MODELLING COLLABORATIVE KNOWLEDGE IN DIGITAL FREE-FORM DESIGN

MODELLING COLLABORATIVE KNOWLEDGE IN DIGITAL FREE-FORM DESIGN

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof.dr.ir. J.T. Fokkema,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen
op maandag, 9 october 2006, om 12:30 uur

door

Tuba KOCATÜRK

Bachelor of Architecture, Middle East Technical University, Turkey
Master of Science in Architecture, Middle East Technical University, Turkey
geboren te Mersin, Turkey

Dit proefschrift is goedgekeurd door de promotoren:
Prof.ir.C. van Weeren
Prof.ir.K. Oosterhuis

Samenstelling promotiecommissie:

Rector Magnificus	Voorzitter
Prof. ir. C. van Weeren	Technische Universiteit Delft, promotor
Prof.ir. K. Oosterhuis	Technische Universiteit Delft, promotor
Prof. Dipl.-Ing. M. Grohmann	University of Kassel, Duitsland
Prof. Dr.-Ing. U.Knaack	Technische Universiteit Delft
Prof. Dr. ir. J.W.F. Wamelink	Technische Universiteit Delft
Prof. Dr. ir. S. Sariyildiz	Technische Universiteit Delft
Dr. R. Oxman	Technion Israel Institute of Technology, Israel

Printed and Distributed by: IPSKAMP
Rotterdam, The Netherlands

ISBN 1-4276-0786-9

To my parents

ABSTRACT

This research focuses on the emerging domain of digital free-form design, and attempts to explicate its knowledge content and characteristics through a systematic inquiry of the free-form design practice. It is claimed that the free-form design cannot simply be characterized by their formal complexities, but should rather be understood in its totality with its unique methodological, technological and theoretical content, which is representative of a larger scale of impact of the digital technologies on architectural design and production. With this premise, the emerging knowledge content of the new domain is characterized with the extensive use of digital tools and technologies, formal and procedural complexities, pluralistic design methodologies, and the unique forms of interactions it requires across multiple disciplines.

Studying a new and evolutionary design domain is a challenging task which requires the selection of a critical strategy with an awareness of the possible contradictions between the past understandings and emerging characteristics about design. There is a critical balance between to what extent to allow the established preconceptions to influence our inquiry, and to what extent to be open to the emergent concepts that will challenge the established understandings about design and design knowledge. This has been an initial motivation for this research which has led to our initial research question: “how can we conceptualize the free-form design domain in order to understand and identify the knowledge content it entails specific to its unique context?”. Any attempt to answer this question necessitates, firstly, a recognition of the key themes which distinguish the new domain from the conventional designs:

1) the extent to which digital technologies are integrated into the design and production processes

2) the emerging formal/tectonic qualities and varieties

3) the changing socio-organizational roles and responsibilities of stakeholders.

While each theme introduces new concepts, working processes and skills into free-form design, the definitive lines between the working processes of disciplines start to blur. Moreover, various types of interactions across these themes start to

define new dependency types between design tasks within and across disciplines contributing to the evolution of the final artefact. In such a framework, collaboration becomes an instrument for the creation of a collective body of knowledge which we will try to explicate in order to describe the emerging knowledge content of the domain. For the purpose of this research, the cross-disciplinary processes are identified with a specific focus on the working processes of three disciplines – architectural design, structural design and manufacturing – according to the extent to which they influence one another and contribute the definition of the emerging knowledge content.

A grounded theory approach and case study analyses have been undertaken as a methodology in order to develop a context-based and process-oriented description and explanation of the domain under study. Our knowledge elicitation and explication goes parallel to the development of a theory, grounded on the analyses of real cases. The theory describes and explains the free-form design processes in terms of the interaction of contextual conditions and according to the different ways design problems are perceived and formulated by the members of the design teams.

The research proposes a taxonomy - a representational, hierarchically organized vocabulary of domain concepts - providing a common structure and shared set of descriptive terms. Parallel to this, a theoretical model has been developed, which is a set of propositions expressing the relationships between these concepts. This has led to the definition of a knowledge framework which is composed of a collection of concepts, principles and experientially verified relationships useful for explaining the free-form design processes. The knowledge framework intends to serve as a reference model to frame and evaluate different design experiences and their associated knowledge. However, such a framework can never be complete given the continuous evolution of new concepts, methods and technologies in design. These have led to our final research questions:

- How can such a model accommodate change, incorporate different design experiences and new information?
- How can it evolve by the actual creators of the knowledge themselves, thus contributing to a collective and collaborative creation of knowledge?
- How can this facilitate knowledge transfer between designers within and across disciplines?

The answers to these questions have been sought through the development of a practical application. A web-based system has been developed by integrating our knowledge framework into an existing database (InfoBase) and by adding supplementary functionalities to its representational structure for efficient access to the related knowledge content. A long term goal and motivation for the development of this prototype has been to support the collective creation and transfer of free-form design knowledge where new knowledge can be added and retrieved by different design participants. In this system, the growth of the knowledge content is intrinsically dependent on user participation. Therefore, instead of aiming a fully functioning complete system, the research rather focuses on the development of a prototype. Using the characteristics of the domain content identified earlier, the prototype aims to provide a flexible and extendable structure for the organization and representation of the situated and collaborative knowledge elements.

Finally the prototype is evaluated according to the factors that would influence its effectiveness, applicability and further development in varying collaborative contexts. The system is evaluated according to different user-profiles within and across disciplines. Such an evaluation becomes crucial given the fact that the system is intended to grow with user participation and their reflection on design processes, contributing to the collective and collaborative construction of knowledge.

The following are the applicable outputs of this research and can be utilized as described below:

1. *A taxonomy* (a representational, hierarchically organized vocabulary of free-form design): By capturing the knowledge that designers use to accomplish their tasks in an explicit manner, we can study these methods and possibly improve upon them.

2. *A Knowledge Framework* (formal and theoretical representation of the domain semantics): The representation of knowledge forms a transferable, teachable body of knowledge, thus contributing to the education of new generations of architects.

3. *A prototype* (a web-based environment to support collaborative knowledge construction, sharing and re-use): Modelling knowledge in a form comprehensible to computers, forms the basis for developing design support tools which could respond to the specific knowledge content and the knowledge needs of the designers.

ACKNOWLEDGEMENTS

I would like to express my special thanks to both of my promoters Prof. ir. C. van Weeren and Prof. ir. K. Oosterhuis for accepting to start this long research journey together with me. I am deeply indebted to Prof. ir. C. van Weeren for his continuous support, guidance and assistance along the years of my employment in his chair. I would like to thank to Prof. ir. K. Oosterhuis, his design team at ONL, and all the members of the Hyperbody Research Group for the inspiration and space they have given me to develop and test my ideas. I am also thankful to my daily supervisor ir. Wim Kamerling for his commitment to my thesis and for his challenging and critical insights.

Prof. dr. D. Schodek and Prof. dr. Spiro Pollalis provided invaluable assistance and support toward this study during my resarch visit to Harvard Graduate School of Design and Centre for Design Informatics in Cambridge, USA. I would like to thank Prof. dipl.-ing. M. Grohmann, Prof. dr.-ing. U.Knaack, Assoc. Prof. dr. Rivka Oxman, Prof. dr. J.W.F. Wamelink and Prof. dr. I.S. Sariyildiz for being in my committee. These professors not only took the time to review the initial draft, but also made themselves available to personally discuss several of the points and ideas raised within the thesis.

My hearfelt thanks to Rudi Stouffs, for providing me the InfoBase database model and for his generous guidance for the development of InDeS; Seyfi Bal, my programmer, for his endless commitment and contribution to the implementation of the system. Very special thanks to my dear friend Bige Tuncer, for being an excellent co-worker, for our inspiring intellectual discussions, for her contributions to BLIP, and for sharing both the hard burdens and the joys of a PhD process. Many thanks to my old friend Sinem Cinar who has never given up on me and has been my favorite motivator; Martijn Veltkamp for being an excellent team player during the development of BLIP and in the technical studies we taught together.

For their endless love and encouragement, I would like to thank my family members Ayse, Nazmi, Umut, Esra and Patrik. And my heartfelt thanks to my fiancé, Gerben Dangremond, for all his support, for his patient love and care, and for being there.

CONTENTS

LIST OF FIGURES AND TABLES

Figures:

List of Tables

CHAPTER 1

INTRODUCTION

> *"… the multiplicity of architectonic effects, made possible by the new digital paradigm of architecture is still an exception, rather than a rule… But it is equally obvious that the formal experimentation itself cannot by itself lead to a new architecture, perhaps to a new style… One can only hope that architecture will resist such trivialization and, having discovered the form of this paradigm, will go on to discover its performance."*
>
> *(Ruby 2001)*

This thesis stresses the need for a critical understanding of the structure and the state of the knowledge that has emerged with the new digital approaches in Free-From Architecture. Digital free-form design can be characterized by its formal and procedural complexities which owe their existence largely to the introduction of advanced digital design and manufacturing technologies. Although the formal qualities of this new style are, to some extent, reminiscent of the non-uniform and non-cartesian characteristics of some of the earlier styles of architecture, the processes through which these building forms are generated, represented, constructed and assembled distinguish themselves from the conventional methods of building design and production. In this research, we propose a methodology that covers the study of the digital free-form design. We attempt to conceptualize the free-form design in order to understand and identify the knowledge content it entails specific to its unique context. Norberg-Schulz (1966) proposes the description of the architectural totality by means of three basic dimensions, namely; building tasks, forms and techniques. A number of theoretical approaches also emphasize the criticality of formal, technological and organizational context in shaping design knowledge (Hales 1987; Konda et al. 1992). Such a conviction also informs this research, and the use of an appropriate methodology allowing the inclusion and investigation of the following themes which distinguish digital free-form design as a new design domain:

- the extent to which digital technologies are integrated into the design and production processes
- emerging formal/tectonic qualities and varieties
- changing socio-organizational roles and responsibilities of stakeholders.

One of the most striking characteristics of the new medium is its “pluralistic approach”. As Bandini (1997) points out; “design is no longer perceived as an organized or organizable set of notions which can be taught within recognizable patterns and hierarchies of complexity”. Design knowledge becomes interdisciplinary and interpretive. The integration of material and mental processes of creation re-defines the role of architect and his/her relation with other disciplines.

The motivation to start this research has been to develop a model and a structured framework capable of framing, evaluating and comparing the multitude of design knowledge emerging in the field. The rationale behind the development of such frameworks is to support the designers in their knowledge acquisition, knowledge construction and sharing with a common structure and shared set of descriptive terms. However, such a framework can never be complete given the continuous evolution of new concepts, new methods and new technologies. Thus, our enquiry has focused on the development of a framework which can accommodate change, grow by the actual creators of the knowledge themselves and facilitate knowledge transfer among an interdisciplinary group of designers.

The research refers to and borrows theories from the fields of Knowledge Management, Knowledge Representation, Collaborative Design, Design Learning and Design Theory and Methods. This multi-disciplinary approach has become inevitable given the multi-dimensional aspects of the knowledge content we attempt to investigate.

In order to avoid confusion and misinterpretation, it is essential to first clarify what we exactly mean by “Free-Form Design”. The term “design” has a double connotation referring both to the artefact and to the overall design and realization process from conceptual generation through the production of the artefact. In the context of this thesis, free-form design is identified and distinguished not only with its highly curvilinear formal characteristics, but also with the processes that are used to create and realize these complex forms. At a formal level, digital free-form architecture can be described as a new architectural language of computer constructed curved surfaces with minimum repetitive parts and compositions. The constructional realization of these free-form surfaces may vary between the extremes of:

- a macro level free-form overall shape, composed of straight, flat and even repetitive components at the intermediate level
- a macro level free-form overall shape, composed of only curved and non-repetitive building elements and components.

Within the specificity of our context, we distinguish the “designed form” and the “constructed form”, and the various situations and factors that contribute to the distinction between the two. Rather than focusing merely on the formal characteristics of the domain, we focus on the interrelationships between the FORM and the various mental and material creation PROCESSES that are used to generate and realize this form, in a technological and interdisciplinary context.

1.1 FREE-FORM DESIGN IN A TECHNOLOGICAL CONTEXT

The design and creation of complex, highly curvilinear, organic and non-cartesian building forms have long been a fascination for architects throughout the history of architecture, from the ancient times to the curvilinear, floral forms of Art Nouveau, from the extremes of Baroque architecture to the organic design vocabularies of the early and mid-twentieth century. (Kloft 2005). Common to all is the representative nature of these forms of the various technological, stylistic and/or ideological characteristics of the era they have been created in, each differing in their spatial manifestations and the material treatment of forms.

