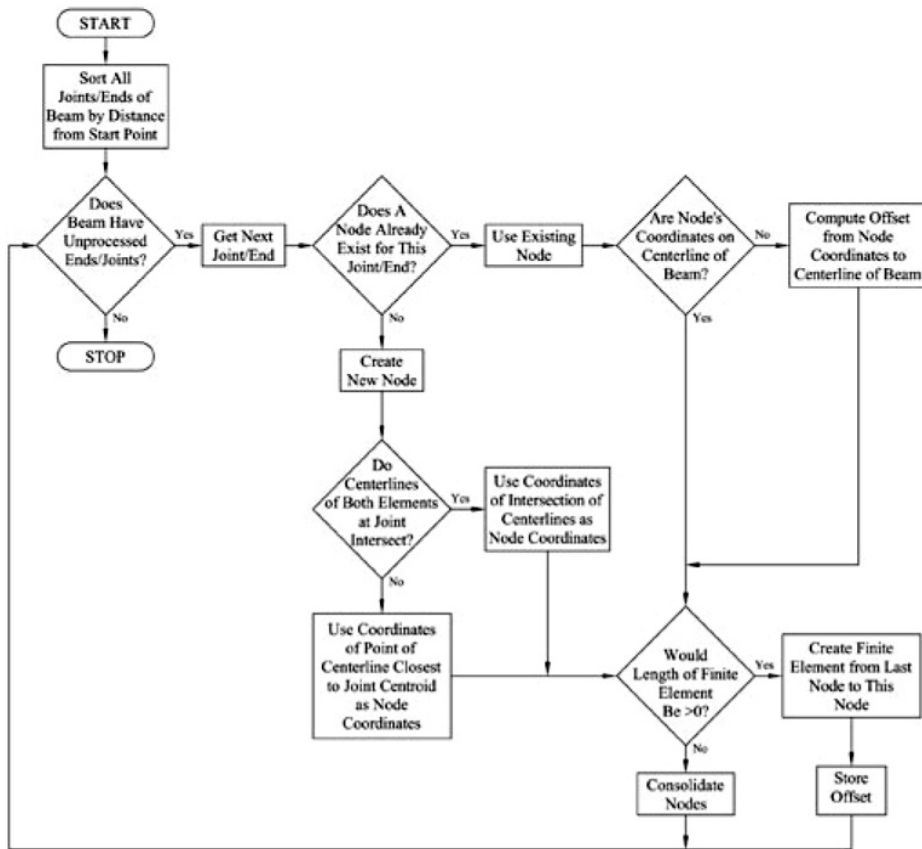
Figure 56: Logic for producing an abstraction of a beam (or column), Source: Johnson von Buelow and Tripeny

Semi-fictitious design elements have to be introduced by practitioners to bridge the semantic gap between element representations of disciplines. Hinting at the object-based methodology for data exchange, Johnson, von Buelow and Tripeny (2004, 231) conducted tests using rough architectural representations with de-emphasis on model correctness. Implementation for idiosyncratic geometrical shapes were not successful and their efforts were constrained by the limited formal expression they could achieve using coarse geometry models.

During the interviews at Arup, an environmental sustainability designer stated that a common problem in the setup of geometry models for analysis purposes is the

issue of *defeaturing* [54]. Not only would it be unnecessary to include detailed information in some types of analysis models, it would also increase the time needed to analyse a model exponentially and sometimes even produce incorrect results.

The scale in which the *defeaturing* process has to take place can be both problem and discipline specific. I list various thresholds in the size of objects to be modeled in the discipline-specific summary in the *Disciplinary Tables* in Chapter 4.8.

Next to *defeaturing*, *equivalencing* [55] is a second method applied by designers and consultants to prepare and arrange their geometry models for analysis. The process of *equivalencing* is highly profession-specific and it requires experts with grounded knowledge drawn from precedence studies and reference projects.

While I have pointed out general observations about the interoperability of computational geometry models in this section, I will describe characteristics of geometry models used by individual disciplines in the following section.

4.7. Geometry-model constraints by discipline

In this section I focus my research on the various types of computational geometry models that are required for the setup of design representation and analysis by each discipline. The description of geometry-types, modeling techniques and modeling tolerances stems from responses I received during the interviews and during follow-up meetings with practitioners at Arup who provided a detailed description of how they set up their 3D geometry models.

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[54] Whilst 3D geometry models for architectural representation require a high amount of detail to display visually correct information, analysis models for most building performance analysis need to be stripped of such detail. I refer to this process as *defeaturing* in the context of my PhD thesis.

[55] The process of *equivalencing* is not so much related to issues of scale and detail, but is a necessary simplification and transformation of geometrical entities with an equivalent that holds information representative of that entity.

4.7.1. Architectural Design

When architects adopt geometric modeling software, they are appropriating disciplined ways of image-making from the computer graphics community. This discipline has standardized communication among architects and their professional partners. (Turkle, et al. 2005, 76)

My interviews with architects associated with Arup revealed that 3D computer models generated by them mainly serve the purpose of visualising ideas. For the majority of projects I observed embedded at Arup, architects firstly created computational 3D geometry models to pass them on to specialists at Arup who subsequently based their work on them.

A closer look at 3D geometry models passed on to engineers at Arup by architects revealed that in most cases they were one way streets. They were tailored to communicate architects' design *to* others instead of communicating it *with* others.

Architects generally use geometrical representations of those surfaces to a building that are required to visualise a project. During my research embedded in practice I uncovered that in most cases, the architectural geometry model setup required modelling the exterior skin of a building. In some cases, architects modeled the internal visible surfaces to illustrate the appearance of an interior. In the process of generating the surface models, architects were not required to ensure the surfaces are connected to form an enclosure. Engineers at Arup were able to import the architect's geometry in their proprietary software as templates, but they then had to redraw it to fit their individual purposes. These purposes vary from profession to profession.

In my discussions with engineering consultants at Arup I questioned them about the value of the architect's models for their work. Most engineers seemed to accept the limited usefulness of the architect's models as simple backdrop to the generation of their profession-specific models for performance analysis. Further, they argued that redrawing the models for their own requirements would at times allow them to understand better the original design. At this point opinions were

split. While some emphasised on the usefulness of redrawing the model, others contemplated the extra required to do so and they expressed their wish for smart translators that would allow them to (semi)automate the transformation process.

In the following sections I point at the different requirements for 3D geometry-setup by engineering consultants.

4.7.2.   Structural Analysis

The most common way for structural engineers at Arup to build up their geometry models was to define the centrelines or centre-surfaces of geometrical objects. In contrast to architects who represent the outer boundary of building elements such as columns, beams, walls or similar, structural engineers abstracted geometric objects as simple centrelines (or surfaces) and attached a thickness or predefined section types from a library of structural elements to them. Interviewees revealed that structural systems are represented as a network of interconnected centrelines (or surfaces) for conducting member-size optimization and structural code checking (Figure 57).

The important aspect for structural engineers was the load that applies on the (nodal) connection of members and the stresses that occur within the members. For this purpose, structural engineers at Arup used software that had the capability to interpret networks of interconnected nodes as surfaces in order to equally transfer distributed loads (such as wind-loads) to their neighbouring nodes.
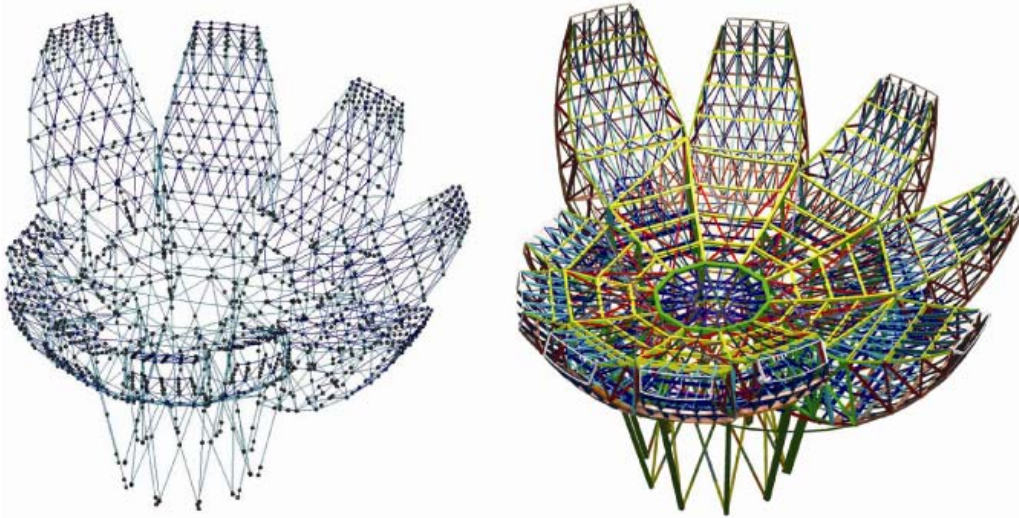
Figure 57: Centreline model for structural analysis and 3D model of the steel-framework. Arts and Science Complex, Singapore (Moshe Safdie and Associates), Source: Arup

Structural engineers at Arup also conducted analysis on (freeform) surface models, based on the Finite Element Analysis (FEA) method. This method is suited inter alia to analyse local stresses in the material of complex-shaped design elements. When using FEA, any shape of the underlying building-geometry can be used and imported into structural engineering software as a Nurbs[56] surface-model. It then gets subdivided into a mesh of (finite) elements that are individually analysed in a consequent process.

Depending on the base-type of element used for the mesh, FE meshes can approximate any 3D shape to high levels of accuracy.

Practitioners from the structural-engineering domain at Arup pointed out that the general level of accuracy for structural analysis models depends on the design stages. Whereas structural engineers approximate their models in a range of about 100mm in the earlier design stages, a higher accuracy of their 3D geometry models become essential towards the later design stages where they often operate with millimetre precision. The level of accuracy required also depends on the structural material in use. Whereas concrete structures allow for tolerances of up to 30mm,

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[56] Non Uniformal Rational Bezier Spline (Piegl and Tiller 1997)

steel structures, only allow for tolerances of 15mm (or less in the early design stages).

Comparing structural engineering models with architectural models uncovers strong differences in their setup. Architects have no use for centreline or centre-surface model geometry as they are not revealing the correct visual information in renderings or other forms of representation. The centreline or centre-surface approach is similarly ineffective for evaluating performance of facades, ESD or MEP. There, the effects of light distribution, heat-loads, air-pressure, and others are analysed regarding their distribution in or around enclosed volumes and surfaces that form physical boundaries.

4.7.3. Building Physics
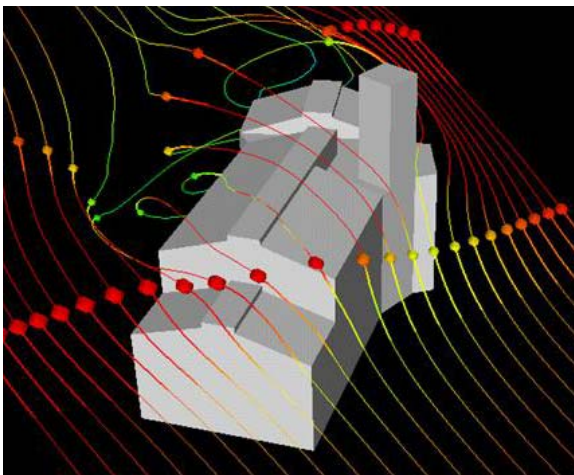
Figure 58 : External CFD model, Source: Arup

I summarised information about computational geometry models for façade design, ESD and MEP engineering under the topic of *Building Physics*.

Practitioners at Arup divide modelling for building physics in three sub-categories:

1. *thermodynamics,*
2. *lighting analysis, and*
3. *fluid dynamics.*

All geometry models used for thermodynamic analysis had to consist of closed (watertight) spaces because thermal modeling requires the definition of zones. Zones can be defined hierarchically via sub-surfaces. Computational energy analysis software requires the overall volume that individual surfaces enclose, and

information indicating how the surfaces relate to each other, to simulate radiant heat-transfer. After engineers and planners at Arup defined thermal zones in their models, the thermodynamic analysis software could auto-detect the volumes by emitting rays around from predefined points within the enclosed spaces to find out where the boundary-regions were. Experts at Arup stated that software tools for CFD allow users to import architectural geometry models to create meshes from surfaces that could follow freeform geometry[57].

The architects' 3D models had to be appropriated for the CFD analysis as they could not be used without substantial hand-holding. The reason for this is as follows:

Geometric features smaller than 500mm for walls or about 200mm for particular small scale elements did not get included in the CFD model. Depending on this scale, some external shading devices did not get drawn, but they were abstracted as virtual surface representation. This is a process of *equivalencing*. Instead of drawing 20 horizontal slats of a shading device, engineers generated one equivalent vertical shading surface with a transmission factor. If the CFD mesh grid-size is 200mm or larger, elements that are smaller in scale would get lost when creating the grid, even though they are vital features for the analysis model.

The issue of equivalencing is less crucial for 3D geometry models used for daylight analysis. 3D geometry models for light analysis required little appropriation by engineers who were able at times to use 3D surface models straight from the architects. The interviews at Arup revealed that most daylight-analysis models work on geometry built up from planar polygonal-meshes.

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[57] Meshed 3D models for CFD are different from 3D meshes for fire modelling FDS. For FDS *Cartesian* meshes are used. *Cartesian* meshes can only be orientated orthogonally in the XYZ directions and therefore curved geometrical entities are transformed into stepped orthogonal elements. (see examples at: www.ansys.com/products/icemcfd-mesh/aiaa-97-0196.pdf)

Thicknesses of walls including the interior wall-surfaces were not represented in the geometry models, but their build-up and material-properties were specified in associated material-libraries.

If polygonal meshes were important from external sources, the direction of surface-normals needed to be checked to make the daylight analysis software distinguish interior from exterior planes. Results were either plotted back through colouring the geometrical entities in the 3D model (see Figure 74), or they were plotted in a graph and spreadsheet

4.7.4. Acoustic Analysis Models

Acoustic engineers at Arup applied 3D geometry models for acoustic optimisation and auralisation to test the acoustic properties of interior spaces such as auditoria, meeting rooms, concert halls, and foyers. Acoustic engineers set up their models as rough representations of the inner surface areas of a particular space for broad geometrical shaping or to simulate reverberation times from sound sources to their surrounding surfaces (Figure 59).

The level of detail included in acoustic geometry models cannot be defined uniformly as it depends on the frequency-range that is being investigated. Some acoustic-specific features such as deflection screens needed to be included in the model and represented with all their surrounding surfaces to ensure sound bounces-off them in the most accurate manner.

Acoustic engineers at Arup pointed out that they attempt to create enclosed spaces when generating the interior boundary surface for their computational analysis models.
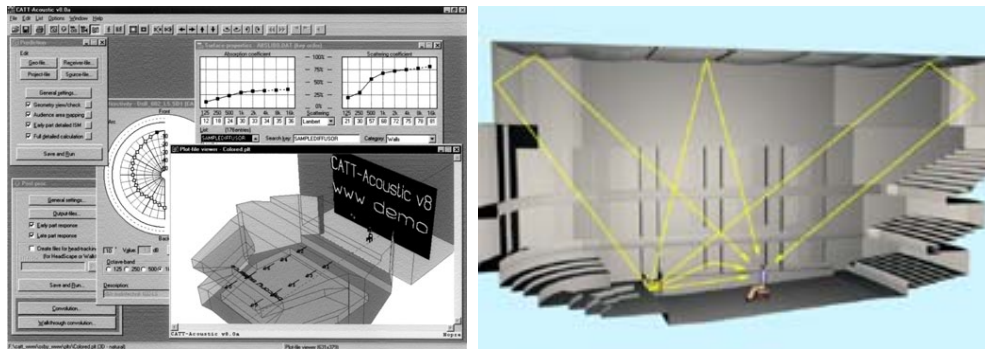
Figure 59 : CATT™ Acoustic v8 modelling interface and acoustic analysis of an auditorium, Source: CATT/Arup

4.7.5.   Fire Engineering Models

Fire engineers at Arup used their 3D geometry models for investigating three main design-issues:

1. *smoke-spread,*
2. *egress modeling, and*
3. *heat flux*

The most common aim was the analysis of *smoke-spread* within building using fire dynamics simulation (FDS) on the basis of computational fluid dynamics (CFD) to study air and smoke movement over a certain period of time. The second type of analysis undertaken for fire engineering was *egress modeling* to study people-movement within and out of a building in the case of fire, and the third type of analysis were simple tests for understanding *heat-flux* using radiation modelling.

Egress models used by fire-engineers at Arup to analyse people-movement in a building could easily be converted from architectural models (the analysis mainly needed to understand geometrical boundaries for escape-routes), whereas smoke movement analysis worked on a different principle.

Geometrical entities were either generated or (if imported from a third party model) subdivided on the basis of a user-defined grid that depending on the granularity of the information required for CFD analysis and the available computing-power. In order to analyse smoke-movement within a building, fire engineers at Arup used the interior surfaces of a room to define obstructions in

their 3D model that prevented smoke from spreading. Buildings were then set up by fire engineers as a series of connecting surfaces that get interpreted as volumes by the analysis software.

Wall thicknesses of the boundary surfaces of a volume were defined in the geometry model according to the minimum requirements of the grid, as seen in Figure 60. Problems in the appropriation of third party models occurred if surfaces in the geometry-model had been drawn using non planar elements such as Nurbs-based geometry. Cartesian meshing applied by fire engineers for their models resulted in a rough aliasing of otherwise rounded elements.

The fire engineers interviewed stated that the smallest size of geometric objects in the model needs to be greater than 300mm in order to enable standard grid sizes to recognise them during meshing (a wall that is modelled more thinly might otherwise not be represented in the model). Depending on what is to be analysed, the fire dynamics simulation model can also include objects in the interior (such as furniture) that have an effect on the smoke-movement.
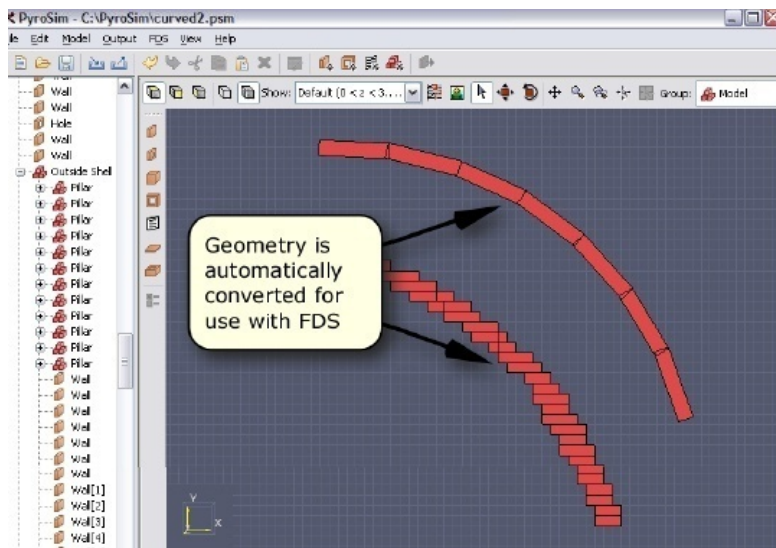
Figure 60 : Interpretation of curved geometry to fit the analysis tool, Source: PyroSim™

Geometry model constraints in summary:

My investigation of geometry models used by different experts within Arup illustrates that design professionals not only use different types of computational 3D model representations, they also apply different methods to appropriate and *defeature* them according to the requirements of their analysis tools. Size and proportion of geometric entities within the model are major contributing factors in appropriating geometry according to specific types of analysis. Expert knowledge and manual intervention for converting and generating computational geometry models according to professional specificity are currently required in this process.

A building's geometry is the common ground for design communication between practitioners from varying backgrounds. Even though the computational geometry models generated by each discipline for a given project are similar, the small differences in their setup put them worlds apart. They are currently unusable as common interface across professional boundaries apart from their purpose as a visual backdrop. This dichotomy is a contributing factor to the semantic idiosyncrasies between professions that I discussed previously.

During the interviews, engineers at Arup highlighted one additional problem in regard to the setup of computational geometry models. When architects change their design and update their 3D geometry model, their task is complete. For engineers this is not the case as any update to the model is just the starting point for their investigation and consequent simulation of building performance. The intervals in which design changes occur are particularly short during the early design stages.
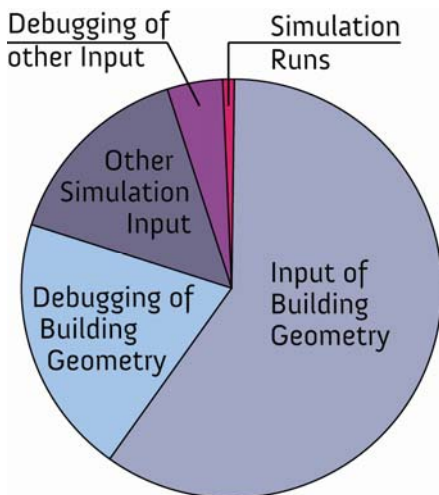
Figure 61 : Estimate of building geometry as portion of overall effort to prepare simulation input, Source: Bazjanac

As Bazjanac (2004, 879) points out in the context of energy performance simulation, the input and debugging of building geometry can consume up to 80% of the effort for the preparation of performance simulation. Such requirements jeopardise concurrent work methods between architects and engineers and they may hinder communication and obstruct timely feedback from engineers. Bazjanac states:

> *"By the time the simulation of a state of building design has been finished, the design has already moved to a new solution or alternative. Decisions on issues raised in one meeting usually have to wait until another meeting in the future, because it takes so much time to prepare and do the simulation before the results can be analyzed".* (2004, 882)

Chaszar highlights additional dangers associated to the above dilemma:

> *"The way it happens now is that the consultants cannot keep up with the number of design changes made by the architects, so they hang back. They think: 'Well the architect is going to be changing this 20 times in the next week anyway so we'll do our analysis next week'".* (2008, n.p.)

Chaszar urges architects to consider the differences in the amount of time that is required to set up geometry models and the time it takes to carry out engineering analysis. According to Chaszar, architects should account for the downstream effects of the way they set up their 3D computational geometry models to ease requirements for engineers to recreate their models. He warns:

> *"If the architects are not willing to produce the kind of information the consultants can use then you end up in a deadlock."* (2008, n.p.)

Next to issues of different durations of design and analysis, legal considerations play a role in the sharing of 3D geometry models. In times where each profession was working on their separate representation of a building project through 2D plans and sections, liabilities for the correctness of the information provided were easily defined. If a design team considers sharing digital 3D representations of a project, it is not always clear who is responsible for errors in the model. Such responsibility may obstruct collaborative efforts in practice. Chaszar argues:

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"This is another argument possibly in favour of not even trying to pass information through the digital pipeline. ... deliberately introducing these moments where things come to a grinding halt and somebody has to re-build the model in order to possibly find the error in somebody else's model might be good for finding errors, but it is not good for the overall process." (2008, n.p.)

Integrated Project Delivery (IPDs) guidelines, as proposed by the AIA, are a step forward in resolving the division of responsibilities and liabilities on virtual representations of building projects. My research suggests that only if the AEC industry finds a consensus on how to share models to the benefit of all, progress in the interoperability of geometry models can be made.

Baring in mind the differences in geometry models used by various practitioners and the problems in practice I addressed in the previous paragraphs, there are nevertheless possibilities for sharing 3D geometry models across disciplines in the early design stages. If relations between members of design teams are built on trust (e.g. through *Partnering* as described previously), and if designers and consultants could find methods for facilitating more effortless updates of computational geometry models, there would be a case for higher interoperability within the building industry. I will highlight three distinct methods for linking computational geometry models across disciplines in section 5.2.2 *Modes for linking computational geometry to building performance analysis.*

Up to this point in this chapter I have reported on my findings as a researcher embedded in the Arup engineering practice. I first profiled seven disciplines according to results from a questionnaire to discuss responses from one-on-one interviews I conducted with members of those disciplines, and finally, I listed particularities of geometry models used by the distinct profession in the Arup *Buildings Group* and their collaborating architects. In the following section I will summarise the key findings of my investigation in practice in the form of disciplinary tables.

4.8.   Disciplinary Tables
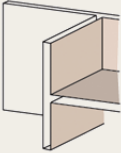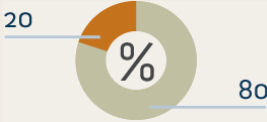
At the summary of the previous chapter I highlighted my motivation to comprehend better the various notations and worldviews used by the different design and engineering disciplines involved with the Buildings Group at Arup. The results I presented in this chapter from my investigations embedded in practice draw a detailed picture about the priorities, concerns, and particularities of the seven disciplines I investigated. The material I researched is broad and multilayered.

In order to concentrate my findings into a format that can be accessed easily by members of the *Buildings Group* at Arup and other observers, I summarised the findings from the quantitative questionnaire, the qualitative interviews and the geometry survey in a set of *disciplinary tables*. Each of the seven professions which I investigated in my research (acoustic engineers, architects, environmental sustainability designers, façade planner, fire engineers, mechanical engineers, and structural engineers) is represented on a single page.
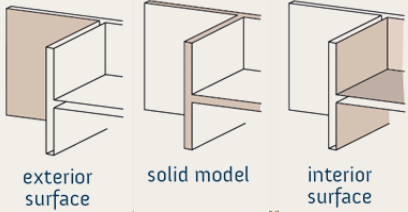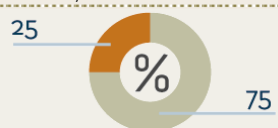
I have included the following ten responses from each of the seven disciplines:
1. Their primary concern in early stage design,
2. Their performance-indicators in early stage design,
3. Their awareness of cost implications for design changes,
4. The feedback they mostly required form others during early stage design,
5. The type of geometrical entity used by them for performance analysis and representation,
6. Their modeling tolerances,
7. The types of modeling or analysis required,
8. Their ratio between group decision making and sole investigation,
9. Their preferred media to pass on information to others, and
10. Their preferred media for receiving information from others.

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topic	ACOUSTIC
Primary concern in the early design stages	room sizing adjacencies noise levels type of interior finishes types of room volumes
Type of performance indicators in early design stages	reverberation times noise cancellation room acoustic targets
Measurements and units	sound intensity **(W/m2)** reverberation **(RT60)** frequency **(hertz)** sound pressure **(dB)**
Awareness of cost implications for design changes	More information desired
Feedback mostly required from others	architectural: building shape and volume façades: cladding material interior: finishes, material usage
Type of geometrical entity used for performance analysis and representation	 interior surface
Modeling tolerance	Approximately 400mm, depending on frequency level that is investigated
Types of (geometric) modeling required	auralisation acoustic response reverberation
Ratio between group decision-making sole investigation	
Preferred media to pass on information to others	Auralisation reports combining text-based and visual means
Preferred media for receiving information from others	2D plans and sections charts, maps, graphs reports combining text- based and visual means verbal explanation

Table 1: Summary of topics describing characteristics of acoustic engineering

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topic	ARCHITECTURE
Primary concern in the early design stages	fulfilling the program design aesthetics functionality spatial synthesis cultural relevance ....
Type of performance indicators in early design stages	depending on local -building-codes net to gross ratio massing budget compliance
Measurements and units	Area　　　　　(m2) cost per m2　　($/m2) height/length　(m)
Awareness of cost implications for design changes	More information desired
Feedback mostly required from others	**all/QS**: basic costing **structures**: grid, sizing **environmental:** daylight **mechanical:** service zone requirements
Type of geometrical entity used for performance analysis and representation	 exterior surface　　solid model　　interior surface
Modeling tolerance	Building: approx. 50 -100 mm Urban: 1000-2000 mm
Types of (geometric) modeling required	2D/3D visualisation massing, overshading surface interior/exterior
Ratio between group decision-making sole investigation	 25　%　75
Preferred media to pass on information to others	3D digital models 3D physical models hand-sketches
Preferred media for receiving information from others	charts, maps, graphs 3D digital model section with analysis results exemplary photographs 3D digital models (ideally shared)

Table 2: Summary of topics describing characteristics of architectural design

199
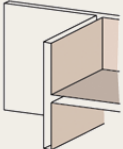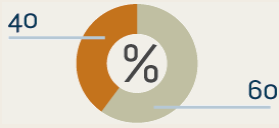
topic	ENVIRONMENTAL
Primary concern in the early design stages	sustainability initiatives carbon footprint / CO2 resourcefulness, lifecycle cost Green Star/LEED/BREEAM
Type of performance indicators in early design stages	Energy use, Water use Carbon output Thermal transmittance, Lighting demand
Measurements and units	Daylight (lx) skylight glare (% - index) emission (CO2) ....
Awareness of cost implications for design changes	More information desired
Feedback mostly required from others	mechanical: energy efficiency façades: glazing type fire: zoning requirements architect: massing
Type of geometrical entity used for performance analysis and representation	 exterior surface solid model interior surface
Modeling tolerance	Walls: 500mm Small scale elements: 200mm
Types of (geometric) modeling required	life-cycle analysis lighting analysis fluid dynamics
Ratio between group decision-making sole investigation	 43.3 % 56.7
Preferred media to pass on information to others	charts, maps, tables, 3D digital model section with analysis results mapped on graphically hand-sketches
Preferred media for receiving information from others:	3D digital models, 2D plans and sections, hand-sketches, charts, maps, graphs, reports combining text- based and visual means
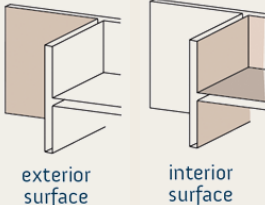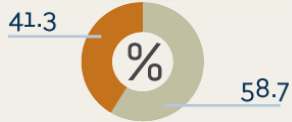
Table 3: Summary of topics describing characteristics of environmental sustainable design

topic	FAÇADES
Primary concern in the early design stages	building orientation architectural aspiration access and maintenance glazing system façade modulation
Type of performance indicators in early design stages	energy targets, skin heat flow wind loads, shading coefficient noise levels
Measurements and units	solar radiation **(W/m2)** conductivity **(W/m2K)** deflection **(mm)**
Awareness of cost implications for design changes	Sufficient information available
Feedback mostly required from others	structural: secondary structure connections architectural: aspiration acoustic: noise cancellation fire: fire rating of façade
Type of geometrical entity used for performance analysis and representation	exterior surface / solid model
Modeling tolerance	early design: 50-100 mm detail design: Approximately 5-10mm
Types of (geometric) modeling required	secondary structure - façade connection cladding detailing
Ratio between group decision-making sole investigation	40 / 60 %
Preferred media to pass on information to others	hand-sketches reports combining text-based and visual means exemplary photographs verbal explanation
Preferred media for receiving information from others	hand-sketches, reports combining text-based and visual means. exemplary photographs

Table 4: Summary of topics describing characteristics of façade-planning
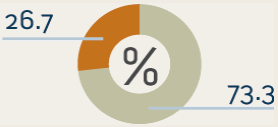
topic	FIRE
Primary concern in the early design stages	safety of occupants space configuration space characteristics number of building-users smoke movement ....
Type of performance indicators in early design stages	building-code compliance speed of smoke spread exit route measurements travel distances
Measurements and units	flame spread **(index)** egress **(mm)/(min)** emissivity **(W/m2K)** temperature **(˚C)**
Awareness of cost implications for design changes	More information desired
Feedback mostly required from others	**architectural**: occupancy numbers **mechanical:** risers/plants **structural:** material type and fire protection
Type of geometrical entity used for performance analysis and representation	 interior surface
Modeling tolerance	Approximately **300mm**
Types of (geometric) modeling required	smoke-spread (CFD) egress modelling heat-flux
Ratio between group decision-making sole investigation	40 / 60
Preferred media to pass on information to others	hand-sketches 2D marked-up drawings charts, maps, graphs verbal explanation
Preferred media for receiving information from others	3D digital models 2D plans and sections

Table 5: Summary of topics describing characteristics of fire engineering

topic	MECHANICAL
Primary concern in the early design stages	heat loads overall areas and volumes spaces for plant rooms duct-work layout/sizing comfort levels
Type of performance indicators in early design stages	thermal comfort speed of air circulation energy targets air-change effectiveness
Measurements and units	thermal comfort (% of°C) air quality (m3/h p.p) energy (W/m2) humidity (%)
Awareness of cost implications for design changes	More information desired
Feedback mostly required from others	architectural: floor to floor height, volumes structural: space requirements for beams/columns environmental: energy
Type of geometrical entity used for performance analysis and representation	exterior surface interior surface
Modeling tolerance	Walls: 500mm Small scale elements: 200mm
Types of (geometric) modeling required	Thermodynamics fluid dynamics
Ratio between group decision-making sole investigation	41.3 % 58.7
Preferred media to pass on information to others	3D digital models (live) 2D marked-up drawings hand-sketches (over model projection) verbal explanation
Preferred media for receiving information from others	hand-sketches equipment selection charts, maps, graphs verbal explanation

Table 6: Summary of topics describing characteristics of mechanical engineering

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topic	STRUCTURAL
Primary concern in the early design stages	structural system select. design aesthetics loads/massing cost compliance risk aversion
Type of performance indicators in early design stages	member sizing stress distribution deflection foundation loads utilisation
Measurements and units	mass (tonnage/Kg) stress (KN/m2) deflection (mm) bending moment (Nm)
Awareness of cost implications for design changes	More information desired
Feedback mostly required from others	mechanical: duct sizes architectural: distance of core to façade, façades: weight of façade system plus cladding
Type of geometrical entity used for performance analysis and representation	centreline/ centersurface
Modeling tolerance	early design: 100mm detail design: 30mm (concrete) 15mm (steel)
Types of (geometric) modeling required	centre-line model centre-surface model
Ratio between group decision-making sole investigation	26.7 % 73.3
Preferred media to pass on information to others	hand-sketches (over projection) 3D digital models (live) 3D physical models charts, maps, graphs
Preferred media for receiving information from others	hand-sketches 3D digital models 3D physical models charts, maps, graphs 2D sections & dimensions

Table 7: Summary of topics describing characteristics of structural engineering

Summary Chapter 4:

The findings I presented in this chapter were motivated by my aim to understand better the worldviews and the particularities behind disciplines in the AEC industry in relation to the question I am asking about early stage design collaboration. I explored the different professional biases associated with six engineering professions at the *Buildings Group* at Arup and their collaborating architects. My investigations into professional specificity encompassed the notations different disciplines use to communicate with others and the priorities they assign to various tasks in early-stage design. The purpose of my investigation was to study firsthand how the seven disciplines make sense of each other's design input and the obstacles they face in doing so.

In order to conduct my research in practice, I engaged with colleagues at Arup through four different means of interaction:

1. participation in a case study project – the *Melbourne Rectangular Stadium*,
2. observation of the knowledge-exchange during design meetings and the consequent design-processes,
3. workshops to address issues cutting across all disciplines in the *Buildings Group*, and, in response to the issues listed above,
4. research interviews in practice.

The participation on the *Melbourne Rectangular Stadium* project (see Appendix A) made me aware of the information gaps in the workflow between various disciplines. It prompted me to focus my research on the analysis of collaborative design processes to consider different ways of engagement. My observations embedded in practice introduced me more profoundly to the work-methodologies of structural engineers and façade planners. The observations made me aware of the necessity to address design collaboration in a holistic way. In order to engage with representatives from all disciplines of the *Buildings Group* at Arup, I organised workshops to discuss knowledge capture, trade-offs of design priorities and the use of geometry models across disciplines. All of the above investigations fed into my preparations to the interviews I presented in this chapter.

In my account of the interview results I presented feedback from architectural and engineering practitioners from within Arup and associated partners about their profession specific priorities in early stage design. I mapped professional specificity based on responses by practitioners from each discipline about 36 topics that affect then during the design of a high-rise office tower.

Configuring the data gathered from the questionnaires according to topic-specificity has allowed me to map and compare the different response to each topic from the seven disciplines of acoustic engineering, architecture, ESD, façade-planning, fire engineering, MEP and structural engineering. Some of the responses to different topics surprised me, such as the overall high rating of the *floor to floor height,* or the *ratio of window to facade area.* No aspect of my previous research and practice would have suggested those topics to have such priority.

The graphic representation of professional identities using spider-diagrams demonstrates the differences in the emphasis of particular design aspects by distinct professions. The distinct professional profiles that were derived from this process demonstrate the different approaches taken by members of the disciplines I interviewed. Such was the difference between the profiles, that I was not convinced initially about the validity of the data I collected. What if the outcome was random due to the limited number of participants (4) per group? What if the responses were tarnished by personal preferences of participants?

In order to address the above issue I tested the validity of my sample by checking the fluctuation of answers from interviewee to interviewee. In most cases clear profiles were emerging after including data from the third member of a profession and the profiles consolidated substantially with the inclusion of the fourth representative. As described previously, I could detect a stronger *professional coherence* between answers of engineers from a discipline than between answers given by architects.

The most relevant finding stemming from the analysis of the spider diagrams is the fact that some professions only assign priorities to a limited set of design aspects (such as acoustic engineers and fire engineers). What did come as a surprise to me in this context, was the high divergence of answers given by the ESD consultants from the *total average* by all participants. I would have expected environmental sustainability designers to rate more similar to the *total average*.

By superimposing two professional identity-graphs on top of each other I started to uncover the differences in the approach to design that each of the two disciplines brings to bear. Confronting engineers from professions represented in those pairs of spider-diagrams, upon completion of the overall mapping process, resulted in lively discussions about the reasons for some of the discrepancies and shared values.

In addition to this quantitative analysis, I summarised and discussed responses from the interviewees around ten questions that closely relate to sense-making in early stage design. Half of the questions in this qualitative analysis related to the work methods of individuals, the other half dealt with collaboration issues in early stage design. The results provide a firsthand account of the obstacles to sharing knowledge across disciplines during early stage design practice.

A key finding from my one-on-one interviews was revealed by several accounts where practitioners expressed their *need for a design environment to analyse the combined impact of various building-performance data to inform their decision making*. The reason for a lack of such a system was explained by the following three arguments.

Firstly, practitioners from individual disciplines generate their own profession-specific tables, spreadsheets and tools to evaluate design in the early stages. These resources are highly domain and office-specific and they often do not reveal useful information to members of the design team with different professional backgrounds. Interviewees expressed the need for more visual representation of performance outcomes to make better sense of their partner's design-input.

Secondly, every discipline has different performance criteria for their work and different types of measurements are in use to analyse them. Trade-offs between various performance aspects are difficult to achieve and engineers currently rely on the architect to take over the role as the integrator.

Thirdly, the preferred media for communicating design intent differs from discipline to discipline. The only common ground during design collaboration in the early stages appears to be the hand-sketch. In addition to this, the geometry models for performance analysis and design representation of each of the seven disciplines are often incompatible to each other and they require profession-specific appropriation or time-consuming redraw.