As observed by Klinger (2001), the creation and production of architecture had been intimately related throughout the history of the profession. The construction technologies and the media of representation have always been influential for the evolution of new formal vocabularies, design methods, organizational principles and design theories in architecture (Mitchell & McCullough 1991; Novitski 1987); just like the formal vocabulary of the most part of the 20th century, which was formulated to reflect the technology of the time - industrial mass production. Recent advances in architectural design and adoption of CAD/CAM/CAE (computer aided design/computer aided manufacturing/computer aided engineering) technologies in the building industry can be considered as one of the most radical shifts in architectural history concerning their immense formal and procedural implications. On the one hand, digital media have provided means to generate and describe complex architectural forms challenging the orthogonal doctrines of modernism and industrial mass production. With the emerging design techniques facilitated by various digital design tools, "architectural form" is envisioned and created not by simple addition of elements, but is conceived, transformed and created as a 3D physical and/or digital construct. According to Chaszar (2004), such techniques and approaches to form generation have given rise to a different cognitive model of form as well as a different vocabulary of forms than was available to designers accustomed to work previously with straight, planar and orthogonal forms.

On the other hand, CAD/CAM technologies provided means to describe, represent and produce these customized non-orthogonal complex forms. While NURBS (Non-Uniform Rational B-Splines) expanded the representational capabilities of modelling software, CNC (computer numerically controlled) fabrication technologies enabled the production of complex forms directly from the digital data (file-to-factory processes) (Kolarevic 2003).

Benne (2004) draws attention to another inevitable impact of digital technologies on design practice as not just a simple addition of information technology to an existing process, but rather as a combined techno-organizational change, where the respective roles and the links among the project participants change across the disciplines along with the technology. Compared to the conventional design processes, the impact of such a transformation in the organizational culture of stakeholders is much more evident in the practice of free-form design than any other architectural domain. Based on these observations, it has become apparent that the practice of digital free-form design is not only assisted, but also shaped by the influence of the new tools and technologies. In this research, technology is not perceived as simply the provider of new tools for the generation and production of complex forms, instead, it is identified according to the extent to which it contributes to the evolution of a new design culture.

1.1.1 Emerging Attitudes in Practice and Academy

Until recently, architectural practice and academy have started to build separate discourses about digital free-from design. The free-from design practice is mainly characterized with diverse practices of an international group of design firms (e.g.

Frank Gehry Associates, Franken Architects, Jakop & McFarlane, Oosterhuis NL) who have contributed to the creation of new architectonic morphologies, design strategies, design/build documentation and bidding processes, organizational culture, and structure. These characteristics have emerged in various designs, among which the Guggenheim Museum plays a prominent role for the theorization of new directions in design, and postulations of new design methods. With this building and its design process, we have been introduced the complexity of new geometric and digital approaches "freed from a priori formalisms" (Oxman 2006). The firm further introduced new methods for the continuous integration design, materialization and production processes around digital technologies.

In academy, divergent but interrelated discourses have been developed which mainly focus on 3 distinct areas: The first attitude, called "paperless architecture", concentrates on the computer graphics for the transformation of design techniques and geometric compositions of the built environment (Andia 2002). The second approach is not too much concerned with designing analogue spaces but rather concentrates on formal experimentations within the digital space. And finally, the third approach focuses on experimentations with various CAD/CAM tools to discover the potentials of digital and physical creations of building forms and components.

1.1.2 Related Work

There is a large body of literature that covers various aspects of digital free-form design. Though, there is still not an established consensus within the profession pertaining to whether the "free-form design" is a mere formal experimentation, or it defines a new design domain of its own. Among the characteristics of the publications in the field, we identify those that focus on; formulations of a theoretical discourse in digital design (Kipnis 1993, Lynn 1999, Oosterhuis 2002, Kwinter et al. 2004) and changing theoretical and methodological directions (Berkel & Bos 1999) which provide significant theoretical and discursive content and monographs of current design practice. Additionally, recent works by Kolarevic (2003) and Zellner (1999) provide an in-depth focus on the episodes of design practice with its emerging technological and methodological content, and the emerging digital form-generation and fabrication techniques. In her recent paper, *Theory and Design in the First Digital Age*, Oxman (2005) reviews the recent theoretical and historical background of digital design, and defines a generic schema of design characteristics through which she formulates the paradigmatic classes of digital design.

This research distinguishes itself from the existing work in the field, with its particular focus on free-form design and with its specific focus on its evolving multi-disciplinary knowledge content.

1.2 PROBLEM DEFINITION

The emphasis of the publications in the field, as described in the previous section, is upon the documentations and explanation of the design objects on an individual basis. They provide a sound basis for the recognition of the emerging design content and the influences of the new media upon the design processes and design thinking. However, there is a lack of systematic examination and formulation of free-form design. Much of the literature is based on case-specific analysis of various approaches to form generation, and innovative use of digital design tools, fabrication technologies and representation techniques on a project specific base. These findings and observations render an account of the impact of these technologies on design practice at large, while neglecting how the use of technology in this context shape and influence the emerging design knowledge embedded in the tacit experiences of the free-form design practice. Moreover, there is a limited range of available knowledge sources related to knowledge elements, problem-solution concepts, decision making, the design activities, actors, and how various aspects have contributed to the overall design is restricted. The result of this in a knowledge re-use scenario is to force designers to think in terms of design specifics, with limited applicability to the earlier synthesis stages of designs, and restricts re-use principally to support detailed design. In addition, it presents problems when attempting to partially re-use a design solution, or its associated knowledge. The designer has no or little understanding of the evolution of the artefact, and consequently, the potential benefits of knowledge re-use can not be realized due to the incomplete knowledge content of the available sources, which in turn restricts its re-use capabilities. Therefore, how to represent the evolving knowledge and to manage the cross-disciplinary processes are among the most essential issues in the relatively new domain of digital free-form design, and the main scope of this research.

1.3 RESEARCH OBJECTIVES

The research presented suggests that the variation and differentiation of mental and material creation processes of the free-form design domain can be conceptualized in such a way to allow us to identify, explain, and evaluate different experiences in different organizational contexts, and to explicate the knowledge elements embedded in their tacit experiences.

In order to do this, we try to frame the knowledge that the free-form design entails and develop a theoretical model and a knowledge framework to organize its knowledge elements. It is claimed that such a framework could be an effective approach to formalize and structure the emerging design knowledge which can provide the designers with a greater knowledge resource to construct and share new knowledge.

1.4 RESEARCH APPROACH

The knowledge framework is developed parallel to a theory of free-from design. In this framework, the proposed theory is not purely prescriptive trying to recommend universal methods, but is also explanatory based on a semantic investigation of the knowledge content. The semantic investigation aims to explain various interrelations that form the knowledge content, and facilitates the identification, capture and evaluation of various design methods, techniques, tools in relation to the tasks, while presenting certain conclusions about their ability to solve these tasks. The theory is based upon empirical knowledge but aims at helping the creative architect to plan and predict, to compare and criticize. In his well-known book, *Intentions in Architecture*, Norberg-Schulz (1966) provides us with one of the first propositions for a systematic and complete structure of the description of architecture. According to this proposition, any theory should consist in dimensions of comparison which make possible description (analysis) of any architectural totality.

Norberg-Schulz (1966) proposes the description of the architectural totality by means of three basic dimensions, namely; building tasks, forms and techniques. A number of theoretical approaches also emphasize the criticality of formal, technological and organizational context in shaping design knowledge (Hales 1987; Konda et al. 1992). Such a conviction also informs this research, and the use of an appropriate methodology allowing the inclusion and investigation of these elements. Building tasks reflect the organizational structure, work processes and the interactions of the key players taking part in building design and realization. Techniques, on the other hand refer to tools, processes and forms and the manner in which they are used and put together. Similarly, the term form has a double meaning pertaining to the overall building and/or only a part of it. For the purpose of this research, with the term “free-form” we refer to both the overall building form, and the form of the individual tectonic elements that belong to the surface and/or to the structure of the building (claddings, or structural elements), and various morphological relations between the two.

Formal characteristics of the architectural artefacts can be perceived as the manifestations of the situations which have determined them. Based on this premise, this thesis excludes a mere syntactical analysis which describes only the formal properties of free-form elements. Rather, we propose to evaluate these complex forms by asking how the forms are materially constructed, in relation to the tasks and processes which determined them, within the technological and socio-organizational context within which they are created and realized.

Consequently, one of the main challenges of such a knowledge framework is to be general enough to facilitate the analysis of any free-form design process and product. And at the same time, to be specific enough to capture the contextual dimensions of the domain under study.

1.5 RESEARCH FOCUS

It is important to note that it is not the intention of this thesis to present a complete survey of all factors that shape the design and all its associated knowledge. Such an investigation would go far beyond the frame of our study. Therefore we exclude the external factors such as building function, aesthetics and cost.

In this framework, the emerging knowledge is identified not within the isolated working domain of each stakeholder (architects, structural engineers and manufacturers) but according to the extent to which they contribute to the design development during the entire life-cycle of a project and facilitate varying degrees of collaboration among the project participants. Therefore, the design knowledge that the free-form design domain entails is characterized as intrinsically interdisciplinary in which collaboration becomes an instrument for knowledge creation. Therefore, we focus mainly on the explication of collaborative and cross-disciplinary knowledge elements that affect and influence both the processes and products in free-form design.

As pointed out by Konda et al. (1992), the representation of such knowledge requires careful selection of terms and concepts across groups because members of design groups working on the same artefact do not share the same experiences, concepts, perspectives, exemplars, methods, or techniques. One of the most apparent proofs of such requirement lies in the observed differences between individuals in framing a given problem. For the purpose of this thesis, the knowledge framework is intended to address primarily to designers with different levels of experience, and with different functional responsibilities, who are involved in the design and realization process of free-forms. The primary foci are the architects and structural engineers - yet, a special emphasis is given to the manufacturers.

1.6 RESEARCH METHODOLOGY AND DATA COLLECTION

The research methodology followed is that of *grounded theory* with an aim of generating a descriptive and explanatory theory. This approach was adopted here for two primary reasons. First, grounded theory "is an inductive, theory discovery methodology that allows the researcher to develop a theoretical account of the general features of a topic while simultaneously grounding the account in empirical observations or data" (Martin & Turner 1986). And secondly, grounded theory facilitates the generation of theories on design thinking and processes, which is dynamic and does not fit to the static views of a design process.

The grounded theory methodology radically differs from other qualitative research methods in the way that it does not start with a theory or hypothesis to be investigated. Instead, it is based on a continuous interplay between data collection, comparison and analysis which leads to theory development. The methodology of grounded theory is iterative, requiring a steady movement between concept and data, as well as comparative, requiring a constant comparison across types of evidence to control the conceptual level and scope of the emerging theory.

The three characteristics of grounded theory-- inductive, contextual, and processual --fit with the interpretive rather than positivist orientation of this research. The focus here is on developing a context-based, process-oriented description and explanation of the phenomenon, rather than an objective, static description expressed strictly in terms of causality (Boland 1985). This allows a focus on contextual and processual elements as well as the action of key players that are often omitted in knowledge modelling studies. Such a theory describes and explains the process of design in terms of an interaction of contextual conditions, actions, and consequences.

The methodological and epistemological approach employed in this research complies with the doctrines of critical constructivism which presents a holistic, contextualized and interactive view of research. In this framework, the research follows a critical hermeneutic/dialectical methodology in which "reality is constructed through the identification of multiple (including contradicting) constructions and their critical comparison, thus improving the grounds for making informed choices between constructions" (Guba 1990). The research focuses on certain types of relationships with corresponding ideas which gradually determines the facts that will be taken into account and measured as the study progresses (Groot 1972). This fits into the definition of a qualitative research, in which research questions and theories emerge as the study progresses.

The research follows the guidelines of a "reflective research" paradigm as described by Schön (1983). According to this paradigm, a practitioner's fundamental principles are closely connected both to his frames and to his repertoires of examples, and the research tries to frame the ways in which practitioners frame problems and roles. By description and analysis of images, categories, and precedents, the researcher builds a repertoire which the practitioners bring to unique situations. This process of recognition and restructuring helps the practitioners to be aware of and criticize their own tacit frames.

Case studies have been the main sources of our data collection to investigate the free-form design domain with its real life context. A study of multiple cases and their comparative analyses have been carried out to cover the contextual conditions which are highly pertinent in the realm of free-form design. Following the grounded theory approach, we follow a comparative, case-oriented and explanatory methodology for the study of cases.

Throughout the research, data is collected through a variety of methods: unstructured and semi-structured interviewing, documentation review, case-studies, experimental design workshops, and observation. For the purpose of "grounded theory" building, we also included the literature as secondary sources of data collection for the cases, such as; quoted materials from interviews published in literature, filed notes, and other descriptive materials concerning events, actions, settings and actors' perspectives. This triangulation across various techniques of data collection is particularly beneficial in theory generation, as it provides multiple perspectives on an issue, supplies more information on emerging concepts, allows for cross-checking, and yields stronger substantiation of constructs (Eisenhardt 1989; Glaser & Strauss 1967; Pettigrew 1990).

Data collection, coding, and analysis proceeded iteratively with the early stages of the research being more open-ended, and later stages being directed by the emerging categories, concepts, and propositions, hence involving more strategic selection of informants.

1.7 RESEARCH OUTPUTS

March and Smith (1995) in a widely cited paper propose four general outputs for design research: constructs, models, methods, and instantiations (fig. 1.1). According to their definition, constructs are the "conceptual vocabulary" of a domain. A model is "a set of propositions or statements expressing relationships among constructs." They are proposals for how things are, and rather than focusing on an absolute truth (as in natural science) they focus more on (situated) utility. Methods refer to "a set of steps used to perform a task in problem/solution formulation". And finally, an instantiation "operationalizes constructs, models and methods". This research comprises all of these general outputs.

Output	Description
Constructs	The conceptual vocabulary of a domain
Models	A set of propositions or statements expressing relationships between constructs
Methods	A set of steps used to perform a task – how-to knowledge
Instantiations	The operationalization of constructs, models and methods.

Figure 1.1: General Outputs of Design Research

The research proposes *a taxonomy* - a representational, hierarchically organized vocabulary of domain concepts - providing a common structure and shared set of descriptive terms. Parallel to this, *a theoretical model* has been developed, which is a set of propositions expressing the relationships between these concepts which has led to a *knowledge framework* which is composed of a collection of concepts, principles and experientially verified relationships useful to explain free-form design processes. The knowledge framework serves as a reference model to frame, evaluate and share design experiences. And finally, *a web-based environment* is developed, which instantiates the taxonomy, the model and the framework into a prototype to support collaborative knowledge construction, sharing and re-use.

1.8 DISSERTATION OVERVIEW

After this introduction, Chapter 2 makes a review and assessment of the emerging technologies, tools and processes, facilitating the design and realization of digital free-form design, from a technological and interdisciplinary point of view. Constant comparisons are made between conventional and free-form design processes in order to distinguish the unique context of the domain. The chapter also tries to characterize the emerging knowledge content according to; 1) the extent to which digital technologies are integrated into the design and production processes, 2) the emerging formal/tectonic qualities and varieties 3) the changing socio-organizational roles and responsibilities of stakeholders. The knowledge elements and their dependencies that are explicated in this chapter are mainly declarative (what) and procedural (how, when), explicating the objective and factual elements of the emerging domain knowledge (e.g. descriptions, tasks, procedures).

Chapter 3 focuses on the explication of interdisciplinary knowledge, and stresses the need to utilize ways to explicate and structure this knowledge. The theoretical and practical development of a web-based teaching and learning environment. It proposes a conceptual framework to capture and organize the interdisciplinary design processes and their interactions. Later in the chapter, the application of BLIP in two experimental workshops is reported and evaluated. The evaluation is based on the effectiveness of the proposed framework in knowledge capture, construction and re-use, and the degree to which it supports and contributes to creative and collaborative design. Based on these evaluations, a new and extended framework, based on 5 general categories, is proposed in order to reflect the collaborative, situated, and emergent characteristics of the domain knowledge. These 5 categories define the contextual framework for our further investigation.

Chapter 4 focuses on the development of a theoretical model which intends to formulate the characteristics of free-form design knowledge. Rather than starting with a theory to be investigated, this chapter reports on the process of inducing a theory based on the comparative analysis of cases chosen to represent the diversity of the domain under study. The 5 interdisciplinary categories that have emerged at the end of the previous chapter are used as a contextual framework for the selection and analysis of useful cases. The chapter gives an account of how the data collected throughout case-study analysis have been analyzed and conceptualized in order to develop a taxonomy and a knowledge framework.

Chapter 5 presents the development process of a web-based environment to support designers in collaborative knowledge construction, sharing, and re-use.

The implementation is based on the knowledge framework and theories developed earlier in the previous chapters. Additionally, relevant theories such as General Design Theory, Knowledge Representation and Cognitive Theories are used as a foundation for forming the representation model and its utilization according to the specified knowledge content. Following this, the prototype is validated and evaluated according to the factors that would influence its effectiveness, applicability and further development in varying collaborative contexts.

Finally, the conclusion chapter (chapter 6) summarizes the main findings, assesses the contribution and impact of the research in the fields of design research, design practice and design education, and makes recommendations for future research.

CHAPTER 2

AN ANALYSIS OF ENABLING TECHNOLOGIES AND THE SOURCES OF EMERGING DESIGN KNOWLEDGE

Over the past few decades, the CAD/CAM/CAE paradigm, which has initially emerged outside the realm of building industry, has introduced new tools, processes and techniques for the generation and realization of complex building forms and components. Digital technologies do not only assist designers in the creation and realization of free-form architectures, but the different capabilities they provide also start to define new tasks, values and concepts while shaping the new image of the emerging practice. This image is a description of methods, organization, knowledge, and culture of design in relationship to a task. This chapter makes a review and assessment of the emerging technologies, tools, processes facilitating the design and realization of digital free-form architectural design practice. The semantic relationships and dependencies between the emerging properties of architectural form and the digital processes characterize the contextual and dynamic nature of the domain knowledge. The sources of emerging design knowledge are identified in a technological and interdisciplinary context.

2.1 THE NEED FOR THE IDENTIFICATION OF THE DOMAIN KNOWLEDGE

At the most generic level, a design process starts with the generation of a form, according to the formal, functional, tectonic, aesthetic and methodological intentions of the designer. This form needs to be physically and/or mathematically be described and represented for design evaluation as well as for the subsequent engineering and production processes. In the meantime, the overall building form has to be divided into rational cladding components, combined with a rational supporting structure during which the fabrication methods, alternatives and economies have to be taken into consideration in relation to the formal and behavioural properties of the materials comprising the tectonic elements of the surface and the structural system. There is actually no definitive or linear order between these phases, but it is rather a cyclical loop during which the design is continuously re-generated and re-shaped. For conventional design and production processes, designers could manage these iterative processes intuitively, given the experience and familiarity with the standardized building elements and construction methods, which constitutes the general design knowledge of a designer. Nonetheless, in the domain of Free-Form design, the emerging digital processes extends and adds to the existing design knowledge with the definition of new tasks, concepts, organizational structures and dependencies between the cross-disciplinary processes. Therefore, it is essential, first, to identify, classify and redefine the evolving concepts and feedback loops in an interdisciplinary context.

Our analysis of the free-form design domain focuses on the technological and interdisciplinary dimensions of the digital free-form design processes. In particular, we focus on the emerging properties of architectural forms, and various interrelationships between interdisciplinary processes that are employed from generation to the actual production of these highly curvilinear forms, within the context of digital design and production technologies. In this context, these technologies are evaluated not just as tools for producing complex architectural forms, but to the degree that they contribute to the evolution of the digital free-form design practice by introducing new concepts, methodologies, and tasks, overall contributing to the emergence of a new body of knowledge.

2.2 IDENTIFICATION OF DOMAIN KNOWLEDGE ELEMENTS

The qualities of the complex surfaces and the processes required to generate and realize these complex forms are rarely generic, but rather dependent on the domain to which they apply. Among the domain dependent types of knowledge we can identify:

- Knowledge related to domain terminologies
- Knowledge related to the formal characteristics of the artefact.
- Knowledge related to the representation of artefact (geometrical and non-geometrical properties)
- Knowledge related to processes (from design generation to production)
- Knowledge related to the semantic relationships and dependencies between various processes

Domain terminology is necessary to build a taxonomy of the essential concepts of a particular domain. They are necessary to establish the domain semantics. As a consequence of the formal complexity employed, the emerging relations between the tectonic elements (of the surface and the structure) of free-form buildings comprise a new body of knowledge specific to the free-form design domain. The degree and characteristics of the curvature to be employed at the macro, intermediate and micro scales define a new architectonic concept which will affect the geometrical representation of the building at different scales.

The free-form design domain has a particular approach to representing complex geometrical and non-geometrical features of the artefacts. In addition, representation may change radically between conceptual design and manufacturing. Domain knowledge is also related to particular tools, since tools have their own independent processes for particular class of problems.

Domain knowledge is also related to the design and manufacturing processes specific to the formal properties of the artefacts in question. These processes are interdisciplinary in nature, and define the main contextual framework of the focus of this research. And finally, the semantic relationships and dependencies between various processes of different phases characterize the contextual and dynamic nature of the domain knowledge. Thus, we first try to identify the “knowledge elements”, of the domain while capturing the “dependencies” between these both within and across different phases of a project, and the changing “dependency paths” as the artefact definition evolves. The knowledge elements and their dependencies that are explicated in this chapter are mainly declarative (what) and procedural (how, when), explicating the objective and factual elements of knowledge (e.g. descriptions, tasks, procedures). Similarly, the dependencies identified are largely project independent and operational arising from both domain specific and external considerations having both geometric and/or non-geometric influences on the artefact and the processes.

2.3 ENABLING TECHNOLOGIES OF DIGITAL FREE-FORM DESIGN AND EMERGING CONCEPTS

2.3.1 Free-Form Generation Strategies

Today architects are offered an immense set of generative design tools, each requiring not only new skills but also introducing an enormous influence and biases on the creative act of the users contributing to the emergence of new form-generation strategies. Although these design environments vary according to their capabilities and form-generation techniques they provide, they are commonly based on "computational processes of form origination and transformation according to the rules set by the designers" (Kolarevic 2001). These operations engender a different cognitive model of form as well as a different vocabulary of forms than was available to designers accustomed to work previously with straight lines, spheres, cubes, cones and cylinders (Chaszar 2003). As stressed by Kolarevic (2003), the emphasis shifts from "making a form" to "finding a form" while the singular and static concept of form is replaced by the variation and multiplicity.

Digital design tools and techniques allow various approaches to form-generation, conception and search for new design vocabularies to be explored by designers. This approach contradicts the modernist approach to technology which was characterized by the search for a formal language to reflect and became the stylistic expression of technology. In some instances, the designers use the tools to generate the forms, or alternatively, the software environments generate shapes automatically according to the pre-specified rule structures set by the designers, or they provide means to capture the geometrical information of a physical model for further modification with the help of digital scanning. In this section, various approaches of free-form design generation facilitated by the digital media are discussed.

Digital Approaches to Form Generation

One approach focuses on the geometry, and is rooted mainly on the aesthetic and conceptual intentions of the architect. The most common approach used is the creation of shapes by direct use and manipulation of computational tools (e.g. lofting, sweeping, Boolean operations) found in most modelling environments.

Most digital environments also offer a rich repertoire of transformations to explore formal variations of an already conceived geometry. The intentions and applications vary between using external factors, or forces as a “direct generator” of a building’s shape (e.g., twisting, bending), or by creating automatic generation of interpolated states of an object during its transformation from one state to another. Special-effects and animation software are extensively used as design tools to create such complex geometries (e.g. MAYA).

In another approach, shapes are generated according to the predefined sets of rule structures that lead to controlled parametric shape variations. The data sets and algorithms driving these approaches can vary widely; they may have a performance (e.g. construction, structural) rationale behind them or may be driven purely by aesthetic and conceptual intents. The digital environments that are widely used in CAD/CAM applications (e.g. CATIA, SolidWorks, Unigraphics) provide performance based capabilities of parametric design (Schodek et al. 2005). Some of the animation software (like MAYA) also have parametric capabilities, allowing the users to define animation paths along which particular instances of a form can be created by freezing the form at certain instances. The designer may also set variables of dimensional, relational or operative dependencies between the parts of an architectural form.

Rule based procedures which rely heavily on scripting allow the creation of complex models that could otherwise be difficult to generate only by dimensional variation. Some rule based approaches comprise the generation of designs via various forms of growth and/or repetition algorithms, which are expressed as a set of generative scripts defining the evolution of new forms. For example, genetic algorithms is a known method of evolutionary form generation mimicking the rules of nature as mutation and reproduction.

Some other group of designers incorporate a fourth dimension (time) in the generation process. The shape of the building changes as it responds to external or internal factors or influences in a rule-driven manner (Schodek et al. 2005). Another approach carry the discussion of architectural space into a virtual plane, which claims that architecture should not only be concerned with designing analogue space but also digital space, and seek to dissolve the boundaries between virtual and physical (Andia 2002).

Mixed Approaches

The alternative approach to digital form-generation is to sketch and sculpt forms using analog/physical media for the concept generation, and then to build a digital model by fitting the mathematically defined curves and surfaces to the original hand-shaped model. The advent of digital three-dimensional scanning techniques had facilitated an enhanced the transfer the geometry of the physical model to the computer environment. From a physical model, a digital representation of its geometry can be created by using a 3D digitizer, by capturing vertex, edge and surface coordinates. This digital data is then ready for subsequent editing. In a typical process, the patterns of scanned points are used to generate NURBS (Non-uniform Rational B-splines) curves, which are then used to generate NURBS surfaces. This data is then used to build a digital model which is then used as a basis for creating a new physical model. Rapid-prototyping devices, such as 3D printers, can then be used to build physical models for visual inspection and comparison with the original model. This process is iterative and may continue until the design intent is satisfied. Frank Gehry is well known to use hand-sketches and physical models as a basis for generating and exploring design ideas.