I complemented responses from the qualitative analysis by addressing the different computational geometry models that various professions use to conduct their design analysis and representation.

Results from my investigation in practice in Chapter 4 revealed the reasons for the information-gap between collaborating disciplines that my literature review had exposed in Chapter 3. The findings presented in this chapter support my initial claim that architectural design profits from introducing a social and coordinated effort from various design professionals early on. The findings also highlight shortcomings in current design practice such as the lack of coordination between disciplines and the absence of adequate support for design evaluation across professions. In response to these insights I propose methods and tools that can assist more streamlined early stage collaboration between design and consulting disciplines in AEC in the following chapter.

5. New modes of early-stage design collaboration

This chapter encompasses the synthesis of my argument for describing novel ways in collaborative, early-stage design. Based on the background research I presented in Chapter 3, and in consideration of responses from practitioners which I laid out in Chapter 4, I now propose innovative design strategies to facilitate better sense-making across disciplines.

At the outset of this chapter, in 5.1: *Optioneering*, I define a structured way of engaging with decision-making processes to address multiple criteria in the resolution of complex tasks. In Chapter 5.3.3: *Evaluating design-options across disciplines using rule-based methods*, I explore intelligent linkages between building geometry and building performance analysis. I discuss the definition of professionalism that supports rather than impedes collaboration as part of: *Sharing authorship in transdisciplinary design* in Chapter 5.3. There, I analyse how the different notations used by designers and their consultants can be appropriated to assist in sense-making activities. In Chapter 5.4: *DesignLink – A proposal for a collaborative design framework* I conclude my synthesis by describing how a computational framework could be set up to assist in the above and I present the layout of the user interface for the DesignLink framework.

The comments by researchers in Chapter 3 provide evidence about the drastic changes that have been transforming the building industry over the last two decades (in particular). Computational tools for drafting, building performance analysis and exchange of design information have helped to speed up the design process and other processes in its support. What these tools have failed to accomplish to date is to facilitate the process of designing collaboratively as a social activity in architectural practice. The current advance of building information modeling BIM is characterised by a belief that the exchange of standardised design-data automatically enables interactive design collaboration throughout the whole building lifecycle. As much as BIM has gained acceptance for design coordination in the advanced stages of design and beyond, my research

reveals that it has not yet been embraced by designers to assist in the early design stages. In addition to this shortcoming, legal frameworks regulating design responsibilities seem to impede rather than support collaborative design efforts and knowledge-sharing between disciplines.

Responses from design professionals as presented in the previous chapter confirm the segregated nature of the building industry. I demonstrated the distinct profile of seven disciplines from design and engineering based on their design priorities in resolving a common design task in early design. Responses by the practitioners point out that, in spite of improvements in the work practice of individual disciplines over the past two to three decades, there appears to be insufficient support for design communication with others. Support for sense-making across disciplines would not only benefit collaborative efforts in teams, but it simultaneously would offer improvements to the work within the distinct professions as well.

5.1. Optioneering

I claim that the first step for successful collaboration in early stage design in the current architectural context is to rethink the methods according to which designers and consultants exchange information and build up knowledge. Architects and engineers face wicked problems in everyday practice, particularly on large scale building projects. There is no single optimal solution for a design problem, but there is an array of possible design options that can be explored to find a *suitable* solution. The evaluation of options depends on design priorities from a plurality of disciplines participating in a design project.

In this section I discuss a method that enables collaborators to create quickly an array of design options across disciplines in an exploratory, yet informed manner. These solutions are the basis for a new type of dialogue that allows professionals who strive for streamlined collaboration to make better sense of each other's information and to consequently engage collaborative decision-making process.

The method of optioneering is rooted in the need for collaborators to engage easily with the ever increasing amount of information they are facing in their decision making processes in everyday practice. As shown in section 3.3: *ICT in support of design-collaboration across disciplines*, building projects are becoming increasingly information-rich and there is a strong emphasis on sharing manifold design data amongst various team members.

> *"Our current goal at KPF[58] Research is to use simulations to evaluate thousands of alternatives and provide an increasingly comprehensive framework for increasingly generalized solutions."* (Hesselgren, Charitou and Dritsas 2008, 5)

In part of my PhD thesis I firstly explain the method of optioneering as it is currently used in design-practice in section 5.1.1: *Introduction to Optioneering*. I then contextualise the optioneering method on the basis of a case study project in section 5.1.2: *Optioneering in design practice* and I scrutinise prerequisites for optioneering between designers and consultants across disciplines in section 5.1.3: *Optioneering across disciplines*.

5.1.1. Introduction to *Optioneering*

"It is often necessary to make decisions between equally good alternatives as well as needing to satisfy various competing objectives. If none of the alternatives satisfies all the objectives and specifications, the decision maker has to select the best way forward based upon compromise and selection." (Total Interactive Solutions TIS 2009, n.p.)

The term *optioneering* is a hybrid between *option + engineering*. It implies the creation of options that are arrived at through informed decision making, based on a level of scientific rigor similar to that applied to engineering processes. I observed the term *optioneering* being used in everyday building practice at Arup to describe an approach where designers create multiple variations of a design proposal and evaluate those in regard to diverse performance criteria that were set out at the

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[58] Kohn Pedersen Fox (KPF) Associates is an international (architecture*) practice with studios in New York and London. The central concern of the practice is design excellence. KPF is committed to providing designs that create uplifting spaces for people. Source: http://www.kpf.com/main.asp   * added by author

beginning of the design process. As much as optioneering makes part of everyday jargon in practice, I did not succeed in sourcing an official description that properly defines the word in the English language[59].

Encyclo, a UK based online encyclopedia defines *optioneering* as: "*a term increasingly used in industry when management needs to be confident of a course of action; particularly where regulatory or funding bodies seek a demonstration of due process*" (Encyclo 2009, np)

This mention of *the industry* does not indicate which industry is being addressed in the encyclopedia. In my research I encountered industries other than AEC where the term is used to describe a strategy in business-oriented decision-making.

> "*When the consequences of the decision are serious, optioneering is a process that enables clear and structured decisions to be reached.*" (Total Interactive Solutions TIS 2009, np)

"*Total Interactive Solutions*" lists four elements that are necessary to facilitate optioneering processes:

1. identifying the options and the criteria for the option evaluation
2. providing impartial scoring for the options and applying weighting criteria
3. viewing and analysing the results; sensitivity and robustness analyses
4. Ensuing stakeholder participation to achieve buy-in to the decision

In strict technical terms, the method of optioneering can be counted as a process supporting *Multi Criteria Decision Analysis* (MCDA[60]) as described by Malczewski (2006, 705). Multi-criteria decision environments allow for the evaluation of complex problems where decisions need to be taken based on a high degree of uncertainty. According to Linkov et al., MCDA analysis serves "*to evaluate and choose among alternatives based on multiple criteria using systematic analysis to overcome the limitations of unstructured individual or group decisions.*" (Linkov, et al. 2006, 61)

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[59] There is currently neither an entry describing *Optioneering* in the English Oxford Dictionary, nor in the Australian Macquarie dictionary.

[60] MCDA provides a rich collection of techniques and procedures for structuring decision problems, and designing, evaluating and prioritizing alternative decisions. (Malczewski 2006, 703)

The Optioneering method is intrinsically tied to human decision making. Although the search for possible solutions through optioneering benefits from automated optimisation processes in the evaluation of multi-criteria objectives, the ultimate goal is to provide users with the choice of a well considered array of possible options[61]. After considering the general definition of optioneering I now ask: How does the method of optioneering in multi-criteria decision environments relate to collaboration in early design?

Interviewees at Arup and their partner architects longed for support to understand better the combined impacts of their design input on the overall project. They called for methods that would allow them to shorten further the intervals between their analysis and their ability to provide informed feedback to others during team-decision making. In the following section I will investigate how optioneering can be applied in the context of everyday design practice.

5.1.2. *Optioneering* in design practice

By analysing components of design problems, Lawson asserts "*since design problems defy comprehensive description and offer an inexhaustible number of solutions the design process cannot have a finite identifiable end*" (2006, 123). Lawson argues that in the conceptual design process, designers must be capable of keeping many things in mind at the same time for rapid decision making (Lawson 2005, 389)

This comment explains the multi-criteria nature of decision making in the context of collaborative design efforts across disciplines. The argument that there exist an inexhaustible number of solutions in design is supported by remarks from Rittel and Webber (1972, 160) about the wicked nature of the planning process.

What support can practitioners derive from computational processes that facilitate their engagement with complex design problems?

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[61] Various automated performance-optimisation procedures for multidisciplinary design optimisation are listed and described by Flager et al. (2008, 1-19)

Smart interfaces and the use of ICT facilitate the transfer of design data between collaborators in the building industry. In general, the time required to carry out performance analysis is continuously diminishing compared to the time required when architects and engineers had to rely on cumbersome drafting processes by hand, calculations, and manual cross-referencing of results to performance tables and graphs. Figure 62 illustrates an example for the difference in man-hours needed to conduct analysis on two similar tower projects in 1988 and 2008. The numbers shown in the example stem from figures provided to me by structural engineers at Arup in their Melbourne office.
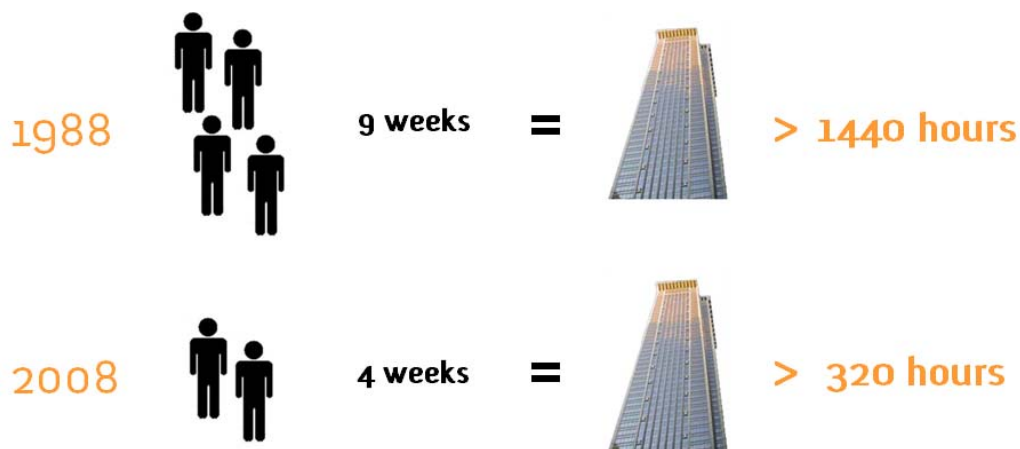
Figure 62: Comparison of time working hours required for the structural engineering of an office tower 1988-2008, Source: Arup

The increase in speed in which design information is currently produced in context with the increase of information that design teams are dealing with, challenge traditional methods for communication and the sharing of knowledge. In order to process the large amount of design data that is now being produced in an increasingly shorter amount of time, optioneering is a method that allows for structuring information better for decision-making purposes.

One example in this context is the work on the *Melbourne Rectangular Stadium* where I explored the path of optioneering with my colleagues at Arup. On the basis of the steel-roof of the stadium project, we first discussed the criteria space we wanted to explore through optioneering.

In contrast to most other projects carried out at Arup at the time of my involvement, applying optioneering principles allowed us to optimise the stadium roof without having a pre-defined idea about the exact geometrical definition of the final outcome. Instead, the optioneering method gave us space to explore and negotiate an array of design options that influenced the morphology of the structure. In accordance to the above observation, Laiserin distinguishes two approaches to architectural design (2008, 236):

1. *form-making, and*
2. *form finding.*

While he defines form-making loosely as *"a process of inspiration and refinement (form precedes analysis of programmatic influences and design constraints)"* he characterises form-finding as *"a process of discovery and editing"* where *"form emerges from analysis"* (Laiserin 2008, 236)

I claim that the concept of form-finding is crucial to the mode of interaction between designers and consultants as it advocates a type of collaboration for co-rationalised exploration. Engineering performance becomes a co-driver of a building's form. The idea behind form-finding postulates a social effort where designers and consultants engage in a discourse at the outset of a project to define, weight and trade-off design criteria. I would suggest that the emerging practice of optioneering facilitates such a discourse.

At the *Melbourne Rectangular Stadium* project, structural engineers and façade-planners agreed to focus their investigation on the variation of the overall roof-curvature as well as the curvature of individual bays that form the roof-structure. A range for the variation of individual elements of the roof was determined in consideration of its appearance from the spectator's perspective, structural constraints relating to the weight (tonnage of the roof), and considerations regarding the standardization of façade-panels. Images of a physical and a digital model of the stadium roof geometry are shown in Figure 63.
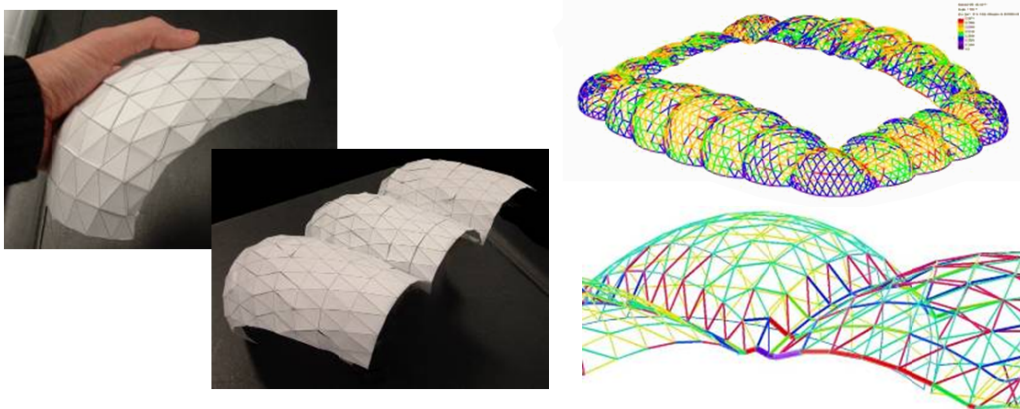
Figure 63: A physical paper model and a digital stress analysis model of the stadium room geometry, Source: Author and Arup

A parametric model was generated that allowed us to interrogate quickly the range of effects of the variations of the roof-curvatures on the physical performance of the roof structure. The reduction of steel tonnage was the predefined goal which required the search for the minimal diameter of each individual steel member.

It was therefore a declared goal of the design team to use the output of the parametric model not only to address aesthetic considerations of the roof, but also to link it as directly as possible to structural performance feedback. This link was achieved by transferring the output of the parametric geometry variations closely to software that allowed for stress-analysis in each tubular steel element that constitutes the roof, to then define a minimum diameter for each steel section. The process described above is illustrated in Figure 65.
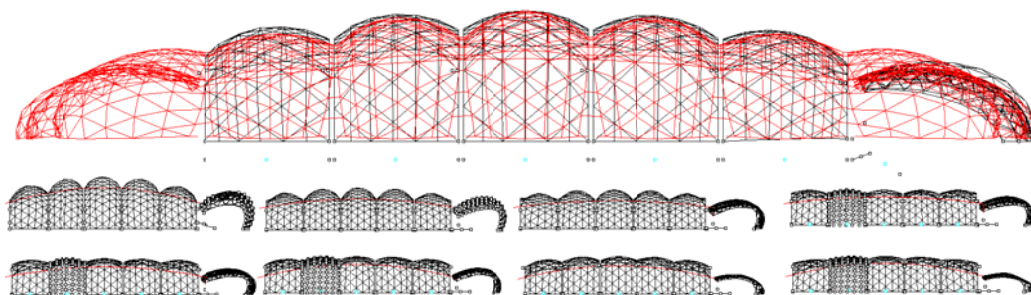
Figure 64: Parametric variations of the stadium room geometry, Source: Author
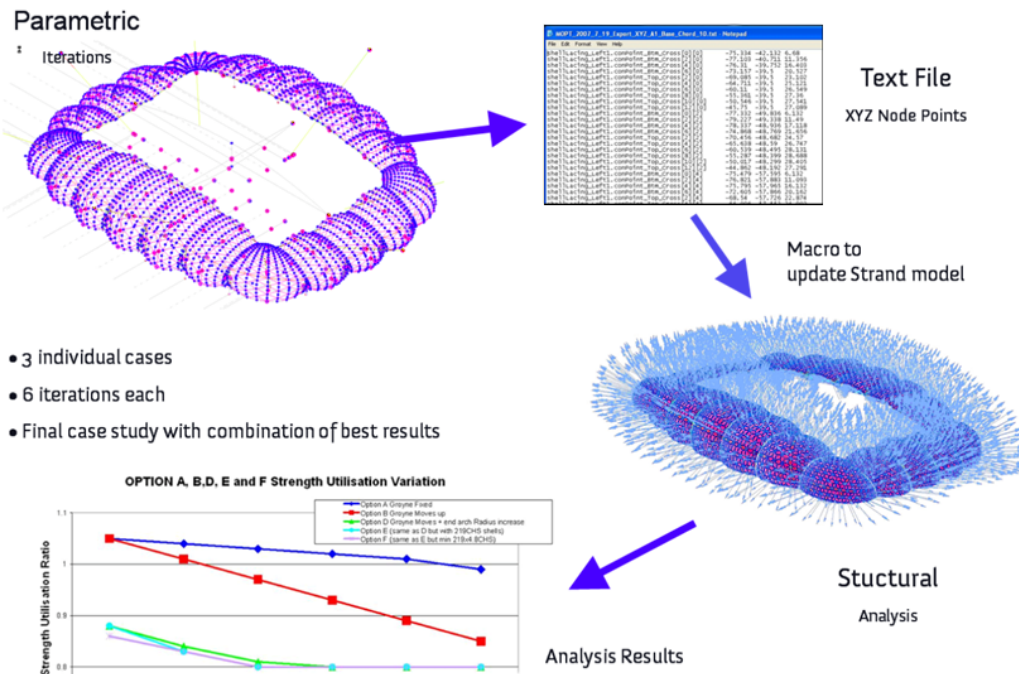
Figure 65: Moving between a parametric model to structural analysis and the comparison of performative aspects from multiple design options, Source: Author and Arup

5.1.3. Optioneering across disciplines

My research in building practice with Arup specialists suggests that processes guided though optioneering do not necessarily need to consider design-criteria across multiple disciplines. Optioneering is well suited to address multi-criteria optimisation within the boundaries of a single, or a selected few discipline. At the same time, I contend that the benefits offered through optioneering in the context of building design are particularly relevant when applied across several disciplines.

Work on the *Rectangular Pitch Stadium* project at Arup revealed that optioneering can facilitate lateral thinking between design professions. In doing so, a network of connections can be established across disciplines that is based on the specific requirements of design performance. The configuration of the network can vary depending on the required evaluation between a number of participants at a given point in the collaborative effort. The scenario described in Figure 66 is an example showing a network of collaborating professions who are laterally interconnected.

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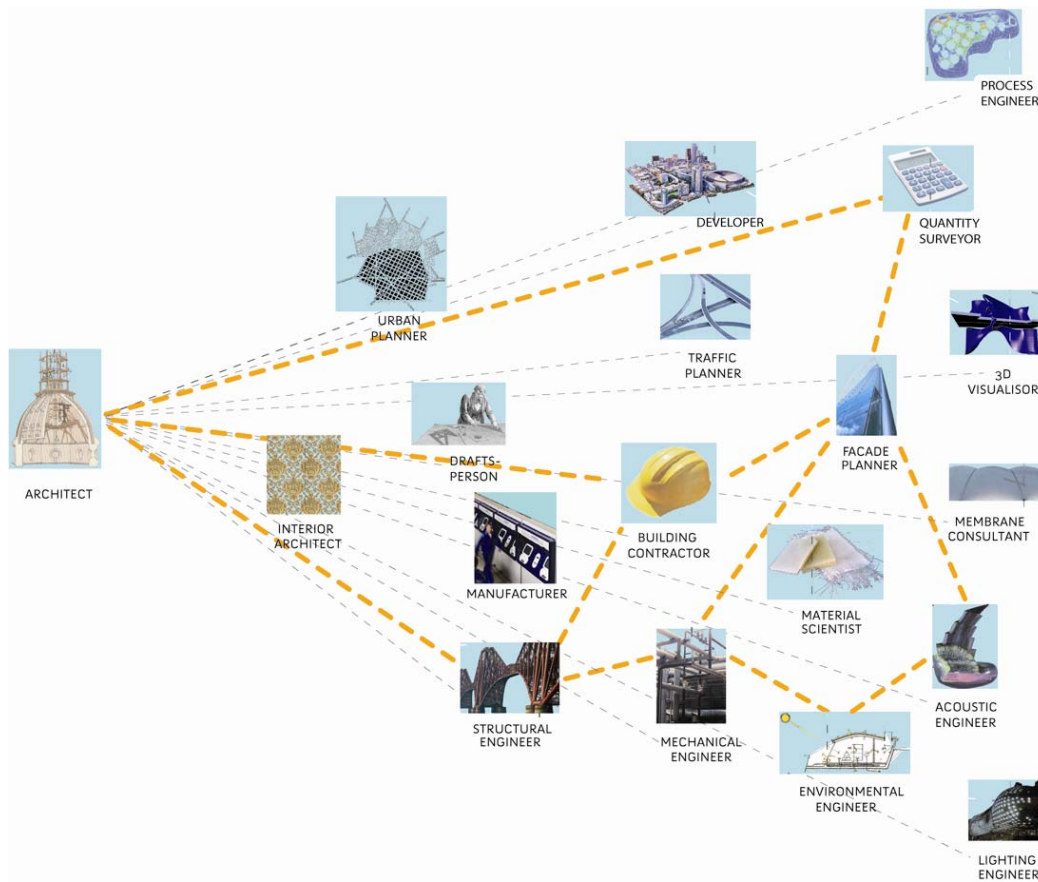
Figure 66: One potential network enabled through optioneering, Source - author

In the above example, a façade planner could collaborate with a structural engineer, an environmental engineer and a mechanical engineer to test the combined effect of a shading system on the building's structural and thermal qualities. In doing so the team could *optioneer out* solutions that are both structurally and thermally disadvantageous as well as for aesthetic reasons. If manufacturing-data and a bill of quantities were involved, the team would be able to assess the feasibility of each option that gets created.

My research about the preconditions for successful optioneering routines uncovers that a selective comparison of building performance information allows professionals to appropriate their way of interacting with their team partners. Results obtained from design processes based on the optioneering method only add to sense-making amongst professionals if the base-criteria are understood by all participants.

Agreeing with the four elements previously listed by *Total Industry Solutions:* identifying options and criteria for evaluation, scoring and weighting criteria, viewing and analysing results and stakeholder participation, I ask the following three questions: Firstly, what are the basic performance criteria that various groups bring to a project? Secondly, how can building performance from one discipline be represented to make sense to other disciplines? And thirdly, how can they best be compared with each other and brought into a system of priorities and design drivers?

I argue that the process of knowledge-sharing in optioneering is dependent on an understanding of the design priorities and the performance targets of various disciplines. My research suggests that optioneering partners need to define the criteria-space of their multi-objective design evaluation at the outset of design collaboration. The definition of the criteria space requires a dialogue where team members discuss the main performance drivers behind the array of possible solutions they aim at during the application of optioneering. Aspects of design priorities from individual disciplines have different impact on the overall outcome of a project. Some performance-aspects are major drivers in the generation of a project and they need to be addressed as early as possible; other aspects have little impact on the overall outcome and they are considered later in the design development process.

In order to work towards integrated practice I believe we require an intensive dialogue with the end parties who receive our information to understand their work methodology, skill sets and the way they interface design-information (be it for design, analysis or production). By doing this, we can gain a better understanding of the requirements of our design partners and use this as a basis to then work backwards to inform our own design-processes.

We need to comprehend what type of information is essential in early decision making-processes and how we can provide qualitative support based on either performance specifications or expertise from previous projects.

As I pointed out in Chapter 4.5.2: *What performance targets are you working towards?*, each discipline operates on the basis of distinct performance targets with different concerns and different units to describe quantitative values related to their field. In the *disciplinary tables* in Chapter 4.8, I summarised examples of basic performance indicators of the seven disciplines I had interviewed as part of my research at Arup. The disciplinary performance indicators illustrate the diversity of criteria applied in everyday work by design professionals. I have extracted the main responses from the individual disciplinary tables to distil them as follows:

- o reverberation times, noise cancellation, room acoustic targets (Acoustic engineering)
- o aesthetic appearance, net to gross (area) ratios, massing, cost compliance (Architecture)
- o energy use, water use, carbon output, daylight factor (ESD)
- o energy targets, u-value (glazing), wind loads, shading coefficient (Façade-planning)
- o speed of smoke spread, flame spread, escape-route travel distance, egress width (Fire engineering)
- o thermal comfort, speed of air circulation, air-change effectiveness, energy targets (MEP)
- o utilization, (foundation) loads - tonnage, deflection, member sizing, stress distribution (Structural engineering)

I reformatted the information from the individual *disciplinary tables* as a multidisciplinary matrix. This matrix contains a compact set of information taken from both the questionnaire as well as the interviews. The matrix is an instrument to compare variables from various building-performance aspects in the early design stages and to check which performance criteria can most efficiently be brought into relation with each other.[62]

Figure 67 shows the matrix as a collection of individual disciplinary tables that can be interrogated for common themes

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[62] A larger foldout version of the matrix is located in the appendix of this thesis.
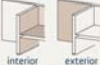
	ACOUSTIC	ARCHITECTURE	ENVIRONMENTAL	FACADES	FIRE	MECHANICAL	STRUCTURAL
primary concern in the early design stages:	room sizing / adjacencies / noise levels / type of interior finishes / types of room volumes	fulfilling the program / design aesthetics / functionality / spatial synthesis / cultural relevance	sustainability initiatives / carbon footprint / CO_2 / resourcefulness / lifecycle cost / Green Star/LEED/BREEAM	building orientation / architectural aspiration / access and maintenance / glazing system / facade modulation	safety of occupants / space configuration / space characteristics / number of building-users / smoke movement	heat loads / overall areas and volumes / spaces for plantrooms / duct-work layout/sizing / comfort levels	structural system select. / design aesthetics / loads/massing / cost compliance / risk aversion
type of performance indicators in early stage design:	reverberation times / noise cancellation / room acoustic targets	depending on local building-codes / net to gross ratio / massing / budget compliance	energy use / carbon output / water usage / thermal transmittance / lighting demand	energy targets / noise levels / room acoustic targets / wind loads / shading coeficient	building-code compliance / speed of smoke spread / exit route measurements / travel distances	thermal comfort / speed of air circulation / energy targets / airchange effectiveness	member sizing / stress distribution / deflection / foundation loads / utilisation
measurement and units:	sound intensity (W/m2) / reverberation (RT60) / frequency (hertz) / sound pressure (dB)	area (m2) / cost per m2 ($/m2) / height/length (m)	daylight (lx) / skylight glare (% - index) / emission (CO2)	solar radiation (W/m2) / conductivity (W/m2K) / deflection (mm)	flame spread (index) / egress (mm) / emissivity (W/m2K) / temperature (°C)	thermal comfort (% of °C) / air quality (m3/h p.p) / energy (W/m2) / humidity (%)	mass (tonnage/Kg) / stress (KN/m2) / deflection (mm) / bending moment (Nm)
feedback mostly required from others:	architectural: building shape and volumes / facades: cladding material / interior: finishes, material usage	all/QS: basic costing / structures: grid, sizing / environmental: daylight / mechanical: service zone requirements	mechanical: energy efficiency / facades: glazing type / fire: zoning requirements / architect: massing	structural: secondary structure connections / architectural: aspiration / acoustic: noise cancellat. / fire: fire rating of facade	architectural: occupancy numbers / mechanical: risers/plants / structural: material type and fire protection	architectural: floor to floor height, volumes / structural: space requirements of beams/columns / environmental: energy	mechanical: duct sizes / achitectural: distance of core to facade / facades: weight of facade system plus cladding
type of geometrical models used for performance analysis and re-presentation:	interior	interior exterior	interior exterior (urban)	exterior centreline	solid-model	interior solid-model	centreline
types of geometric modeling required:	auralisation / acoustic response / reverberation	2D/3D visualisation / massing, overshading / surface interior/exterior	life-cycle analysis / lighting analysis / fluid dynamics	secondary structure - / facade connection / cladding detailing	smoke-spread (CFD) / egress modelling / heat-flux	thermodynamics / fluid dynamics	centre-line model / centre-surface model
ratio between time spent for sole investigation compared to time spent in group decision-making:	20 / 80	25 / 75	43.3 / 56.7	40 / 60	40 / 60	41.3 / 58.7	26.7 / 73.3
preferred media to pass on information to others:	auralisation / reports combining text-based and visual means (problematic)	3D digital models / 3D physical models / hand-sketches	charts, maps, tables / 3D digital model section with analysis results mapped on graphically / hand-sketches	hand-sketches / reports combining text-based and visual means / exemplary photographs / verbal explanation	hand-sketches / 2D marked-up drawings / charts, maps, graphs / verbal explanation	3D digital models (live) / 2D marked-up drawings / hand-sketches (over model projection) / verbal explanation	hand-sketches (over drawing projection) / 3D digital models (live) / 3D physical models / charts, maps, graphs
preferred media for recieving information from others:	2D plans and sections / charts, maps, graphs / reports combining text-based and visual means / verbal explanation	charts, maps, graphs / 3D digital model section with analysis results / exemplary photographs / 3D digital models (ideally shared)	3D digital models / 2D plans and sections / hand-sketches / charts, maps, graphs / reports combining text-based and visual means	hand-sketches / reports combining text-based and visual means / exemplary photographs	3D digital models / 2D plans and sections	hand-sketches / equipment selection / charts, maps, graphs / verbal explanation	hand-sketches / 3D digital models / 3D physical models / charts, maps, graphs / 2D sections & dimensions

Figure 67: Transdisciplinary matrix showing seven professions, Source: Author

Figure 68 illustrates a scenario where the design-team can evaluate the impact of the façade-glazing type on performance-levels from other disciplines. The selection of glazing-type has an effect on sound-pressure levels for acoustic, on the daylight factor as defined in environmental sustainable design and the tonnage of the façade which is relevant for acoustic purposes.

Figure 68: Transdisciplinary matrix revealing common design drivers, Source: Author

The involvement of the whole design team at the outset of a project is currently not common practice. My research at Arup indicates that a useful method to make the design-team understand and develop the main drivers for a given project is to conduct charrettes at the start of a project. Such meetings should include all major participating design and consulting disciplines and the client to agree on the main performance drivers behind a project. The priorities and design-drivers that are agreed on during the early stage-charrettes by the team can be captured in a qualitative manner. They can be made available to the design team as graphs similar to the figures I presented in Figures 34-36.

For the above façade example, professionals could interpret specific topics such as the importance of the cladding type and the skin heat flow (which is related to the thermal transmittance of the façade) to extract information about their importance across different domains. The results presented in Figure 69 illustrate that while the selection of cladding type is of high relevance for all professions, the thermal properties of the façade are only relevant to a few (architect, ESD, Façades and MEP).
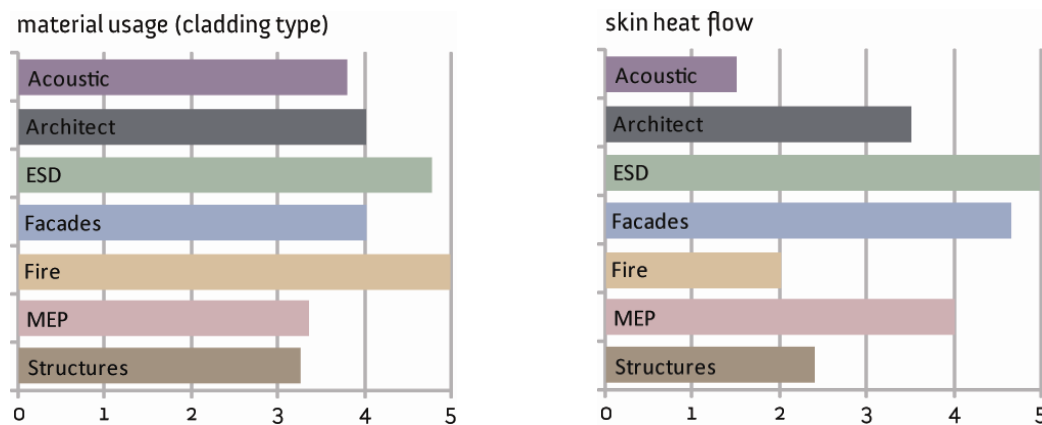
Figure 69: Bar charts with responses regarding *material usage (cladding type)* **and the** *skin heat flow*, **Source: Author**

The system of mapping priorities presented in Chapter 4.3.1: *Profiling disciplines based on their design-priorities in the early stages,* illustrates one possibility to demonstrate design drivers to the whole team in the form of graphically explicit spider-diagrams. A spider diagram colour-coded according to disciplinary

affiliation (as seen in Figure 70) could then set guidelines for common priorities that should be addressed by the team.
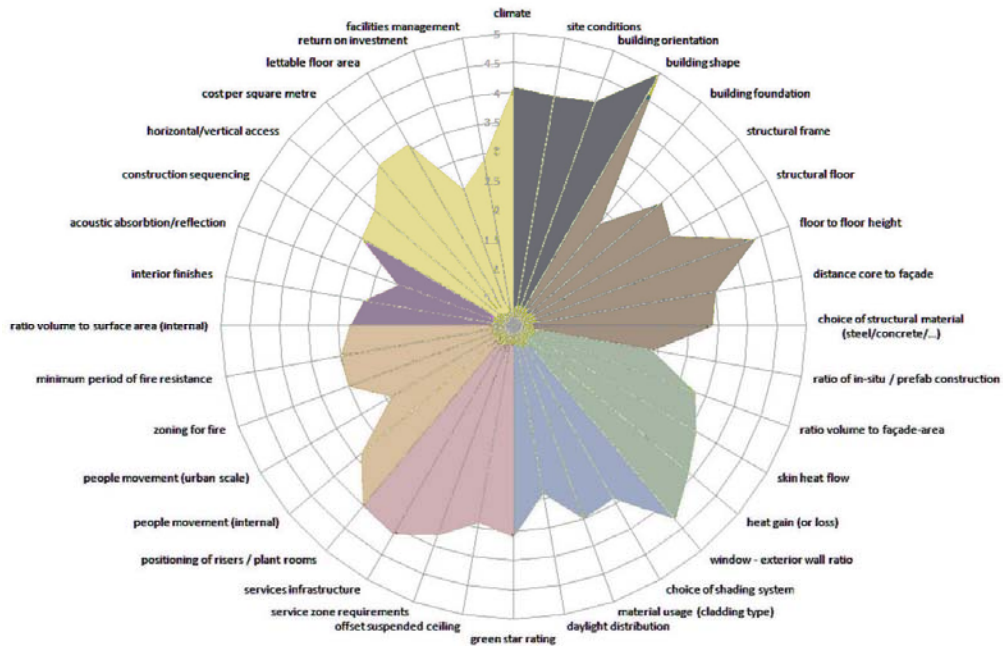
Figure 70: Exemplary Spider-diagram illustrating design priorities colour-coded according to professional affiliations, Source: Author

Figure 71 illustrates the traditional design approach of how parties interact from issuing the design brief until reaching an outcome. The generation of design options and the interpretation and analysis by consultants occur in separate steps. Decision making is at times done in isolation based on one design option.
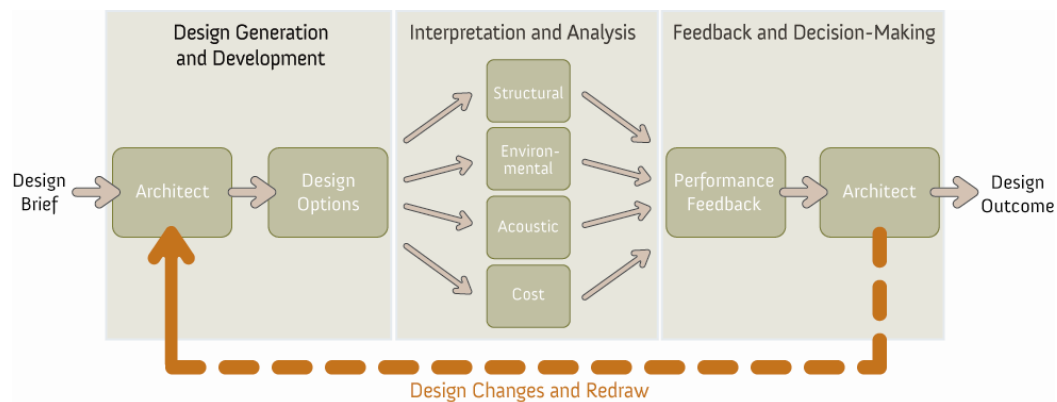
Figure 71 : Diagrammatical representation of traditional workflow, Source: Author

Figure 72 shows a collaborative approach through optioneering where the generation of design options is closely linked throughout the team at an early design stage and multiple solutions are proposed and considered by the design team.
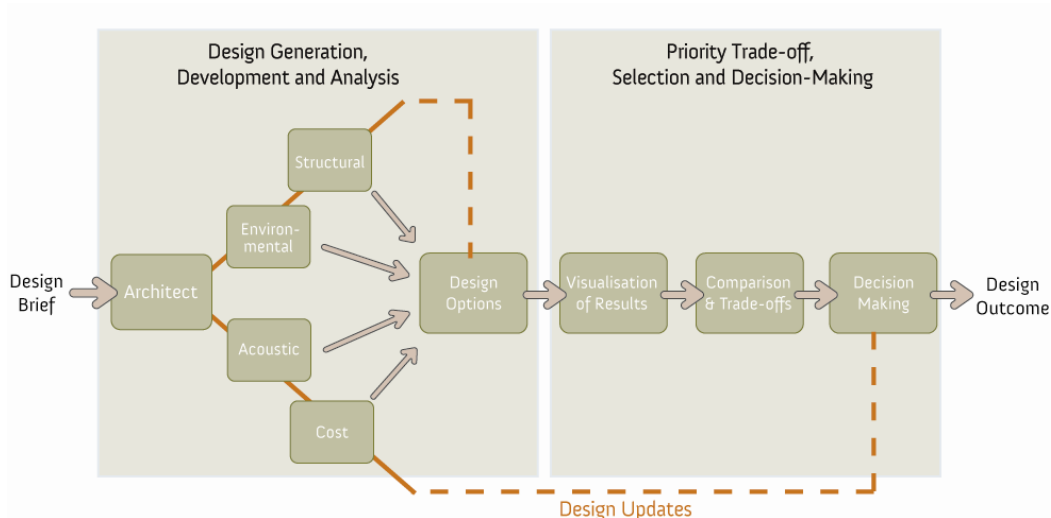
Figure 72: Diagrammatical representation of optioneering workflow, Source: Author

My observations in practice highlight that experienced designers and consultants are able to comprehend many of the dependencies described above if they are involved in group decision-making over a long period. At the same time, my observations reveal that only a few practitioners understand over-arching design issues, and many of the dependencies described in my research are not automatically obvious to them.

Charrettes at the beginning of a project help to determine those aspects of performance that can most usefully be brought into relationship through optioneering. They can assist in sense-making activities during further stages of a project. In the course of design collaboration, team members can then decide which performance aspects to focus on in greater detail. Not all design aspects are always equally important for all team-members during meetings. Optioneering processes should be tailored to suit the most relevant aspects that are being discussed and they should highlight issues that may not always appear obvious to some members in the design team. As one fire engineer in the interviews stated:

"The disadvantage of large multidisciplinary workshops is that often there are large portions that are not relevant to us and we find that this can be quite of a time-waster" (fire engineer 3).

Optioneering empowers designers and consultants to provide their partners with informed feedback about building-performance and other types of decision support in the early design stages. If set up in the right way, optioneering could also enable design teams to compare current jobs with previously undertaken projects and even capture some of the expert knowledge applied within. This knowledge is often not tapped into beyond team-specific or project-specific situations.

The concept behind optioneering is not new. It becomes more effective through new ways of interaction between professionals from distinct disciplines who collaborate using streamlined computational interfaces and thereby delegate faster turnover of results. Designers and consultants can now consider how building performance might drive the overall building geometry, the structural system and façade options.

So far, I investigated optioneering methods for engaging in an iterative process where informed decisions can be made by professionals on the basis of building-performance. In the following section I discuss the quick generation of rule-based design templates that provide links to building performance analysis.

5.2. Evaluating design-options across disciplines using rule-based methods

As revealed in the research interviews at Arup, team decision-making processes in early stage design are often guided by *rules of thumb* and intuition rather than pure rational. Operating with such *bounded rationality*, Simon asserts that we cannot expect to find singular optimum solutions in multi-criteria decision-making processes, but rather *"satisficing"* (satisfice = satisfy + suffice) (H. Simon 1969, 28) ones that provide us with adequate scenarios to choose from.

In this section I analyse the impact of rule-based design methods to assist designers in the creation of multiple variations of their projects. Following from initial successes in the application of rule based design on the stadium project, I investigate further how optioneering processes can advantageously build on rule-parametrically variable geometry. As part of my investigation I ask three questions: First: how can rule-based methods be used in the optioneering process to produce a 'controlled set' of geometrical design alternatives? Second: how can we evaluate options and keep the design flexible enough for input from our partners? And third: how do we combine rule-based design with the generation of multiple design options driven by building performance?

My interviews with practitioners at Arup included a question about a miracle toolbox to elucidate specialists' projections about future needs and potential modes of collaboration. Design professionals described their miracle toolbox as something that would allow them to engage in an iterative process between performance analysis, optimisation and design decision making, in close to real-time. The more immediate results can be communicated across a team, the better the information-flow and the collaborative capabilities. In this context, changes need to be adopted quickly and integrated into a flexible geometrical setup on the spot without requiring lengthy redraws. Figure 73 illustrates the connectivity of a collaborative environment where rule-based design templates are linked to performance analysis through a collaborative environment.

Figure 73: Linking rule-based design to performance analysis through a collaborative environment, Source: Author

> *"…design professionals are now spending less than half of their time doing 'value-added' design and analysis work. The majority of their time is spent managing design information, including manually integrating and coordinating discipline-specific design and analysis representations."* (Flager, et al. 2008, 2)

As expressed in the above quote, designers now spend a substantial amount of their time managing building geometry. The time it takes designers to accommodate changes in a computational geometry model and pass that model onto their partners poses an impediment to real-time collaboration. Any major design change consequently needs to be redrawn by design consultants who analyse performance aspects in their field.

5.2.1.   Precedence of linking rule based design to building performance analysis

I illustrated in Chapter 3.3.3 (*The current state of ICT support for collaborative design*), that advances have been made by researchers and practitioners to use computational design software for connecting implicit geometrical relations through declared parameters. Parametric and other rule-based tools have increasingly been adopted by design professionals in the exploration of their ideas (Turkle et al. 2005, 19; Silver 2006, 11).

In the 2006 AIA Report on integrated practice, Eastman describes how parametric modelling enables project teams to integrate and encapsulate the combined expertise of individuals into a design tool (Eastman, 2006, n.p). Instead of working on a fixed geometrical template, parametric models allow for incorporating various design intentions that "*persist over geometric variations*" (Shelden 2006, 83).

Depending on the level of resolution required and the type of parameters chosen, parametric modelling offers manifold possibilities for addressing a range of issues at different levels of precision from the design ideation phase up to construction. In this context Aish speaks of parametric design as a way to progress from "*intuition to precision*" (Aish 2005, 10). Once an initial desired form is agreed, it may be encoded within a parametric model and used to generate geometry through evolutionary means.

My research suggests, that rule based (such as *parametric*) modeling is currently used in practice to address mainly morphological design aspects where designers

want to maintain tight control over design changes, while being able to experiment with a variety of formal variations and driven by parameters. In my research I wonder what other advantages can be found in the use of rule-based design and I therefore ask: What are the advantages we gain from applying rule-based design methods beyond the faster generation of geometrical variations of the same 'base'-design?

Some answers to this question can be found in the work of a number of designers and design researchers who investigated the possibility of linking parametric design with engineering analysis and optimisation processes to allow for a concurrent testing of design performance on multiple geometry variations across disciplines. The work on the *Parametric Bridge* (Maher and Burry 2003, 39-47) illustrates how a predefined set of geometrical constraints can be the driver for parametric alterations for iterative shape optimisation. In the bridge project, results from the built-in structural analysis package of the parametric software were compared with the analysis software used by the engineers working on the project. Target values were used to drive the shape-optimisation of the bridge through a dedicated interface (Product Engineering Optimiser™).

Optimisation software can address a variety of tasks depending on specific project requirements and the design's overall progress. As described in *Structural Systems Optimisation Techniques for the Building Industry* (Baldock 2004, 11-15), a distinction is required for several structural optimisation tasks between size (member sizes & cross sections), shape (geometry & size of a fixed topology), topology (for a structural system layout) and functional layout optimisation.

Examples of linking performance optimisation to rule-based design are present in the research undertaken by combining *EifForm* and *Custom Objects*, where a generative design tool is integrated with a parametric design environment to generate an array of possible solutions for a complex structure (Shea, Aish and Gourtovaial 2003, 108).

An open source platform for collaboration presented by the *Open Source Architecture* group has some synergies to this principle. It is titled the *Hylomorphic* project. The modes of operation proposed for the project include the translation of knowledge into exchangeable data, the filtering of information into specific parameters for an architectural object, and an iterative evaluation process (Sprecher, Ahrens and Neuman 2006, 31-32).

The examples listed above are a starting point for further investigations. My research is concerned with different modes of connectivities and dependencies of geometric information with building analysis data. I will follow up possible relations between geometry and analysis in the next section.

5.2.2. Modes for linking computational geometry to building performance analysis

In this section I illustrate how practitioners from various professional backgrounds can share their geometry-models for design representation and analysis. Responses from the interviews conducted at Arup illustrate that architects and engineers wish to work with their preferred proprietary software and format for 3D geometry model generation. Both my interviews in practice and my review of literature (Rosenman and Gero 1997, 399) indicate that the *single model* approach is not effective for collaboration. This insight raises two questions. Firstly, how can we share 3D geometry information across software platforms and teams in the early design stages in spite of their different geometrical requirements? And secondly, how do we avoid re-creating information that has already been produced by others?

In Section 4.6.1: *Constraints for Geometrical Interoperability,* I illustrated the difficulties encountered by designers and consultants in their attempts to automate the process of adapting 3D geometry information between architects and engineers. There are currently no tools available that can automatically translate architectural models into engineering models. As previously discussed, the type of notation for computational geometry models differs among all disciplines in AEC.

Questions arise as to how geometry-information can get shared between users of interfacing CAD tools from different domains. Rosenman and Gero (1997, 399) point out advantages of multiple views and multiple models of the same project over a single view approach. They argue that these advantages result from the fact that diverse functional concerns can be accommodated in multiple models for each domain specific category drawn from the same base object. In such a multi-disciplinary work environment, interaction is enabled through filtering only the profession-specific information for each particular view while maintaining geometric and functional integrity for all professions involved.

As I described previously, applying profession-specific geometry filters is not sufficient in order to appropriate models for use in different disciplines. The necessity for *defeaturing* and *equivalencing* 3D design-data indicates the requirement for expert input in the generation of such models. I argue that rule-based design methods can be used in setting up models that are integrated across disciplines.

I propose three types of frameworks for integrating geometric information and for comparing analytical results from across disciplinary boundaries:

1. Disconnected geometries, independent analyses,
2. Connected geometries, independent analyses; and
3. Connected geometries, interdependent analyses

Firstly, tools that act as 3D geometry viewers provide designers with a way of visually comparing their individual analysis models to the current *master geometry* in order to highlight major differences between the models, even if the geometry of the underlying models cannot automatically be reconciled. It is thereby possible to co-ordinate geometry across independently created discipline specific models. (Holzer and Downing 2008, 100). These tools enable design teams to import and represent the data which forms the results of various types of analysis. In Figure 74, results from thermal, daylight and wind analysis were mapped on surfaces and within volumes of a urban 3D model for the *Dong Tan Eco-city*.

Figure 74: Dong Tan; Integrated 3D geometry Environment , Source: Arup

The second type of framework allows users to share the definition of common geometry templates while conducting analysis for various types of building performance independently. In support of the above, software for generating parametric geometry variations enables users to associate discipline specific analysis files to a flexible template. It is then possible to push geometry changes from the master model into a discipline specific analysis model, situated in the desired analysis software, reducing the amount of rework each time a new geometry is proposed. A diagrammatic representation of the relation between connected geometries and independent analysis is shown in Figure 75 where
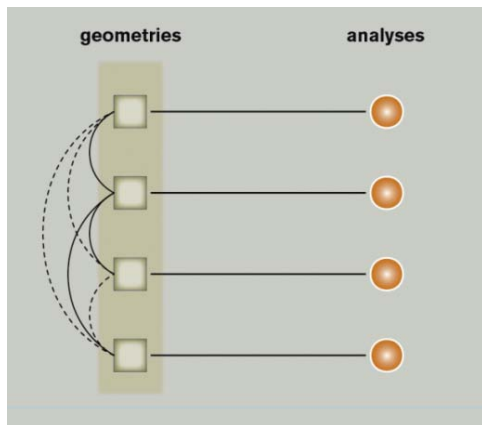
geometric representations across domains are linked while the performance analyses of different professions remain separate.

Figure 75: Creating links between geometry disconnected from analyses, Source: Author

As shown in the Melbourne Rectangular Stadium project, the master geometry becomes a negotiation tool during

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optioneering as it gives designers the opportunity to propose design variations based on those parameters. G*eometry cases* can be developed similar to the way *load cases* are used by structural engineers to test their models for varying boundary conditions[63].

A step further than the previously described method of connecting geometry with analysis independently, is the setup of a collaboration framework which supports bi-directional exchange of 3D data, driven by results from varying types of building performance analysis. This method includes the possibility to setup feedback loops such that the results of engineering analysis can be re-interpreted as a potential input for automated changes to the key geometry drivers (Holzer, Tengono and Downing 2007, 309).

The interpretation of the analysis results, and the effect they have on the key geometry drivers is determined by processing a series of rules hosted within the collaborative framework. These rules need to be authored by the design team as they encapsulate discipline specific suitability criteria and their relationships to the key geometry drivers upon which the design is based.
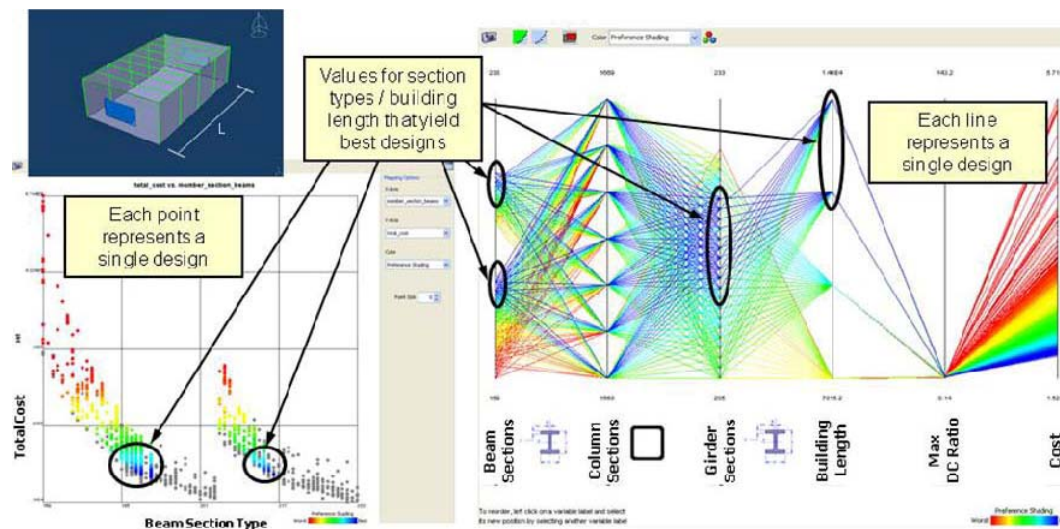
Figure 76 : Optimisation results plotted on graph for comparison and decision support, Source: Flager et al.

[63] Load cases is a terminology used in structural engineering to define (multiple) combinations of load factors applied on a structure

Flager et al. (Flager, et al. 2008, 1-19) describe a case study that applies similar principles to the above, in their description of a classroom-building. Figure 76 illustrates an example where multiple optimisation results are plotted on a graph.

Drawing from experience on the Melbourne Rectangular Stadium project, and in considerations of the possibilities of linking parametrically alterable building geometry to its performance, I propose the following protocol that describes the method of optioneering in a collaborative design environment across disciplines:

1. Collaborators first agree to an open engagement through optioneering.

2. At the outset of a project, key drivers behind the project are discussed by the design team to understand the criteria that guide the design.

3. With key drivers agreed on, the team then discusses the criteria-space that they would like to investigate. (e.g. How does one criterion relate to the others)

4. At this point the team has two choices: either to select those performance attributes that can be most usefully brought into relation to test their combined performance (MADA), or to select overarching objectives to then define and trade-off the contributing criteria that lead to achieving the objectives (MODA) [64].

5. The team needs to apply weighting to the key criteria to trade-off those performance aspects that have the strongest impact on the overall design of the project.

6. Individual team members need to provide the team with quantitative representations of the performance aspects under investigation. This requires the team members to summarise particular performance aspects of their work and distil them into a single numeric figure, or a controlled set of numeric figures.

7. A rule-based computational geometry model is created that allows for alterations of those aspects of the design defined in the criteria space. My experience on the stadium project has shown that it is advisable to limit the

[64] MADA and MODA are both subcategories of the previously described Multi Criteria Decision Analysis (MCDA). MADA stands for Multiattribute Decision Analysis, while MODA stands for Multiobjective Decision Analysis (Malczewski 2006, 709).

amount of associative parameters to keep the flexible model operable. Depending on the quantity of design criteria the design team wishes to test, it is beneficial to distinguish those criteria that can be analysed independently from others. Separate flexible models can be generated to focus on various areas of the design independently.

8. Once the main performance-drivers are expressed numerically, and rule-based geometry-models are created, a link can be established between design analyses where the performance gets tested, and variables that effect changes in the geometry model in close to real-time.

9. The nature of dependencies between analysis results and rule-based design updates is defined by the design team. It can either consist of the creation of multiple design variations within a certain predefined range and interval, or it can be set up as automated search where users define criteria (using *suitability rules*) to search for satisficing design solutions using computational optimisation algorithms.

10. In both of the above cases the computer assists in calculating a wide range of results that can be plotted through colour-coding and graphing them in the criteria-space. Each graphic plot can be associated with its geometrical representation in addition to its performance results. This method allows the design team to analyse and make sense of the combined impact of various design options that were created.

11. The graphs serve as decision-support for the team to decide which design-direction to take and how to re-appropriate their geometry models, if required.

The above protocol is a mere guideline for the use of optioneering in design collaboration. The fact that the optioneering method is available to collaborators does not guarantee that it can be applied successfully. Boundary conditions need to be established first that allow professionals from varying disciplines to respond to the cultural and professional particularities of this new mode of design collaboration. Making sense between professionals requires more than a *method* and I will describe *instruments* that can be used by collaborators to make their intent understood easily to others.

5.3. Sharing authorship in transdisciplinary design

"In the age – now passing – in which formal propositional and scientific knowledge counted as knowledge, it was generally accepted who the authorities were; or, at least, one could readily find out. Now the epistemological authorities are less clear, if indeed they exist at all." (Barnett 2000, 23)

Following my description of the optioneering method and after discussing the role of rule-based geometry in the previous section, I now investigate changes to the professional context in multiparty collaboration. I approach this subject by focussing my research on cultural aspects of professional conduct and the sharing of authorship on building projects.

In section 5.3.1. I will first argue *Against silos of professional knowledge* which are currently apparent in the building industry, to then discuss a transition *from Inter- to transdisciplinarity* in section 5.3.2. In section 5.3.3. I propose new ways for *Making sense in architectural design collaboration* followed by sections 5.3.4.–5.3.6. where I explore three instruments, namely *metaphors*, *analogies*, and *coexperience* that assist in the sense-making process.

I uncovered the reasons for professional specificity in Chapter 3.1: *Professional specificity in current building practice* where I explored literature examining the obstacles that profession-based thinking in silos poses to the creation of common understanding between disciplines (Billington 1991) (Ward, Horton and Brown 1992; Chandler, 1994; Gann and Salter, 2001; Taylor and Levitt 2004; Kalay 2004; Hensel 2006; Pulsifer 2008).

At the outset of this section I ask the following two questions in reaction to my findings from Chapters 3 and 4:

Firstly, what are the preconditions and the requirements concerning professional culture to counter the increasing segregation of professional knowledge in the building industry into ever more distinct silos? And secondly, what the

instruments that assist designers and consultants to share knowledge in the early design stages and to facilitate sense-making across disciplines?

5.3.1. Against silos of professional knowledge

My research suggests that the diversification and segregation of professions in the building industry is not per se a negative development. Such specialisation helps designers, contractors, consultants and other participants in the building industry to embrace projects with a high level of complexity and information-content. However, problems related to the dispersed nature of the industry arise from the disconnectedness of information generated within professional silos. My *Qualitative analysis of interview responses* in Chapter 4.5. illustrates that the progressing segregation of specialised professions in the building industry has neither been complemented by a process of lateral coordination between disciplines (other than coordination-efforts by architects on a project basis) nor by an equal level of, or consensus about, information-management among them. Furthermore, my research suggests that sharing knowledge is seen by some as a jeopardy to maintaining a market edge and professional status (Ward, Horton and Brown 1992, 427; Barnett 2000, 31).

Turkle et al. (2005, 41) are critical of the way experts secure their professional status within their disciplinary silos. They uncover the relationship between the wish of professionals to maintain credibility and prestige, in relation to the necessity to set out professional boundaries to justify their actions. Turkle et al. argue:

> *"In the professions we investigated, claims to direct observation or experience were crucial to how scientists, designers, and engineers secured their status. Experience was a key element in forging disciplinary boundaries and gaining prestige."* (Turkle, et al. 2005, 41)

I agree with Moum that *"globalization and increasingly complex technology and products require more teamwork"* (2006, 414) and I argue that the approach to professionalism needs to be reconsidered in the above context by members of the design

disciplines. Rittel and Webber (1973, 155) state that changes in western society, as they have occurred since the second half of the twentieth century, have altered the requisites of professional conduct. Traditionally professional excellence was defined through expertise in a specific field with clearly definable boundaries. The dangers of acquiring professional status through exclusion rather than capacity for integration have been highlighted by Rittel and Webber. They explain:

> *"The professional's job was once seen as solving an assortment of problems that appeared to be definable, understandable and consensual. ...There seems to be a growing realization that a weak strut in the professional's support system lies at the juncture where goal-formulation, problem-definition and equity issues meet."* (Rittel and Webber 1973, 156)

Rittel and Webber's concern is directed towards the limitations of traditional professional approaches to help resolve or even comprehend *wicked* problems as they occur during planning activities. When planners (such as designers and consultants) face wicked problems, the process of problem finding and problem solving is contextually interwoven. The capability of professionals to resolve wicked problems depends to a large degree on their capability to apply procedural knowledge, or *"knowing in action"* – as described by Cook and Brown (1999, 54) and Orlikowski (2002, 270).

Hartog, Koutamanis, and Luscuere (1998, 2) discuss the issue of situated knowing and expert feedback in the context of integrating analysis in design. Whilst they acknowledge the importance of knowledge-based analyses as prescriptive design guide, they argue that project specific descriptive analyses can facilitate immediate, situated feedback about building performance (1998, 3). The methods they propose to enable users to combine those two methods (prescriptive and descriptive) correspond to answers I received from practitioners during the interviews at Arup. Design professionals increasingly emphasise the importance of being able to quickly interpret and communicate analysis data when interacting with colleagues. In the interviews, professionals described their desire to gauge

their partners' expertise and to be able to interpret combined performance impacts in early stage design.

Nonaka refers to this activity as dynamic knowledge creation by "*communities of interaction*" (1994, 22) and he describes the tacit (individual) to tacit (group) conversion of knowledge as the process of '*socialization*'.

I consider the process of socialisation as a crucial component to sense-making across disciplines next to the definition of communities of interaction. The description of communities of interaction by Nonaka triggers two questions that relate to my research. First, how can such communities be formed? And second, how can knowledge be built-up and maintained within them?

5.3.2. From Inter- to Transdisciplinarity

Communities of interaction on building projects are usually focussed on collaboration within project specific boundaries (Lawson 1997, 264; Taylor and Levitt 2004, 84). Practitioners at Arup highlighted the difficulties in harvesting knowledge beyond project-specific boundaries, but at the same time they stressed the importance of getting "*collective awareness and experience*" about key design issues.

Transdisciplinary collaboration requires partners to understand their colleagues' concerns and design-priorities. Once individual users or user groups have developed their own working method they can enter a wider dialogue with others and take simple steps, one at a time[65]. I claim that sense-making between disciplines in architecture and engineering can be strengthened if those disciplines revise their methods of collaboration. Gibbons et al. (1994, 3) distinguish between homogeneous (Mode 1) and heterogeneous (Mode 2) types of interaction of disciplines.

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[65] In this context Gibbons and Nowotny promote *value integrated* over *value-added* thinking to foster more *socially robust* knowledge that transgresses disciplinary and institutional boundaries. (Gibbons and Nowotny 2004, 67)

While disciplinary *mode 1* is *"hierarchical"* and tends to preserve its form, transdisciplinary[65] *mode 2* is more *"heterarchical and transient"*[66]. Gibbons et al. promote *mode 2* thinking to face the challenges posed by information society to break down traditional disciplinary boundaries and to build up what they call *hybrid disciplines* who *speak in more than one language in order to communicate at the boundaries and in the spaces between systems and subsystems.* (Gibbons, et al. 1994, 37)

They state:

> *"The yearning for inter- or transdisciplinarity and much of the rhetoric to which it is embedded is rooted in the nostalgia for an epoch when the 'unification of science' still appeared to be possible.*
>
> *... Such dreams reveal an understandable nostalgia for a pattern of knowledge production which is the exact opposite of what seemingly prevails today; the relentless increase in further specialisation of scientific knowledge and its diversification into ever more narrow areas. These processes and the speed with which they take place signal the breakdown of a common understanding across scientific disciplines, the loss of an intellectual common grasp for their development and the impossibility of communication across specialisms."* (Gibbons, et al. 1994, 28)

The mention of the *"loss of an intellectual common grasp"* in collaboration between disciplines and the *"breakdown of a common understanding"* relate strongly to my research topic as they run counter to processes of sense-making. The nature of a transdisciplinary approach to design collaboration as proposed by Gibbons et al. implies an effort taken by all parties involved to step beyond the achievement of a specific goal (such as the collaboration on a building project) in favour of changing professional culture collectively in the process of collaboration. This

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[65] Transdisciplinarity was first defined by Jantsch as "*..the coordination of disciplines and interdisciplines with a set of common goals towards a common system purpose"* (Jantsch 1970, 106)

[66] In the context of my PhD thesis, the main distinction between mode 1 and mode 2 is the transformative nature of transdisciplinary (mode 2) collaboration. I argue that transdisciplinary collaboration does not only aim at breaking down professional boundaries, it also aims at changing the professions involved.

approach highlights the social aspects of design collaboration; it further implies shared responsibilities and *"mutual interpenetration of disciplinary epistemologies"*. (Gibbons, et al. 1994, 29)

Taylor and Levitt (2004, 83-99) base their description of systemic innovations in design on the concept of transdisciplinarity:

> *"Systemic innovations refer to innovations that reinforce the existing product, but necessitate a change in the process that requires multiple firms to change their practice."* (Taylor and Levitt 2004, 88)

They compare the uptake of innovation in the building industry that is either driven by localized innovations (focussing on company specific requirements) or systemic (embracing learning and sharing of information across disciplines and companies) innovations. Observations from Taylor and Levitt from case studies undertaken in practice show that systemic innovators follow bottom-up strategies for step by step implementation of innovative work-methods within practices and their partnering firms who learn from common experience of previous collaboration (Taylor and Levitt 2004, 92).

My research from within practice at Arup suggests that there is still a prevailing project-focus in the approach to design collaboration. Practitioners only start to realise that they can strengthen their own position within the design team if they have a better understanding of how their own contribution to collaborative work impacts on others and vice versa.

One common aspect of transdisciplinary collaboration and the quest for systemic innovation is the strengthening of ties between participating parties with long-term prospects. In that sense the philosophy that encompasses transdisciplinary work-methods is well suited for supporting legal frameworks of *Partnering* as I previously described. Partnering implies the build-up of trust between collaborators, the search for mutual benefits between participant parties and a sustained effort by all involved beyond project specificity. Professionals striving

for these qualities will best be prepared to face wicked problems and create better understanding in design collaboration across disciplines.

In the following section I analyse how designers and consultants can make better sense of information they share with their collaborators. I propose methods for making design-priorities explicit, cutting through professional boundaries and specialisms.

5.3.3. Making sense in architectural design collaboration

> *"The sense-making metaphor allows us to understand design practice as action in the face of ambiguity, as action that recreates the lived worlds of inhabitants, and as action that is fundamentally communicative in character"* (Forester 1985, 20)

I previously explored how members from different professions engage with each other using different notations and languages. In this section I scrutinise the instruments that assist collaborating designers and consultants in sense-making processes across disciplines during conceptual design. I believe that it is important to consider those instruments in the context of optioneering in order to support what I described as a method, with actual instruments for implementation in practice. In Chapter 3.2.1: *Sharing knowledge in conceptual work,* I reported on organisational knowledge creation as defined by Nonaka (1994, 20-28). Nonaka lists three instruments that help collaborators to understand the underlying concepts each other's work. These instruments are:

1. *metaphors,*
2. *analogies, and*
3. *coexperience.*

Nonaka describes *metaphors* as instruments that assist in collaboration to reveal hidden tacit knowledge in order to make a standpoint explicit between one team-member and another. Further, *metaphors* assist practitioners in creating a network of concepts to draw future knowledge from existing knowledge. *Analogies* can be used by practitioners to harmonise contradictions incorporated in metaphors, or as Nonaka states: *"Analogy reduces ambiguity by highlighting the commonness of two different*

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things" (1994, 21). Nonaka notes the difference between metaphors and analogies as he points out: *"The association of meanings by metaphor is mostly driven by intuition, and involves images. On the other hand, the association of meanings through analogy is more structural/functional and is carried out through rational thinking."* (1994, 21)

A third aspect in organisational knowledge creation is, according to Nonaka, *coexperience* of participating members in teams both within and across professions. He argues that: *"Coexperience with others enables us to transcend the ordinary 'I-Thou' distinction, and opens up the world of common understanding"* (1994, 24).

In the light of the above comments, I scrutinise how the three instruments described by Nonaka refer to issues raised by practitioners from my industry survey at Arup. In the following three sections, I will discuss how experts in architectural design and in engineering disciplines apply *metaphors* and *analogies,* and how they share information through *coexperience.*

5.3.4. The use of metaphors in sense-making processes

"Especially in the concept development stage, it is critical to articulate images rooted in tacit knowledge. In this situation, individuals can enter each others' area of operation and can provide advice". (Nonaka 1994, 28)

Responses from interviewees provide clear indications of how Nonaka's concepts translate to the early-stage design environment. As I noted previously, practitioners ask for access to past solutions using pictures and drawings as communication devices. One façade designer commented on the use of pictorial representations of successful precedent projects: *"In the early stages, precedence is the easiest to get everyone on the same page"* (Façade planner 1). The metaphorical value of images and pictorial representations rated high in the answers arising from the interviews.

Interviewees emphasised on the commonality of visual representations as medium that could easily be understood by colleagues regardless of professional

affiliations. Responses from the interviews illustrated the plurality of visual information contained in pictorial representations used as metaphors during early design. Answers given to me during the interviews listed the use of photographs of entire reference projects, close-up pictures of specific details of a project, depictions of mechanical units, structural connections, façade-elements, interior finishes, sketches illustrating thermal behaviour, and spatial connections.

Practitioners who could demonstrate that a certain solution had worked in a previous context found it easier to convince others that a similar solution could be possible in a different environment. Beyond providing reference to previous examples, the value of visual representations as carrier of information is also evident in the process of sketching. All disciplines (apart from acoustic engineers) responded that hand-sketches were their primary medium to convey intuitively intent to colleagues at the outset of a project.

5.3.5. The use of analogies in design evaluation

The use of analogies in design environments across disciplines is highly dependent on the analogies' capability of conveying meaning. Responses from the interviews stress the importance of comparative tools that allow practitioners to trade-off one design option with another in the context of the overall building performance as discussed previously. The process of trading-off depends on the availability of analogies that are understood by the design team.

How does option A compare to option B?, What are the criteria for valuing one option higher or lower than another?

Only if designers understand the meaning behind the reasoning that has led to a specific design option, they can provide judgement on appropriate directions to take. The majority of interviewees acknowledged having difficulties in understanding the significance of quantitative information they receive from others. Problems with the interpretation of numerical data were best reflected in comments about impediments for sharing information contained in profession-specific spreadsheets. Practitioners asked for more *diagrammatic and graphic*

representations of discipline-specific results to allow them to gauge the concepts beyond their own domain. Tufte (2001, 13) addresses this issue by stating:

> *"Graphics reveal data. Indeed graphics can be more precise and revealing than conventional statistical computations."*

Tufte (2001, 191) argues that the main benefit in the use of visual representation of quantitative data is the clear portrayal of complexity to facilitate the process of decision support and selection among options. He points out:

> *"Design is choice. The theory of the visual display of quantitative information consists of principles that generate design options and that guide choices among options."*

5.3.6. Coexperience contributing to collaborative understanding

The exchange of metaphors and analogies for dynamic knowledge creation in team collaboration is enabled by processes that allow team-members to share their experience in action. Cook and Brown (1999, 54) describe this as *"knowing within situated interaction".* Factors contributing to the successful design of building-projects are highly interdependent and they cannot be understood in isolation. All participants in the interviews at Arup highlighted the importance of being able to receive feedback from other disciplines as early and comprehensively as possible to interrogate *combined performance impacts.*

The process of interacting with colleagues through coexperience facilitates the possibility for a team to "*sing from the same hymn-sheet"* as described by one interviewee (Structural engineer 4). In practice this is not an easy task. Coexperience is not automatically enabled by co-location or other common activities. Coexperience postulates the use of metaphors and analogies that can be understood and interpreted by all members of a team. According to my research in academia and practice, collaborators require at least two qualities to achieve a common level of understanding,. First is the capability of team members to summarise performance-aspects related to their field in a format that is

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comprehensible to team-members from other disciplines. Second is the capability of team members to engage with information that does not stem from their own field, in order to understand its impact on their own field of responsibility and the overall building project. Simon states that:

> *"Each group must respect the expertise of the other, and must acknowledge the relevance of that expertise to their own problems. Moreover, each must have a sufficient knowledge and understanding of the others' problems to be able to communicate effectively about them. Experience shows that these conditions are unlikely to be satisfied unless members of each group (or a sufficient number of members of each group) have had actual experience with the activities and responsibilities of the other group"* (Simon 1991, 23)

Engineers participating in the Arup interviews highlighted that they were particularly dissatisfied with the level of feedback they received about cost-implications on design changes they proposed. This remark can be explained by the lack of coexperience between engineers and quantity surveyors who provide feedback on cost.

In analysing the interview responses at Arup, an observation can be made that participants sought to receive ad hoc feedback about combined design-performance from other disciplines in order to provide better estimates regarding their own design criteria. At the same time, participants stated that they could not imagine giving simultaneous feedback about their performance criteria themselves beyond basic estimates. They claimed that they require time away from the group for reflection and checking if a certain solution is feasible. The necessity for solitary reflection highlights the limitations of coexperience in design-collaboration. There needs to be a balance between situated interaction in teams and a process of consolidation and reflection away from the team.

In Chapter 3.3.1: *The problem of progressing specialisation in the building industry*, I discussed how tools for simulation and analysis provide new possibilities for designers and consultants to predict building performance, and to interact in design collaboration with new media (Turkle, et al. 2005, 100). My review of the

availability of literature indicates that collaborators profit from computational support through the exchange of 3D geometry models, the increase in speed for drafting (Lawson, 2002, 327), design analysis (Coenders and Wagemans 2005, 86), and from the possibilities of sharing information via networked communication systems (Kalay 2004, 34-81; Hamid, et al. 2006, 91).

Considering Nonaka's (1994) three instruments as previously described, I therefore wonder: How can we support the creation of metaphors, the exchange of analogies or the facilitation of coexperience in early design with the use of Information and Communication Technology (ICT)?

I argue that the starting point for responding to this question does not lie in the search for mere technical solutions of data exchange. On the one hand, systems like Building Information Modeling (BIM) as described in Chapter 3.3.4: *The potential and the limitations of Building Information Modeling,* are well suited for managing design information and coordinating design objects (AIA, 2004). On the other hand they are neither yet capable to communicating design across multiple BIM platforms (Eastman 2006, 5)*,* nor are they well suited to support the early-stage design (Parthenios 2005, 78) where the use of metaphors and analogies as well as coexperience are of highest importance.

> *One way to improve the performance of a building, then, is to increase the knowledge base and experience of the individual decision makers and to increase the communication throughout the delivery process.* (AIA, Rush (Ed.) 1986, 268)

In the concluding section of this chapter I propose a computational framework that allows for the application of optioneering in the context of transdisciplinary design collaboration. I helped develop this framework in consideration of previous research in the field and in scrutiny of the instruments that assist in sense-making across disciplines in everyday design culture.

5.4. DesignLink – A proposal for a collaborative design-framework

"Practitioners need to be able to use tools they trust and are familiar with" (Flager, et al. 2008, 3)

In this section I present the development of an application framework that assists decision makers in design teams to engage with each other through the method of optioneering. Firstly, I describe the background to the framework and the theory behind it in section 5.1. Consequently, I discuss the framework's ability to interface between proprietary software used by experts from various disciplines in section 5.2. I then point out how a *Rule Engine* within the framework facilitates optioneering in 5.3. At the end of this section I present the visual interface of the framework to assist its users in sense-making during early design in section 5.4.

My input as part of the development team for the framework was twofold:

On the one hand I was responsible for the definition of the basic concept that underpins the functionality informed by my research on early stage design collaboration. On the other hand, I explored the practical requirements for the framework through my interviews with design and consulting professionals, as illustrated in Chapter 4. *Observing early stage design collaboration*.

5.4.1. Background to DesignLink

In response to the challenges and opportunities raised in the previous sections, I collaborated closely with colleagues in the DDAA team to propose a computational framework to support collaborative design and decision-making. Based on my investigations about optioneering, my research about rule-based methods in the creation of flexible geometry templates, and my exploration about instruments for sense-making across disciplines I helped to devise the computational framework *DesignLink*.

As part of the conception of the DesignLink capabilities, the DDAA team investigated existing applications in use or in development at Arup. During our research the DDAA team encountered one existing application for linkages between design performance and geometry updates: the *Framework Application File* (FAF). The FAF had successfully been applied in practice by colleagues at Arup to link a structural analysis tool with a parametric model for the *Shakhtar Stadium*, but the creators of the FAF were not able to explore in detail the universal potential of the framework due to time restrictions. The aim of the DDAA team was to take the FAF as a starting point to develop DesignLink as an application framework that enables multiple linkages between 3D modelling and analysis software.

At the outset of the DesignLink development, the DDAA team reflected on the research stemming from academia which I described in Chapter 3.3.3 (*The current state of ICT support for collaborative design*). Below I list seven issues that contributed to the low acceptance in practice of the precedent tools that addressed social design. These issues were considered by me and the whole DDAA team to inform our strategy in the development of DesignLink:

1. extra effort necessary for appropriating information,
2. failure of a *single model* approach,
3. inflexible model setup,
4. object libraries that hinder intuitive engagement with design exploration,
5. failure to recreate processes as they occur in the design studio,
6. limited analysis results due to single optimisation runs, and
7. lack of interaction with software used in practice.

DesignLink has the declared goal to foster multiparty communication of design intent as well as the speedy evaluation of multiple design options. In order to achieve the abovementioned goal, a three part brief for the development of the framework was proposed by the DDAA team as follows:

Firstly, developing DesignLink's interfacing capability to allow communication between multiple software applications; secondly considering DesignLink's

facilitation of optioneering for multi-objective design tasks based on a rule-engine; and thirdly, setting up DesignLink's capability to help overcome cultural idiosyncrasies.

5.4.2. DesignLink's interfacing capability

DesignLink allows users of proprietary design and analysis software to use the tools they are familiar with, whilst being able to interface design data via a *neutral*[67] platform and format for exchange. The framework is easily extensible to allow for the inclusion of future applications by users who do not possess expert programming skills. The DDAA team sees this as an essential quality of the framework as designers increasingly are becoming active in the development of small, tailor made scripts of code to adjust their computational tools (Silver 2006, 7; Chaszar 2006, 15). In response to this development, DesignLink has a low threshold for *end developers* who have basic programming skills and who wish to add to the framework or adjust elements of the framework according to their needs.