The Link between Digital Design Approaches and the Emerging Domain Knowledge

According to Oxman (2006), the main difference of digital based design from the paper-based design is the explication of the cognitive processes in generation and evaluation of designs. Accordingly, she proposes a classification of digital design processes based on the various interactions of the designers with the representational medium. She claims that the distinctions between the paper-based (non-digital) interaction with representations and digital interactions are significant both cognitively and theoretically, having an impact on the characteristics of the final form. Consequently, various relationships between the designer, his conceptual intentions, the design processes applied and the final object form a new body of knowledge revealing the unique content of the free-form design domain.

2.3.2 Multiple And Cross-Disciplinary Modes of 3D Representation

With the development of digital curved-surface modelling environments, the historical means of analog generation and representation of curved surfaces has left its place to digital means. The developments in the curved-surface modelling environments during the course of 1960s and 1970s have facilitated highly specialized concepts and techniques for the generation and mathematical description of complex curves and surfaces, such as; triangulated surfaces, parametric curves, Bezier curves and patches, B-Splines and NURBS (non-uniform rational B-splines). Curved surface CAD software based upon these concepts became an essential tool of automobile, aerospace and ship design utilizing the use of free-form curved surfaces as straightforward for designers as straight lines, planes, circles, and cylinders (Mitchell 2001). In the last two decades, the use of these CAD software in the architectural design domain had facilitated the necessary interfaces and means for the generation and actual realization of complex free-form building designs.

The changing form of representation from analog to digital had also affected the nature of information that is required along with these representations. Representation refers to the representation of information (geometrical or non-geometrical) that is embedded within the design object for design evaluation, collaboration and for the subsequent analysis and production .processes. The digital representations raise the question of appropriate geometric representational formats, and the level of data development appropriate for each stakeholder's function in the free-from building process. Accordingly, the quality and the quantity of the information to be exchanged vary depending on:

- the parties sharing this information according to their design task,
- the media of exchange
- the stage of the design process.

As opposed to the representation of conventional and orthogonal building forms, the spatial form of 3D complex free-form geometries are not defined separately in different plans, elevation, and section, but directly as a virtual, three-dimensional model that is constructed on the computer (Ruby 2001). Digital tools that bring control of data shared by the design team (the architect, the engineer and the manufacturer) can ensure continuity from generation to manufacturing.

The "paperless" process of digital design was experimented by Gehry's office first in the late 1980s in the design and construction of the fish shaped pavilion in Barcelona. The complex geometry of the project brought about additional budgetary and time constraints that would only be attainable by the use of a digital design and manufacturing software environment. This brought about the need to look for a digital environment as the necessary condition for the description and production of the complex geometry with a high degree of precision in fabrication and assembly. The solution has been provided by CATIA, a three dimensional modelling and manufacturing software that has originally been developed by Dessault Systems for the French aerospace industry.

Embedded Information in Representations

The basic modes of representation of free-form geometries are wire-frames, polygonal meshes, parametric surface patches, and solids. The modelling environment of the 3D geometry is very influential for the subsequent engineering and production processes and for the digital continuum and for the post processing. Whether a 3D model is represented using NURBS (Non-Uniform Rational B-Splines), or using a solid modeller becomes crucial when the data will be exchanged between the architect, engineer and the manufacturer. Surface models employ two-dimensional elements to describe a three dimensional object in space. Surface models are widely used for visualization purposes by allowing to assign surface properties (colour, texture, etc.) as well. Since the volumes are defined by bounding surfaces only, they can not support many kind of applications. Properties such as mass or moment of inertia cannot be assigned which limits their use in engineering applications. Analysis tools such as finite element analysis often do not support surface models. However, most software that is used to write CNC toolpaths can import surface models directly, and limited surface models can serve as the basis for the CNC milling of a complex surface shape from one face block of a material without necessarily defining the whole volumetric solid (Schodek et al. 2005). Solid models provide the most complete and accurate digital representation of a shape. They are based on data structures far richer than simpler wireframe or surface models. Since they represent real volumetric objects, they also support mass and volume information that are highly important for engineering calculations. A solid model may also have associated attributes describing its density or other material properties. Solid representations are used to generate mesh required for finite element analyses (structural, thermal, etc), the generation and checking of numerically controlled (NC) toolpaths, and many other applications.

Many modelling environments support more than one type of representation. Surface modelling, which is employed mainly for visual purposes, is a common mode of representation and a preferred way of modelling of the free-form complex shapes. Conversion of surfaces into solids is also provided by some environments in order to support various engineering calculations.

Diverse Nature of Modelling Environments

Professionals faced with the task of designing and building a complex form are likely to employ a range of digital tools instead of a single environment because few environments provide adequate support throughout. While Some environments are better for conceptual and preliminary design, some others support the more structured design development phase. It is not the intention of this thesis to give a complete overview of various design software, however, the range of qualities that the design tools exhibit is useful for evaluating them in relation to the design tasks and the design phase they support. For the purpose of this thesis, which focuses on the form-generation and form-development processes of free-form design, we will identify the general characteristics of conceptual modelling and design development environments, which support these 2 phases respectively.

Conceptual design is very different form the design development or design for construction and production. During the conceptual design phase, which rather focuses on visualization, designers require immediate feedback from the digital (or physical) 3D models. Hence, conceptual modelling environments are primarily used for conceptual design and rendering (e.g. MAYA, form-Z, 3D studio max) relying on both solid and surface representations. As described by Schodek et al. (2005), there is no built-in intelligence in these environments that would pint out conflicting geometry as can be found in various design development environments. Primary outputs of these modellers are 3D and rendered views to communicate design ideas while some environments also comprise animation capabilities. These are mainly stand alone applications relying on commonly supported file-exchange formats, such as DXF, DWG, IGES, VRML to import/export geometrical data from/to other applications for visualization purposes. Many of these environments have no or little interface for constructability or structural efficiency analysis.

Design development environments have evolved primarily to support the design development phase, which is more structured and involves the evaluation of the design intentions developed in the conceptual design phase. They rely mainly on parametric surface patches and solid representations. These design development environments include software such as CATIA, SolidWorks, Pro/Engineer which are based on BIM (Building Information Modelling) systems in which embedded information can describe the geometry, as well as materials, specifications, code requirements, assembly procedures, prices, etc. They intend to support design collaboration with separate modules addressing the needs of design conception, structural analysis, production, etc. The geometrical information of all components and sub-assemblies of a design can be updated automatically in coordination with the overall configuration (Ibrahim & Krawczyk 2003). Each application generates the individual representation or view model of the same data which is either stored locally, or in case of a network-based system, is accessible through from a central server.

Critical Considerations for the Modelling Environments

The way in which models are built and manipulated is quite different in these various digital environments in regard to the support they provide at different phases of the design with different tasks. Similarly, data transfer from one application to the other may require varying file exchange standards for each application. Moreover, although geometric data transfer is quite successful for most applications, non-geometrical information embedded in these representations may be lost due to lack of support and the extent of the design task each application provides. Therefore, the designer must initially have a clear understanding of the expected design outcome to efficiently use these environments.

The power of these environments become more evident once the basic understanding of the intent and structure of these modelling environments is gained. This requires not only new skills for architects but also an understanding about this changing nature of tools, their potentials and limitations, and above all, having a critical understanding of the theories behind these tools to use them effectively. This would also eliminate a dysfunctional relationship that might occur between the tools and the tasks at hand. (Kalay 2004). For example, using CATIA early in the form generation process –where ambiguity and flexibility are needed more than preciseness – requires the designer to decide on issues that are too early to decide on, thus may interfere with the evolution of design ideas. It is also important to note that although 3D representations are the main sources of data communication and information exchange in the realm of free-form design, the support of conventional 2D documentation still remains a requirement for successful operation in construction practice.

2.3.3 CAD/CAM Technologies

The implications of today's digitally controlled machinery differ radically from those of the earlier industrial technology. CAD/CAM technologies enable the direct and indirect manufacture of custom, digitally crafted architectural components by reducing traditional tooling costs and automating the operation of machines by translating a three-dimensional file into a full-scale physical reality. They allow the design and produce complex free-form components that were previously either impossible or prohibitively expensive (Rotheroe 2000). Mass customization is particularly useful for the mostly one-off products of the free-form building components and the need for variation of components in response to their particular contexts. CAD/CAM technologies do not impose a certain type of design approach or a fixed formal language but allow the designers to explore new formal varities. This approach contradicts the modernist approach to technology which was characterized by the search for a formal language to reflect and became the stylistic expression of technology.

As suggested by Klinger (2001), a clear classification of fabrication processes in direct relationship with digital form-making potentials would provide a necessary outline for the development of new principles in the realization of expressive form into physical architecture. CNC manufacturing processes may be examined by categorizing them from a number of perspectives. Designers may be interested in the geometric varieties these machines could allow, the range of materials they are capable of processing, or their shape-making potentials. In current practice, they are mainly categorized according to their distinct process types; as Subtractive (based on material removal); Formative, (by applying heat and force); Additive (adding material layer by layer) which are also referred as direct processes eliminating the need for tooling. On the other hand, many indirect processes such as casting and moulding require tools to be made by direct CNC machining in order to produce a part such as a mould or pattern, and require a combination of various techniques (Schodek et al. 2005) .

There are generally three application areas in which additive, subtractive and forming processes can be usefully applied in the design and production of complex double-curved forms. During early phases of design, they can facilitate the production of scaled study models. In the form development process, CAD/CAM techniques can be effectively used to create prototype components and assemblies for evaluation and verification (Rotheroe 2000). Most importantly, they enable economically viable production of limited quantities of project specific components. Although the merit of CAD/CAM technologies applies to all custom architectural applications, they are most useful and cost-effective when applied to more complex, free-form designs.

Common Applications of CNC Fabrication in Free-Form Design

Subtractive Processes: CNC-cutting, or two dimensional fabrication, is the most commonly used fabrication technique. It comprises various cutting technologies, such as plasma-arc, laser-beam and water-jet (Kolarevic 2001). CNC cutters and routers have been extensively used to cut flat sheet material into arbitrary shapes. Curved sheet elements after being unfolded can be cut in this manner and later be re-bent by on-site or off-site forming techniques. Applications of CAD/CAM technology to structural steelwork has been particularly effective to cut out planar load-bearing steel sections. CNC machines can shape, cut and drill steel sections efficiently. This way, the steel frames can economically be formed into complex shapes.

3D-milling involves the removal of a specified volume of material from solids using electro-, chemically- or mechanically-reductive (multi-axis) milling processes. The milling can be axially constrained according to the translational motion of the milling head. Multi-axis milling machines have also been extensively used to produce the formworks (and moulds) for the casting of concrete, metal and glass elements with double-curved geometry. For example, sheets of glass can be shaped by heating and slumping them over moulds, the geometry of which could be defined by a 3D-milling machine.

Additive Processes: Also known as layered manufacturing or solid free-form fabrication, rapid prototyping is a computer-controlled, additive fabrication process used to fabricate physical objects directly from CAD data sources. Rapid prototyping technologies employ unique methods of adding and bonding materials—polymers, paper, or powdered metal—in successive layers to create objects that can be used as concept models or functional prototypes. However, they have a limited application area in the actual production of large scale building components, due to the limited size of objects that can be built with high production costs. Among the methods currently in use are stereolithography, selective laser sintering (SLS), fused deposition modelling (FDM), and three-dimensional printing (3DP). Rapid prototyping is extensively used to enable project teams to visualize concepts, evaluate new designs, and test functional models of complex curvilinear geometries before committing to expensive tooling.

Formative Processes: Formative or deforming processes change the shape of a material by application of heat, or mechanical forces. According to the types of stresses to which the material is subjected, the processes are named as compressive, tensile, shear forming and bending, among others. Forming and deformation of both planar and linear building components are possible. Sheet forming usually refers to the use of sheet materials that are cut, stamped or bent, or otherwise formed, while bulk forming generally refers to the shaping of geometrically complex metallic components, which may be quite large (Schodek et al. 2005). The materials that are formed by using formative processes are generally capable of plastic deformation, such as; aluminium, steel, copper, and other metals. The tensile and yield strength goes up as the bending process is being performed and the ductility of the material goes down at the same time. This means that, generally, new material properties are obtained during forming processes. Forming techniques also allow the production of structural components with different or varying cross-sectional shapes along their length (Dohmann 1999).

Critical Considerations for CAD/CAM Applications

Each of these technologies poses different dimensional, behavioural and formal limitations on the materials that can be processed via each machinery. Whether a building component will be manufactured using a CNC cutter, a milling machine or any other will depend largely on the material to be processed, the complexity of the form, its size and scale and the availability of the specific technology in a given context.

The specific properties of each material, such as ductility, modulus of elasticity, minimum bending radius influence the decisions related to which manufacturing processes may be applied to them. For example, if a material is resistant to ductile deformation, it will be resistant to being forced into shapes with any in plane deformation. In contrast, highly ductile materials will easily take up shapes. Some processes, such as laser cutting or casting may be applied to a wide variety of materials, while others can only be applied to a few. Relatively few machines are utilized for the manufacturing of large scale building components, especially the ones with load bearing capacity.

There is a crucial link between the design and CNC manufacturing during transition from CAD to CAM machines. Verification of geometrical accuracies is a crucial part of the transfer between CAD and CAM software. Parameters need to be checked to ensure that the designs can be manufactured using the available tooling and method. If the component will be produced by milling out of solid material, or be cut out of flat sheets to be folded, or be cast into a mould, or any number of combinations of these techniques are decisions to be considered during as early as the form-development process. Hence, there is a particular balance between the repeating and unique elements, as well as between traditional and CNC fabrication to be employed. One of the critical design issues is to figure out where and to what extent these applications may effectively be utilized for a particular project.

2.4 RATIONALIZATION AND MATERIALIZATION ASPECTS OF COMPLEX CURVILINEAR SURFACES

Rationalization is related to the concept of "constructability" of the tectonic components, the structure and the skin. It refers to the description of complex geometric forms in a way compatible with the construction requirements. Therefore, the design surface must first be developed into rational cladding components combined with an appropriate supporting structure. Rationalization mainly refers to the geometry of tectonic components which could be re-arranged into straight or flat, radially bent, double curved, or highly complex shaped components. This means, the variations may range between, at one extreme; a macro level free-form overall shape composed of straight, flat and even repetitive components at the intermediate level, and on the other extreme; a macro level free-form shape may be composed of only curved and non-repetitive components at both intermediate and micro levels. The reasons and the degree to which such re-arrangements take place might vary (e.g., cost, aesthetics, technological availability) as well as the strategies used for the rationalization process. Critical considerations common to any rationalization strategy are as follows:

- the degree and characteristics of the curvature to be employed at the macro, intermediate and micro scales according to design intentions and constructability constraints
- material qualities of the surface elements
- the relation between the surface and the structure (architectonic intentions)

The form-generation strategy of a complex shape may yield enormous insights into the understanding, as well as the physical realization of this shape. We observe two common generic approaches of surface generation in present free-form design. The first approach concerns the generation of the overall surface form initially without little or no reference to constructability criteria. In this scenario, the overall surface is rationalized afterwards during the form-development phase according to the constraints of the preferred materials and production processes (post-rationalization). The second approach concerns the inclusion of constructability criteria early in the form-generation process by applying these criteria as constraints on the surface descriptions that are allowed (pre-rationalization).

It is imperative that the exact nature of the curvatures present in a surface be well understood if the intention is to transform the digital model of a curved surface into a physical reality. Constraining the surface forms based on constructability criteria is one of the highly employed approaches in surface rationalization, which has been a widely employed technique in Gehry's office. Other approaches rely on rationalizing the forms into canonical shapes, such as cylinders, planes, conics, for the ease of constructability. As observed by Shelden (2002) each of the approaches present differences in the qualities of shapes generated by rationalizing which may be quite different than the ideal surfaces. There is also almost always a continuous discrepancy between the initially modelled forms (physically or digitally), those that can possibly be fabricated, and those of rationalized forms representing the limits of the designers' predictive capabilities of what can be built (Shelden 2002).

2.4.1 Understanding the Surface Curvatures

Any surface that can be generated by the translation or rotation of straight lines is called a ruled surface. Ruled surfaces are particularly simple to represent and to construct. These include developable surfaces such as sections of cylinders, cones, and planes as well as non-developable surfaces such as hyperbolic paraboloids. Developability of surfaces is one of the most frequently applied techniques used for constructability modelling of free-form surfaces which refer to the ability of a curved surface to form into a flat plane without stretching or cutting. A cylindrical shell, for example, could simply be flattened into a planar sheet. A non-developable mathematical surface, by contrast, requires cutting and/or stretching if it is to be flattened into a planar sheet. A sphere, for example, has to be cut into pieces to be flattened.

Architects like Felix Candela, Eduardo Catalano have also worked with ruled surfaces by using rather analog means of computation. These are basically generated by taking pairs of curves in space and connecting them at regular intervals by straight lines (Mitchell 2001). This process has mostly been applied to the construction of wire models and to the actual wooden formwork construction of complex shaped concrete surface structures.

2.4.2 Analysis of Surface Curvatures

Most advanced surface modelling environments provide utilities to visualize and analyse surface curvature, such as Gaussian and Mean Curvature analysis. Gaussian and mean curvature analysis are found to be more appropriate for building components that will be manufactured from isotrophic materials (like metals). For non-isotrophic materials, instead, such as wood and plastics, usually a normal curvature value in a certain direction would be a point of interest for the users (Schodek et al. 2005). When the Gaussian curvature value of a surface is positive, the surface is referred as synclastic surface, which are not developable into flat sheets without cutting or distortion (e.g. sphere). If the Gaussian curvature is negative, then the surface is referred as an anticlastic surface which is normally not developable (e.g. hyperbolic paraboloids). A "zero" Gaussian surface curvature implies that the surface can always be developed into a flat plane without cutting or distortion (e.g. cylinders and cones). Such analysis methods are based on constraints of geometric representations of NURBS surfaces which do not necessarily include the variety of fabrication constraints. However, rationalization requires the representation of the curved forms (surface or linear components) in a manner through which their constructability can be attained. This requires further development of representation techniques, in addition to pure geometrical representation capabilities, which can accurately reflect the fabrication constraints. In either case, there is an obvious need for more rigorous ways of defining and understanding surface shapes and curvatures in more complex forms, and to develop the surface into smaller cladding components by various subdivision methods for the actual production process.

2.4.3 Surface Subdivisions According to Constructability

The strategies for the organization of the surface cladding components will have implications on the qualities of the surfaces. These qualities are to some extent determined by the design intentions of the architect, and/or by the constructability constraints due to a preferred method of fabrication. Many building envelopes are assembled from individual sheets or plates that are derived as sub-divisions of a larger digital surface model for constructability reasons. Therefore, there is a compelling interrelationship between the representation of surface elements at micro level, and a macro scale perspective of the assembly's organization as a whole in relation to the mathematical smooth curvatures of the initially generated form.

Automated design techniques are rarely available for the subdivision of complexly curved surfaces. Thus, designers need to execute series of steps to execute desired results. For ease of constructability, a free-form surface can be decomposed into developable surface classes. This can be done by certain functions present in various CAD/CAM software (e.g. Rhino) or by customized techniques developed by the architects according to various criteria, e.g. the design intentions, constructability constraints, allowable material sizes and desired architectonic effect on the surface. Some design firms have developed subdivision techniques by developing and programming add-ins to supplement these functions in the existing software, and/

or by parametric definitions of curves on the surfaces to be subdivided. Commonly used techniques are the regular or irregular tessellation (quadrilateral, triangular, etc.) with or without direct reference to surface isoparms. The individual parts may be composed of flat or curved individual plates.

2.4.4 Materialization Aspects for the Constructability of Surfaces

For the cladding components to be efficiently assembled and welded together, they need to be shaped and cut accurately. Flattening of developable surfaces into planar sheets has been automated in many software used in current practice. It is important to note that physical sheet materials, unlike mathematical surfaces, always have a thickness and its own material properties that need to be taken into account for the actual unfolding and folding processes. The CAD/CAM cutting machinery can accurately produce each unfolded shape from a flat sheet material. And these machine-cut sheets can effectively be transported to the construction site, where they can be bent back and fixed in place to produce the desired surface effect, as was the case in Web-of-North-Holland project by Kas Oosterhuis (see chapter 4). Alternatively, these sheets can also be bent off-site and mounted in place afterwards. The flattening of non-developable surfaces is more problematic which involves stretching and/or compression of material. In this case, the maximum strain and stresses of the material and the constraints of the available manufacturing process need to be defined into the digital flattening process (Schodek et al. 2005).

The choice of the framing strategies supporting the surface components proves to be crucial for the actual construction of the individually produced cladding components. The surface components are either directly attached to the main structural elements or by a secondary system according to the degree to which the structural system follows the design surface geometry. When the main structural system is an approximation of the design surface, there will be an obvious need for a secondary sub-framing strategy for the finishing of the surface enclosure. Similarly, the patterning strategies for the individual cladding elements and the organization of the sub-framing systems will have mutual influences on one another, influencing the fabrication economies. It is also possible to employ several different systems on different regions of the building depending on the complexity of the localized surface form (Shelden 2002). For example, the rationalization of the less curved surface areas may be constructed with more straight forward construction, while the highly curved areas may employ a less economic fabrication approach. The geometrical and dimensional control between the structural and surface elements will affect the type of collaboration and data exchange between the parties responsible for the design and production of these systems.

2.5 EMERGING TECTONICS - RELATION BETWEEN THE STRUCTURE AND THE SKIN

Free-Form Architecture focuses predominantly on the generation of the surface (skin). Although, the process of working from the skin to the structure has long been a common practice in automotive and aerospace industries, it is relatively new in architectural design compared to the "primacy of structure" logic of Modernism in which the emphasis has been from the structural grid towards the outside. In the digital free-form design approaches, the starting point becomes the skin. The exterior surface of the building –its skin- becomes necessarily emphasized due to the logistics of formal conception inherent in the NURBS-based software. Therefore, the explorations in constructability of the geometrically complex envelopes have led to a re-thinking of the surface tectonics and to new explorations to unify the skin and the structure in contrast to the tectonic solutions of the Modernist era.

One approach is the distinct separation of the skin and the structure in which the skin has little or no load-bearing function. In such an arrangement, the structure may or may not follow the exact surface geometry depending on the architectonic expression desired. The structure may then be composed of a regular geometry creating an additional layer which supports the geometrically more complex interior and/or exterior surface layer(s) (fig. 2.1). Another approach is integrating the structure and the skin in which the structure becomes embedded or subsumed into the skin as in both semi-monocoque and monocoque constructions (fig. 2.2).

In monocoque construction, the external skin transfers some or most of the load on the structure. This is opposed to using an internal framework that is then covered with a non-load-bearing skin. In semi-monocoque constructions, the outer skin is inadequate to carry the primary stresses, and is reinforced by internal structures such as frames. The principle idea is to conflate the structure and the skin into one element, thus creating a self supporting form. The idea of a structural skin does not only imply a search for new materials, but also geometries, such as curves, folds that would enable the continuous skin act structurally, eliminating the need for an independent system. In both approaches mentioned above, a reciprocal relationship is established between the skin and the structure having direct implications on the exchange of the geometrical and non-geometrical information between the parties responsible for the design, analysis and production of the these tectonic elements. In the modernist and industrial production, various

Figure 2.1: The separation of the structure and the skin (Kunsthaus, Graz)

Figure 2.2: The integration of the structure and the skin (The Wave, Munich)

systems that were created for the structure and the surface elements were created as autonomous and independent as possible. Instead, in free-form approach, the "independence of parts" is replaced with "relations between the parts" and the degree to which these relationships are set characterizes the emerging design strategies for designers to cope with the constructional challenges.

In current practice, the main structural systems for the complex geometrical forms are most commonly used either to approximate the design geometry, requiring the use of a secondary system that has to be adjusted in the field. Or, to define the design geometry only at regularly spaced intervals, typically by "ribs" ('Peter B. Lewis Building, Case Western Reserve ' 2002). This system requires the use of specially shaped panels, to comply with the design geometry between the rib locations.

There are also more individual approaches such as the case in which the locations of the structural steel ribs were decided according to the constructability criteria for the surface claddings. This was a strategy employed in the design of Weatherhead project by Frank Gehry. In this particular approach, the overall free-form surface was subdivided into individual cladding components each of which could be unrolled into a flat surface. Therefore, in order to comply with the developability criteria, the surface had vertical and horizontal lines of ruling. The primary steel structure was placed on the vertical lines of ruling, while a second system was designed for conditions where the lines of ruling coursed in horizontal direction (Shelden 2003). Locating the structural members according to the constructability criteria allowed direct connections between the structural system and the cladding components, minimizing the need for field adjustment.

2.6 IMPLICATIONS OF THE NEW TECHNOLOGICAL CONTEXT – INTEGRATION OF MATERIAL AND MENTAL CREATION PROCESSES

As observed by Kieran and Timberlake (2004), the industrial approach to design was merely a linear process in which design preceded the realization process. One of the most striking consequences of such a view has been the isolation of the designers from the act of making and from the processes through which the products were created. In digital free-form design, on the other hand, new forms of design representation and direct communication between the architect and the fabricator start to eliminate the division between the architect and the act of making.