Furthermore, the framework enables the import and export of geometrical and non-geometrical data from multiple proprietary tools in addition to storing this information in a central repository. Integrity of information between various tools and the application framework is facilitated by tool-specific data schemas that act like a filter to homogenise the manifold types of design data apparent in a project. The diagram in Figure 77 displays an array of proprietary design and analysis tools with their connection to the DesignLink framework. Connections and exchange formats that were established at the time of the conception of this thesis are drawn as solid lines, while connections that are under consideration are drawn as dotted lines.

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[67] *neutral* in this context refers to an environment that does not depend on any of the software applications it is interfacing and the eXtensible Markup Language XML is used to communicate design information between the a framework and proprietary software form different design and engineering disciplines.
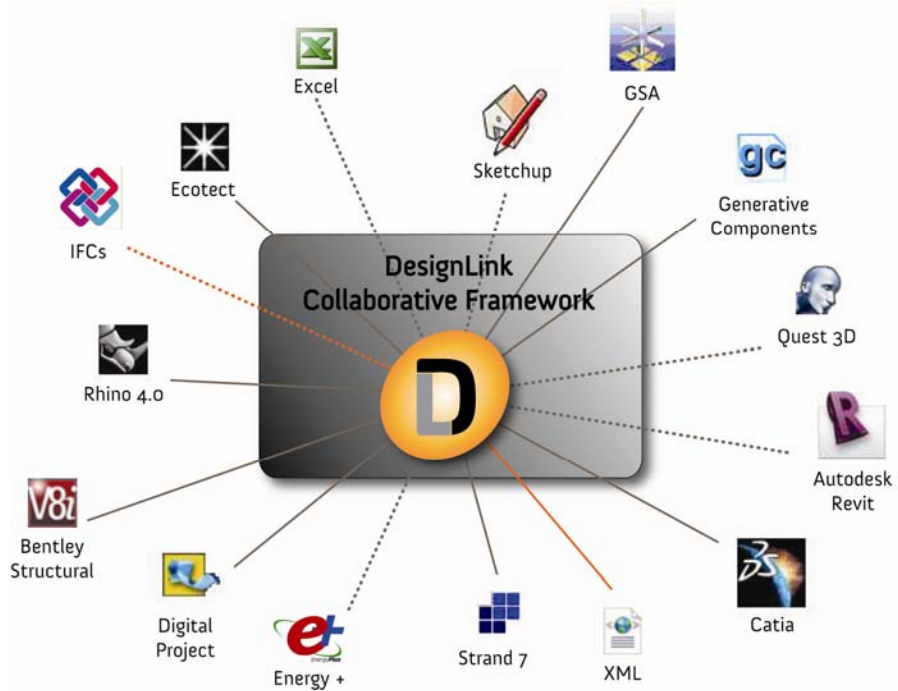
Figure 77: DesignLink connecting various design and analysis software, Source: Author

DesignLink's extensible information schema is one central element of the framework which facilitates adaptation and flexibility from project to project. The information schema supports a superset of all the information required by any tool acting as part of the framework, so that all the relevant information can be made available at every step during the design process.
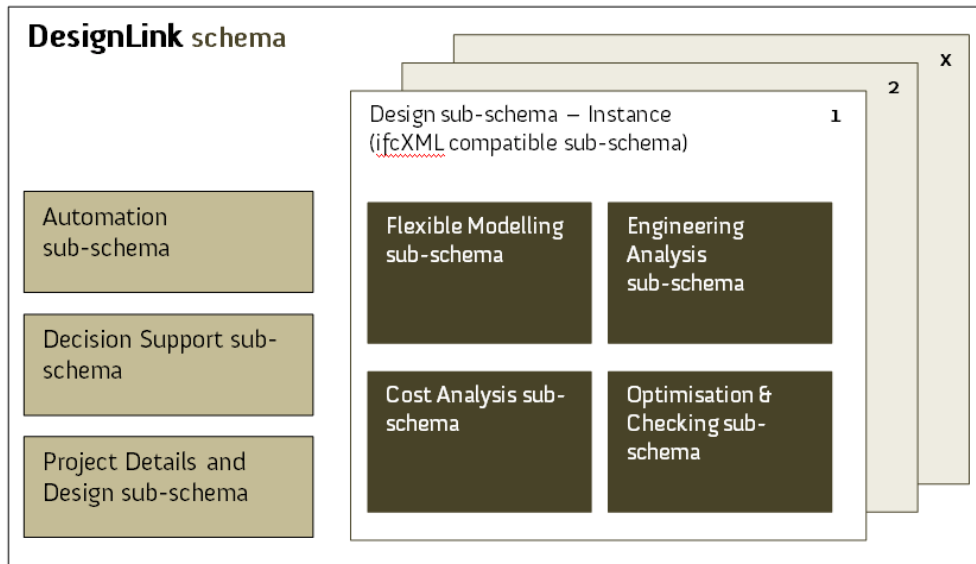
Figure 78: DesignLink information structure, Source: Author & DDAA

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The overall DesignLink schema is broken down into a number of sections which target particular roles supported by the framework. As shown in Figure 78, the main sections are *Automation*, *Decision Support*, and *Project Details and Design*.

Data gathered through the use of DesignLink is stored in XML (eXtensible Markup Language) format which, as a widely supported format, offers well documented, strict syntax combining machine readability and human readability. The use of XML language in turn lowers the barriers for the end developers using the framework who may be AEC designers, rather than professional software developers. It also offers related technologies to enable transformation of the data into other text based file-formats.
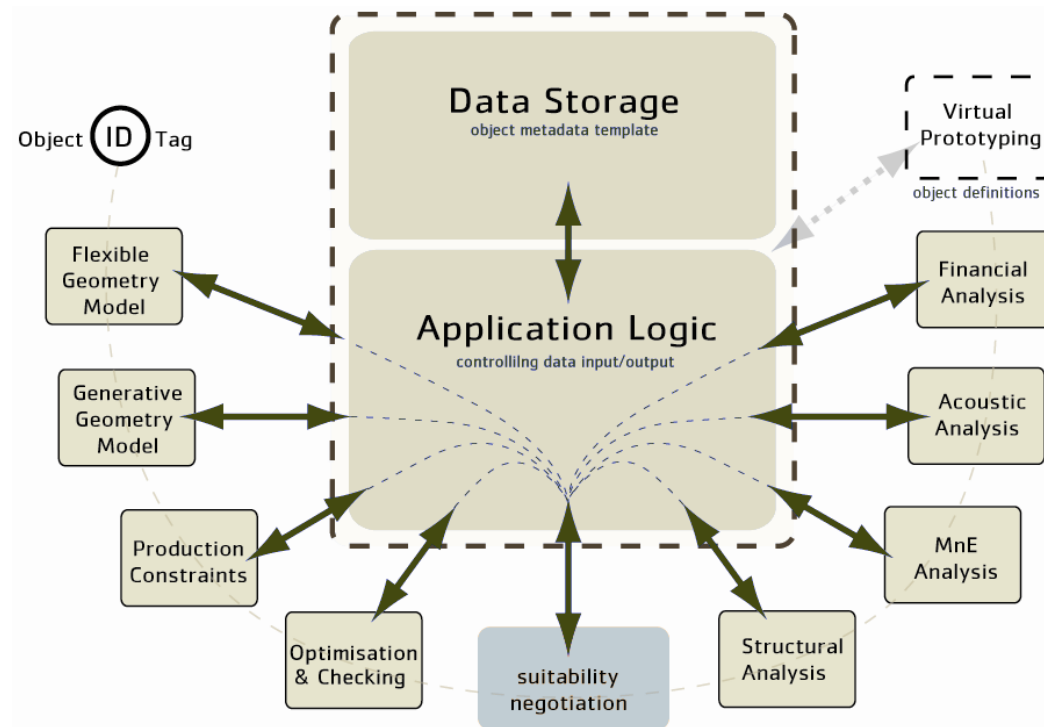
Figure 79: DesignLink application logic and data storage, Source: Author

The DDAA team acknowledged the value of IFCs as a possible aid in augmenting the feasibility of the DesignLink. We examined compatibility-interfaces between IFCs and our application framework. On one hand, the requirements for the application logic do differ from those of the IFCs while at the same time the extensive IFC structure does not provide enough flexibility to encompass all the

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data required by the framework. The IFC format does provide a good starting point for the requirement of an open, extensible data format

Since the bulk of design software used by the AEC industry is software running on the Windows™ platform, the DesignLink application framework is implemented using Visual Basic.Net™ (or other *.Net* compliant languages). This allows the framework to interact with other design software using *.Net* interoperability methods. This provides AEC designers who may be familiar with scripting, and are generally not professional software developers, an easy transition into being able to modify or develop modules for the framework.

5.4.3. DesignLink facilitating optioneering

The second part of the DesignLink brief deals with the Multi Criteria Decision Analysis (MCDA) capacity that ultimately facilitates optioneering of complex design tasks:

Central to the concept of MCDA is the semi-automated generation and analysis of multiple design options based on quantitative design performance data. The DesignLink framework hence allows users to work with a *Rule-Engine*, where geometrical configurations and the definition of non geometrical data (such as material properties, cost components, and others) can be brought in context with performance analysis to produce multiple informed options. Design options can be generated by defining rules that govern a range for variation or by searching for more automated solutions using fitness criteria or optimisation algorithms. The nature of connectivity between geometry and analysis can thereby span from disconnected and independent to connected and interdependent. Results from the multi-criteria design optimisation ultimately are compared and traded-off by the contributing parties to inform the decision-making process.

To support optioneering, DesignLink is responsible for maintaining the data schema between different functions and the framework acts as a bridge to connect between them as shown in Figure 80.
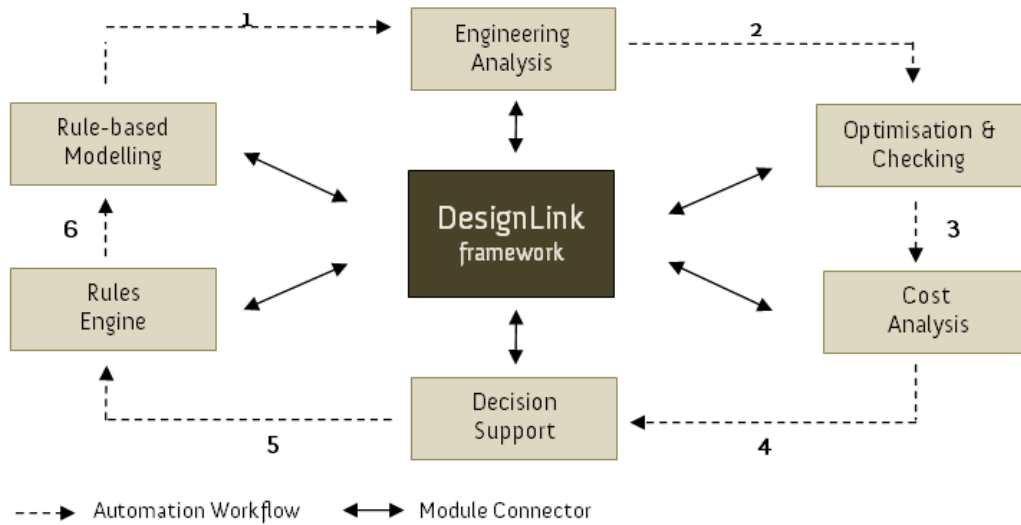
Figure 80: DesignLink modular framework, Source: Author & DDAA

The DesignLink schema contains the geometric data, analysis requirements and analysis results for a particular design instance. Where automation and optimisation is considered, the schema is capable of coordinating and comparing multiple instances of these same data sets. When automation capabilities of the framework are used, automation management information is stored in the schema, not just the information being manipulated by the process.

The link between rule-based modeling and engineering analysis across varying domains is a pivotal aspect in the facilitation of optioneering. Figure 81 shows DesignLink environmental and structural building performance data connected to a parametric geometry modelling tool via ModelCenter™, a multi-disciplinary trade-study environment by Phoenix Integration[68].

At the time of the conception of this thesis the DDAA team had access to the non architecture specific, multi-criteria design optimisation environment Model Center™ that was appropriated by the DDAA team to interact with DesignLink.

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[68] ModelCenter™ gave the DDAA team access to existing MODA and MADA functionality for DesignLink. Schemas for integrating building-related tools to ModelCenter™ were custom-written by the DDAA team.

Researchers at Arup have since started to investigate the inclusion of an independently developed Rules-Engine within the DesignLink framework.
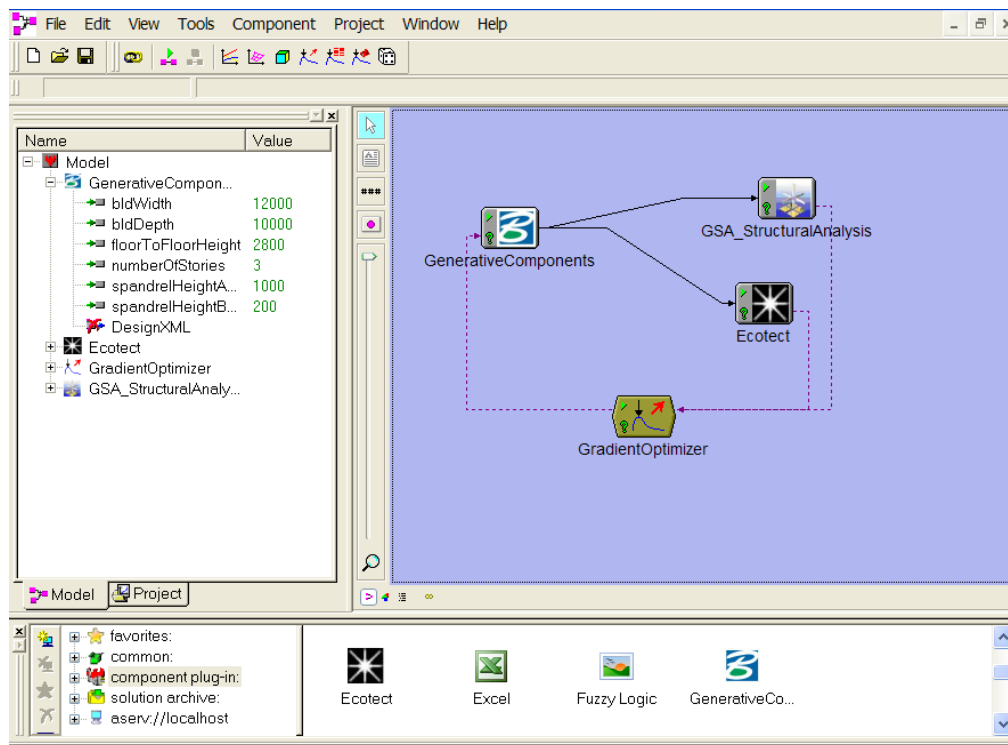
Figure 81: Multidisciplinary analysis for DesignLink using a trade-study function in ModelCenter™ (Phoenix Integration), Source: DDAA team

5.4.4. DesignLink helping to overcome cultural idiosyncrasies

"Form-making and form-finding are more rigorously defined with respect to designers' ways of knowing. Distributed cognition posits that knowing occurs not solely as mental constructs, but is distributed in external representations as well" (Laiserin 2008, 237).

The third part of the brief encompasses DesignLink's capability to help overcome cultural idiosyncrasies and the different notations used by practitioners from multiple disciplines. As discussed previously in this thesis, *sense-making* processes between collaborating team members can be assisted through the use of *metaphors, analogies* and *coexperience*. In this section I analyse the user interface that enables professionals from various backgrounds to visualise, juxtapose, and compare design information relevant to their fields.
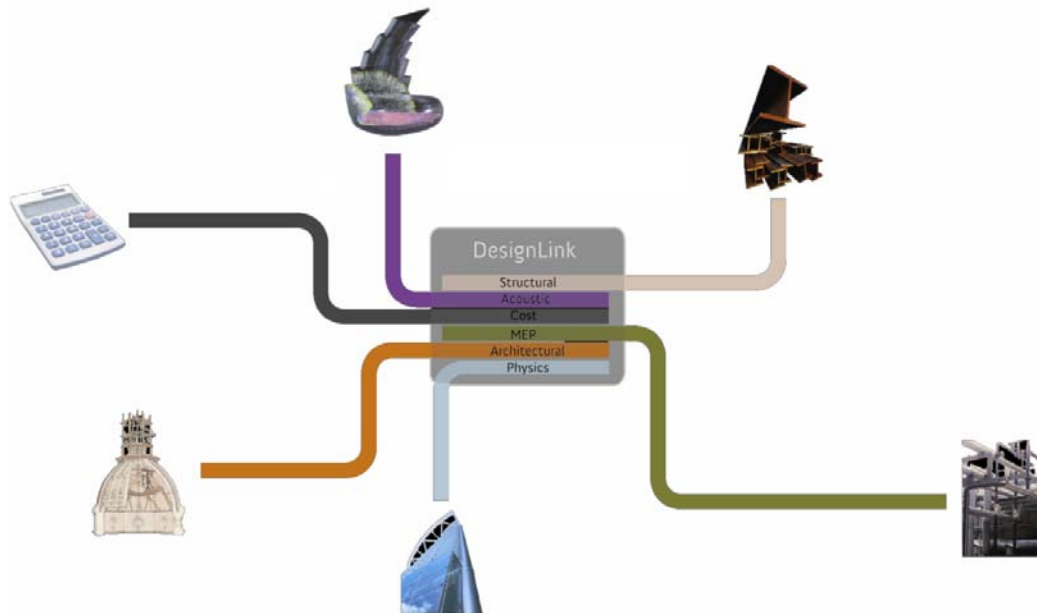
Figure 82: DesignLink as a common platform for multiple disciplines, Source: Author

The DesignLink visual interface provides a common ground for simultaneous interpretation of performance indicators by practitioners from varying background. DesignLink facilitates the customisation of the information that displays most adequately the combined building performance impact the design team wants to look at for trade-offs and decision making. The main problem in the use of most current software applications is their focus on serving the purpose of one specific profession either in the way geometry is modelled, or in the way it can be analysed for determining profession-specific performance aspects.

Previous investigations (Mueller 2006, 40) illustrate that computational tools need to be integrated carefully with conventional (non computational) work methods to ensure computers are used to support the design process instead of being limited to a production tool. As stated earlier, DesignLink is conceived as a decision support environment that allows professionals from different backgrounds to share their data, make sense of each other's information, and trade-off performance results.

Those aspects of DesignLink that rely on computational calculations for complex tasks of Multi-criteria Decision Analysis (MCDA) are running in the background while the user interface allows practitioners from distinct disciplines to engage with each other's information in an intuitive way. The main purpose of the DesignLink visual interface is thus twofold:
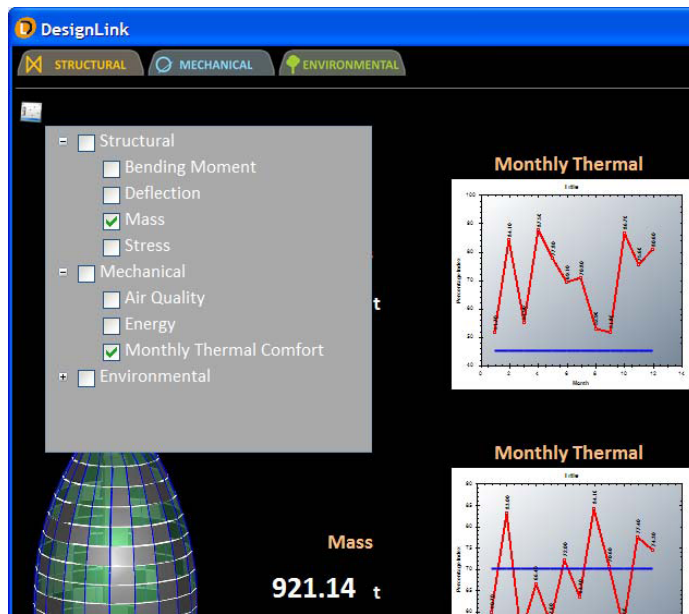
Firstly it allows users to select which information should be displayed. A right-click will open a menu that prompts users to select the performance criteria they would like to investigate.(as shown in Figure 80: DesignLink modular framework, Source: Author & DDAA)

Figure 83: DesignLink visual interface drop down menu, Source: DDAA team

Secondly, the visual interface provides design and consulting professionals with a simultaneous display of multiple representations of design data. The performance data is portrayed as graphical and numerical information from charts, numeric summary-variables, pictorials and explanatory text.

The challenge in designing the user-interface for DesignLink was to consider lessons learned both from literature in the AEC field, as well as responses from practitioners within Arup.

> *"If affordances determine or constrain the potential for action within or upon representations (in their role as tools), and if representations embody a necessary component of knowing (as constituents of distributed cognition), then knowing is determined or constrained by the choice of representation"* (Laiserin 2008, 237).
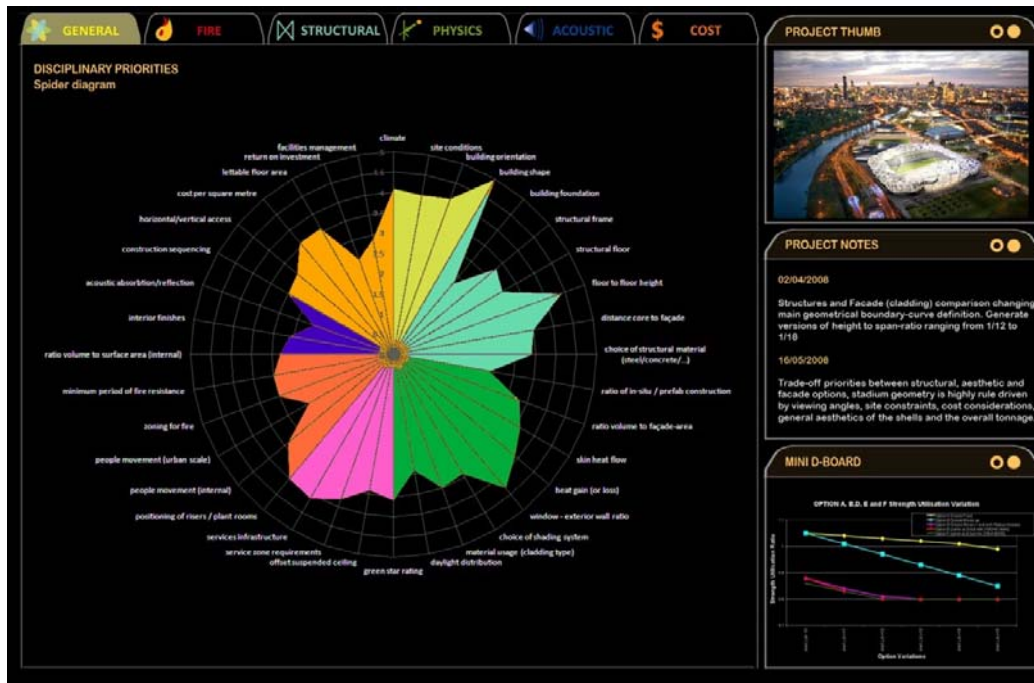
Figure 84: DesignLink User Interface mock-up *General* mode, Source: Author

Similar to the flexible plugin strategy pursued by the DDAA team for the software-architecture of *DesignLink*, the user interface is designed as an environment that can be adjusted according to specific needs. One important aspect in the layout of functions is the fact that *DesignLink* is being developed to serve as a communication interface between multiple professions as much as it can generate useful information for individual professionals. Users therefore have options to select either a *general* view of the project containing information relevant to all involved, or to choose from various possibilities to display information specific to distinct professions.

Next to these options, users can also chose a comparative mode where they focus on comparing up to three different disciplinary inputs. The concept behind the DesignLink user-interface is to reserve the main window as display for the numeric and graphic performance-data and to maintain a smaller area on the right of the screen for basic project information such as images, text and mini-dash boards. This concept is illustrated in Figure 86.

Figure 85: DesignLink User Interface mock-up: Structural Comparison mode, Source: Author

Figure 86: DesignLink actual user interface Structural / Environmental Comparison mode, Source: Author and DDAA team

The DDAA team then extended the capability for comparing options by allowing users to select design criteria they want to analyse across disciplines. Figure 86

displays a screenshot of the actual application framework with a comparison of structural (mass and deflection) and environmental (thermal analysis and skylight glare) data.
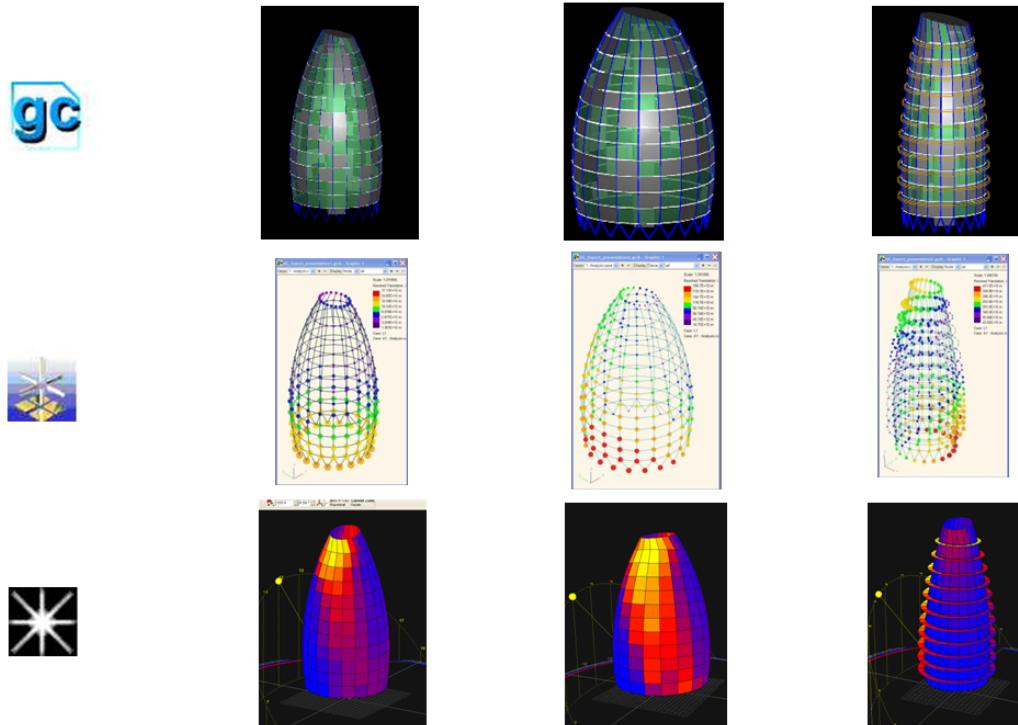
Figure 87: DesignLink output of 3 parametric geometry variations in GC™, their related structural analysis in Strand™, and solar gain in Ecotect™, Source: DDAA team

When using automated processes in design optimisation, it is often crucial to understand how certain results were derived (how they evolved) for rapid interpretation and consequent design decision making (Baldock 2004, 14). If a project team has access to automation routines at any point in the design process, members of that team can guide the direction of the optimisation to propose alternative design solutions. At the same time such methods enable the recording of information trails for showing how design decisions impact long term goals (Onuma, 2006, np).

Summary Chapter 5

In this chapter I discussed new paths for professionals to define their identity through the ability to interact with others in applying their expertise in a *social context*. In my PhD hypothesis I argue that the social aspect of design needs to be acknowledged by collaborating disciplines in order to be able to face the ever more complex task of building design. A social effort is required by collaborators in AEC to balance the effects of increasing specialisation in the building industry and to create lateral knowledge-exchange in an ever more networked society.

Optioneering is one method that lends itself to the exploration of design ideas and concepts in a non-deterministic way, yet it allows the project team to make informed decisions when selecting a preferred option (or a range of preferred options). Optioneering is as yet a sparsely defined terminology and its exact meaning is still open for debate.

I explored possibilities for linking building geometry to building performance analysis in support for optioneering processes and I pointed out how sense-making processes can occur in collaborative practice based on the exchange of metaphors, analogies and common build-up of knowledge through coexperience. Metaphors convey meaning through pictorial references whereas analogies serve as basis for comparing one possible option with another. Coexperience assists members of teams to share their knowledge in the act of apprehension.

Finally, I presented the DesignLink application framework in greater detail that assists in the sense-making process between participants in collaborative work in the early design stages.

The proposals stemming from my synthesis are informed by my research from the background chapter and the responses from practitioners who I engaged during my work embedded in practice at Arup. My findings respond to research from academic sources and, at the same time, they reflect on pragmatic concerns as they occur in everyday design and building practice.

In the following chapter I take a step back from the synthesis of my research so far, to analyse possible consequences of my findings in a wider cultural context. I scrutinise possible effects of a transdisciplinary approach to collaboration on current design practice and education. I bring the relevance of my research regarding early-stage design interaction in perspective with consequent design stages and I question the limits of *social* interaction in design collaboration.

6. Critical analysis and discussion

> *"If we are to make sense of our world and prosper in it, new forms of knowledge - at once process-oriented, collective and pragmatic in character - may well have to be embraced."* (Barnett 2000, 23)

In this chapter I consider possible consequences that my proposal for sense-making in a social context can have on contemporary design culture and I focus in particular on potential changes to current practice-mentality in AEC.

In Chapter 6.1: *Obstacles to Transdisciplinarity in Practice,* I discuss paths that warrant further research into their potential for facilitating a move from a multi, to a transdisciplinary approach of design collaboration. I investigate possible obstacles to the formation of systemic knowledge across disciplines and beyond project-boundaries.

Chapter 6.2: *Challenges for architectural and engineering education* analyses possible challenges for architectural and engineering education against the backdrop of increasing specialisation and compartmentalisation of the professions. I scrutinise methods that could allow academic institutions to educate students more effectively to face the challenges of an increasingly networked practice, and to make more sense of their partners' input.

In 6.3: *Social Design - between authorship and authority,* I examine the implementation of *social design* and I point out some possible dilemmas of social aspects of design around the distinction between design authority and design authorship.

Finally, I explore how my concepts regarding sense-making in early-stage design may influence collaborative strategies in successive design stages in 6.4: *Beyond early design* ...

6.1. Obstacles to Transdisciplinarity in Practice

"In a global world, saturated by information available through the internet, openness may turn out itself to be a pragmatic option that 'works'" (Barnett 2000, 29)

I made a plea for transdisciplinary approaches to design collaboration in Chapter 5.3.1: *Against silos of professional knowledge.* There, I stressed the advantages of long-term relationships between collaborating firms in the AEC industry who wish to build up systemic knowledge beyond project specificity.

My findings at Arup regarding the difficulties for practitioners to build up knowledge beyond project and organisational boundaries are consistent with those by Acha, Gann and Salter (2005, 276) who highlight difficulties for project-based firms to *"harness knowledge, technologies and techniques developed on projects."*

Developing long-term relations in collaboration comes at a cost. To step outside well-known professional hierarchies towards more networked operational structures requires firms to invest in new sets of skills.

"A critical task for participants enmeshed in a web of many relationships is to take the problems learned from one project and make them systematic, that is portable across multiple relationships." In other words, the differing groups of participants from one project collaboration to another make systemic learning or change difficult." (Powell 1998, 230)

Taylor and Levitt (2004, 91) identify the greater effort that is required, particularly at the start of setting up inter-organisational knowledge-transfers. They (Taylor and Levitt 2004, 91) point to limits to the amount of partners a firm can have to strengthen systemic innovation by proposing that: *"an increase in the variety of project participants from project to project will decrease the ability for inter-organizational knowledge to flow through the industry."*

The above observation leads to the assumption that transdisciplinary links between inter-organisational teams work if the number of participants is kept to a

manageable level. In the case study undertaken by Taylor and Levitt (2004, 90), they found that diffusion of innovation was difficult to achieve due to the exponential number of partners who may be involved with a project. Taylor and Levitt conclude their findings by arguing:

> *"In cases where innovations span multiple project specialist firms, an organizational strategy of integration may be necessary to reduce organizational variety and thereby increase capability to adopt and diffuse an innovation. Other organizational strategies that would reduce organizational variety for systemic innovations that span multiple specialist organizations include; partnering and co-location of cross-disciplinary teams."*

The consideration of partnering as an organisational strategy to reduce organisational variety is consistent with the findings I presented in Chapter 3.4.1.

There I highlighted the advantages for firms to engage in longer lasting partnerships based on trust and mutual interests. As stressed by Smyth (1999, 6), parties engaged in partnering need to consider *strategic partnering* in spite of potential higher initiation cost, to avoid leaving all benefits to the client. The risk associated to partnering is the dependency of one firm on another. As partnering firms build up their knowledge-base in tight collaboration they will engage with each other with a high level of trust and the willingness to sacrifice intra-organisational benefits (at times) for the sake of inter-organisational progress.

The claim for mutual benefits for all who engage in transdisciplinary collaboration on design projects is one that I cannot make as part of this thesis. To make these claims with certainty, new practice structures will need to be tested in the AEC industry over a period of years. What I can do, based on the research I have undertaken in academia and the experience I gained during the three years at Arup during the DDAA research, is to propose transdisciplinary methods as promising alternatives to current building practice to strengthen sense-making in collaboration during early design.

In the next section, I analyse the role of academic education to bridge epistemologies between collaborators in AEC.

6.2.   Challenges for architectural and engineering education

"Transparency, openness, unrestricted use of peer-assessed journals, scrutiny by expert panels, the development of professional associations and increasing contact with the academic world (in which these values and practices are hopefully surviving), and structural links between companies and universities: these would be among the possible constituents of such an epistemological infrastructure for openness and debate." (Barnett 2000, 29)

In the above quote, Barnett discusses possible contributions to an open and transparent *epistemological infrastructure* for knowledge-creation across teams. Barnett lists structural links between companies and universities as one crucial contribution to the generation of knowledge in practice.

My research suggests two main activities that foster epistemological links between academia and practice in the building industry. Firstly, academic research that is embedded in the context of practice to create strong bidirectional links between academia and R & D in practice. Secondly, design studios that are run across otherwise disconnected academic curricula such as architecture and civil engineering. Such studios allow architecture and engineering students to get acquainted with each other's world views early on thereby playing a pivotal role in eroding professional compartmentalisation. Whereas I hope to have proven the relevance of the former activity in the context of my PhD thesis, I describe the latter activity in more detail below.

In Chapter 3.1.2: *Distinct professional theories, education and disciplinary silos,* I pointed out that the origins of the segregated professional identities between architects and engineers originate during academic education. Here I address issues of design collaboration across disciplines which already form part of the definition of academic curricula.   Literature describing design studios across architectural and engineering domains (Maher and Burry 2006; Tunçer, de Ruiter and Mulders

2008) report of mutual benefits for all disciplines involved. Thomas (2009, 384) highlights the necessity for a change in design pedagogy where students get confronted with aspects of building performance as a driving element on the generation of projects:

> *"In the current climate, where concerns range from effective responses to global warming to the ever widening scope of architectural curriculum content, an integrated approach to architectural design pedagogy is needed in order to produce graduates capable of synthesising the array of complex considerations they will confront."*

Thomas (2008, 378) describes how students were able to optioneer multiple design solutions in the early stages, based on an iterative process of performance analysis and design development:

> *"Our focus was on methods to gain useful feedback in the early design-stages, where one was not too precious about design concept and there was the willingness to develop and generate a number of design possibilities. In this context, the iterative process of performance analysis and design development emphasised the shift from form making for purely aesthetic considerations to outcomes evolved through form finding."* (Thomas 2008, 378)

Maher and Burry (2006, 200) investigate the concurrent development of studio projects involving both architecture and engineering students who co-rationalise their input during the design-project. One of the engineering students participating in the project remarked: *"The most telling misunderstandings were clearly evident when an engineer tried to use the terms or phrases used by architects, or vice versa... It became clear very quickly that understanding the language and terminology used was to play a very large part in the success of any co-rational design work."* (Maher and Burry 2006, 205)

Maher and Burry (2006, 210) point at difficulties in the setup of design studios that cut across academic curricula as it *"seems inevitable to multiply the workload of studio directors"*. They suggest running combined architect-engineer design studios earlier in the students' careers rather than later to have a stronger impact on disciplinary attitudes.

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The above examples illustrate new modes of academic enquiry that help prepare students for the challenges of collaboration in a social context in the realities of design practice.

In the following section, I allude to the limits of *social design* as previously defined in my thesis.

6.3.   Social Design - between authorship and authority

When you don't have a clear authority – an ultimate decision maker, the design process gets bogged down in indecision. (office Principal, Arup)

I have repeatedly alluded to the importance of acknowledging social aspects of design in the previous chapters of my thesis. In this section I scrutinise implications of social activities for decision-making during the design process. I analyse possible limits to *social* interaction regarding design authority and design-authorship.

The size and complexity of projects we are dealing with today prompt designers and consultants to rethink how they evaluate building-performance trends, share knowledge across disciplines, define performance-priorities, and how they trade them off from early stages onwards.

My research suggests strong links between processes of sense-making and the understanding of architectural design as a social endeavour undertaken by a group of experts. As much as architectural design is a creative process that requires expert-input from various backgrounds, it is also a process of constant negotiation, weighting of priorities, and decision-making in teams. My research in practice and in academia suggests an increasing involvement in the decision-making by multiple experts of design teams. Theories behind both transdisciplinary methods, and the process of optioneering postulate sense-making in a social context of practice with strong interdependencies between participants

in the design process. Yet three questions stand out. Firstly, does the term *social* imply decision-making based on popular vote? Secondly, is the definition of *social design* tantamount to the *integration of performance requirements* of a building? And thirdly, who owns design authorship and who regulates authority in social design environments?

I suggest scrutinising the meaning of the term *social* in order to answer the above questions. If we acknowledge a greater involvement by multiple stakeholders in the decision-making process based on *social* evaluation of common performance criteria, the traditional notion of a *lead-designer* or *lead-author* of a project is placed in greater jeopardy. Acknowledging shared authorship does not necessarily mean that authority over the decisions being made is shared by the team.

> *"One can reject authoritarian design strategies without taking the posture that design should proceed by popular vote. What is at stake here is precisely legitimate design authority and its constitution."* (Forester 1985, 18)

The Oxford English dictionary references *authorship* to *literary origin or origination* (OED2, 1989) whereas *authority* is defined as *power or right to enforce obedience; moral or legal supremacy, the right to command, or give an ultimate decision* (OED2, 1989). Even though the two words are etymologically similar, their semantics are far from being related. There is a strong distinction between provenance of, and control over, factors that drive the development of a building project.

I argue that the distinction between authorship and authority may help resolve the dilemma in the definition of *social* design if it is associated with authorship, but not with authority.   I do not contest that in any design process an ultimate decision maker is required. We do need leaders to create design visions and to oversee the direction that is being taken by the team who follows those visions. In this sense, *social design* cannot be relegated to design-integration.