As defined by Kolarevic (2004), the ability to digitally generate and analyze the design information, and then to use it directly to manufacture and construct buildings fundamentally re-defines the relationship between conception and production. Kalay (2004) draws attention to the impact of the use of information technologies and how they shape the profession. He states that the use of digital technologies is not just a simple addition of information technology to an existing process and organizational method and he describes it rather as “a combined techno-organizational change”, where the respective roles and links among the participants change along with the technology, alog with the knowledge content.

2.7 SUMMARY AND CONCLUSION

This chapter tried to identify the enabling technologies and the emerging sources of free-form design knowledge by stressing key themes which distinguish the new domain from the conventional designs: 1) the extent to which digital technologies are integrated into the design and production processes 2) emerging formal/tectonic qualities and varieties 3) changing socio-organizational roles and responsibilities of stakeholders. While each theme introduces new concepts, working processes and skills into free-form design, the definitive lines between the working processes of disciplines start to blur. Moreover, various types of interactions across these themes start to define new dependency types between design tasks within and across disciplines contributing to the evolution of the final artefact.

The knowledge elements and their dependencies that are explicated in this chapter are mainly declarative (what) and procedural (how, when), explicating the objective and factual elements of the emerging domain knowledge (e.g. descriptions, tasks, procedures). Similarly, the dependencies identified are largely project independent and operational, based on various interactions between formal characteristics, specific tools employed, technical limitations, and the properties of the materials comprising the tectonic elements of the building form, among others (fig. 2.3).

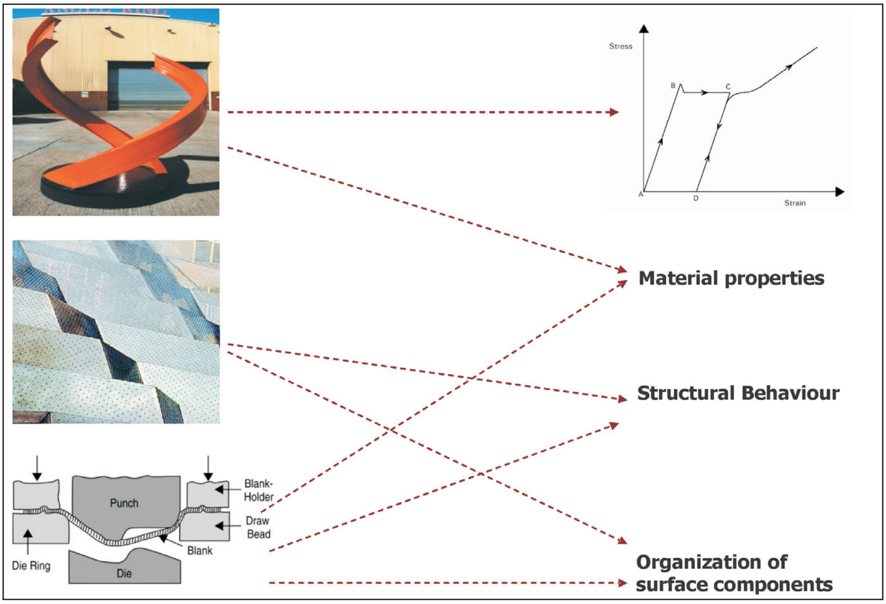


Figure 2.3: Emerging interrelationships between fabrication processes and various interdisciplinary design concepts.

In addition to the technical and interdisciplinary view of the emerging domain knowledge documented in this chapter, the next chapter will try to organize and structure this unique knowledge content for the acquisition and the construction of a body of concepts and their context specific interactions in varying design contexts.

CHAPTER

3

DEVELOPING A FRAMEWORK TO CAPTURE AND EXPLICATE THE KNOWLEDGE CONTENT - TWO DESIGN EXPERIMENTS

The previous chapter provided an overview of the emerging processes, tasks and concepts in free-form design domain from a technological and interdisciplinary point of view. Although much of the emerging knowledge grows mostly from design practice, as Friedman (2003) states, the practice of design is only one foundation of design knowledge. In order to understand, discover and identify the knowledge embedded in the tacit experiences of the designers, we need to utilize ways to explicate and structure this knowledge for its efficient sharing and re-use. This would require a systematic and methodical inquiry into practice for the creation of design knowledge as a common property.

This chapter will introduce the theoretical and practical development of a web-based knowledge environment (BLIP) which aims to help the explication of interdisciplinary knowledge content of free-form design. BLIP is initially developed as an interactive database and a collaborative teaching/learning environment to support the construction of knowledge which has been implemented in an educational context. It proposes a conceptual framework to collect, analyze and compare different design experiences and construct structured representations of concepts and their relationships specific to the free-form design context. Later in the chapter, the application of BLIP in two experimental workshops is reported and evaluated. The evaluation is based on the effectiveness of the proposed framework in knowledge capture, construction and re-use, and the degree to which it supports and contributes to creative and collaborative design.

3.1 THEORETICAL GROUNDING OF AN APPROACH FOR DESIGN LEARNING

3.1.1 Theories on the Formalization of Knowledge and Learning

Design is a complex process that involves a large amount of information with numerous dependencies. Logan (1985) discusses the necessity of formalization of design knowledge models for providing tools for further research. He refers to the structure of relationships in design activity and claims that design research should focus on understanding these relationships, rather than solving problems. Akin (1986) introduces the formalization of knowledge as a system that explicates the behaviour of the problem solver during the design process, which can also be used in design education for the study of uncertainty. Landsdown (1986) defines design as a transformation of an object from an initial, incomplete state to a final complete one. Since the transformation is brought by the application of knowledge, he sees design as an information processing concept, and he stresses the need to focus to formalize this transformation process. In this respect, what makes each design unique is in part determined by how the designer(s) bring different items of knowledge together in varying contexts. Oxman and Oxman (1990) propose a structured multi-level model of architectural knowledge and stress need to provide meaningful relationships between levels, proposing a formalism which represents the linkages between concepts.

3.1.2 Learning through classification of knowledge

Laxton (1969) argued that design learning should pass through three stages. First stage is the accumulation of experience and knowledge in a reservoir. Second stage is to generate or initiate ideas which, he claims, depends upon having the reservoir well filled. And the final stage refers to the development of the skills for critical evaluation of these ideas in order to interpret and transform them in new contexts. The argument here is that recognizing design situations is one of those key skills. Seeing some kind of underlying pattern or theme that enables a designer to recognize this and make a connection with some precedent in the episodic memory. Remarkably that episodic memory may relate to something from an entirely different context. Lawson (1980) draws attention to the necessity to explore the perception of design situations and in particular how they are recognized and classified. Through recognizing and constructing representations of knowledge of previous designs the novice designer (the student) gradually builds up an ability to think in designerly ways. Design learning then may be considered a process of knowledge acquisition and development in which the knowledge is physically constructed. The constructional form provides a representation of the structure of knowledge which the student acquires.

3.1.2 Knowledge Structuring and Acquisition

Oxman (2001) stresses the importance of the organization and development of conceptual structures for knowledge acquisition. This framework provides the means, for both teacher and learner, to explicate their knowledge. Educational research suggests that the organizational structure of knowledge is at least as important as the amount of knowledge in understanding any particular knowledge domain (Baron and Steinberg 1987). In his well-known paper, 'Designerly Ways of Knowing' Cross (1982) points out that design has its own things to know, ways of knowing them, and ways of finding out about them. Meta-knowledge in this sense is the knowledge of how to analyze and organize what one knows (Oxman 2004). Analysis intends to bring out the knowledge that is tacitly embedded in design, by using a system of classifications and abstractions. The classification is a reflection on the design knowledge and implicitly refers to what is knowable, and proposes a framework to construct and model knowledge.

Following these arguments regarding the formalization of design knowledge, how can we formalize a framework for a conceptual understanding of the emergent and cross-disciplinary knowledge content of free-form design? The following sections will introduce the theoretical development and implementation of a computational environment (BLIP - Blob Inventory Project) which proposes an a priori framework to formalize the interdisciplinary knowledge elements in free-form design.

3.2 THE BLIP PROJECT

BLIP[1] has originally been developed as a database, a computational environment to guide the users (researchers and students) to collect, analyze, identify and construct structured representations of collaborative design concepts and their

---

[1] BLIP is a project developed as a joint work by three PhD researchers (Tuba Kocatürk, Bige Tuncer, Martijn Veltkamp). Bige Tuncer's research provided a flexible and extensible framework for knowledge modelling that acts as the backbone of the information structure of BLIP. Tuba Kocatürk's and Martijn Veltkamp's research provided the main context and the related knowledge content for the application which contributed to the cross-disciplinary richness of the knowledge content due to the separate research foci and disciplinary background of the two researchers. The authors would like to acknowledge Joost Beintema for his contribution to the programming of BLIP. For further information on the development and implementation of BLIP, see the related article in the appendix.

relationships in free-form design context. It proposes a knowledge framework to categorize the interdisciplinary knowledge content of the domain under study. The knowledge will be extracted from various sources, such as; the literature, case analyses and design experiments. It is developed as a working prototype and has been extensively experimented in the context of a design studio. Consequently, it has been continuously updated with new data entry.

In the following sections, rather than a complete and detailed description of the BLIP project, which would go beyond the intention of this thesis, we will give an overview of the system according to the extent to which it has contributed to the development of a contextual framework for our further investigation in this research. This contribution is based on the applications of its proposed knowledge framework and its basic representational formalism in two design workshops which resulted with the identification of the essential requirements for an improved representation of domain knowledge. This will be reported later in this chapter. The following sections will give a brief overview of the development process of the system, its main functionalities and representational formalism.

3.2.1 An Interdisciplinary Framework for Knowledge Construction

A conceptual framework has been proposed to construct representations of domain knowledge according to 3 interdisciplinary and generic aspects of design: formal aspects, structural aspects and production aspects. The framework is used to discover and organize the knowledge elements under each category and their cross-disciplinary interactions.

This representational scheme does not, however, aim to propagate a division of roles, but it rather intends to stress the concept of change to be able to compare the conventional understanding of domain roles and tasks with that of free-form design. Such an approach is supported by various cognitive psychologists who postulate that learning is a process that new knowledge is added to an existing knowledge web/network by creating associations to existing knowledge (Anderson 1992). Thus, it has been anticipated that building the categorization of emerging tasks, processes and concepts according to these three aspects could also hold a key for the identification of new interdependencies among design activities across disciplines (fig. 3.1).

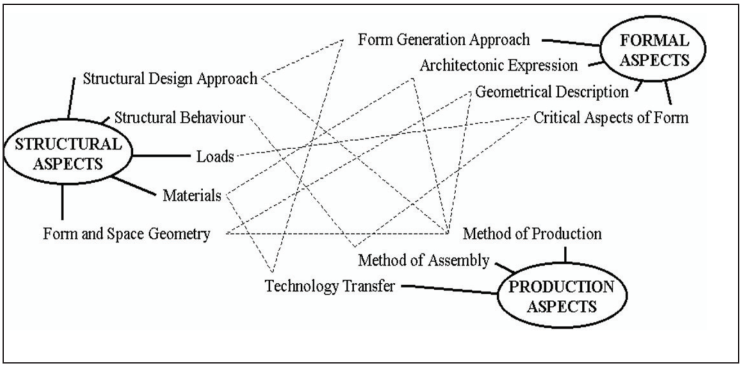


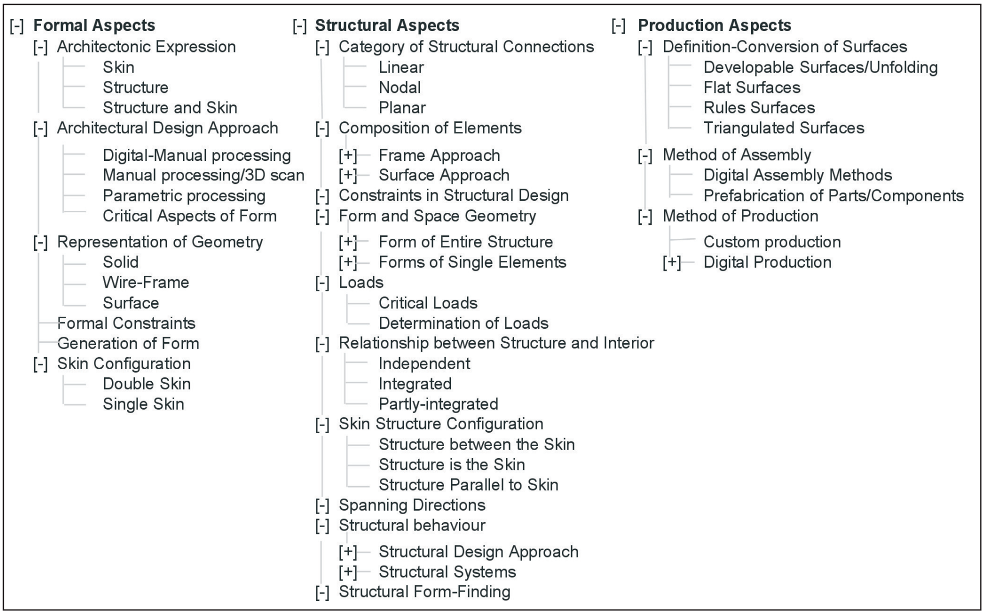
Figure 3.1: Interdependencies among interdisciplinary decision activities. The relationships are indicative rather than final

This could further clarify the changing roles of stakeholders and the degree of roles that different stakeholders play in problem formulation, solution and in the overall creative act. In this framework, *formal aspects* refer to the tasks, processes, tools and techniques used for the generation and development of the architectural form, as well as the tectonic and geometric qualities of form. *Structural aspects* refer to the tasks, processes, tools and techniques that are used for the development of the structural system and components. And finally, *production aspects* refers to the manufacturing techniques, processes, methods and tools used to produce the architectonic elements of the skin and the structure. In summary, the database proposes a qualitative framework in order to capture the free-form design process by showing its elements and their relationships.