Chaszar (2008, n.p.) warns about the misinterpretation of *social design* without leadership or direction:

> *"For the most part when you get a bunch of specialists together, they are going to tend to all try to pull the project in their own direction. If you let you let them all have a voice in that, you are going to end up with a project that is not in any direction."*

At the same time, Chaszar points out limits to collaborative efforts taken by design teams which see social design as a process of compromise leading towards finding average solutions. He states (2008, n.p.):

> *"The more social you get, the more mediocre you get (typically) because you have to accommodate more different opinions which leads you to an average."*

I argue that design-teams need to negotiate the roles of design-authority and design-authorship from the outset of each project and there is no general formula that can be adhered to by the team.

In the following section of this chapter, I look beyond the early design stages to contextualise my research in relation to the consequent design stages.

6.4.   Beyond early design

My PhD research explores innovative methods to support sense-making processes in the early stages of collaborative architectural design. Up to this point in my thesis, I analysed design collaboration across disciplines from ideation to scheme design and design development. In this section I hint at possible consequences of my findings for the advanced and late design stages.

As I previously illustrated, the early design stages are exploratory in nature with constant and major changes occurring based on a multitude of criteria. The design team aims to assess quickly manifold design-options and to analyse coarse building-performance to understand general trends and characteristics. My research suggests that it is during the early stages when practitioners find it most difficult to make-sense of their colleagues' input. This difficulty is due to the speed

in which information is exchanged and the level of uncertainty with which the design team deals.

The tasks for designers and consultants in the consequent design stages, such as detailed design and the creation of construction drawings, are different from tasks during early design. Here, exploration of the design space is traditionally substituted by the aim for coordinated integration of design components, error checking, and a focus on (less expensive) constructability. Collaborative processes during the advanced and late design stages aim at converging rough design towards being continuously more precise design objects[69].

> *"During this phase, focus shifts from WHAT is being created to documenting HOW it will be implemented."* (AIA California Council 2007, 6)

Design changes occur at a slower pace and usually on a smaller scale with less impact on the overall outcome of a building project. Organisational effort is focused on the act of consolidating and coordinating design data from an increasing number of participants. In the context of this comment I ask: How do my concepts of sense-making in the early stages inform the subsequent design stages?

I did not find any evidence during my research embedded in practice that would suggest that the transition from early to advanced design stages occurs by introducing a greater level of detail in the design data. In contrast to this assumption, I argue that a different dataset is required when aiming at early stage *sense-making* or at design coordination and virtual pre-assembly.

The method of optioneering is principally suited to accommodate any type of dataset depending on the level of detail of the design project that needs to be investigated by the team. Optioneering could therefore be used in the advanced

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[69] My research of the generation of computational geometry models suggests that precision in terms of *accuracy* is less of a problem than the *quantity* of information contained in any model. File-sizes of computational 3D building-data for documentation are large and their assembly is elaborate.

design stages and beyond. My investigations in practice revealed that with increasing levels of detail of the design data, the capability for maintaining a truly flexible 3D geometry model diminishes. The structuring of constraints and dependencies becomes difficult to manage. My definition of optioneering is based on the capability of design team-members to update their models quickly without major effort. I therefore see a conflict in the speed in which models can be created and changed, and the quantity of information contained by models that are used for design-documentation and construction purposes.

I see a major possibility for the impact of my research on the later design stages in the inclusion of the contractor in the optioneering process early on. If production constraints (as represented through contractors and sub-contractors) can be accommodated in the sense-making process from the earliest point possible, buildability issues and cost information can be included in the optioneering process.

Building information modelling (BIM) has great advantages for collaboration once the design is already finished, but it currently does not seem to encompass and link into processes that occur in the creative, conceptual design phases. The way information currently needs to be structured for BIM implies a very detailed object-based description of design elements that is too overwhelming for early design exploration.

BIM has shown great promise over the past years to embrace wide sets of information from an ever growing group of stakeholders. If those propagating BIM acknowledge the lack of support it currently offers to early-stage design across disciplines first steps can be made by researchers and practitioners to consolidate ideas presented in this thesis with the principles behind BIM.

The motivation for this chapter stems from my goal to look beyond the main focus of my PhD to examine possible consequences of my findings for AEC design practice and education.

The critical analysis of my research outcomes suggest that transdisciplinary relations in collaboration come at a cost due to high requirements on integrating design information from multiple stakeholders. There is also a limit to the number of close partners with whom a firm can usefully collaborate in order to streamline epistemological exchange in *networks of knowledge*.

My investigations regarding sense-making in the early stages reveal that academia can and should play a pivotal role in diminishing the discipline-specific boundaries early on in professional education. Academic support for sense-making can occur through combined design studios between architects and engineers that help erode professional silo-mentality, or through strong research links between high-level academics and firms which wish to strengthen their R&D.

I investigated some debates around *social design* to understand its impact on decision making. As part of my exploration, I distinguish between design authorship and design authority. While I argue that the former can be shared, my research suggests that the latter requires strong leadership and vision.

Finally, I investigated links from sense-making in early design as propagated in my research, to collaboration in the successive design stages.

7. Conclusions

This thesis has explored sense-making across collaborating disciplines in the early stages of architectural design. The parameters of my research and the context of my thesis derive their relevance from firsthand exploration of collaborative design practice on a day to day basis supported by background research in academia. My investigations in practice were guided by participation, observation and targeted action research through workshops and interviews. In this final chapter I summarise my findings and I review the key insight of my research: *Sense-making in support of wicked problems as they occur in architectural design requires a high level of social-interaction between participants to bridge epistemological boundaries and professional specialisms.*

In my hypothesis I claim that one of the main ingredients to successful design collaboration in architecture is for colleagues and project members to make sense out of the information provided by different design professionals as early as possible. In my thesis I have, therefore, sought to understand processes that foster *sense-making* between collaborating partners and I identified the obstacles faced by designers and consultants in the AEC industry when seeking to communicate across disciplines. I have used my position embedded in a major, entrepreneurial engineering practice to scrutinise disciplinary biases and familiarise myself with the different notations used by the seven professions which I investigated. All these opportunities have allowed me to explore new methods for professional-engagement between architects and engineers in consideration of the possibilities ICT lends to support new types of collaboration.

7.1. Thesis Paradigms

Within the *Introduction* in Chapter 1 I flagged my research topic and I presented the conceptual framework to my thesis.

Chapter 2: *Approach and Methodology* presented my research context as embedded practitioner in the *Buildings Group* at Arup and it laid out the areas of literature I

investigated to draw from knowledge of colleagues in the fields from (mainly) architecture, engineering, and social sciences.

In Chapter 3: *Epistemological barriers between professions in the building industry* I reviewed literature regarding professional specificity in the building industry, sense-making in a social context, the support of ICT in design collaboration, and legal and financial aspects affecting knowledge-transfer across disciplines. The literature has provided me with insights suggesting that sense-making relies on the capability of individuals and teams to bridge epistemologies to create meaning. Sense-making processes have become increasingly complex in our networked society, and procedural knowledge is increasingly applied in action at the forefront of collaboration between professionals. Due to the increasing level of regulation and legalisation in AEC, combined with the continuous segregation into specialised disciplines, a stress upon process and structure in working methodologies has become ever more important.

The literature review further suggested that the introduction of computational tools for design, drafting and evaluation of building-design-performance allows designers and consultants to work in an increasingly concurrent fashion. Many of the time-intensive calculus-based operations for performance analysis are now taken over by computers with exponentially higher speeds.

This change of process in AEC has affected the epistemological nature of design collaboration. The change has gone hand in hand with a change of the work-relationships between architects and consultants. What seems to be missing in this context, are tools that support professionals from different backgrounds to interact in the social process of sense-making and design evaluation. In spite of numerous efforts by researchers to develop tools across disciplines in AEC, there is still a lack of adequate frameworks that support the early-stage design process.

BIM promises to support collaborative activities during the whole building-lifecycle, from ideation to demolition, but I have not found evidence that substantiates this claim in the context of early stage design. Further, the mode of

interaction through informed computational geometry models requires designers and consultants to put extra effort in the creation of such models. At this point there appears to be an imbalance in the industry about the compensation of those who profit most from BIM technology, and those stakeholders who do the extra work. These financial considerations, as well as the legal basis for project procurement, have additional impact on the way we make sense in design collaboration. The potential for ICT support to strengthen the information flow in design teams is inhibited by procurement methods that favour competitive tendering. Partnering on the other hand is a procurement method that lends itself to foster sense-making processes in design teams if long-term strategies are considered.

Within Chapter 4: *Observing early stage design collaboration* I extended my investigations from the literature review in the context of design and engineering practice. The nature of my research embedded in the *Buildings Group* at Arup has offered me the possibility to explore first-hand the issues regarding design collaboration from multiple disciplines. At the outset of my period as embedded student, I participated in the design of the *Melbourne Rectangular Stadium* project where I uncovered major gaps in the information flow between architects and engineering consultants (See also in Appendix A).

My participatory role on the project exposed me to major obstacles in the exchange of design information and it prompted me to investigate new ways for linking aesthetic considerations of a project to its physical building performance. In order to research how such links are possible, I got to the bottom of processes as they occur in daily design operations at Arup. These observations consequently led me to invite members from all disciplines in the *Buildings Group* at Arup (acoustic engineers, ESD consultants, façade planners, fire engineers, MEP consultants and structural engineers) and their collaborating architects, to join me in discussions about three topics that cut across disciplines:

1. knowledge transfer,
2. the trading-off of design priorities,

3. and common geometry models.

The discussions around these three topics, in combination with key issues emerging from my review of literature (disciplinary world-views in architecture and engineering, notations used to communicate design-ideas, and the impact of ICT on collaborative design), led me to conduct a survey of early-stage design collaboration. In this survey, consisting of face to face interviews and a written questionnaire, I mapped the different priorities various professions bring to the table to understand better the particular biases of each of the disciplines involved. Furthermore, I questioned practitioners from seven disciplines about aspects of their work that informs their individual sense-making, and aspects relating to sense-making with others. Responses I received during my survey indicate unequivocally the different professional profiles from each discipline.

The results of my formal discussions with the selected professionals also confirm, at least from within the experience of the Arup firm and its associated partners and projects, that the building industry is currently undergoing a rapid transformation where 2D design representations are gradually being substituted by computational 3D geometry models. Simultaneously these models are becoming the new interface for design professionals to evaluate and trade-off building performance concurrently, even in the early design stages.

The different types of model-formats also act as a barrier to the sense-making processes between different disciplines who work on the same project. Often geometry is reinterpreted and redrawn to fit the purposes of each single profession, thereby slowing down communication in the design team.

Full automation of the appropriation of 3D computational geometry models across diverse (engineering) performance analysis still remains unresolved. I propose instead that we learn to interact using *geometry statements* or *recipes* (as they are called at Arup) that provide designers and consultants from different backgrounds with a clear description about the parameters that drive the generation of the overall building geometry. The use of such recipes would allow

various team-members to set up their analysis-specific models independently, but at the same time to update them flexibly, driven by shared parameters.

In Chapter 5: *New modes of early-stage design collaboration* I sought to counter the disconnected way in which design and consulting practitioners engage in everyday practice. Motivated by the findings from the *Melbourne Rectangular Stadium* project and the responses from practitioners in practice, I proposed a new definition of *professionalism* based on *transdisciplinary* principles.

Rule-based links between geometric representations of diverse disciplines and performance analysis offer promising alternatives to facilitate quick comparison of design options. After outlining the issues of my core question in Chapter 3, and collating professionals' differing work procedures and concerns in Chapter 4, I put forward optioneering as a plausible means answering these concerns.

In my thesis I proposed optioneering as a useful method to provide professionals with support for creating metaphors and analogies in a shared environment across disciplines. I proposed several ways of linking geometry to design analysis, either independently or interdependently, and I presented DesignLink as a tool that has been developed at Arup to facilitate sense-making and optioneering processes across collaborating disciplines. Its usefulness will need to be tested in the near future.

7.2. Key findings

From my literature I gathered clear evidence that *the ongoing segregation in the building industry into ever more specialised professions is a necessary development* in order to support the ever increasing complexity designers and consultants are dealing with on building projects. The *problem* lies not in the quantity of professions we are dealing with, but in their *incapacity to interface knowledge laterally*. Design and consulting professionals often seem to operate from within professional silos of knowledge. As Rittel and Webber point out clearly, the activity of planning (and I argued that designing is a planning process) depends on solving wicked problems that require

thinking in networks rather than hierarchical structures (Rittel and Webber 1972, 160).

I therefore conclude that a *social effort is required* by design and consulting professionals *to make sense in collaborative design as the architect alone cannot reasonably be expected to integrate all design aspects with the level of complexity we see on building projects today.*

One other key insight stemming from my review of literature is the *lack of dedicated support of ICT systems for early design collaboration.* Despite numerous efforts by researchers such systems are currently not available to professionals in practice.

My review of literature further suggests that *much of the obstacles we are currently facing in AEC for sharing information and making sense in teams stem from the different notations and worldviews that are linked to distinct disciplines.* This claim was later tested through firsthand investigations in practice where I gathered clear evidence that these differences exist.

Furthermore I have mapped disciplinary profiles in a visual format to learn about the distinct world-views by engineers and architects. *My investigations revealed strong discrepancies between professions which considered manifold design-inputs, and those professions which assigned priorities only to a selected few design aspects.*

Architects demonstrated their capacity of understanding best the various concerns brought to a project by multiple disciplines. Their priority-listing rated closest of all professions to the *total average* in the spider-diagram. At the same time it was commented by engineers during the interviews that they do see architects as most capable to decide on trade-offs between design priorities from various disciplines. In this context, the architect's position as integrator is unquestioned.

The problems resulting from the above finding are twofold: Firstly, *the increasing complexity inherent to the exchange of design information we currently witness in the building industry may challenge the architect's capacity to effectively coordinate the quantity information at hand.* And secondly, the unquestioned reliance on the architects' role as integrator

may prevent engineers from actively engaging in lateral design-thinking across disciplines in a *social* manner. In this context I highlighted the necessity of distinguishing between *authorship* and *authority*. I believe such a distinction is crucial to allow social design processes to unfold without conflicts regarding the contribution to decision-making processes and the ultimate design leadership.

During my one-on-one research interviews in practice, members of all seven participating disciplines highlighted the need for support for *evaluating combined design impact, across disciplines, ideally in close-to real time.* Comments made by interviewees confirmed the lack of computational systems to address the above, therefore concurring with the findings from my literature review. I address this gap in Chapter 5 where I describe the principle methods for evaluating design options concurrently through *optioneering* and I present a system (DesignLink) that has been developed by me in collaboration with the DDAA team to respond to the need for collaborative sense-making in practice.

One conclusion I make in response to comparing my review of literature to results from the practice-based interviews lends itself in particular for further speculation: If we assume that computing power will reach a level where consultants can provide building performance feedback *on the fly* during design meetings (as they aspire to), will design partners be able to interact with the quantity of information available to them? As much as interviewees stated their wish for real-time performance feedback, the percentages they provided to compare the level of sole-investigation to group decision-making revealed that both *designers and consultants spend the majority of their time in isolation (from the group) in order to reflect on design problems.*

Limits of *bounded rationality,* the point where the capacity of the human mind to register information is saturated, may at the same time lead to limits in *optioneering* capabilities. This is not necessarily a negative sign. On the contrary, design teams could well profile themselves through their capacity to select carefully amongst performance aspects for optioneering among those that represent best their particular interest and *design signature.*

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In light of the above observation I see potential for my PhD research to be extended by colleagues who wish to *investigate optioneering processes as they unfold on various design projects*. These investigations could include the consideration of the *aesthetics of performance driven by social interaction of design teams*. I also see the potential for colleagues to elaborate in more detail on the distinction between design *authorship* and design *authority* and the cognitive dynamics that are associated with such a distinction.

More research is needed to understand how sense-making processes such as described in this thesis can be integrated better with current efforts by the BIM movement. I have exposed the insufficiency of BIM methods in the early design stages and I have shown alternative paths for early design collaboration. My research suggests that design collaboration in the early stages is not just about automating information exchange or data-interoperability, but it is *about informed decision-making in teams*. This process of decision-making can only occur if all design partners can *first make sense of the information provided* by others quickly and unmistakeably. The Holy Grail might be found in a combination of the methods presented in this PhD thesis and current efforts relating to BIM

The DesignLink framework that I helped to develop is currently being adapted and carried forward by a group of colleagues at Arup with the aim to *open-source* it, and to make it available to a wider constituency in the AEC industry.

With regard to the promotion of transdisciplinary work environments, I am convinced that strong links between practice and academia, such as the embedded research project between Arup and RMIT that I was part of, break down epistemological boundaries. These links between practice and academia facilitate the research about design collaboration in a manner that acknowledges professional responsibility, concurrent workflow and the exchange of specialist knowledge. Furthermore, a nexus between practice, research, and academia will allow speculative, but productive analysis of architectural experience and activity, currently and in the future.

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Appendices

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Appendix A

Sense-making across collaborating disciplines in the early stages of architectural design

Introduction

At the outset of my involvement embedded in practice with the *Buildings Group* at Arup in their Sydney and Melbourne offices, I was a member of the design team to help analyse the various instances of a stadium roof structure during the late schematic design, and the design-development phases. I use this participation on a live project as a case-study to highlight the status quo in early-stage design collaboration between the architectural and engineering disciplines. I will provide an example of architect-engineer collaboration through hands-on experience.

Whilst working on this *live* project during the early stages of its conception, I investigated the interfaces in design communication between architects and structural engineers. Next to my role as parametric modeler of the 3D roof geometry, my task also consisted of monitoring the design process closely and to propose possible alternatives to current practice, optimising design collaboration across disciplines on a social as well as technical level. In this sense I have become an observer and participator. My involvement in the project led to further questions about integrated practice not only between the various parties who were involved in the project, but also between all major types of consultants on building projects.

Some of the findings I present in this Appendix have previously been published as a full paper[1] in the double peer reviewed *International Journal of Architectural Computing* (IJAC) with myself as lead author (Holzer, Hough and Burry 2007)

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[1] Parametric Design and Structural Optimisation for Early Design Exploration

Participatory exploration - Case Study project –
Melbourne Rectangular Stadium

In this appendix I lay out my day participation and observations at Arup engineers on the basis of a case Study project – the *Melbourne Rectangular Stadium*. The specific context of my involvement in the project which has been twofold:

Firstly, the context allowed me to undertake qualitative research of designers and consultants *in action* working on a common project that is subject to budgetary constraints and a strict delivery-timeline.

Secondly, I participated in the delivery of the project with the aim to introduce innovation to the collaborative process by strengthening the information-loop between architectural designers and engineers. As part of this investigation I explore the potential and the limitations of rule-based modelling on a large scale commercial project.

I will provide insights on how engineering and architectural expertise can be assisted by a process of digital optimisation to promote structural awareness regarding design alterations in the conceptual design stages. Drawing from work undertaken on the *Melbourne Rectangular Stadium*, I will demonstrate how building geometry can be set up computationally to render it sensitive to structural input and I will elaborate on the computational software tools that are required to foster this interaction. As part of my investigation I will point out the kind of decision support that was needed to allow the team members to interact concurrently and make sense of each others' design input in the process of optioneering. In order to explore this matter in greater detail I have collaborated with researchers and practitioners involved in the previously mentioned *Delivering Digital Architecture in Australia* (DDAA) team. We have combined our efforts to assist the *Buildings Group* at Arup and to address the issue of interconnecting design intelligence across disciplines and advancing work methodologies in practice fostered by academic research.

1. Project description

My participation in the design development of a live project to give me direct exposure to an actual design problem with a high level of complexity. The project (a stadium roof structure; Cox Group as architects, Arup as structural and façade engineers) was in an advanced stage of schematic design at the commencement of my involvement.

Figure 1: COX Architects/Arup, birds-eye view of the Rectangular Stadium, Melbourne

Working in this conceptual design stage facilitated design input during design development of the project to test structural performance for a variety of alterations to the geometry. I was confronted with several unresolved design aspects concerning the steel-roof structure, which required optimisation whilst bearing in mind structural stability, geometrical constraints of site limits, sight-lines to the stadium-pitch, possible rationalisation of facade-panelling elements for easy constructability, and aesthetic considerations of the architects. The last included inter alia a lightweight appearance for the stadium roof – in particular at the cantilever, a dynamic integration of *gridshell* elements into the overall curvature

of the stadium roof, and the spacing of the underlying triangulation for the grid-shells. I have been participating in the design and optimisation-process of the roof-structure using rule-based design methods both parametrically as well as through scripting. Next to this participation, I have documented the design-interaction between the parties involved in a daily log-file where I noted major design-aspects that were being tackled by the team during a four month period. This documentation process included the analysis of interaction between the architect and the structural engineers, the quantity surveyor, the engineering drafts-people and the facade planner.

Figure 2: COX Architects/Arup, Elevation of the Rectangular Stadium, Melbourne

The AUD $267.5M *Melbourne Rectangular Stadium* (MRS) project is located in the heart of Melbourne's sports district the *Olympic Park Precinct* along the Yarra River (see Figure 1). The stadium which was initially projected to host 20.000 spectators (with the option to expand this to 31,000 seats in the future) will accommodate rugby league, rugby union and soccer on its 136 x 82 m rectangular pitch. Designed by COX architects in collaboration with Arup and *Norman Disney and Young*, the stadium's most striking feature is its lightweight *bio-frame* roof design which will cover most of the bowl seating. Next to giving the stadium its unique character, the use of adjacent shell elements that form the bio-frame is aimed at limiting the amount of steel required for construction hereby reducing the weight of the roof significantly (as shown in Figure 2). Figure 3 illustrates that a total of 20 shells are arrayed around the pitch following two overall vertical sweeps in the long- and the cross-section of the stadium. Whereas the sweep on the long-section is convex, the sweep on the short section is concave. This feature does not only

give the stadium a dynamic appearance, but it assists the distribution of structural loads through arching-action and it allows for additional seatings to be placed at the areas of the highest sweep.
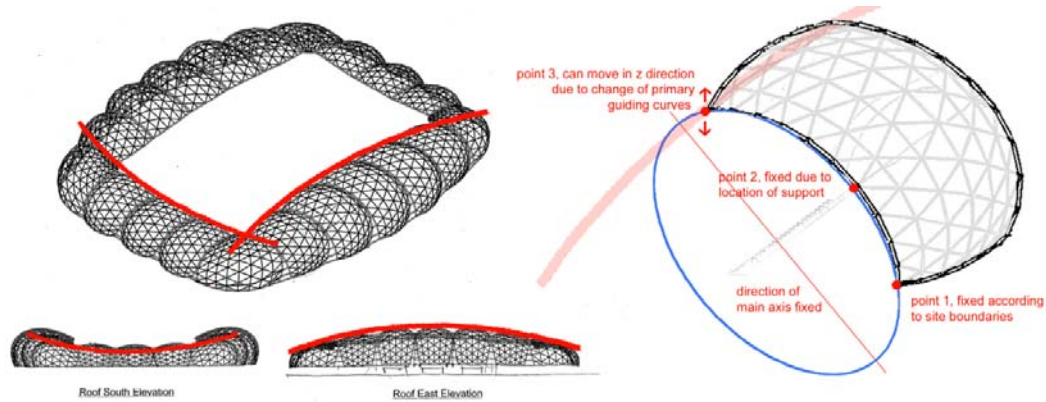
Figure 3: Arup, Isometric view, elevations and detail of the stadium roof structure showing the triangular network grid and the overall curvature of the roof.

The individual shells are highly sculptural provide spectators with a dome-like cover; they double up as stiffening elements for the roof and assist in rain-water collection. To provide constructability for the roof as a lightweight steel structure, each shell is formed out of a triangular network of steel tubes that are visible from the underside of the roof and carry the secondary structure for the cladding. In order to give the shells a smooth appearance, the maximum size of any edge of a triangle was limited to 6 meters. The cladding itself is consisting of triangular panelised facade-elements made up of a combination of glass, metal and louvers.
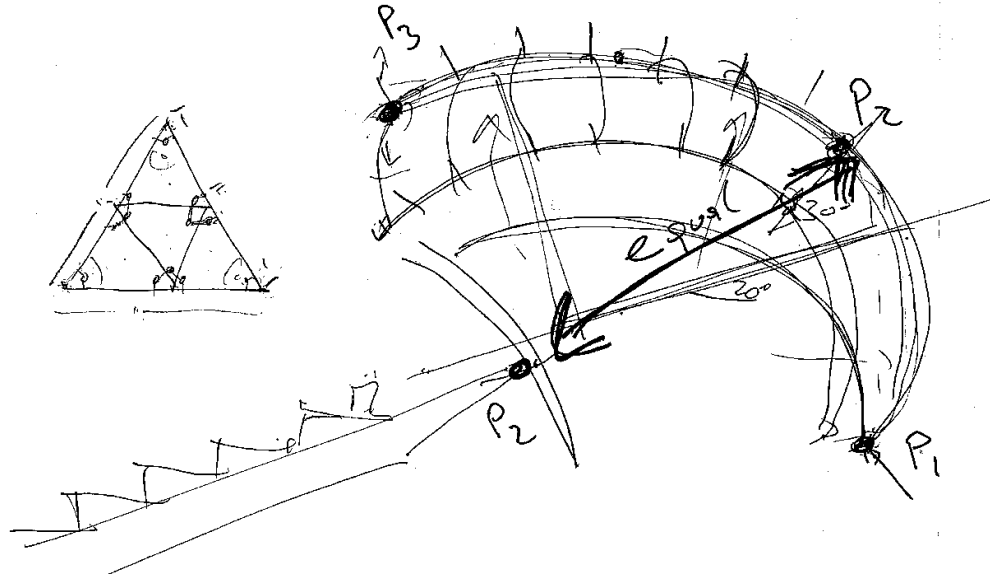
Figure 4: Arup/Author, Section of a roof-gridshell explaining the relation of the main geometry describing the curvature of the roof.

2. Goals of the collaborative effort

The basic aim at the beginning of my involvement in the project was to optimise the shape of the roof structure to make it aesthetically pleasing, structurally optimised and as visually lightweight as possible. In this phase of design-development, a range of major design changes occurred which had to be accommodated in the rule-based geometry model schema. The long term aim was to gain insight into the process of negotiating geometrical alterations with structural behaviour and to then propose a framework for both architects and structural engineers to communicate their design in a more streamlined fashion.

I analysed the individual steps that were required for communicating design intent, establishing rules for geometry alterations, setting up a parametric model, exporting geometrical information from that model to the structural analysis program, setting up load cases and carrying out structural member-optimisation.

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Ways to most clearly present the information resulting from the structural optimisation to the whole design team for decision support were also investigated. In addition, simple physical working models of parts of the structure were produced to provide a haptic interface beyond the digital representation on the computer monitor. Figures 5 and 6 show shell elements of the roof with the subdivision in triangular facets which were cut from flat cardboard sheets.

The project team at Arup, consisting of structural engineers and design documenters expressed their interest in being able to create variations in the geometry of the project and to run structural analysis and code-checking to determine the feasibility of the project given various load distributions, the overall tonnage and the member sizes required. In order to address these issues, a precise definition of the type of analysis required was communicated amongst the team of architects and engineers in the beginning. *Suitability rules[2]* were defined by all involved, which related architectural and aesthetic considerations to structural performance by setting up design variables in direct relation to parts of the geometry which had a strong influence on structural behaviour.
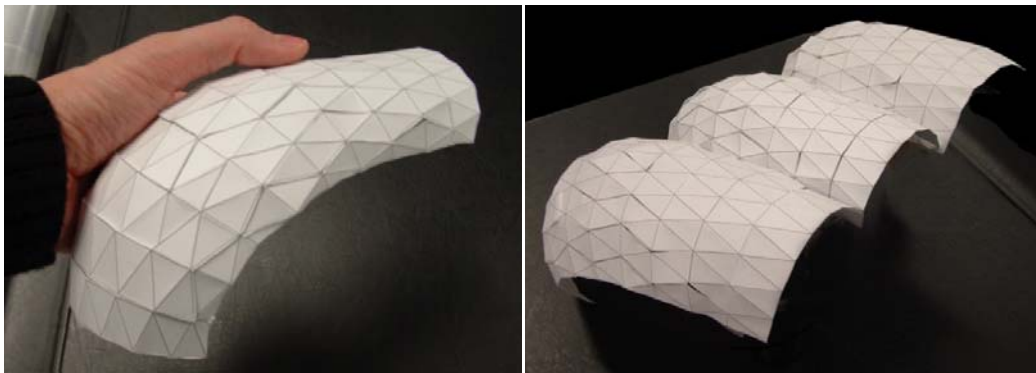
Figure 5: Physical model of one stadium roof-shell and three shells attached to each other.

In order to narrow down the extent of geometry alterations to an acceptable margin for structural analysis, boundaries were defined within those rules to determine the range of changes in the length to height ratio for the main curvature

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[2] The expression suitability rule was used by the design team to define the criteria suitable for driving the parametric geometry alterations of the project in consideration of structural performance-changes.

of the roof as well as the individual curvature of the shells at their supports at the outer stadium boundary, the highpoint of the tribunes (the groynes) and the cantilever. This basic configuration required simultaneous input from both architects as well as structural engineers.

3. Creation of a rule-based model

Once the principles for the relation between the flexible design parameters and the structural optimisation requirements had been defined, I created a flexible 3D model in the parametric design software CATIA™ which allowed for varying the main stadium roof sweep and the sweep of the individual shells of the stadium roof through simple numeric input of a curvature ratio. The range of change for the overall sweep was defined by the *high-ball line* – a minimum height for the roof in accordance to the field of vision of the spectators towards the pitch – and by structural considerations where a sweep of approximately 1:15 (height to length) was desired. In addition to these criteria, the architects (COX Architects) wanted a strong articulation of the individual shells comprising the stadium geometry. Figure 6 shows the guiding curves of both the long and short edge of the stadium roof with the boundary curves of the shells attached. All curvatures are governed by parametric variables. The figure displays three variations for the overall curvature with a height to length ratio of 1:12, 1: 18, and 1:24.

Figure 6: Parametric variations in roof curvature definitions
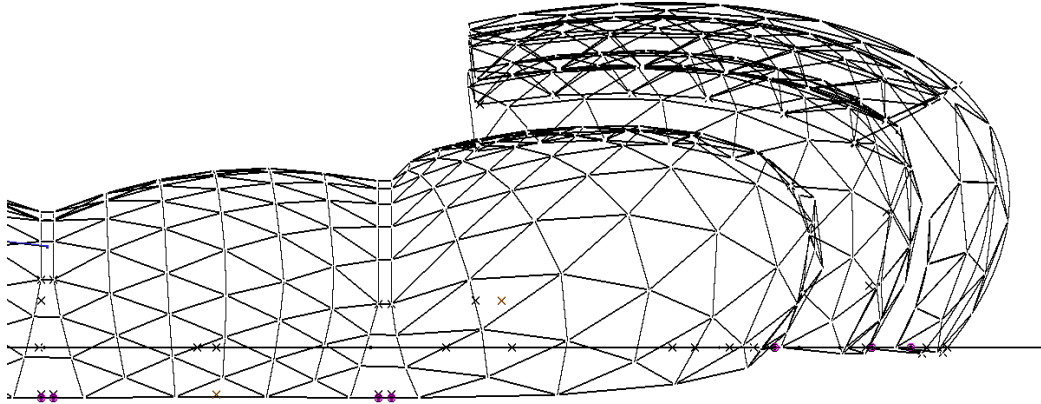
Figure 7: Arup/Author, Detail elevation of one version of the stadium roof.

In order to link the overall stadium geometry that was defined through the boundary curves of the individual shells I have co-developed a custom script running from within CATIA™ to create a lattice sitting on the imaginary outer surface of each shell. The lattice was representing the centre-line of steel members for subdividing the individual shells of the stadium roof which would consequently carry the secondary structure supporting the cladding of the roof. Several options for the density and rotation of the grid were generated as part of the script. The advantage of embedding the script in the parametric model was that the grid-subdivision updated automatically once the boundary curves of the shells were altered. To facilitate this functionality a strict naming convention had to be followed. Each shell consists of a *Boundary Curve*, and further *Field*, *Centre* and *Slab Guiding Curves* (as shown in Figure 4).

Results from the flexible model were exported from CATIA™ (via Rhino3D™) to the structural analysis packages GSA™ and Strand™ in dxf format. Geometry updates were generated and read into GSA/Strand™ within a timeframe of 5-10 minutes. Figure 8 displays the elevation of 8 variations for parts of the stadium as taken from CATIA™ into Rhino3D™. The different variations for the overall curvature and the individual shells can be recognized. The large elevation on top shows an overlay between the architect's original model and one approximation from the parametric file.

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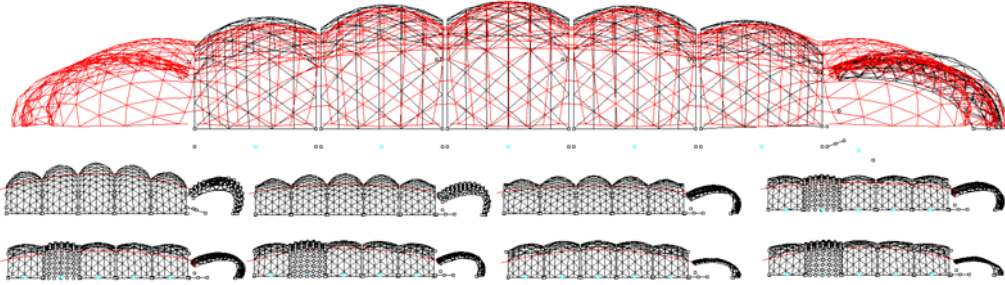
Figure 8: Author: Parametric variations in roof curvature definitions.

Load-cases and restraints were transferred from the basic GSA/Strand™ setup without requiring manual input as long as the number and logical definition of nodes and elements did not change. The structural engineers were then able to run a code-checking application (the *optimiser*) over the model. Once the optimisation was completed, the software displayed member performance, associated with varying colours which directly corresponded to stresses in those members. Figure 5 shows an isometric view of the stadium roof with an overlay of varying stress distributions. This diagram confirms the assumption by the structural engineers that the structure is too complex to be analysed 'by hand' as the distribution of stresses over the whole roof is highly irregular.
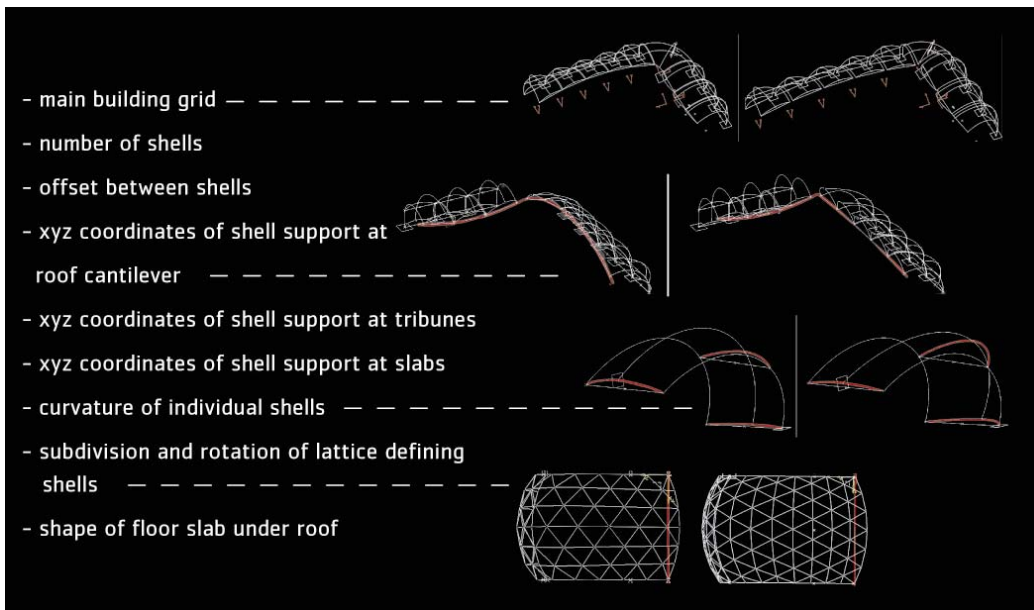
Figure 9: Author: Rule-based variations of the stadium-roof geometry and its grid-subdivision.

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4. Linking geometry updates to structural analysis

The optimiser is a custom-developed application that has been developed within Arup. In contrast to the traditional engineering method of deriving member sizes for stressed elements from tables and charts, it allows iterative evaluation of the most appropriate member size of each structural element individually. The process is not one of optimisation in the true sense – its intelligence is limited to finding better solutions only for one element of a group at a time without understanding the consequences of change to the neighbouring elements. Instead the optimiser works on the very simple principle of constraint satisfaction which carries out design strength checks for each member in a group. One constraint is active each time while a series of checks is being carried out. Other methods would be more rigorous but they cannot be applied for strength analysis as constraints cannot be defined properly (they would work for displacement, buckling or frequency analysis).The setup of any routine for the optimiser is highly input-sensitive depending on a suitable initial choice of a set of section sizes. The significance of this is explained below. It requires expert input as one can otherwise easily get stuck in local minima. The main challenge consists of optimising the section-sizes of a large array of members individually under different loading combinations while aiming at a global optimum for reducing the tonnage and maintaining structural stability.
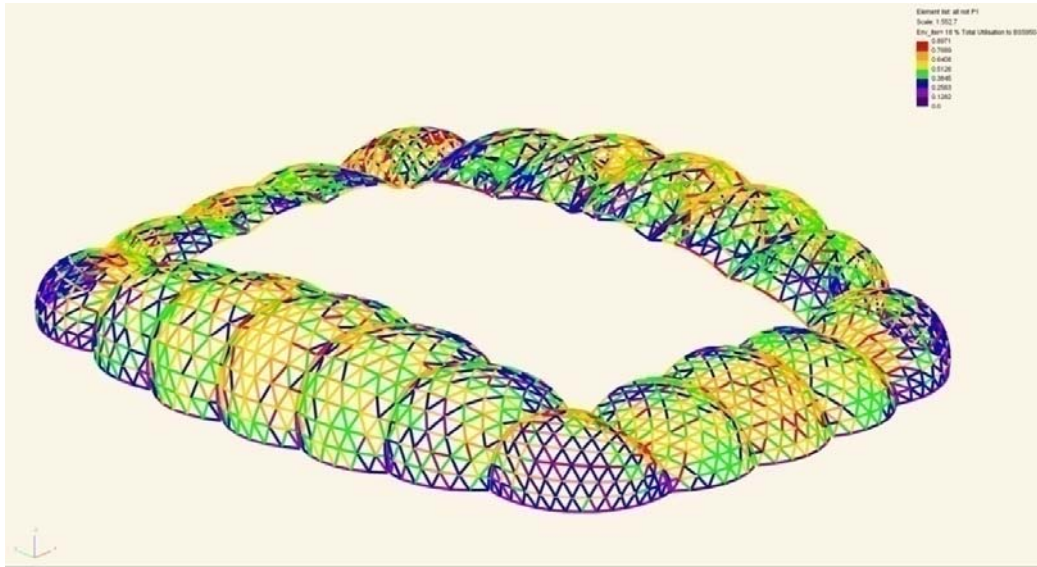
Figure 10: Arup/Author: Stadium roof stress distribution diagram

Prior to commencement of the optimisation process, a limited set of section sizes for specific sub-groups of the structure was chosen by the engineers according to production constraints. The grouping occurred according to design variables which dealt with effective length of the steel members, their purpose in the structure, the architect's requirements and the aim to derive a nicely graded set of member-sizes. This resulted in the definition of five groups of members: The groynes, the groyne-ties, the shells, the front edge and the back edge. After initially selecting the smallest section for each group of members to be optimised, the results were compared to the requirements of the design codes applicable to the project. If all the constraints were satisfied the optimisation was complete, if not, the iterative process resizes those members which did not satisfy the set criteria either up or down. Member size increments were limited to one size increment per iteration. All results were communicated to an MS Access™ database via an application programming interface that allowed the engineers to read information in and out of the structural optimisation software directly from their custom software. Results from the optimisation process were obtained within a timeframe of approximately 30 minutes. This short analysis-turnover assisted the research team in their effort to narrow the gap between evaluating

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results and proposing changes for updating the parametric geometry. Figure 12 displays a close-up of the corner-shell of the roof structure after optimisation. Output from the *optimiser* shows the varying thickness of the grid-members for the roof as part of their cross-section group. The steel members within the shell have the same outer diameter for construction purposes, but the different strength-requirements need to be picked up in varying wall-thicknesses of the hollow steel sections.