3.2.2 Constructing the Framework

A data structure has been developed composed of 3 aspects (formal, structural, production) and their related features under each. The features are determined by an heuristic process of examination of the free-form design context (literature review) as well as an extensive case study analyses of built examples.

Among an infinite number of features that could have been selected to define the characteristics of each category, we have targeted and determined a number of those according to the degree of change that has been observed to occur most in their understanding and practice, as well as according to the degree of influence they have on the two other aspects. For example, Generation of Form, or Method of Production are two generic features of any design process. Both of these processes are included in the data structure because how these processes are practiced, and the techniques/tools used to perform these processes have greatly changed in the context free-form design. Similarly, while new approaches to form generation have been observed to have an enormous influence on the design of structural systems to support these surfaces; various methods of forming processes are observed to change the properties of materials they are applied to. The generation and identification of features and their sub-features has been an iterative process, rather than a priori. They have been inductively derived from the study of the phenomenon they represent under each category. The features are generated through an analytical process of making comparisons to highlight the similarities and differences that is used to produce lower degree features. Features are organized to have first and/or second degree sub-features. While the features at the upper levels are characterized by context-independent and generic terms, the sub-features at the lower levels are characterized by more specific terms revealing the context-specific vocabulary of free-form design, extracted through the analysis of cases and various other sources of literature[2]. This hasled to the organization of the features in a hierarchical structure, as illustrated in Figure 3.2.



- [-] **Formal Aspects**
  - [-] Architectonic Expression
    - Skin
    - Structure
    - Structure and Skin
  - [-] Architectural Design Approach
    - Digital-Manual processing
    - Manual processing/3D scan
    - Parametric processing
    - Critical Aspects of Form
  - [-] Representation of Geometry
    - Solid
    - Wire-Frame
    - Surface
  - Formal Constraints
  - Generation of Form
  - [-] Skin Configuration
    - Double Skin
    - Single Skin

- [-] **Structural Aspects**
  - [-] Category of Structural Connections
    - Linear
    - Nodal
    - Planar
  - [-] Composition of Elements
    - [+] Frame Approach
    - [+] Surface Approach
  - [-] Constraints in Structural Design
  - [-] Form and Space Geometry
    - [+] Form of Entire Structure
    - [+] Forms of Single Elements
  - [-] Loads
    - Critical Loads
    - Determination of Loads
  - [-] Relationship between Structure and Interior
    - Independent
    - Integrated
    - Partly-integrated
  - [-] Skin Structure Configuration
    - Structure between the Skin
    - Structure is the Skin
    - Structure Parallel to Skin
  - [-] Spanning Directions
  - [-] Structural behaviour
    - [+] Structural Design Approach
    - [+] Structural Systems
  - [-] Structural Form-Finding

- [-] **Production Aspects**
  - [-] Definition-Conversion of Surfaces
    - Developable Surfaces/Unfolding
    - Flat Surfaces
    - Rules Surfaces
    - Triangulated Surfaces
  - [-] Method of Assembly
    - Digital Assembly Methods
    - Prefabrication of Parts/Components
  - [-] Method of Production
    - Custom production
    - [+] Digital Production

Figure 3.2: The hierarchical organization of the features under each aspect

---

[2] The process of constructing and updating the features has been a collaborative process between the authors of the BLIP project and the students under the supervision of the authors. It has been based on a process of discovery rather than following a rigorous methodology. Therefore, the hierarchical structure does not illustrate a complete structure, though it is representative of how the domain data has been collected.

3.2.3 Choosing the Formalism for the Knowledge Structure

The formalism of the knowledge structure is closely related to the specific characteristics of the knowledge content and context of study which will affect the choice of an appropriate formal representation of the knowledge elements that are intended to be captured, shared and represented. Cognitive science has contributed significant approaches to general structures of knowledge representation, however, a discussion of these approaches are beyond the purpose of this research. To understand which representational schemes may hold the most value to support the design process, it is important to identify those characteristics which are relevant to the asynchronous design representation and communication process. In the specific realm of free-form design where problems are ever changing, the representation of knowledge, should also be able to represent changing issues, evolving concepts and their mutual relationships. Semantic networks is one of the most commonly referred approaches in knowledge representation. Quillian (1968) developed semantic networks as a representation that could support meaning (or semantics). The basic structure of semantic networks has been subsumed by a more recent notion of the associative network, used to represent not only meanings but also physical and/or causal associations between concepts. Since the knowledge construction of BLIP focuses on the capture and understanding of the relations between the features in the system, semantic networks held a better value to this inquiry in the context of BLIP.

3.2.4 Data Representation

The system provides an extensible and flexible outline by allowing the addition of new features and sub-features as new concepts are discovered. The features and sub-features are organized both in a hierarchical tree-structure and a keyword network (fig. 3.3). While the hierarchical structure provides the general outline and the classes of the knowledge content, the keyword network represents the semantic relationships between the features within and across categories. Both the keyword network and the tree-structure provide an outline for organizing and categorizing information while providing a structure to relate new contributions in the system (Kocaturk et al. 2003). The tree-structure also serves as an access point into the system.

The system allows the creation of semantic links between features. Features can be linked and interrelated via documents. In this respect, the links between the features are not predefined (except for parent-child relations between features and their sub-features). Interrelating features is made possible via document entry.

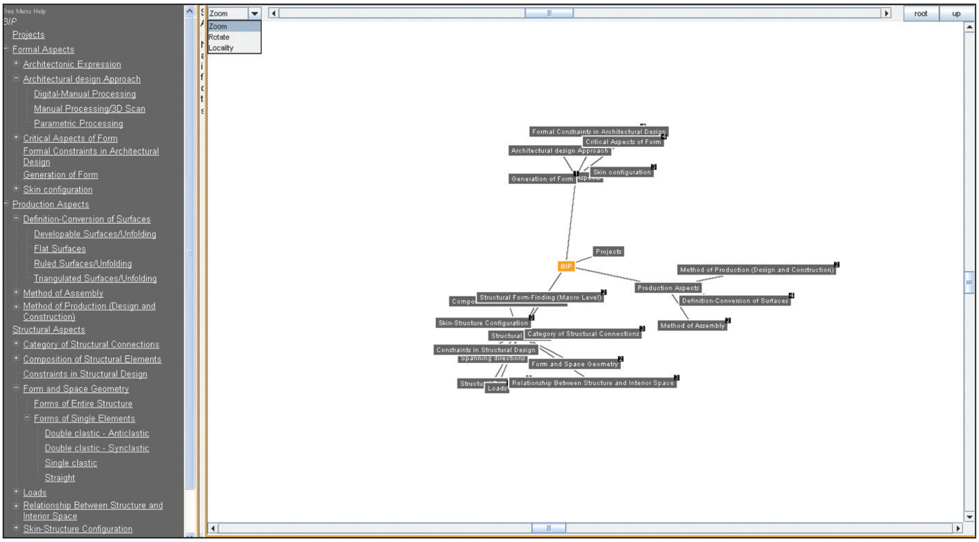


Figure 3.3: The hierarchical tree-structure and the keyword network

Documents contain information chunks (case-specific or general information) which exemplify or describe in what way the features are interrelated. This aspect complies with the initial aim of the system which tries to discover and document those interrelationships.The keyword network depicts the semantic structure for this document structure, in which each document is assigned to one or more keywords from the keyword network. Documents provide data, information and knowledge elements specific to the feature(s) they are associated with. Documents that are associated with one keyword are referred as “feature documents”, whereas documents that are associated with two or more features are referred as “link documents”. Link documents exemplify how the associated features are brought together and how they mutually inform one another in a specific situation.

3.2.5 Data Entry and Document Organization

Integrating various contributions (new document entry) necessitates the specification of relationships between the documents across all contributions (Tuncer et al. 2001). In BLIP, the documents are related to one another with a separate semantic structure for the categorization of the documents. Authors only need to be concerned with associating the documents of their contribution to this semantic structure. Relationships to documents from other contributions are automatically provided through these associations. (Kocaturk et al. 2003). The semantic structure and how the link documents are attached to the features within this structure are shown in Figure 3.4.

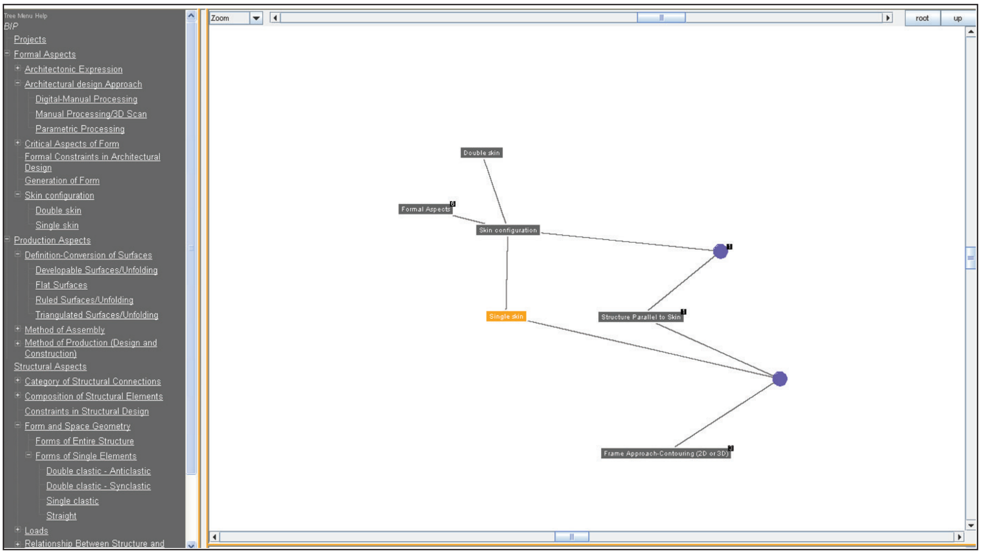


Figure 3.4: Link documents attached to the semantic structure

As can be seen from the figure, the user who searches the *single skin* feature will not only have access to the documents associated only with the feature, but will also be able to see other features that were previously associated with this feature via document entry (as depicted with the circular points in Figure 3.4 connecting; single skin-structure parallel to skin-frame approach). It can also bee seen that any feature can be associated with any other feature or sub-feature at any level.

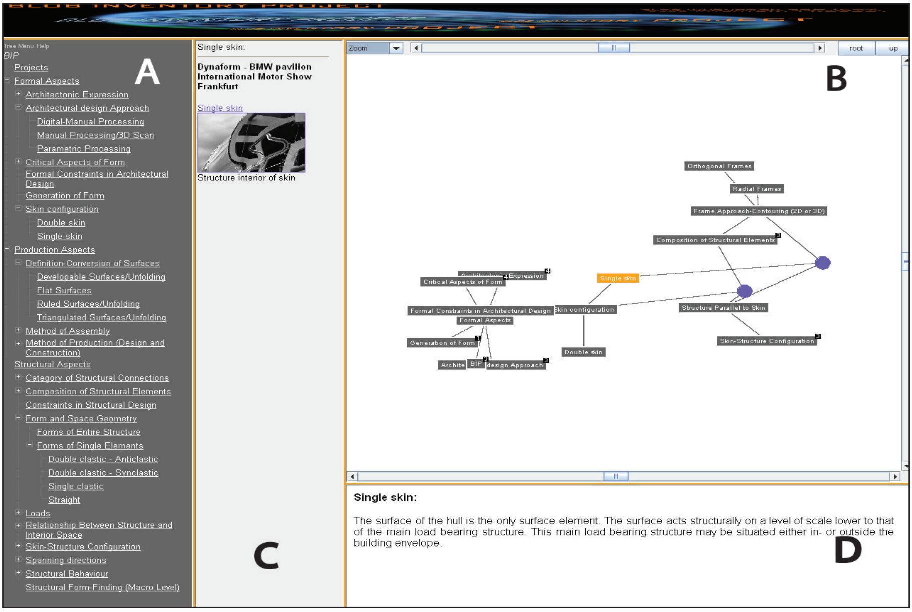
To summarize, the keyword network and the semantic structure provide the authors with a structure to categorize and to relate their contributions to other documents in the system . Therefore, the keyword network defines the context for the organization of documents. As this relational structure becomes denser,the system is anticipated to provide better support for searching and browsing the information space, unrestricted by the original boundaries of the contributions (or projects) (Kocaturk et al. 2003).