The structural engineers decided to first run tests to find the optimal shape for the arches and then to subsequently focus on the curvature in the individual shells. Once this was done, the structural engineers focused their investigation on varying the curvature of the shells for the arch which displayed the best results.

Observations of the results of the geometry variations led to the proposal of a new (smallest) member size for one of the groups (shells)
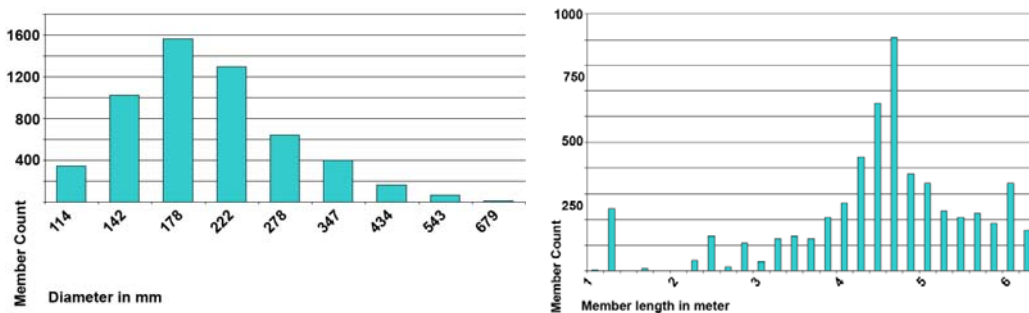
Figures 11: Arup/Author: Graphs displaying member-size groups and required steel-member length. which initially did not seem achievable.

The structural engineers could see that almost 90% of the members in the group were under-utilised. Detailed information about the required diameter and length of steel members was generated by the optimiser and could then be put out as an MS Excel™ spreadsheet and visualised in graphic tables as a by-product of the optimisation process as seen in Figure 11. The information at hand provided essential decision support for determining the direction in which to alter the

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curvature sweeps of the stadium. Informed by the graphs, coarse resolutions for the stadium roof geometry were derived initially and then refined over time.
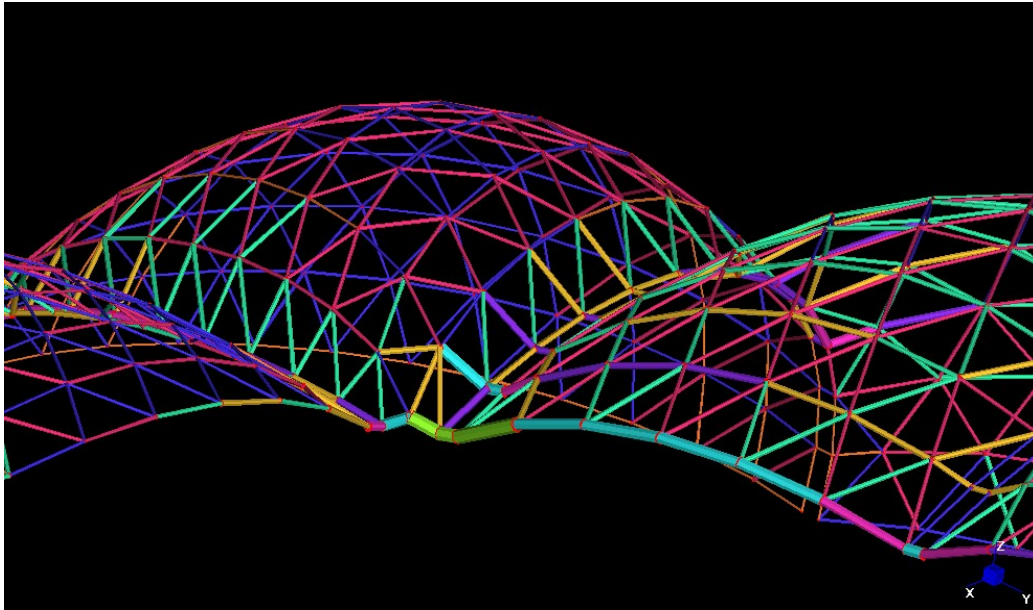
Figure 12: Detail of roof with optimized member sizes.

5. Lessons learned

During the first four months of the development and testing of the parametric model, I was logging all ongoing changes in the stadium geometry. In this stage, a series of design parameters which were assumed fixed, had to be altered and consequently the flexible model had to be updated constantly. These changes were required due to aesthetic, convergent, planning, or financial considerations and included inter alia a revision of the main structural grid of the stadium, an alteration in the position of the main roof supports and the variation of the extent of the roof cantilever towards the pitch. Planning considerations were addressed by investigating the *best fit* of the parametric stadium model to the given site-boundaries and the *high-ball-line* being the minimum required field of vision to a ball in play. In most cases, the changes could be accommodated in the CATIA™ model, which led to a setup that was increasingly built on dependencies as shown in Figures 13 and 14. At the same time the complexity of these associative

dependencies increased, which had its effect on the hierarchical organisation of design parameters within the CATIA™ file. As the main geometry of the stadium was based on a rectangular grid and the arrangement of the roof support at the outside boundary of the stadium was based on a circular array, some variations of the curvature led to complex intersections.
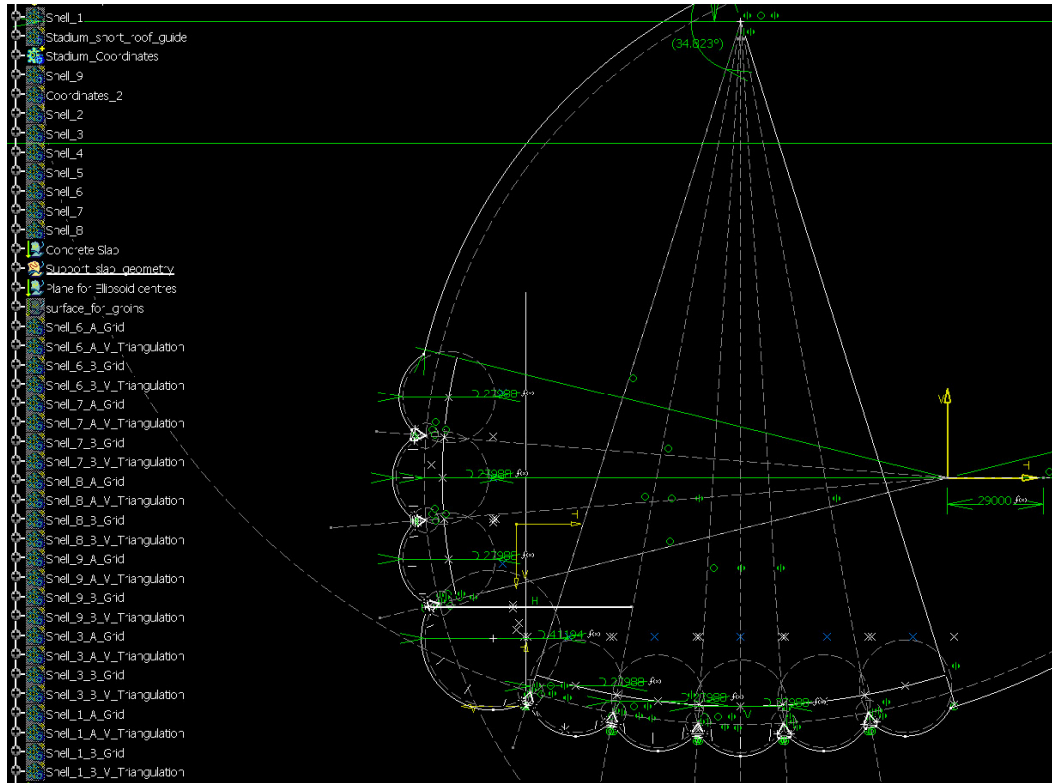
Figure 13: Author, Plan of the parametric definition of the boundary edge of the stadium
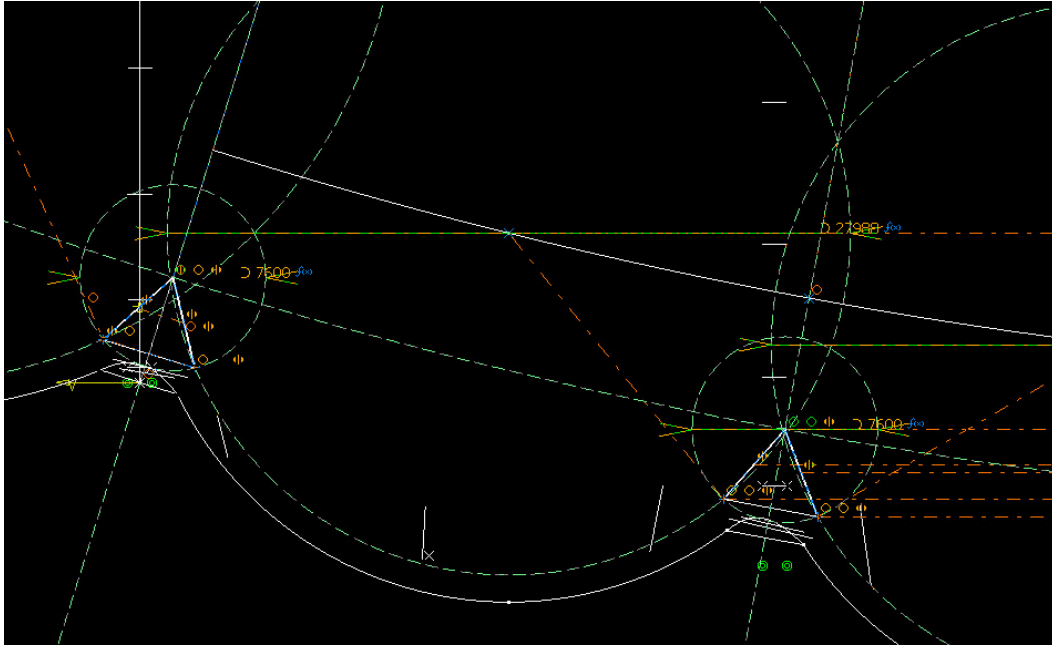
Figure 14: Author, Detail of the parametric definition of the boundary edge of the stadium

This required the introduction of transfer elements which had to be accommodated in the parametric model retrospectively. For some variations of the grid and shell curvature, the numerical definitions of the parameters would not allow a possible solution to be rendered. Inconsistencies in the model occurred when design elements were over constrained by two or more design criteria. The design team assessed that the intelligence derived from analysing the decision making process which led to the alterations of the conceptual geometry template, was more important than the geometrical *status* of the parametric model.

As illustrated in Figure 15, one particular observation made by me was that instead of an expected decrease of indeterminate factors in the design, the number of variable design factors increased during the four month design development. Because of this fact, the necessity to scrutinise the design intent had become particularly evident, which consequently assisted in developing the structural system in more detail.

This insight exemplifies that in the given case, *detailing* in a parametric context is neither a question of scale nor dependent on fixed parameters, but rather depends

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on design logic and the correct parametric relations. The fact that many numerical definitions of the stadium geometry were unknown did not raise concerns as long as the parametric template could accommodate them and meet the requirements of the design intent. In addition to this, the structural engineers pointed out that the analysis they required as decision support for understanding the structural behaviour did not have to be taken from the final 'correct' model, but it could be generated from approximated parametric templates.

As much as the possibility to work with geometrical information which was not 100% accurate did not cause major concern to the structural engineers, it did pose problems to the design documenters in the industry partner's practice. A member of the design team has therefore developed a custom script that provides the drafts-people at Arup with a software tool for mapping the analysis geometry onto the models they were producing for design documentation which were in turn to be passed on to the steel manufacturer via a database. By doing so, the script allows the documenters to define a tolerance within the range of which the script will compare the precise positioning of nodes in the documentation file with geometry coming from the analysis-geometry, and so to subsequently map between them.

In order to avoid errors which might occur during the comparison, the process includes support for visual checking by colour-coding of results in the 3D documentation environment. As much as the increased shift from fixed numerical coordinates to a more associative geometry allowed the design team to gain a better understanding of the 'design intent', it proved a difficult task to accommodate changes in the parameter schema setup *on the fly*, in particular when tight deadlines for submission were involved.

At one point in the setup of the parametric model schema, changes required by the design team were of such a disruptive nature that the parametric model schema could not cope with them.
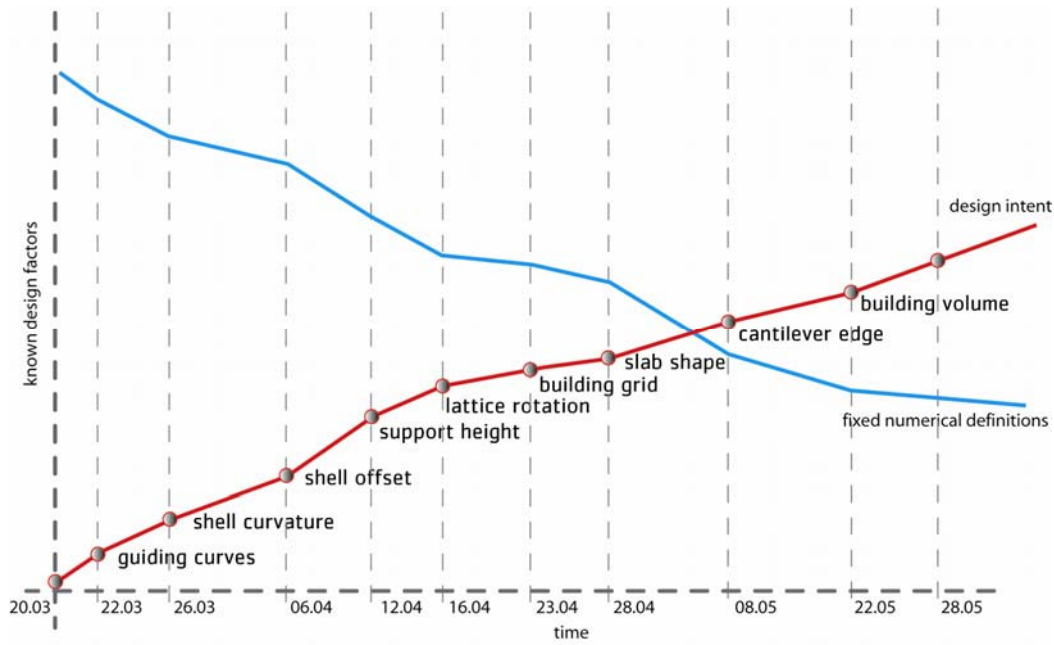
Figure 15: Diagram comparing the amount of known design factors with the understanding of design intent.

The attempt to introduce variations of the values of parameters sitting on a high level in the design hierarchy caused dependent *child* parameters to lose their logical associations. As illustrated in Figure 16, the 3D model consequently fell apart and parametric integrity could not be re-established in the original model.

Lessons learned from this experience led to the insight that the setup of one all-encompassing parametric model schema, capable of accommodating any kind of changes to the geometrical setup of a project is not advisable in the conceptual design stage. As the definition of alterable parameters responds to a clearly defined optimisation process, major changes are likely to interfere with the logical structure of the parametric model. The alternative approach is the setup of not one, but several 'lighter' parametric models that each can each address a particular aspect of the performance optimisation being sought in any given project. The generation of these

models is dependent on the standard of knowledge about fixed or changeable design constraints according to the progress within the design stages and the corresponding performance requirements. In the case of the stadium roof project,

a parametric model schema was built up from scratch to provide more robust test-beds for targeted optimisation of the roof curvatures without any changes to the stadium-grid or the spacing between the main structural elements.

In regard to increasing the transdisciplinary workflow and the aim for real-time feedback, the link between parametric software (CATIA™) and the structural analysis package GSA™ via dxf was inappropriate for facilitating automation in data transfer and hence real time interaction between architects and engineers. Direct output of geometrical information from the parametric model via a custom script offered the team the structural engineers and me a better alternative and we facilitated it through direct binary data transfer from CATIA™ to GSA™. The duration of the optimisation process of approximately 30 minutes was dependent on the complexity of the project and on computational processing speed. Assuming computational processing will become faster in the future, this obstacle will become less time-consuming to the point where real-time optimisation may be possible.
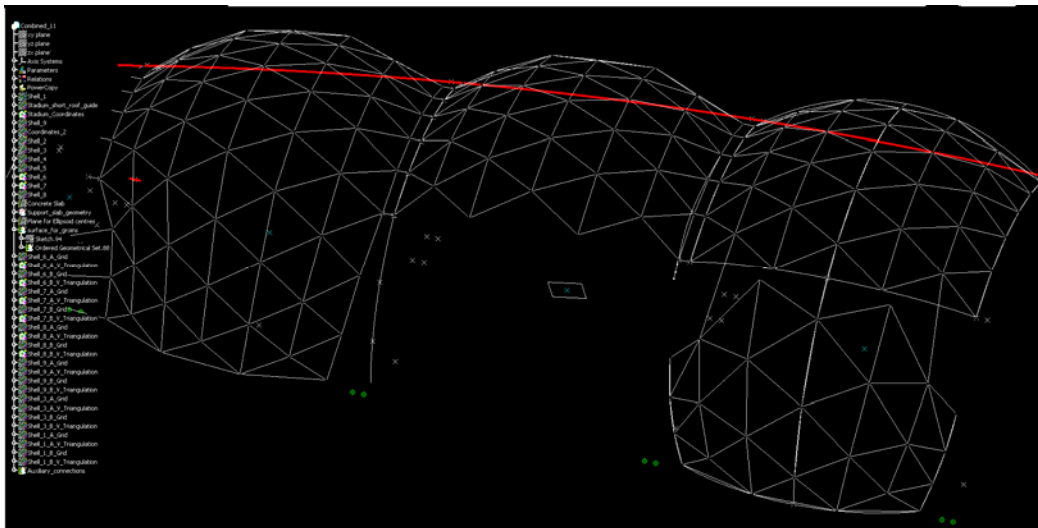
Figure 16: Display of the broken parametric model.

I explored design in the conceptual design phase by linking parametric design to structural analysis and optimisation through informed geometry alterations. The setup of any such flexible work environment required a priori input from

architectural and engineering experts to define suitability rules that guide the process towards a specific performance goal. The rate of success depended on the precise definition of quantifiable design variables across disciplines and the awareness of the extent of variations being sought. The implementation of this method and the type of parameters chosen were dependent on the progress of the project according to the design stages. In the case presented, it was neither aimed at finding an initial shape for the project, nor for optimising the design for manufacturing and construction, but at fine-tuning a design-idea with the help of close to real-time performance feedback. The link between parametric design and structural optimisation on the stadium project was applied in an advanced stage of conceptual design where variations of a proposed design solution were sought by the team.

6. Knowledge capture and sharing with the Buildings Group:

As much as my contribution on the project showed successes in the application of a new design-methodology for bridging the gap between architectural design generation and engineering performance analysis, the long-term benefits for the office were not automatically guaranteed. The reason for this was the limited availability of parametric software in the office at the time of my commencement in the project. The Arup offices which were involved in the Melbourne Rectangular Stadium project did not use the software CATIA™ and alternatives had to be found in order to allow Arup to pursue the path that had proven successful by me and the design team on the stadium roof.

In the search for alternative applications that would provide easy access to parametric modelling capabilities to a large number of designers and drafts-people within Arup, the tool Generative Components™ (GC) that forms part of the Bentley software bundle showed to be a possible alternative to CATIA™. Arup possessed multiple licenses of Bentley's Microstation™ and Triforma™ 3D

architectural and structural drafting packages and GC™ could easily be added to that. Encouraged by first successes in applying GC™ on a bridge project (Marina Bay Bridge) in Singapore and in order to replicate the link between geometry and analysis as shown on the CATIA™ model for the stadium, several designers and drafts-people within Arup started to study parametric design methodologies using Bentley's GC™.

The pickup of advanced skills in GC™ by those employees occurred within a few weeks and as a next step we investigated how I could best inform the main drafts-person at Arup to reproduce the CATIA™ stadium model in GC™. Simple file transfer from one parametric software tool to another is not possible due to an entirely different data-structure of the two computational software packages. In contrast to non-parametric tools where geometry is expressed explicitly, parametric software requires implicit knowledge about parameters and their function in controlling geometry in a relational manner; parameters can currently not be exported form one file-format to another. It was therefore was not possible to simply export the parameters that would provide the stadium model with appropriate flexibility to be tested structurally under varying geometrical conditions. The solution for this problem was to provide the drafts-people with a detailed description about the ontology of the parametric model. By describing step by step how the geometry model was set up in terms of relations, dependencies and constraints, I provided the Arup team with a text-based description all fixed and flexible design elements in the model in addition to a set of images locating the elements in their respective position with the 3D parametric model. By following this description the Arup drafts-people could easily recreate the model in an unmistakeable fashion in their computational software tool GC™.

The first image (Figure 17) illustrated the setup of the main 'sweeping' curves that control the height of the bio-frames on the cantilever edge of the stadium.

Attached to these curves are the connection points for the field-curve defining the cantilever of each shell over the seating area.
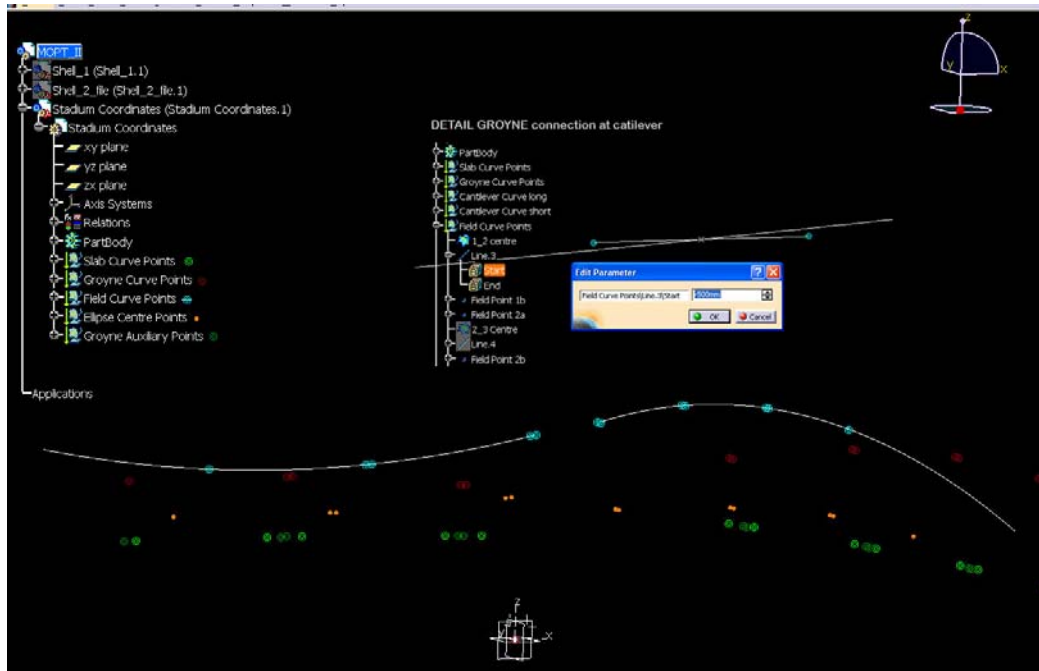
Figure 17: Author, Recipe for generating the first step of the parametric model

As a second step I described the creation of the boundary curves of the individual shells by creating an elliptical shape constrained by the endpoints of the field guiding curve, the centre curve-guiding curve and the slab-guiding curve (as seen in Figure 18). Most of the above curves were defined by intersecting the predominant geometrical elements (first-principle geometrical constraints) of the stadium-base geometry such as the slab for pedestrian circulation and the angle of the tribunes. The field-guiding curve was defined by a plane derived from the analysis of viewing angles and the high-ball line.
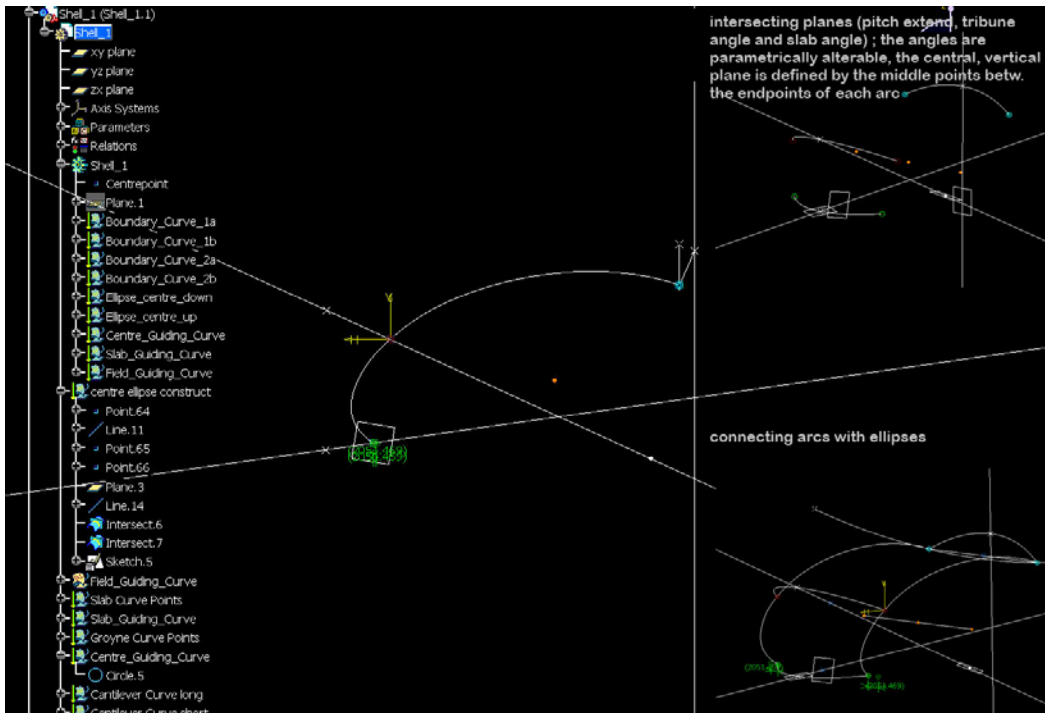
Figure 18: Author, Recipe for generating the second step of the parametric model

In a final step the description of the parametric model explained the slit that occurs at the bottom of every grid-shell (Figure 19). In spite its simple appearance, it is difficult to construct parametrically, and rule-based auxiliary points were required to regulate the opening of the slit parametrically in a consistent manner for all shells.
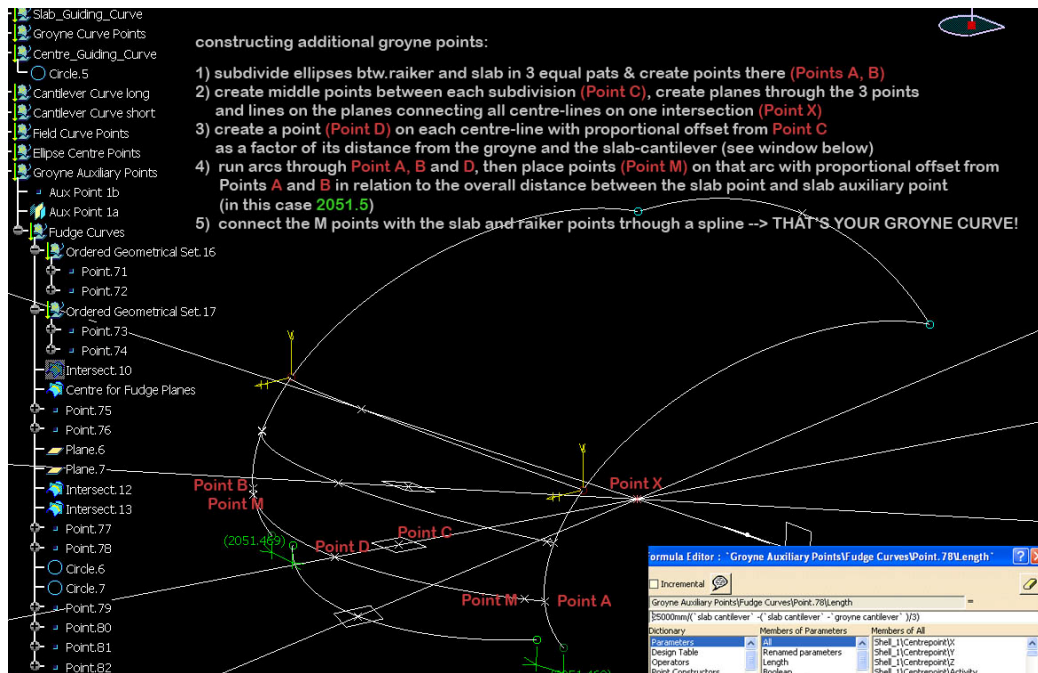
Figure 19: Author, Recipe for generating the consequent steps of the parametric model

Upon completion of the boundary curves, colleagues at Arup were able to apply a custom-script for generating the triangular subdivisions that define the centre-line of the steel members for construction. Results of the final GC™ model are shown in Figure 20. The working of the script in GC™ was partly derived from analysing the initial script that was produced for the CATIA™ model and the overall process of *translating* the model between the two parametric tools took only one week from start to completion. The task of communicating geometrical entities between the two diverse platforms was an issue of understanding process and the implicit rules that the geometry followed rather than retracing an existing geometrical construct.

Following the completion of the model, the same process of linking the geometry model to structural analysis were successfully repeated. An array of 32 variations was generated to allow for quick analysis of the model as shown in Figure 21.

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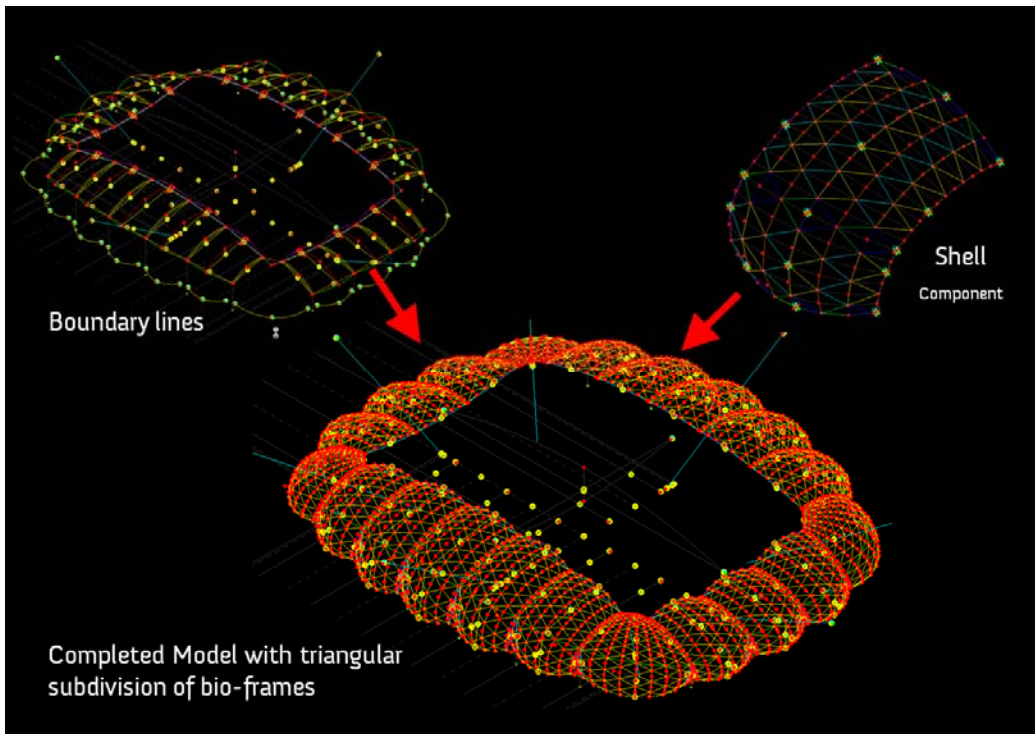
Figure 20: Arup/Author, Finalised new parametric model using GC™
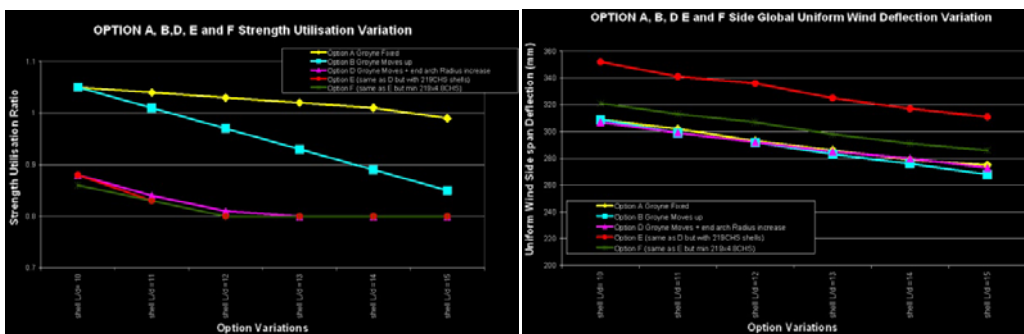
Figure 21: Arup, Plotting results from several variations in regard to strength utilisation and wind deflection

From an architect's perspective, the immediate visualisation of structural feedback provided by the structural engineers proved valuable to understanding the effects of changes which might otherwise only be driven by aesthetic considerations. In this context, immediacy and clarity of information-display proved to be a decisive

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factor in facilitating shared authorship. The opportunity of visualising and distributing results from structural optimisation in close-to-real-time enabled the transdisciplinary team to evaluate options and propose changes in a highly informed manner. The more quickly results were communicated across a team, the better the information flow and the collaborative capabilities. The graphic output of the optimisation results gave a clear impression not only of the intelligence the structural engineers are deriving from it, but also allowed the architects to get insight into the working methodology of the engineers.
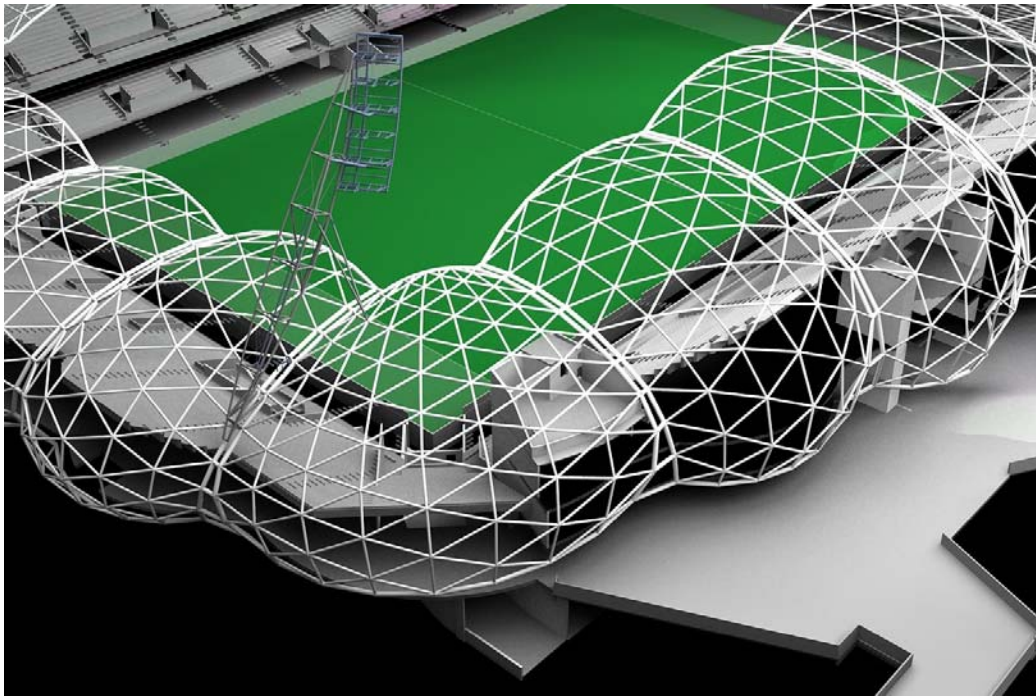
Figure 22: Arup, rendering of final stadium-roof geometry (without cladding)

Tests on the stadium project have shown that if a project team relies on automation routines within a project, members of the team require access to information at any point in the design process for decision support to guide the optimisation process and to propose alternative design solutions. The automation routines run in the background as silent partners whilst open access to the information helps avoid black-box scenarios. The application of parametric variation was not only done to benefit the structure, but it was actually necessary due to the complexity of the structure at hand. Without the iterative

experimentation, it would have been impossible even for the experienced structural engineers to understand the nature of the stress-distribution in the structure and to consequently get a feeling for its behaviour. The experience gained in the stadium project has served to underline the need and definition for a more generalised software tool to act as a data manager in an iterative design process, with a robust but flexible schema for transport of data between proprietary packages. The data manager would require package-specific plug-ins, which could interface with the target package through API's (Application Programming Interfaces).The data manager would also have a degree of *intelligence*, to allow some minor manipulations to the data in transit between packages – particularly user-specified spreadsheet-type optimisation rules. These rules, and the data itself, would equally well apply to other aspects of design optimisation beyond structural or aesthetic concerns. In order to comply with BIM standards, I propose to make the schema for data transport compatible with the common standard of Industry Foundation Classes (IFC), given the recent uptake internationally in IFC as a CAD-CAD (and to a limited degree CAD-analysis) vehicle.

The process described in this appendix has since become a new worldwide reference for linking parametrically driven design geometry to building performance analysis in structural terms. In mid 2008 the project was awarded the highly prestigious *Bentley Award of Excellence*, winning the price in the category of *Innovation in Commercial or Residential Building.*

List of Figures:

Appendix B

Sense-making across collaborating disciplines in the early stages of architectural design

Interview with André Chaszar

Amsterdam 24.09.2008

DH: My first question is a bit provocative: Tools for multidisciplinary design, is something like this possible – does it make sense?

AC: I think it does make a certain amount of sense. I still support the idea of multidisciplinary design tools which I was getting at back when I was writing the article on collaborative design titled "Bridging the Gap …". The years since have brought some better insight on how this is possible and how it is not. The key is that they do need to be limited in some way. The idea of making them comprehensive just does not seem feasible, but something of limited scope can be. This could occur in terms of limitation in the number of disciplines, limitations in the scale or the level of detail, limitation in the accuracy or the complexity – the linearity vs. the non-linearity of calculations that may be involved. If those limits are defined properly then you can still come up with useful collaborative design tools. We might have a conversation among the architect, the structural engineer and the fire engineer, or some other combination of three, but not eight design partners. It is very hard anyway to have a productive conversation with eight people each of whom is supposed to be representing a different point of view. Correspondingly, it is difficult to create a tool that is able to address all of those things in a simultaneous fashion. Of course that does not mean that you could not take the results of a tool which is intended to address a pair or a triple and throw that out into another environment which then gives you

slightly delayed – not exactly concurrent – feedback on a number of other points. In this way the problem remains manageable.

DH: What would you be able to do with such a tool? Would it rather be a decision support environment, or would it be something where you can actively change information? Would it be something where you can compare data, where you set up rules that drive analysis? What would be the ideal use in your point of view?

AC: I would assume that the rules that the different parties or the different criterion sets (we can talk about disciplines that way) are brought already to the table. That is the disciplinary knowledge. There might be some rules developed "on the fly" specific to the project or specific to the interests of the parties gathered for that project – those might be carried on to other projects, but most of the rules come in the heads of the people who participate in this. The main purpose of a tool like that would be for running through scenarios. Whether that's comparison of data ... I am not sure if I am understanding what you mean with 'comparison of data' – or is it of analysis that has already been done?

DH: We see it as setting up variables in your design that would allow you to run test scenarios under specific geometry conditions.

AC: If you have done some analyses on some base-assumptions. Let's say you have an overall building form or a basic organization of a building which has three or four main variables and you can do an analysis on the base-case of those variables, then you could in such a collaborative tool conceivably bring together the results of two or three of these kinds of pre-analyses and then try parametrically varying those to the extent that they are scalable. Especially if there is a linear relationship between some (of the) variables that are controlled in the collaborative environment and some of the outcomes of the pre-analyses, then you can very quickly get a sense of: well – what if we changed these parameters now.

The other approach of course is to try to keep the analysis very simple as I was saying at the earlier question. Keeping the minimum level of detail that still gives you a useful answer, which would then enable you to do the analysis right then. There are these two different and both appropriate ways of approaching the situation.

DH: From my experience it also depends on how far down the track you sit with your design problem. If it is something very early on in the design process you want to be as stupid, as coarse, as rough as possible because you need to be able to mock up a model in close to real time. If you are talking about analysis that is a bit more differentiated which might involve two or three different professions, at some point you might look into more elaborate rule-based models or at least models that allow you a bit more extended set of variables. That way you get a bit more differentiated picture of what the outcome would be. This is a bit further in the game – still not at a time when your design is already finished, because all of what I am talking about is before the 'design-freeze' or documentation period. I am not talking about BIM here.

AC: Yes, we are talking about schematic design and design development.

DH: How do we support sense making? Initially I would talk about decision making but I have realized that sense making comes before that and that it is probably the most critical part in the beginning of design collaboration. Very often when you have different practitioners on one table it is more about making other people understand first of all what the issues are before you get to decision-making.

AC: I completely agree!

DH: How could we support that with a tool (as discussed before) What does the tool need to be able to do in order to support sense-making and give decision support as a next step; how would the interface have to look? (or: "what would the interface have to look like?")

AC: It is a truism, and it is probably obvious to anybody that the greatest power in the communication aspect (as opposed to the calculation aspect) is graphics. Visualization, the ability to take simulations of complex phenomena or the results of complex calculations and display them in a digestible way. However, the fact that you can do that does not mean that you are going to be understood, because most people's graphic output is oriented towards someone who has the same knowledge they do. It still requires some skill to translate that graphic output to a form where someone who is not an expert on that particular subject can make sense of it. I am not sure that enough attention is devoted to this.

DH: *This is central to my PhD, this is where I am currently digging in deeply at the moment. At the same time I've been reading material from the field of social science (such as Nonaka) to understand the way sense-making works. The way you internalize and externalize knowledge.*

AC: (*I'm guessing there was some other stuff here in which you said more about Nonaka, otherwise this next statement seems a bit odd, but anyway …*)Your observation from Nonaka points to the observation that there is no such thing as knowledge sharing. What is really shared is just data. It is not knowledge until it is reconstituted as knowledge inside ourselves. It is debatable then if a group of people who come up with a term for something – such as a complex concept - and they agree to refer to it through a certain word, if that then is an example of knowledge-sharing. I don't think so because by telling somebody that word, you have not conveyed the knowledge to them. By giving them the word and the definition of the word you still have not conveyed knowledge, because they are not using the word which is the encapsulation of the knowledge, they are using the definition which is composed of all its sub-words which they have to reconstitute and then agree or disagree with you.

DH: *Is this then not going back to the idea of sense-making? The moment you are able – with the words and the data that you use – to show to others, visualize and convey sense of the information you hold - is this not the point where you start creating knowledge?*

AC: It is getting close but I think it is really a trial and error process. I don't want to get too far off on this as it is maybe not to the point and it is not really something that I can support either. It is my understanding about these things, having reflected on it for some years, that the way we communicate is in reality a trial and error process. When anybody says anything - whether it is a fact or not - and you have a group of professionals sitting around trying to make decisions about how certain aspects of a building should be designed, they may present data, they may present arguments, but the terms that they use and the numbers that they show – none of those are a hundred percent effective. Anything that you say or show, or gesture – anything communicative is only absorbed in some fraction by the other party. Some part of that fraction that is absorbed actually overlaps with what you intended, but I would argue much of the time most of it does not. It could be that really only five or ten percent of what is going back and forth is actually corresponding. The reason we can still communicate is that we fill in and assume things. A lot of the times those assumptions are close enough to allow us to proceed. Another reason is that we do not want to argue (unnecessarily), so we just agree and move forward.

Both of these strategies can lead to a lot of problems down the road. A lot of the difficulties you have with clients' dissatisfaction with the problems they get from building designs has to do with this. Earlier in the process people use quite vague terms, and anybody can read what they want to into it. It is only when the project becomes more and more specific and detailed, that the possibility of true understanding of what might result becomes possible. By then there is not really time, there is no money, commitments have been made to a number of things the ramifications of which were not really understood at the time. The end-result is something that is not really satisfying unless it is a well known design like a type. Then in a sense you already know what you get before you even begin, which is a great argument against innovation. Why are a lot of business people so

conservative? – To avoid the risk! Being interested in the innovative side of things we are trying to increase the size of the overlap of truly common understanding.

As for what a tool needs to be able to do to help that, I think one thing it needs to do is to enable you to test different alternatives and different scenarios. You do have a chance to test that what you understood was actually what was meant. It is in a way like asking the same question three different ways. Some people are very skilled at that. They really want to be sure that somebody will give them a proof (*words missing in this sentence?*). They indirectly ask about the same thing from different angles. This is one possible way of using a multidisciplinary tool – trying different scenarios which are aimed at the same end-result and trying to get it from different directions perhaps.

Another way that a tool could support the 'sense-making' would be to be able to display the same information in different ways. This is not a new idea – you can take the same data and display it as a line, graph, a bar-chart, a pie-chart or whatever. There may be some quite reliable guidelines as to which type of display is best for which kind of information, but I am not sure that those should be taken as set in stone. In case you are not understood it is more sensible to show the data in another way.

DH: *Common geometry in early design - is it a dream? How could we set up an environment where we work on the same geometry (not necessarily on the same model) and share at least parts of the geometrical information of a project? How would that play out in practice? Can this happen through smart translators and automated filters, or is it rather going to be a person whose job description as center-point of information is to collect and appropriate geometrical information to then distribute it to the individual designers in the project team in regular intervals?*

AC: I think the second alternative you are proposing is responsible(? reasonable). Some people are proposing that it is quite an attractive business model to become a 'digital modeler' to then act as a clearing-house for all geometrical project information. I am not sure that this is a responsibility that one person or one firm wants to take on. If it goes wrong it screws up everything. I tend to think that it

might be better to de-centralize the process just from the reliability point of view. I would say that maybe there is a third alternative which leans a little towards the translator except I don't think that the translator really needs to be automated. My own research in fact concerns this question: How does a structural engineer get the information he needs out of the architectural model, how does a lighting-designer or an acoustic engineer do it? Usually the point of reference is the architectural model because that one tends to be the one which has the most information. The different disciplines tend to work with sub-sets of the architects' information. Then of course they have to contribute significant quantities of information to those sub-sets in order to make them workable for their own purposes.

DH: But is this really part of their job description? – they are often not getting paid for it in the contract and they would have to guarantee for the correctness of information - this is where the situation is getting really tricky.

AC: If they are going to use the architect's information directly, then they need guarantees that it is reliable, they need a contract that says that they are not responsible for any errors coming from 'there' . This is another argument possibly in favor of not even trying to pass information through the digital pipeline. Introducing these points where things need to be checked and somebody conceivably finds an error. I am not sure that this is actually going to work. Just because of the time-pressure. The technology exists to push information through the pipeline. Because the technology exists, the expectation has arisen that things can be done much more quickly. That expectation is not going to be removed. People will be forced to continue working as quickly as they think they can. Therefore deliberately introducing these moments where things come to a grinding halt and somebody has to re-build the model in order to possibly find the error in somebody else's model might be good for finding errors, but it is not good for the overall process. It is not until you get to the fabrication stage where you are actually going to materialize the stuff that it becomes critical that things

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are right. Even then, smart designers will design in a way that they include some tolerances. Even if the thing is not manufactured perfectly, if things were not coordinated perfectly, it is not the end of the project, it is not going to cause months of delay or millions of dollars in overruns – it can be managed. That is just smart design. Saying that, I think it is valid to expect that consultants should be able to use digital information more or less directly, but I don't think that they need to be able to get the information they require in an automated way. They have some knowledge about what they need, they do not need to explain that to a third party, they can with the assistance of what I'm working on – strip out the information they need relatively simply and then add in the additional information that is specific to their discipline, which should not necessarily be in the model of the architect nor in some 'master model'.

DH: When you say 'strip out' it sounds a bit as if the architecture model has a surplus of information and all that's needed is to have the right filter to get your view of what you need. Doing my interviews within Arup I realized that this notion would be incorrect. Sometimes you need much more information to what the architect's model does contain, sometimes you need different information to what the architect's model does contain. There are two things that a colleague of mine calls 'defeaturing and 'equivalencing'. The defeaturing process is about getting the level of detail that's coming from the architects model to the point where it has the adequate threshold for the type of analysis individual consultants require.

AC: It is too detailed! There you do need a subset of the information, but if you just took a subset you would still not have the right information because things would not connect. That means that if two larger elements are separated by something that is below a certain threshold you would have an empty space there. You need to react on this and fill in the missing bits. That's part of the information that you add but it still makes sense I believe to do that initial filtering such as: give me all the interior surfaces of all the spaces in the building and chuck out any elements that are smaller than (let's say) 300mm in any dimension or in more than one dimension. This can be done by a tool. The recipient of the model

(e.g. the acoustical engineer) has a tool that allows him to take the architect's model and apply some filters to it. This is something I am currently developing – this is what I hope is going to be my contribution to the current state of affairs. It does not exist as yet. This is one example of the kind of thing you ought to be able to do with the model instead of just looking at it and recreating it from scratch. I'd propose this third alternative – rather than the automated filtering/conversion/translation, and rather than the go-between third party modeling specialist. If the user, the recipient has enough knowledge (and presumably they do) about what information needs to be in the model and what the relationship between that information and the information they receive is (how you can define those relationships), then every time the architect produces a new model – the first time is the hardest, you have to go through and figure out which rules are going to give you the information you need – on the subsequent passes when the project/design/model gets revised, you should be able to apply pretty much the same rules to get the updated geometry out. You may want to try some sort of tracking – but I don't think there is much to be gained there because the filtration process occurs rather quickly. Therefore you would be working on the same geometry because the geometry that each consultant uses is related by a nearly fixed set of rules to the base geometry which is not the entire architectural model, but some parts of the architectural model. That part of the architectural model is not the same for each of the other disciplines.

DH: What we are talking about now is testing in design development. Very few architects would take the effort to build up an architectural model that is more than a visual representation from three of four angles that they could show to the clients. There is no incentive for architects at this stage to work in 3D and to have a model that contains volumes, a distinction between interior and exterior surfaces and so forth. You could argue that the whole BIM-idea goes down that direction where you have this complete set of 3D objects connected. To build such a model you are already in design documentation, you don't often do it in design development.

AC: I believe that this is the case now, there is still obviously a lot of design work that does not happen in 3D, and therefore part of the assumptions in my research is that this approach that I'm taking is useful in the stages where you are using 3D, and there are enough stages where 3D is used or will be increasingly used in coming years, that it is worth helping that along. I am not trying to tackle the 2D aspect of it because I think it would be too difficult. I feel that when you take a 3D concept and represent it in 2D, you are throwing out a lot of the information that you need in order to translate it into another representation of that concept. Let's talk it through:

Let's say that an architect produces a model that is three dimensional only to the extent that there is a form which is an exterior surface and that the only information available about the inside are some hand-sketches; let's assume this to be the worst case. There is no sensible way to take the architect's hand sketch and turn it into a structural analysis model. That's beyond us – maybe 10-20-50 years from now it can be done if anybody is still making hand sketches then (and I hope they are, because I think it would be a mistake to lose that). Our understanding of visual perception is not at the point where we could extract that information either automatically or in a semi-guided way. The closest thing I can think of is that the architect's sketch gets stuck on a digitizer patch and instead of a mouse someone is taking a pen and they click on points which create a structural frame-model which is approximate. Then you do some massaging to get the horizontal lines horizontal and the vertical lines vertical if that's necessary and then you go on. If that continues to be the workflow then that shows a certain unwillingness on the part of the architects to let the engineers keep up with them. I think that to the extent where the architect and engineer perceive themselves as a team, there ought to be some accommodation on the part of the architects that they need to produce more easily translatable information, in large enough quantities and of high enough qualities to let their consultants keep up with them.

The way it happens now is that the consultants cannot keep up with the number of design changes made by the architects, so they hang back, they think: 'Well the

architect is going to be changing this 20 times in the next week anyway so we'll do our analysis next week. We'll fudge a bit now to give them an answer that's probably correct. ' But it is not going to be nearly as 'near correct' as it could be, and therefore you are going to get a very fuzzy answer which undermines the potential of the project right at the beginning. If the architects are not willing to produce the kind of information the consultants can use then you end up in a deadlock.

The architects may say: 'The engineers are lazy – if I can produce 20 designs in a week, why don't they do 20 analyses in a week?' ; not realizing two things: One is that the amount of time necessary to set up and carry out a structural analysis is more than the amount of time required to redraw some sections typically (although that is not necessarily the case – if you set that structural analysis up parametrically you may be able to massage the model rather than rebuilding it)

DH: Can I jump to the question of rule based design at this point: what is the role of rule-based design in all of this?

AC: I think the rule-based stuff in the first place is really oriented towards technical solutions. It is best for doing variations on already well-known solutions. I wouldn't be surprised if that continues to be 90% of its use in terms of hours. In terms of value it might be that you could introduce parametrics at the conceptual level. The problem of course there is that some concepts just cannot be 'morphed' into other concepts. There is no number of parameters or no way in which you could adjust the parameters of this particular model to arrive at that model. How do you do that? The dream solution is that if you have so many parameters 95% of which are essentially set to zero – but actually all the parameters are present, all the possible things you might need to do are present. This comes from the argument about genetics, about how they are discovering that all the features from the different species may be present in the DNA and it is just certain triggers that cause some feature to appear or not appear. The corresponding concept to that in a parametric associative model is that you've got tens of thousands of parameters,

you happen to somehow miraculously decide which 500 are appropriate at a particular stage of your thinking about a project, and you set all the others to zero and then, when you want to re-mold your concept you turn many of those 500 off and you turn a bunch of others on. Nice idea – but only on paper.

The other way that most people favor is to find tools that allow you to build not only static but also dynamic (parametric or variable) models quickly enough that you can make one, examine it, scrap it, make another, examine it, and so on in a reasonable amount of time. Genetic algorithms and other evolutionary algorithms fall in between those two I suppose. There you are not generating the variations yourself, but the total space in which those models could occur is already pretty much known based on the parameters you set up in the algorithm. Of course it is possible to make algorithms that re-write themselves and people in AI have been working with ideas like these for 30-40 years. Then it is not evolutionary design – but rather evolutionary programming leading to design. It might be that we'll overcome that hurdle, but that's not in a short time. Probably the best solution therefore is to rapidly make simple models and chuck them out .

DH: This is exactly the same conclusion that I got to, and I would go so far as to say that when you hit a certain problem that you want to explore in a multidisciplinary environment, you need to talk to the parties involved and ask: If we could have a model that helps us solve this problem, what variables have to be involved, how are they weighted roughly? Then you set up your parametric model and you run certain 'geometry cases' (as we call them) and you test them through various analyses for finding out how they perform. I've discussed this with Jeroen: either you just set up a set of variations to spit out x-number of solutions that you then analyse in more detail - an experienced engineer would understand why this and that happens and be able to judge what's going on - or you apply 'directed search' where you have some sort of feedback loop between a certain outcome and the way the model updates.
The last question I had in here was: how concurrent can we go?

AC: I guess we have touched upon this already in a few of the earlier points. You can get more or less complete concurrence when you limit the number of criterion sets, which also means limiting the level of detail. You can also get improved concurrency when you are able to quickly create new models, although it is always more concurrent to work with the existing model and try variations of it than to build new models. We are not too far off from the point where there will be significant numbers of people using the right software tools which enable them to build models concurrently and collaboratively 'on the fly'. Let's say there are three people representing three different disciplines sitting either at the same computer or at their own computers but working on a model in a collaborative way. It still seems like a bit of a dream. Right now it seems more likely that you have one person who is quick at building models and the other two are sitting next to him (or her) and tell him: why don't you put this in here, we need to add that kind of feature that we need to be able to test and so on. This is fairly concurrent, but again it is for a limited number of criterion sets. Then at the next level out you get a small delay of time if you are able to link those limited models on a one-to-one basis with the next level of priority of criterion sets that you want to ask about. You have the three people or the three disciplines whose input is critical to a particular issue, they have their discussion, and within a day that can be passed on to the others to get their feedback. That is pretty concurrent – if you can get an answer from everybody who has anything important to say within 48 hours that's pretty good.

DH: In a way the question was posed a bit cynical: How concurrent can you go? What is the point where it is not anymore a computational or a process issue, but where it becomes an issue of understanding and having to take your time for reflecting on a design issue. If you constantly have updates on everybody's current state of where they are in their design, you'd find yourself in this perpetuum mobile.

AC: You need a summary – you need the end of the day.

DH: *Yes you need summary periods, you need certain reflection times where design is accepted as it is and there is not more information coming to it so you can 'swallow up' the information that's currently there and work with that. Experienced designers at Arup seem to be critical about the idea of the 'ultimate real-time environment'*

AC: Yes, I think it makes no sense because it becomes a sort of cacophony. Information is coming in from all different directions. You might be able to set up some sort of filter which prioritizes, so some people's messages get through to you more quickly than others, but in fact you are potentially shooting yourself in the foot, because somebody whom you normally consider unimportant may have something very important to say at a particular moment, and then you didn't find out about it until a week later. That's kind of dumb too. It is like anything else: It is like RSS feeds or instant messaging. All these communication technologies basically are distracting people. They are providing more distraction and less time to digest something that is of significance. That does not mean that technology is bad, it means that the people who are using it are not being very smart in the way they are using it. If you turn on the tap of the sink, you don't need to turn it on all the way – you turn it on as much as you need. Take as much information as you need, set it up and get it in doses that you can deal with. That raises another problem in the collaborative environment: Some people may say: 'I want information every four hours, and if I can deal with information every four hours then you should be able to, too'. Well, sorry – technology is not going help with that. It is more about getting people with compatible working-styles working together.

DH: *I have an add-on question for you: In your opinion is design really social? Is architectural design a social process?*

AC: Yes, it is forced to be. It may not want to be, but it is forced to be. Some architects and engineers are more inclined to view it as a social (act?) than others. I guess the ones who are most successful at the business of design are the ones who

regard it as the most social. They are not necessarily the ones who come up with the most interesting designs. Coming up with the most interesting design may indeed require just a sort of climbing inside your own head for an extended period of time - or having a small group of people who can climb inside each other's heads. That opens a whole other debate: What is business about? Does it produce value through reliable mediocrity or unreliable innovation or spectacle? There isn't any answer for that because there is demand for both. When we talk about developing tools, working methods or workflows (or whatever) we really have to keep in mind that there are at least these two different ways of approaching the assignment. The same tools are probably not going to be working equally well for both approaches.

DH: *I wonder if this is not a bit oversimplified; you can have unreliable mediocrity and very reliable innovation.*

AC: Of course. I am talking about the Pareto front here. Of course there is crap down there… The more social you get the more mediocre you get – typically. Because you have to accommodate more different opinions which leads you to kind of an average. Maybe I'm getting the wrong take on social. You can have a social situation in which there is a dictator who forces it to go one way. You get ten opinions but you ignore nine of them. Is that social or is it not social? I'd argue it is not social but it appears to be social. For the most part when you get a bunch of specialists together, they are going to tend to all try to pull the project in their own direction. If you let you let them all have a voice in that, you are going to end up with a project that is not in any direction. It will be a middle-of-the-road direction. Maybe there is a pinnacle of 'middle-of-the-roadness' . A perfectly integrated project which is so well balanced that it is just amazing. I don't think anybody would notice the amazingness. That project definitely would not get published, and most people who actually occupied it – if you walked into the building you would not notice it – if you worked there or lived there you might after some time how unobtrusively perfect it is. … *seems very choppy – missing words?*

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How do you convince an owner who does not occupy the building that there is any value in that? You can't – it is impossible. For one thing the public is not educated enough to value it. People who are going to move in, people are going to buy or rent it, won't perceive the quality that's there. People who will perceive the quality are typically not the people who are responsible for the decision about what was designed.

DH: I think we have to be very careful about how we define 'social' (as you have said) and how we define strong guidance in the design process while at the same time being capable of being a good integrator. I believe you can have a very strong mind in the way you guide a project and at the same time you can be very aware of all the dynamics required to integrate the parties who work with you in the right way to achieve your goal.

AC: The use of the word 'dictator' was probably too strong. My point is that there would be an overriding decision which has the discretion to disregard any part of the incoming input. I don't think that that's necessarily a bad thing; when taken too far obviously it is a bad thing, because then you get spectacular projects which are miserable. I've spent almost my entire career working as an engineer but I animatedly defend the role of the architect not just as an integrator. This makes it sound like an administrator or liaison-coordinator. Of course this is important but other people can do that. In fact construction managers try to do that. If you let a construction manager do it (that is, design) you get crap. I think what the architect really brings to the process is the ability to pervert the logic. There is all this information – really good solid technical advice coming in – and the ability to view that in a poetic frame of mind and say: Oh, yes – that 'suggests' something – it does not direct, it suggests. It is a metaphorical transformation – it is a re-interpretation of rationality into something that is not quite as rational. If you don't have that, what you end up with is not human, it is mechanical. You could program the whole thing and some people would propose that in fact what the building industry needs is to get these rules in a row, get it all sorted out and program the production of building. You just put in how many people, what

budget and then you have a nice skin put on it. There again you are in the realm of mediocrity, you balanced all the technical considerations out. That I would again call a social process even if it is automated – an automation of a social process.

DH: *Dana Cuff in her book on the 'Practice of Architecture' talks about the architect's process being social just simply because no architect can do a job on his or her own. Every architects requires input and feedback from others.*

AC: Yes, from a certain scale. That is what makes it tricky. If you are building a single dwelling or even a small cluster of dwellings it is entirely conceivable that you would be able to do it yourself. I don't think enough attention is paid to why it is exactly that at a larger scale you suddenly need to have a lot of people involved who actually are not able to communicate with each other effectively. That's the sad truth. We say it is acceptable because in the end most buildings do get built. Projects are not being cancelled left and right because the *design* (*I'd suggest 'project' here … including builders, clients, etc.*) team couldn't get their shit together. Most of them are neither falling down nor burning down, nor are they uninhabitable hot or cold. We say: 'Well, I guess we are communicating effectively', but we are not really communicating effectively – we are just getting by. Where is that threshold where you have to go from one to many? What is critical about that point? How can you push the effectiveness of one person's thinking further up the scale? What is the largest or most complex project that a single person could design?

DH: *Would this person necessarily have to be an architect or could this also be a talented engineer as long as he or she is capable of introducing that extra bit of' irrational logic' into their work?*

AC: Conceivably! If it is the right scale of project that person could deal with it themselves. The best counter-argument to this that I know of is that you can actually get (not negative but positive) results coming from collaboration that you

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would not have gotten without the collaboration. There are certain pairs or slightly larger than pairs (I don't think it is ever going to be even half of a design team) who actually bounce ideas off each other in a way that really pushes them both (or all). We might be able to produce tools or design processes to help people like that, but that's not really what it comes down to. It comes down to the right people. The more important problem would be: how do you find those people who can work together and put them together. Maybe what we need is more like a 'dating-site' for designers. If you are trying to assemble a team who is really going to work well together – how do you do that?

DH: My colleague Paul Nicholas has researched this and his investigation leads to the observation that it is a lot about mutual trust that needs to be built up over a certain period of time to enable people to collaborate effectively.

AC: It is through repeated working with each other.

Appendix C

Sense-making across collaborating disciplines in the early stages of architectural design

Original transcripts of research Interviews with practitioners at Arup and collaborating architects. One representative interview from each discipline was chosen.

A. Sensitivity-study interview questions Acoustic Engineer

1. *Please name some of the basic rules-of-thumb you usually apply.*

Depending on what we are designing, we look at volume of the spaces, distances from different areas to sound sources in rooms. Generic calculations for noise levels (roads)

    a. Do you base them purely on your expertise or are there any charts / computational tools to assist you?

Generally ROT are based on successful projects. There are some projects where we might need basic calculations and often we will do a couple of spreadsheet calculations as well for rooms with various sizes to get fundamental understanding of its properties and the sort of absorption is required.

2. *At what stage of a project do you generally get involved? When would you like to get involved?*

We are often involved from concept and scheme design. Sometimes we get involved a bit later, generally we are involved reasonably early. We normally have some stroke to influence things, there are projects where a lot of stuff is already done by the architect before we even start, but that does not happen often (20% of the time)

3. *What sort of information would you like to have at your fingertips during meetings with designers/clients/colleagues in conceptual design?*

Generally example pictures and drawings. *Do you want to do something like this or that?* Potentially sounds – we are trying to do more and more auralisations to introduce audio demonstrations. We have done a lot of them in a very early stage of design – as scheme design is going into detail design. We do it to assist decision making if buildings need to be vibration-isolated from trains etc. Those are easy ones to do. For opera houses we generally do auralisations. It happens early in the design stages because if somebody is trying to make decisions what volume the room should be or whether it should be long and skinny or short and fat, they will manage use an auralisations to demonstrate the difference between those two schemes. In coarse environments we can still can do helpful stuff, maybe not auralisation but certainly spreadsheet calculations or visual-ray tracing to show different room arrangements. You might have very basic floor plan arrangements and show different options of floor plan options in terms of evenness of coverage.

4. *Would you be able to provide better/quicker estimates during conceptual design if you had simultaneous feedback about design performance from others? If so, which feedback would you mostly require?*

Yes sure, generally acoustics relates to building shape and volume of the building we are talking about

Very early

    a. *Do you always have sufficient feedback about cost-implications of design alterations?*

Not sufficient, but we have a reasonable understanding of it. We are talking about some software where you could change the volume of a room and tell you what the acoustic difference would be and tells you how much more it is going to cost – that would be fantastic. At that stage most of the QSs are only basing stuff on volume size and rate anyway. It is a very coarse state.

    b. *Would you benefit from ad-hoc cost feedback during conceptual design or might it limit the creative aspects of your input?*

Could limit, obviously clients are always concerned about cost so it depends on the relationship with the client who is paying the money. Sometimes you would want to switch the cost column on, sometimes you would want to switch it off. It is not about the absolute cost, it is about value. All of these aspects are depending on the client aspirations. Better acoustic performance in most cases means higher cost. A part the problem with acoustics is that people always try to multitask there – the quest for the ultimate thing – at minimum cost. If you want to do it properly you build 2-3 different things. One for each task – that's then three times as expensive. So you try and incorporate elements in your design and enable it to be multi-purpose at a cost which enables some multi-purposeless. Then it depends on how much priority your client gives to trade off various options. There is lots of grey area in there as well. Some functions cannot be compromised, others can. It depends on the client and it changes from project to project.

6. *During conceptual design, at what instance might it be beneficial for you to retreat from group-discussions to reflect on a design-problem on your own (or in a small group)? What is the ratio between time spent on collaborative work and sole investigations to inform decision-making?*

Clearly we need to go away and do some work sometimes. We do this very often. It is almost as if you need a bit of this and a bit of that. It does depend on how much what you are doing affects other people. There are certainly times when you don't realise that what you are doing is going to have a negative impact on other people and design elements. You want to get those coarse things out of the way at the very beginning, identifying the 'show stoppers'.
Percentage: 20 collaboration 80 own

During conceptual design:

7. *What type of media is most appropriate for you to communicate your design-intent to others in a meeting in order to 'make common sense' and support decision-making?*

While our preferred methodology would be to play others an auralisation and let them decide, it doesn't happen often because it is expensive. We end up doing it in written and visual means. We are writing reports telling others: Your noise levels are going to be between 35-40 and you should be aiming between 30-35. This often results in them asking us what does of that mean (35-40) . We have done auralisations in the actual locations (theatres) to give people a comparable experience. You don't need to give people a special room.

8. *What type of media is most useful to make you understand the design-intent of others in order to support your part of the job in the clearest way possible?*

2D CAD information is the key ones it tells you all you need to know, then diagrams and reports, verbal communication, at this time we do not deal too much with 3D interactive environments,

9. *How could we extract information from previously completed Arup projects and make it accessible to designers (in bite size) as reference on live projects?*

They would generally be acoustic specific with cost information attached. We would need information specific to the type of project (Opera house, road, office etc.). A database is helpful. We have several databases in acoustics already. You can sort a concert hall-database by size, number of people, volume, and reverberation time and rank them in the order of those parameters. At this point there is no cost-information attached. The database has all of this information in it with the objective parameters – number of seats, general form etc as benchmarking process to do a new one. There is a good way to how to use this sort of material: People used to photocopy the scale drawings on overheads, put them on top of each other and flick through them – it is really effective. Floor plans on transparencies which you can overlay – it works – I'm not sure there is a computer way of doing this. A part of the problem is – how does an acoustic engineer overlay floor-plans of opera houses? Most of us don't know how to drive CAD – We are not CAD users of sufficient skill to overlay computer files. That's why we use the print-outs.

Textbooks, a lot of the historical rooms we didn't have involvement in, and they are only documented in textbooks. We do not have sufficient database-information for offices, but we do have material libraries on our intranet – material masses, transmission wall databases, absorption co-efficiencies. A lot of this information is also coming from textbooks as well as manufacturers. Now a harvester would have to start at the intranet, as we have put in our historical project – and Arup reference project information in there. All of this has been pulled out and put in the individual databases. If you are after a noise level, the idea is that somebody measures a helicopter and puts that information in the database where others can search for it. 25 years ago we started to collect that information in a paper-based system. If you wrote a report on something there

was a page that you fax off to Winchester where the acoustics library was held and every six months you would receive a floppy disk with an update of the database.

10. *If you had a miracle toolbox during early stage design, what would you like to put in there?*
    a. *(Coarse tonnage, Average Co2 emissions, Coarse cost, …*

A number of vehicles, distance, sound power levels, distance and size, for a particular project. We want to know how loud something is going to be and how far away it is going to be heard. You could have a coarse 3D environment where you place sound sources and get instant feedback like: how loud are the things going to be that surround my project, how big is my project, and its 3D relation to the sound sources.

B. Sensitivity-study interview questions Architect

1. *What sort of information would you like to have at your fingertips during meetings with designers/clients/colleagues in conceptual design?*

What's the budget? If I meet up with a structural engineer and I have a certain idea in mind, I'd want to propose a certain forma and I'd want to understand the limits of the materiality of the form that I'm presenting. What are the limits of the behaviour of the shape that I'm asking for? How can this material behave against the shapes that I'm trying to create? That has to do with cladding, steel, and the structure. In many offices designers come up with shapes and they'll learn after the fact that the metal-panelling module cannot bend in the way they imagined. The rationalisation process should start from the get-go. It is about the appropriateness of systems - being it structural or environmental - and we would like to know that sooner rather than later. That often determines where we are going with the design.

2. *Are there any performance targets that guide your design thinking:*

Even though Moshe is a very intuitive designer, ultimately everything comes down to engineering targets in a certain way. He describes his way in a certain fitness between the building form, the formal language the architecture and the engineering of the building. This doesn't say that you'll achieve perfect fitness, but I think that ultimately all these things come into play depending on the type of the building. Sometimes we have to 'engineer around' issues such as daylight studies, looking at steelwork efficiency and so forth. I'd like to hear something about the relation between secondary structure and the primary and get some sort of optimisation there after you answered the question: how does my shape behave. There are acoustical targets, there is environmental control ... Often architectural

targets are to ensure that visual impact is well coordinated with other performance targets.

3. *Would you be able to provide better/quicker estimates during conceptual design if you had simultaneous feedback about design performance from others? If so, which feedback would you mostly require?*

Particularly in conceptual design you need a decision every 15-30 minutes so ideally you would put together a smart team between architects and engineers that sits together on one table on a (at least) weekly basis. Basic costing would help, program-schedule impacts, frequently what is discussed is the analysis of function relative to efficiency in terms of the architectural planning – that is quantifiable for instance with net to gross ratios. How much of your floor-space is circulation. You know that with stand-alone project like the Arts and Science museum from the beginning you know that you will not meet any standard as it is a very complicated building. With those projects in the beginning you might want to know more about the light coming in, floor levels relative to the structure so we can get a better picture about the mechanical zones. You could probably address this in a parametric model. How could we make a building as green as possible? There is a spectrum of 'greenness' of a building. You could be more integrally green down to for instance steelwork or other aspects. It is not an integrated system yet.

4. *How would you like to negotiate design-priorities with others in the future?*

From the perspective of a dictator! My dream situation would be to have sliders that you can move backwards and forwards. At the beginning of any design process when I work with the engineers it would be nice to say – "the ?flatters? that are played here are the following 10 items and I'm going to give you an eclectic mixture of what I'm interested in – it could be structure and lightness – but also an abstract feeling that is harder to grasp. You could basically set

priorities no matter if they are from a left side or right side brain. It would ensure that later down the road if you were to propose an alternative and you are waiting for answers to your feedback you'd at least have a little sense of what would come back. Maybe at some point you would not be needing engineers anymore. Where this is headed is really about an integrated approach where everybody has bought into a database-software-solution that is flexible enough so everybody can work creatively in their own discipline. In the near future that will probably not be the case. Traditionally the architect would get a large team together, build a building and direct all the work; at a certain point the way they work all together and the project gets more complex engineering-wise the architect would hand over responsibilities for all sorts of things like documentation. The issue of documenting an idea and translating them back into a building. Maybe now we are at a point where this sort of translation does not have to occur. We can build it virtually and all this information can be in a virtual simulation of the actual thing. If together we buy into that process and get the tools ready for that process with everyone working on that same information. That is the ultimate goal. The question remains: If everyone works together in the same model – who is responsible for the model?

5. *How early in your involvement in a project do you consider cost-issues?*

The first principles you apply should give you some indication. On the other hand if you have a stand-alone design how the hack you can be certain – do you think we talked about how much it might cost? I think it is there, behind the scenes right from the get-go but the accuracy of it and its relevance to the time it takes to do it on each project should be taken in account. There are already many examples all over the world that show how expensive is an irregular structure in rough terms – maybe one can extract information from that?

a. *Do you always have sufficient feedback about cost-implications of design alterations?*

Do we know where are the big (construction) costs? It depends of what we're doing; for the most of the items that matter – it is essentially a certain type of cutting edge – I don't think anybody has the right information at the moment. Still you could look at the total amount of square meters and there could be some type of guidelines that one should be able to use.

6. *During conceptual design, at what instance might it be beneficial for you to retreat from group-discussions to reflect on a design-problem on your own (or in a small group)? What is the ratio between time spent on collaborative work and sole investigations to inform decision-making?*

20-30% with others 1 day a week in conceptual stage

During conceptual design:

7. *What type of media is most appropriate for you to communicate your design-intent to others in a meeting in order to 'make common sense' and support decision-making?*

We use a lot of 3D models we exchange those – it always based on the lowest common denominator – in terms of who is using what type of software – even Rhino is not used much. Acrobat 3D seems to be this amazing tool now even for somebody who does not use 3D at all can take the model and turn layers on and off. The information that is communicated in our 3D models is always going to be the most useful. We use hand-models as big part of this process as well. The level of support for decision-making urges us to use whatever we think looks best at any given moment to make the point. Moshe would also often demolish his own models to make a point. We did persuade Arup facades and Arup structure to use our Rhino models and in the beginning they were very hesitant. Our ability to generate these kind of models and the time-schedule is so short so you want to capture as much intent as possible. Then you run into this block where people can't extract information from that and they put up their own wall. Why would

you want to waste time to extract 2D information out of your 3D model? You can just hand over the 3D information. This is our biggest problem. On the one hand we're dealing with a team in Melbourne on a very sophisticated high level and on a different part of the same project when working with another team they would require 2D information that slows the whole process down. It is a probably contractual and a cost issue. We've become more rigorous in setting out work in order to solidify design. It is a representation of the complex level that we are trying to address in the formwork or the geometry. Once you have created that somebody then needs to get to that level and either understand it and accept it as something that's out there or back off. It is not just about pretty pictures – it is also a learning process for us. We use recipes in this instance – a breakdown of how things are actually put together. In our case it was a 20 page Pdf with step by step process-description, not only defining what the set-out was but also how it was built. It had a software logic to it as well, plus colour coding. The way he built it was important too and to make sure that there was never any line that you couldn't draw in another program. Everything could be interpreted down to a common denominator across software. It comes from the background of a rule-based parametric setup.

8. *What type of media is most useful to make you understand the design-intent of others in order to support your part of the job in the clearest way possible?*

Graphs of whatever their area is, images. Principally a visualisation of whatever they are doing instead of text and numbers. The thing that you create going out would be a nice thing to get back. Whenever we receive 3D models from contractors etc we'll review it. We have now a standard in terms of a report that we issue with a series of screenshots from that 3D model with some text that highlights those points we find that are problematic. There is a dialogue evolving around the shared 3D model that is going back and forth that reports issues that are key to the overall design progress and helps finding errors.

9. *How could we extract information from previously completed Arup projects and make it accessible to designers (in bite size) as reference on live projects?*

Couldn't you extract the functional efficiency or inefficiency of buildings and their shapes in a finite fashion – in a almost historical perspective? That kind of analysis we do by hand sometimes against other buildings we've done, sometimes against other buildings that exist. It would be a fabulous tool for architects to have to be able to make their assumptions in a more informed manner. It is the art of the practice to a large measure that architects offer and seen in another way – if we had easier access to that kind of information our buildings would get better. We would like to know what is the ratio of the area against the structure, how stupid or smart is my design.

Envelope area... We haven't done a lot of this but there is a design element to use and extract information: we see it as kind of packaging information: All information isn't really useful unless you start directing it. In some cases some numbers might be helpful as support but usually it is a visual thing of most relevant concepts that a juxtaposed or compared or otherwise shown. Ultimately the architecture is broken down in discrete moments and we compare that in particular one to ones such as cost per spm, net to gross ratios, spans etc.

Active viewports within shop drawings in the way Arups are currently embedding them in their drawings would be very interesting – and to make more out of those. We are literally just starting to see these linked in way where you can click on in the pdf and you spin around the 3D model and you can cut the model. You could make a library available of interesting conditions. You could categorize those in manifold ways. Maybe it is more about having good references about projects that you did up to 5 years ago.

10. *If you had a miracle toolbox during early stage design, what would you like to put in there?*

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a. *(Coarse tonnage, Average Co2 emissions, Coarse cost, …*

All these things. How does the shape behave and has it ever been built before? When you talk about the kinds of parametric models and systematised things – all that information at your fingertips – it brings to my mind a future where you can go to Target or K-Mart (freeform Ikea) and in a not so elegant way and dial up or dial down design – that would be the scariest part. That would take away the intention of a signature architect and what you would be left with instead is a DYO printing of your house one day. You don't need specialists anymore.

Two quick comments: The first is the danger in parametric design is that somebody has to be judicious about the parameters in first place and not just be able to use them.
Who is controlling the parameters? Secondly I'd like to know is there a way to systematize and standardize/discuss design as being integrated or not being integrated? As you develop your design how integrated is your approach? Imagine you have a series of tools that let you dial up and dial down the level of communication with the other engineers and the client and help you decide how honest you are being about with what you actually trying to put together. That would be a very good tool because ultimately it might bring the issue out to a larger audience of people beyond our profession about what it is that architects do or pretend to do. Ultimately there is a myth there in practice and I think there is a social level to having integrated design.

The last thing I would like to put into the toolbox would be something that would allow myself to break rules. If you set all your parameters I want to also have a parameter that allows me to break that parameter 10-15-20% of the time. Otherwise the rigidity of the parametric model is too overwhelming.

C. Sensitivity-study interview questions ESD

1. *Please name some of the basic rules-of-thumb you usually apply.*

The breadth of the analysis we do is huge. If you are looking at daylight there are things that stand out: depth of floor plates and type of glass that automatically indicate if something might work or not. There might be some fundamental aspects of the building form that stand out pretty quick. There might be aspects of the building orientation that can obviously tell you impact on energy use or type of materials insulation and external shading. Ventilation orientation in respect to prevailing winds. There are some rule of thumbs you don't need to do any analysis about, it is just about understanding the principles of what would work in terms of good daylight, solar access (northern sun) etc.

     a. Do you base them purely on your expertise or are there any charts / computational tools to assist you?

Just based on expertise.

2. *What sort of information would you like to have at your fingertips during meetings with designers/clients/colleagues in conceptual design?*

Let's assume we can get there, it would be the basics of the building form, such as volume, orientation, massing of the building, facade type, climate – I need to have my fingertips on 'where is the building and what are its climate conditions.

3. *Would you be able to provide better/quicker estimates during conceptual design if you had simultaneous feedback about design performance from others? If so, which feedback would you mostly require?*

Yes, a lot of our analysis has different timescales associated with it, a daylight study could be done in a few hours, an energy model might take a few days, a CFD model might take a few weeks depending on the complexity. There are some constraints as to how fast you can feed all this information in, but they do overlap. If it is all done in house (Arup) if we have the full ESD commission and the glass changes we can look at the impact on daylight, energy etc and feed that back in, they are all interrelated especially things like facade optimisation. *Is it just a question of speed?* Sometimes it is speed but on most projects it is man hours for setting up models and looking at the actual building and finding out how to make an abstract representation of it that the software can handle. The software is not going to get to the point where you just throw a hugely complex thing at it and it tells you where energy use is. You always have to simplify and abstract it – That's where most of the time gets lost. You do press the button and wait for the result but that's not a current limitation except for the use of CFD.

4. *How early in your involvement in a project do you consider cost-issues?*

I don't. Because we are still not quite free enough in the work that we do to be designers, because the processes are not quite in place; we are usually further down the chain a bit. The questions are: should we use this glass or that glass and the cost is often the same. Usually there aren't any cost implications in our general advice because it is not really a design issue. *Does that haunt you later on?* The only time this is really happening is when we discuss glass types. Nowadays I would ask first what it costs. There is a risk with glass but not many other things ever follow.

a. *Do you always have sufficient feedback about cost-implications of design alterations?*

A typical design meeting would be more like: We are a fair way down the line, people in the meeting throw up ideas: could we do this or that with the building. I can say yeah we'll go away and test these two option. Generally in the meeting

people understand at some level the cost implications of what is being discussed. Problems get constrained in the design meeting.

b. Would you benefit from ad-hoc cost feedback during conceptual design or might it limit the creative aspects of your input?

5. *During conceptual design, at what instance might it be beneficial for you to retreat from group-discussions to reflect on a design-problem on your own (or in a small group)? What is the ratio between time spent on collaborative work and sole investigations to inform decision-making?*

We do that a lot because we tend not to go away and design in isolation, we go away and analyse. We tend to be in a design meeting, then we'll take away a few chunks of the analytical work and go and do them to return the results to the design team. That is kind of the definition of the way I work – you retreat to do your individual kind of analysis. 10/90coll alone

6. *What is the value and what is the burden of second-guessing and interpretation of third party information (design as a solution based activity – dealing with the unknown)*

Whenever we do that we get in a lot of trouble. Analysis = crap in – crap out. If we haven't confirmed all of the inputs upfront, the outputs will get criticised. Often we can't guess otherwise the results are meaningless. Our work has to be fairly precise, we can't quite approximate results. This response would be different if we are able to push into much earlier stages of the process because then we'll define our whole way of working which would be: give us the design space, we'd go and analyse it, tell us what's the variation in parameters that we can explore as a design team and it is still going to meet our objective. This would change a lot.

During conceptual design:

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7. *What type of media is most appropriate for you to communicate your design-intent to others in a meeting in order to 'make common sense' and support decision-making?*

A3 type documents with simple representations of analytical results: Bar charts, contour maps, table of figures, 3D model showing slices through it, showing the comfort levels or wind speed at a certain section through the building. In a recent design meeting I took in CFD results which was a 3D model which spun around on the screen and you could look at the results, look at streamlines and look where the airflow was. It is a risky option because you need a computer setup with the right software and a projector etc.

8. *What type of media is most useful to make you understand the design-intent of others in order to support your part of the job in the clearest way possible?*

Data set of some sort either CAD drawings, hand sketches, diagrams, report from other consultant with e.g. mechanical system, glass type.. From a geometry point of view I would use an appropriate 3D model much rather than plans or anything, it doesn't help me from a collaborative point of view to understand it. It is simply a better input – it saves me having to build my one model. Having said that, if there is a 3D model available early on, I get a much better feel for the project to understand the basic form of the building and that would be very useful as a communication tool for me. (like a massing model from the architect)

Multimedia like projecting stuff and having 3D models would be a big improvement a lot of the times, I just avoid it because of the risk. 3D modelling is continuously improving

9. *How could we extract information from previously completed Arup projects and make it accessible to designers (in bite size) as reference on live projects?*

My view on that is to have people interviewed after they complete projects. To 'suck' information out of people in order to compile it. Making sure it is accessible and can be searched easily by others. Along the lines with the technical nuggets that appear on Arup projects. It is almost like there needs to be an easy database for typing in keywords and finding those nuggets and to be able to work with that.

10. *If you had a miracle toolbox during early stage design, what would you like to put in there?*

    a. *(Coarse tonnage, Average Co2 emissions, Coarse cost, …*

What's the green star rating on my building

How much energy does it use

How much daylight gets in?

The ultimate design tool would be: if we are sitting with an architect and we have a building form and some basic floorplate, or window wall ratio and materials then you stretch it, you pull it and turn it around and you see your *Green Star* rating change instantly as you change the building. Underneath that it is doing a daylight calculation and a 'something else' calculation. That would be awesome. Such a model/tool would need to:

1. Be set up in a parametric way
2. Easily manipulated
3. Lots of defaults set on the model (pre input by experts)
4. Be able to export quickly to all the underlying analysis packages (they won't be built in)
5. Input – output filters
6. Common feedback form to get information back to see what the impacts were
7. History log that shows you: during this design meeting we made these 12 changes and this is how it influenced what we did. You like to remember how you go to the answers you got to.

One could probably get a concept going for this tool already. Something like green star has great value early on if you have a rough idea of where you are sitting with the building and you could then refine it later.

D. Sensitivity-study interview questions Facades

1. *What sort of information would you like to have at your fingertips during meetings with designers/clients/colleagues in conceptual design?*

In facades a lot of what we have to provide during conceptual design is pretty basic. Our involvement starts to become important when we get to detail design because that's when our main input happens. The architects will come to us with a concept of how things would look like and we then go back and look up what kind of products and markets we can do to fit the architect's intent. In conceptual type work our knowledge about having actual product data is not that useful. It is always great to have past work references such as images of projects we have worked on to share during meetings. The hardest thing is to understand what the architect wants, if we have images of interesting reference projects to look at it is very helpful to get across intent. Those images can be sections, shading options, at that early stage. That makes it easier down the track and gets them thinking about daylight factors and shading at the start of the project.

2. *What summary target-values are you working towards?*

Thermal values such as the U-value, shading and heat-gain coefficients, the architectural aspiration, daylight-factors.. The intensity of working with environmental engineers at that early stage varies from project to project and it also depends if we work with Arup for environmental as well.

3. *Would you be able to provide better/quicker estimates during conceptual design if you had simultaneous feedback about design performance from others? If so, which feedback would you mostly require?*

Yes, because what's useful in a facade (specially in a curtain-wall building) is the type of glazing. If you look at high performance glazing and if you choose to have

double glazing you need feedback about cost and environmental performance of such a system. What quite often keeps us from pushing forward is the lack of immediate feedback we get from others.

There are two ways we can go about it. Either the ESD guys can say: " In order to achieve this you need the performance of the glass and the framing to be this" or you can go the other way and the mechanical people can say:" we've designed that system to meet these energy loads so you need a minimum of this performance for the glazing." The quicker you get information from all those parties, the quicker we can come up with a range of options for the architects.

Ranking of information required: It does change depending on the project. Quite often ESD and Mechanical input is required simultaneously; that has to do with the energy-loads of the air-conditioning and heating depending on the performance of the facade. At the same time we collaborate with the ESD guys to model shading options that visually have a great impact on the design which is important to the client and the architect. Further down the track is structural. Next would be acoustics to reduce the noise from outside. It is more about checking and looking for different options to meet an acoustic target value. Fire would be last (we generally just put their input in our report). We interact with ESD generally right from the start (usually on the more successful project). If they are being brought on board later on, they find it much harder to carry out and implement their analysis. All that modelling should be done at the start to give the client options, that makes it much easier for everyone else. Generally either the ESD or the mechanical people will give us the performance, we get an idea from the architect about the appearance, then we go back and look up products and get samples to show to the architects or we call in architectural glass consultants and tell them what kind of performance we need and what the architects are looking for.

We have to have the ability to sometimes address other consultants directly without having to go via the architect as 'middleman'.

4. How would you like to negotiate design-priorities with others in the future?

The biggest issue is getting the ESD guys in early to give architects options and then they have got to choose one and go with it. We find that architects keep three options and they work with them all the way down the track; this way lots of key aspects the ESD guys had in their options get lost and watered out. You find that you're designing sun-shades that are actually not appropriate anymore to do the job. Architects tend to mix options together without understanding the reasoning behind it. Not everyone has a great understanding of the work that others have done.

In structural terms the biggest thing with facades are tolerances, and the cut-off between the facade/structural work and the rest of the building. Sometimes it might be easier to hand-over steelwork for the facade to the structural engineer to put it in their package. We have to make sure that facade-relevant tolerances (which are much smaller) are considered.

The quality of information we get from manufacturers depends on the supplier; some give us fantastic packages, others are difficult to reach and to make appointments with. It also depends on the person: I prefer to look at digital content on my screen and get material off the internet, other colleagues prefer hard-copy catalogue to flick through. It is a hard job to keep those catalogues up to date for everyone.

5. How early in your involvement in a project do you consider cost-issues?

That depends on each project. Cost issues are considered usually later on. It is always talked about a bit at the start. … *we would love this or that glass* and then we would tell clients – *well, that costs this and that much per m2* .. Generally in design we would specify something and then we look up how much it costs. We are always

aware of the budget right from the start and we know if something has got to stay off the shelve or if we have room to 'play'. We'll do rough estimates and call up contractors if we need additional information

   a. *Do you always have sufficient feedback about cost-implications of design alterations?*

Yes, generally we are aware of changes in regard of the cost information attached. It is depending a lot on experience.

6. *During conceptual design, at what instance might it be beneficial for you to retreat from group-discussions to reflect on a design-problem on your own (or in a small group)? What is the ratio between time spent on collaborative work and sole investigations to inform decision-making?*

Generally we'd have a consults meeting then, we'd have one with the client, at times we bring in other consultants with the architect. After most of those meetings we'd have to go back and do our own research and put information together. It is hard to find a particular point – it depends on how the meeting goes.

The ration for time spent on decision making would be 25 group to 75 sole (within Arup)

During conceptual design:

7. *What type of media is most appropriate for you to communicate your design-intent to others in a meeting in order to 'make common sense' and support decision-making?*

We are using a lot of sketching in facades. We use coloured markers because we find that facades are quite detailed and complicated system and using colour markers for sketches and sections makes it easier for the client and contractor to understand what we are trying to show them. It makes our work appear less

definite; I've we show them CAD drawings-they feel "that's it", that's the final decision and they can't change it. We don't want that, we want to show them options and we want their feedback to then go back and change it.

8. *What type of media is most useful to make you understand the design-intent of others in order to support your part of the job in the clearest way possible?*

Sketches again and any type of CAD drawing. Obviously 3D is useful for us, if we get our hands on 3d material either CAD or sketches, it makes our work much easier. We have lots of verbal contact with other consultants and with the architect.

9. *How could we extract information from previously completed Arup projects and make it accessible to designers (in bite size) as reference on live projects?*

The thing that I find most useful is being able to get in contact with people who were involved in a project. It is great to have Arup forum. It is the most valuable tool at Arup for me because you have got a direct link to hundreds of very nice people. All you have to do is type in your message, send it out and usually within 24 hours you get back a whole range of very good answers from experts or at least someone who guides you in the right direction saying: 'I can't help you but you should talk to this person'. If there is something that could be ameliorated in regard to the forum, it would be a way for capturing information that is provided on the forum by sorting it, to offer others a Q & A type interface where some main topics can be searched**.** That way we could avoid that the same question gets asked twice (this is currently happening a lot)

We had problems with the 'Arup Projects' database. It is not always up to date and a lot of entries are simply empty. A way around that might be to employ someone who manages the information on a long-term basis. Generally it is a great tool.

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10. *If you had a miracle toolbox during early stage design, what would you like to put in there?*

   b. *(Coarse tonnage, Average Co2 emissions, Coarse cost, …*

I'd like to be able to transfer the intent of the architect directly to my brain. That is the hardest part: understanding exactly what they want. Sometimes they might tell us this or that and we think we understand, go away and work on our own interpretation (which might be wrong). That's why at some point sketches and images of past projects are important to get across that understanding. Currently we scan all our sketches but there is no collection in a folder as such; it is not a difficult process. You want to be able to pass a piece of paper around the table in a meeting where people put down their sketches and sometimes people draw over each other's sketches straight away to push an argument forward. That way you get a good understanding of what people are talking about.

E. Sensitivity-study interview questions Fire

1. *Name some of the basic rules-of-thumb you usually apply.*

We look the building and space configuration. It is critical that we establish two dimensionally and three dimensionally what the spaces are like and that the spaces are used for. This includes physical volumes – whether they are square or elongated – the room characteristics. There are some rules of thumb we apply linked with the physical characteristics of the spaces and its use. The uses are critical – whether there are large population of people in there or not. We are interested in the interrelationship between a large space and a large number of people. The first time we get involved is when there are issues with respect to the building not complying with what the regulations specify for travel distances, number of people and width of distances.

Technical rules of thumb often become issues; such as 100 people – when there is more than 100 people in a space. There are rules about the 100 people and one meter of door width, that comes back to the regulations

a. *Do you base them purely on your expertise or are there any charts / computational tools to assist you?*

There are computational exercises that can be done and equations that can be used. Some of those are in a fire engineering sense endeavouring to pull some of those standard things that we use into being something that everyone could use. Individuals often have their own equations on a spreadsheet format that they would use, we're looking at the benefit of how we will actually achieve something having a standard spreadsheet system. We use those spreadsheets in the early stages as well as the more advanced ones. A lot of the times you are able to work out the standard arrangements in your head.

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2. What sort of information would you like to have at your fingertips during meetings with designers/clients/colleagues in conceptual design?

The information that we need to make any judgement and comment does relate to what spaces are useful and some idea of their shape and characteristics. Sometimes you are involved very early when you don't have a building form. We would like to be involved at that stage so we can get some input about where those critical things could be located (such as exits etc). We want to assist the designer in modifying the layouts and moving then in order to get the most effective configuration. The spreadsheets that we bring with ourselves are very rough ones but they are based on equations which have been well recognized. Those we would use in the early stages to get basic concepts of what would work and what won't. Computer power at the moment won't support that because we are doing CFD modelling where one run of it to get results takes 3-4 days. We then interpret the results and with the CFD modelling it has not developed to the point where it tells us where the problem is. We need to analyse it visually to determine what can be done and what not. Part of the characteristics of fire engineering is that we develop a strategy that we think will provide the safest environment we then go back and justify it to get approval from the authorities. Authorities are starting to accept that a working CFD model can 'overrule' the standards. It is a scientific approach that is tested and compared to real situations. At least for smoke-movement – not yet for people-movement

3. Would you be able to provide better/quicker estimates during conceptual design if you had simultaneous feedback about design performance from others? If so, which feedback would you mostly require?

Yes, there are a lot of design workshops that are useful for this because instead of taking something and going away to work it out and bringing it back, you can

draw on the knowledge base there at the time. It becomes more efficient. We mostly require interaction with the architect, which is related to the occupancy numbers, then dropping down to other aspects such as mechanical/hydraulic and structural. We rely a lot on feedback from consultants with previous experience from other projects . 3Dimensionally getting volumetric information back out has always been a problem.

4. *How early in your involvement in a project do you consider cost-issues?*

We do consider cost issues from the start.

   a. Do you always have sufficient feedback about cost-implications of design alterations?

No, there are other aspects that are equally important – not only initial cost but ongoing cost which relate to aspects such as: is something that's being proposed able to be maintained and serviced in a continuous operation. We'd like more feedback as to the cost of various options. The main problem is that in the early stages, an option may not be fully understood as to what is necessary for that option.

   b. Would you benefit from ad-hoc cost feedback during conceptual design or might it limit the creative aspects of your input?

We would benefit from it, the only problem is that sometimes it is difficult to get to a point where it can be adequately estimated. You don't always get cost associated with implications of changing certain things.

5. *During conceptual design, at what instance might it be beneficial for you to retreat from group-discussions to reflect on a design-problem on your own (or in a small group)? What is the ratio between time spent on collaborative work and sole investigations to inform decision-making?*

You find that there is a point where you do, when it occurs is related to the complexity of the design and you'll get to a point where you have to retreat and gather more information or do some initial analysis which might take an hour or so. With lots of decisions that need to be made within a project, it is not always clear who you need in order to make a decision until you start making it. And you don't necessarily want everybody to be seeing you when you do it. The percentage varies within a project timeframe. All up we are probably doing 60 own and 40 group. In the initial stages joint decision making is more beneficial (maybe 70%)

6. *What is the value and what is the burden of second-guessing and interpretation of third party information*

I would call it professional judgement. The value in that is that you will often have experience that tells you what is appropriate in a situation. What has worked before will assist you in that. The disadvantage of that is that someone may consider that you are stepping beyond the boundary of that they are expecting you to do and they might find it offending. You may not have been given all the information that allows you to step beyond in the direction that you should .

During conceptual design:

7. *What type of media is most appropriate for you to communicate your design-intent to others in a meeting in order to 'make common sense' and support decision-making?*

Once you come up with a concept you want to support that basic concept. You often turn up with a visual display+ overlayed with marked up drawings of the concept. Getting something down on paper so you can convey the concept. + 2D sketches are probably more appropriate in the early stages, diagrams, … We verbally communicate the concepts that you have derived from looking at your spreadsheets

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8. *What type of media is most useful to make you understand the design-intent of others in order to support your part of the job in the clearest way possible?*

3D models sometimes do help, but I don't have a problem with 2D. I've grown up with 2D plans and sections so I understand those, there are some bits of information that are more useful in a tabulated form, particularly when you talk about characteristics of certain areas and amount of people.

9. *How could we extract information from previously completed Arup projects and make it accessible to designers (in bite size) as reference on live projects?*

We do endeavour to do that by comparing to results (calculations & assessments) that we have achieved in the past. On some simple task we have assembled a storage bank of information that can be reused. It is a folder on our computer system. It contains information about the way analysis has been put together and the way it is constructed as an argument to be presented to authorities. It is entirely text based and there are individual bits to address individual 'NON Compliances' to compare them to non-compliances of current projects. It is not easy for someone who is not trained in the basic concept to use that information (other team members). If we make it that simple that others could use that information, it would have to be brought back to criteria that currently exist in legislation.

10. *If you had a miracle toolbox during early stage design, what would you like to put in there?*
    a. *(Coarse tonnage, Average Co2 emissions, Coarse cost, …*

I do have the starting of that – which again comes back to the spreadsheet, because a lot of fire engineering is looking at things and then exploring the impact that fire would have. One sheet tells me that I can input information and it gives

me implications about smoke. Another one would give me information on people movement, the next one might be about temperature transfer etc. I type in the input, I change certain things such as the room characteristics, the volume, wether there are exhausts or vents within that volume and the number of people within that volume (others not) . You look at how that volume interplays with other volumes and people within that volume. There are just 4-5 numbers you fill in per room and you look at problem-areas first. There has to be a point where you want results – even if they are very vague – within minutes.

F. Sensitivity-study interview questions MEP

1. *What sort of information would you like to have at your fingertips during meetings with designers/clients/colleagues in conceptual design?*

In concept meetings it is mainly about understanding how the building is going to be used in the context of its site. Typically we would need floor areas, particular function of the building, and the context of the site. Any visions from the architect or the client in terms of the core-values of the building and what they want to portray with it – or what they want to use it for. In many ways our design is a response to those visions.

Energy consumption at concept stage is derived from rules of thumbs and experience generally for a given type of building and given operation of that building. We have a back –catalogue of typical energy figures; as we go through the design it starts to become more detailed. The first protocol is published data, second stage is the use of spreadsheets which you might consult at concept stage for the energy model; that's the most detailed you'd get to at that stage.

2. *What are the performance targets that guide your design thinking in early design?*

Energy: Mega joules per m2 (MJ/m2),

Air changes per hour, litres per second per m2 of air flow through a building, Those are really check figures, we use those as a facts-check in our different designs. At concept stage we'd actually: for an office you should have this and that figure and using that we can then work out the approximate size of air handling units and the size of our risers to a basic concept design. From that size we can then determine the chiller-plants.

The third is thermal energy, measured in Watts per m2.

In order to determine duct sizes, we are determining the 3D spatial allowance for a room. Here it is important to measure velocity of air flow in m per second, based on noise and pressure drop in ducts – here again we can rely on published guidelines and rules of thumb we have. Usually this is fairly well defined for particular noise criteria – you need to size your ducts for this kind of velocity.

Even though Moshe is a very intuitive designer, ultimately everything comes down to

3. *Would you be able to provide better/quicker estimates during conceptual design if you had simultaneous feedback about design performance from others? If so, which feedback would you mostly require?*

It is important to have that information early on. Definitively elements like the structure, facade, and how the mechanical system affects those designs are important to know early on. We usually feed into setting performance values for glass selection that we recommend. The architect designs a bit in term of appearance, the facade designer provides input and interaction of this interaction can become quite complex. The most important feedback is knowing what the client wants, then the architectural vision on the appearance of the building and how they see it being used, after that it is structural concerns – what type of structural system is it and then the type of facade in use. There is a lot of negotiation required for that. Noise is does not come into it too much , it is not a defining factor unless it is a theatre.

4. *How would you like to negotiate design-priorities with others in the future?*

Interact earlier in workshop settings. If you come into such a workshop having done a little bit of work having thought about the design, you can then discuss the definition of priorities and try to understand why these priorities are important for each different discipline. You can then create common evaluation

criteria being it money, energy targets, functionality, or how well it meets the brief – whatever the key performance criteria for the building are.
be

5. *How early in your involvement in a project do you consider cost-issues?*

a stand-alone design how the hack you can be certain – do you think we talked about Usually we do consider cost issues right from concept stage

        a. Do you always have sufficient feedback about cost-implications of design alterations?

Yes, we always have sufficient feedback

6. *During conceptual design, at what instance might it be beneficial for you to retreat from group-discussions to reflect on a design-problem on your own (or in a small group)? What is the ratio between time spent on collaborative work and sole investigations to inform decision-making?*

Usually when I don't know the answer, I come into meetings well prepared knowing the type of building and rough figures to then be able to propose a typical system and its impact on a building.   OOPs forgot percentage.....

During conceptual design:

7. *What type of media is most appropriate for you to communicate your design-intent to others in a meeting in order to 'make common sense' and support decision-making?*

Plans with marked-up areas on them, quite often hand mark-ups are sufficient to get across what you need. Sometimes photos if they are relevant to explain a system

8. *What type of media is most useful to make you understand the design-intent of others in order to support your part of the job in the clearest way possible?*

Visualisations, 3D models, images for the architecture, for the structure just floor-plans. For other packages it is usually just words etc we'll review it.

9. *How could we extract information from previously completed Arup projects and make it accessible to designers (in bite size) as reference on live projects?*

There is intranet data available that is good and there are outside sources that we use. It is quite hard to make everyone aware of this information. It is good within our office because we quite often talk to each other and we have an electronic library here, but between offices it is less good. That probably has to do with the fact that we are all busy with projects in the various Arup offices and we do not put enough thought into how we could share our resources – the intranet is quite good for sharing. Arup project is not quite there – I generally look up past projects, but I would not rely on Arup projects to provide me with all the information I need. I prefer to ask questions in the 'skills network forums, they often provide me with useful information

10. *If you had a miracle toolbox during early stage design, what would you like to put in there?*
    a. *(Coarse tonnage, Average Co2 emissions, Coarse cost, …*

Reference information of either existing buildings or specific types. A miracle tool would ideally provide me with a more complete list of key parameters of single building 'statements'??? and basic variables for more building types. The toolbox would also comprise attached information about cost for mechanical systems including past Arup jobs.

G. Sensitivity-study interview questions Structures

1. *What sort of information would you like to have at your fingertips during meetings with designers/clients/colleagues in conceptual design?*

Depends on the project: all the stuff I talked about, natural ventilation – glass air system, what are the consequences – but project & site specific!

      a. Would you be able to provide better/quicker estimates during conceptual design if you had simultaneous feedback about design performance from others? If so, which feedback would you mostly require?

Yes, typically heating/cooling (thermal) and lighting as the main one
Secondary: structural services coordination, basic duct sizes & routes.

If we do think about tooling in conceptual design: would you need a 3D representation to work from in the very first instances or could you work from template for basic twisting and tweaking to work from to get ad hoc feedback?

Here it immediately gets complicated – duct work runs the more options the more choices (as with structure) you haven't got loads the same way – I can't imagine getting real time feedback, you'd have to work through with an experienced mechanical engineer to see what the options are. *In that sense it would always take time* .. It takes time and collaboration. I don't know what the mechanical engineer wants to support him in that conversation but I don't think I want it directly. Example: people should work in 3D – answers from public – architect wanted to move the core of a building with all the ductwork already drawn, things would go too slow in 3D – they didn't use parametric design everything would have to be remodelled – my response – if you had to do this in 2D you have to adjust 150

drawings to deal with which is worse– answer from public – No, because I would not have drawn them yet. The fundamental issue there is that they have put in too much detail too soon. You've got to watch the same issue here. When you are at the conceptual stage, people use an awful lot of judgement as to what zone or size or volume of a building they think they will need later; people don't do it precisely at that stage they simply want to get a good feeling. Parametric models might help but you have to be aware if you can benefit from it given that you have to set up all the parametric linkage compared to any benefit downstream and the risk that you actually link the wrong things together compared to what is actually going to change.

2. *How early in your involvement in a project do you consider cost-issues?*

Right from the beginning

        a. Do you always have sufficient feedback about cost-implications of design alterations?

No. *How would you imagine getting more feedback if you don't have a QS constantly sitting next to you – is it simply 3D software that gives you quantities?* Schedules of quantities would be a lot better than what we normally have. QS not doomed – they'll be giving cost advice. If we design projects I'd be happy for us to be responsible for the performance of those projects and get paid accordingly. The performance being the quality of the work-space or the cost of construction relative to the market norm. What I'd never like to be responsible for is market rise and fall and the same applies when it comes to cost measuring. I'm happy to measure the amount of concrete and be responsible for that, I don't want to have to say, what's happening in the market place etc…

        b. Would you benefit from ad-hoc cost feedback during conceptual design or might it limit the creative aspects of your input?

No – that's a foolish concept, the more information you have the more opportunity you have as long as you can handle it. You'd benefit enormously from all cost feedback at all stages.

3. *During conceptual design, at what instance might it be beneficial for you to retreat from group-discussions to reflect on a design-problem on your own (or in a small group)? What is the ratio between time spent on collaborative work and sole investigations to inform decision-making?*

All the time at least 75 is on own (or small group) rest is collaborative. *Is there a certain instant where it becomes particularly necessary?* It is part of the way things run anyway. If you don't immerse yourself personally as deep as you can in the issues in private, then you can't come to the table and collaborate properly. When you get new information from the other parties you need to go off and have another go.

4. *What is the value and what is the burden of second-guessing and interpretation of third party information*

I think the biggest problem there is that you can make some basic fundamental decisions at the beginning of a project on some assumptions when you haven't got everybody around the table and before you know it you have locked in a solution without ever really having tested those assumptions. There are huge risks because you assume something early on when the other party isn't there. The effort to value ratios in typical design is all wrong. You skip over the fundamental stage and everyone gets stuck into the nitty gritty optimisation of a concept that's already locked in. Whereas people would be much better off going back saying we got the right concept. *In an engineering environment how would imagine this to work, wouldn't it require in most cases a rethinking of the way architects (unless you have a very good relation) and the engineers to come together at the outset?* Yes, and engineers don't like doing that – they prefer to be working within a frame (of a well known problem)

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so it never seems to be in their interest to go and take the frame away and say maybe the solution is over here. There is an engineering mentality which is: let's keep going with what we've got and if it all becomes a bit too vague: let's stop working. Instead of asking in this vagueness: where is the right answer? *Within the attempt of getting rid of that frame is it depending on the engineer's experience or is it about being open enough and smart enough from the beginning?* I think it is about being open enough – prepared to go back to the beginning, you have to be prepared if you are a little way into a problem to still go back again. People hate redoing it.

Value: When you are in that vague context it allows you to move forward – it is essential. The Trick is to make sure that anything you second-guessed then gets confirmed or re-evaluated. It has to do with having all the people around the table at the right time.

During conceptual design:

5. What type of media is most appropriate for you to communicate your design-intent *to others* in a meeting in order to 'make common sense' and support decision-making?

Almost always 2D (manual or digital, can be output form analysis) and views (3D).on paper.

What I don't tend to use much are live 3D models, we still tend to work off paper in meetings rather than projections. 3D interactive representations are coming, you have to make sure your meeting room has an ability to display that electronic material, All meeting rooms need a projector. That is beginning to change – Architects are beginning to use ppt or pdf rather than drawings. They are moving into that mode at which point you could easily embed 3D models.

6. *What type of media is most useful to make you understand the design-intent of others in order to support your part of the job in the clearest way possible?*

Same in reverse. There is a recent increase in 3D-model usage, but it is very slow. For me the medium does not really matter that much.

7. *How could we extract information from previously completed Arup projects and make it accessible to designers (in bite size) as reference on live projects?*

Tough question: It is hard to know what is useful and what is not useful. There is currently a project on the way at Arup where we see if we can systematically find all scheme design reports and link them into Arup projects> for example if you know of a project you can find its scheme design report and see what information is in there. How to extract information from the Scheme Design Report: We've tried tons of basic data collection before – like typical weights of steel for different spans, it never seems to be worth having.

Would people go the intranet and look these things up? Yes they would for classic sizing of structure in the concept stage. We always wanted more: what do buildings cost etc. It is very hard to know that parameter.

Information that is going to be useful should be linked to the internet application called Arup Project and or once it is digested and one step further it should be in the skills network.

8. *If there were a 'harvester' who would be given this task, where would he/she have to start to get a hand on the 'stuff' you need most?*

Example in Europe: seemingly successful: University interns get sent to ask exactly the questions you just ask me: what have you got on your desk that you use during concept/scheme design? People pulled out their favourite charts or

similar and that was then assembled and handed over to the networks. Arup Europe Buildings: Invest in Arup application to look up! KM team Knowledge Management team Dominique Poole

9. *If you had a miracle toolbox during early stage design, what would you like to put in there?*
    a. *(Coarse tonnage, Average Co2 emissions, Coarse cost, …*

It would have everything in it: My dream of the future is that I'm able to go into some modelling program like Sketchup and I draw things and then I get real time information about stresses, quantities, cell behaviour and lighting and acoustics and everything we do at the moment offline. That's where I see the future as being where all these offline analyses that we do now to justify design are actually available in real time online as you design.

Is it a computational problem or something else?

Both speed and complexity of the software of the software that would be required to do that and therefore the amount of development required. All the trajectories say we are heading in that direction, the question is when we are going to get there!

There is a distinction between having ad-hoc feedback that designers would like to have in a miracle toolbox and what is currently possible given the time it takes to reflect on analysis.

I'm not sure I agree with that. I think this distinction simply exist because people are currently not in any way tuned to starting in a 3D model. They are starting with sketches in 2D. People who are designing at the moment are not the most technically literate. They rely on all this other information. I can see no conceptual reason why you should not in the future start with a 3D model. It's a bit like – at the moment we can explore structures and find out whether they stand up or

otherwise in a 3D virtual world, but most people still prefer to start with something they can draw, they can look at and think about and then they'll go and analyse it.

If you had a perfect 3D world would you not have the problem that each group of engineers would require a different set of geometrical information that is required?

I can see all of that from a conceptual basis being approximated sufficiently within a program which is making intelligent decisions that help you do that in an automated fashion. There are some fundamental issues, but lot of it would already be there.

Freestyle:

What I want to be able to do is to build a model and get almost automatic analysis, the next thing I want to do is to build another model and another model and change it constantly; meanwhile I'd like to get feedback of what effect that's having on other people.

In that case you have to change the type of meetings you have.

You do, I think there is going to be a need for far more interaction. At the moment a typical design process (in London at least) is a Monday morning design meeting and then everybody goes off and does their own thing for a week and then they come back and show what they've done. Then they make a decision at the end of the meeting on what to look at next. When you have to set up your CFD models, lighting models and analysis this is appropriate, but if you can get instant feedback on everything, the Holy Grail is not to have to take a whole week to do your CFD but to do it on the spot. And therefore CFD analysis is not a proving tool, it is a design tool. How do you do that when you haven't got all the

disciplines doing it on the spot all at once with instantaneous feedback between everybody?

There is something even worse in amongst all of that: Currently the average design person cannot cope with instantaneous feedback and the pace of change that this brings with it. The 75/25 ration will probably change from one day a week being together and 4 days separated to being together 10minutes every hour or similar. Therefore at the end we're probably have to have more project teams. Are people asking the questions they should be asking? Is there somebody at the centre of the project team pulling and pushing all the different disciplines saying: Can they do better? Are they only solving their own problem or are they thinking about everybody else's problem. You need that continual push to cross-fertilise and collaborate. I still see the architect as the person to do that. I see them becoming less and less skilled in their own right. Currently they do project management and contract admin and those sorts of skills, I see them do less and less of that and more and more of being the conductor or orchestrator of the people involved. The number of specialists involved in a project is growing.