In this organization of keywords and documents, various kinds of document relationships can be distinguished. Documents are grouped under projects. By assigning keywords (architect, project name, etc.) to documents, documents that share the same keywords are implicitly related.

The documents are further related with the features they share within the keyword network. The distinction between semantic (keyword network) and the syntactic (document structure) structures ensures the extensibility and flexibility of the overall representation, because the semantics can be easily altered at any time without requiring an adaptation of the syntactic structure (Tuncer et al 2003). The database is designed to be used for extensive cross-referencing and interactive searches in order to capture and share information and knowledge.

3.2.6 User Interface

Since the aim of the database is to allow cross-referencing between multiple projects, the user interface is optimised accordingly. At any time, the screen layout provides feedback to the user about which aspect or feature he is exploring and to which documents or projects they are associated. This allows both browsing to a more specific feature – so called forward browsing – as well as for a more general feature – referred to as backward browsing. Currently, the main starting point for data-retrieval is the predefined keyword network, in frame A, on the left hand side of the screen (fig. 3.5, A). The selected feature will be highlighted and displayed in the frame B on the top right hand side with the other features associated with it (fig. 3.5, B).



Single skin:

Dynaform - BMW pavilion International Motor Show Frankfurt

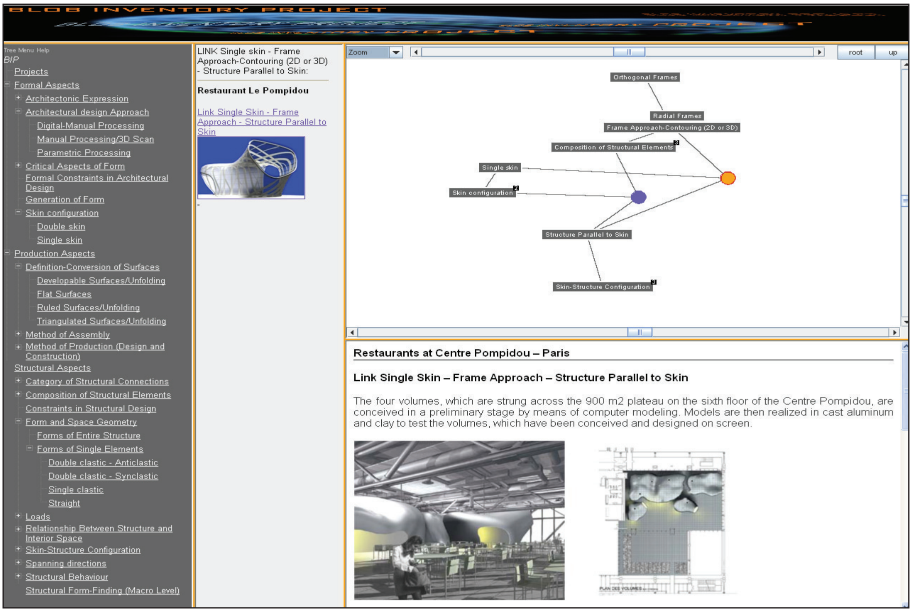
Single skin

Single skin:

The surface of the hull is the only surface element. The surface acts structurally on a level of scale lower to that of the main load bearing structure. This main load bearing structure may be situated either in- or outside the building envelope.

Figure 3.5: A Screen-shot of the interface; Frames: A) aspects and features, B) relationships, C) documents, D) content

This window only displays the features, and their associations via the link documents. For example selecting Structural Behaviour feature under the Structural Aspects may be associated with features such as; Composition of Structural Elements under the Structural Aspects, Skin Configuration under the Formal Aspects and/or Method of Assembly under the Production Aspects. By the use of a menu window in combination with the slider, the user can choose the degree of sub-features to be displayed in this window (locality), rotate relationships web, or zoom in or out in this window. Clicking on a feature in window A or B will display the related feature documents in frame C which may contain textual, graphical and/or numerical data containing information on the selected feature (fig. 3.5, C). At the same time, frame D will display a description of the selected feature (fig. 3.5, D). If a document is selected from the document list in frame C, frame D will then display the content of the document. Similarly, double clicking on a link document (depicted as a circle) in frame B will display the document thumbnail in frame C. Similarly, clicking on the thumbnail in this window will display the document content together with its associated features in frame D (fig. 3.6). It is also possible to start the search via projects. Clicking on the projects in frame A, will list all the projects in the system in Frame C.



LINK Single skin - Frame Approach-Contouring (2D or 3D) - Structure Parallel to Skin:

Restaurant Le Pompidou

Link Single Skin - Frame Approach - Structure Parallel to Skin

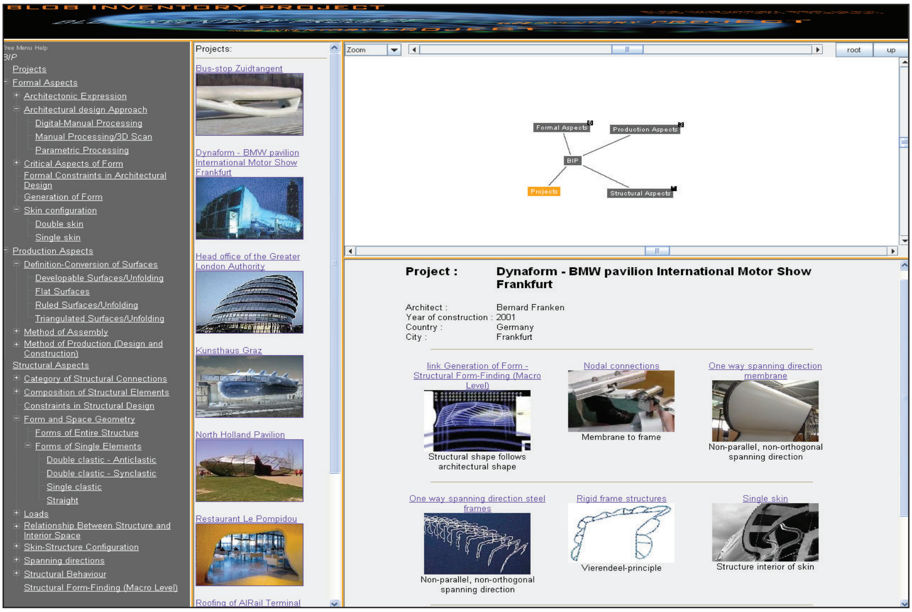
Restaurants at Centre Pompidou – Paris

Link Single Skin – Frame Approach – Structure Parallel to Skin

The four volumes, which are strung across the 900 m2 plateau on the sixth floor of the Centre Pompidou, are conceived in a preliminary stage by means of computer modeling. Models are then realized in cast aluminum and clay to test the volumes, which have been conceived and designed on screen.

Figure 3.6: Screen-shot of the Interface displaying the “link document” content

Clicking on any project in this window will display all the feature and link documents that are indexed under this project, in frame D (fig. 3.7).



Project : **Dynaform - BMW pavilion International Motor Show Frankfurt**

Architect : Bernard Franken
Year of construction : 2001
Country : Germany
City : Frankfurt

Figure 3.7: Screen-shot of the Interface displaying the project list and the documents indexed under a project

It is not only the features which are searchable but the links between two or more features can also be searched by the user to access more specific information on the relationships between the selected features. Thus, the links between the features are also designed to store documents and project specific information as well as general domain knowledge. The database is automatically updated with feedback and serves as an interactive medium to discover new relations among existing and new features.

3.3 THE DESIGN WORKSHOPS[3]

The following section will describe the application of BLIP in two collaborative design workshops conducted with 2 separate groups of master's level students. Each workshop comprised of an extensive study of the free-form design context

---

[3] The design workshops were conducted within the "Technical Study" module of the E-Motive Architecture programme, in the Faculty of Architecture, at Delft University of Technology. Both workshops were developed and taught together with Martijn Veltkamp.

(based on case studies) followed by a collaborative free-form design assignment. The main goal of the workshops was not to further develop the application, though its been extensively used for the purposes of data storage and capture. Thus the workshops provided a medium to:

1) further identify the additional knowledge content (features) constituting the free-form design domain and describing them by their relationship to other concepts (gained through direct design experience)

2) test and evaluate the effectiveness of the proposed framework for efficient knowledge capture, construction and re-use (with regard to both the knowledge of the individual student and the knowledge that arises out of collaborative work)

3) evaluate the existing organization and structure of knowledge in BLIP to the extent to which it supports and contributes to creative and collaborative design.

4) recognize particular cognitive aspects of design required for knowledge acquisition and for the construction of useful knowledge structures.

3.3.1 The Workshop Set-up

The criteria to evaluate the effectiveness of BLIP for efficient knowledge capture, construction and re-use is defined as the capability of the system to extend the user's ability to utilize design knowledge, modify existing knowledge and to generate new knowledge. In order to do this, we have included the two crucial elements of learning throughout the both workshops: analysis and design. While analysis is viewed as an effort to rationalize and explicate the knowledge embedded in past designs, the design process can be viewed as the acquisition and utilization of knowledge. While learning helps to maintain experiential knowledge, activities such as "abstraction and generalization" extend the utilization capabilities of knowledge in a re-use process (Duffy 1997).

Both workshops started first with case study analysis in order to help the students to get acquainted with the design context. They were asked to analyse precedent designs and production processes and then to extract knowledge from these analyses to store in BLIP by adding new links and features into the system where necessary. and later continued with a free-form design assignment. Case study approach to learning utilizes real or imagined scenarios to teach students about their field of study. The key in this technique is that the students are challenged to learn by doing, develop analytical and decision making skills, internalize learning, learn how to tackle real life problems, develop skills in oral communication and team work (Barnes et al. 1994). The significance of case-based learning is that it links theory and application to real or possible circumstances. Students were also expected to acquire knowledge and understanding from the readings before attending class in order to apply the information in small discussion groups. The second phase of each workshop was the design assignment. The knowledge identified in the case studies were formalized, reshaped and reorganized and integrated into BLIP, encouraging the students to generalize and abstract ideas that are explicit in particular situations, and later to use them in analogous situations in their design assignment.

The experimental setting for both workshops complies with the two philosophical models of experiential learning as described by Kolb (1984) and Piaget (1972). Kolb's emphasis is on the experience, followed by reflection, which in turn is assimilated into a theory where new hypotheses are tested in new situations (Kocaturk & Veltkamp 2005). Piaget focuses on knowledge and the ability of its assimilation. This assimilation is related to the students' cognitive schemata which is influential for the acquisition and utilization of knowledge. In both workshops, although all students who took part in the design experiments were Master's level students, each student had a different level of experience and familiarity with the design context. Moreover, we were limited with the small number of students who participated in the workshops (5 in the former, 3 in the latter workshop).

Since the students, as novice designers, are known to have less experience in clustering of concepts, generalizations and abstractions, they have been provided assistance on these aspects. The set-up of the workshop and the design assignments were also optimized on this particular aspect by by the following arragements:

- The role divisions between collaborating students intended to scale down the individual tasks to manageable quantities and help them to focus more on the aspect of exploring multiple alternatives rather than one single solution
- As a final product they were asked to generate various conceptual solutions and compare them rather than one single solution worked out in detail
- They were asked to generate conceptual solutions at different levels of abstraction in a collaborative setting, thus encouraging them to develop a "parallel lines of thinking" (Lawson 1997)
- They were asked to define their design solutions in relation to the problems they have formulated, thus encouraging them to make generalizations of the possible problem structures of the domain

3.3.2 The First Design Workshop

After the case studies and getting acquainted with a base knowledge and the terminology of free-form context, the students were asked to generate a double-curved free-form roof surface, to develop a structural supporting system and to generate alternatives for the fabrication of the structural elements.

In this particular design experiment, the students were asked to work as a team (throughout the whole process) in which the team members were all assigned a specific role associated to the three aspects of BLIP: an 'architect' responsible for the formal aspects, a 'structural engineer' for the structural aspects and a 'manufacturer' for the production aspects. Part of the assignment, in addition to the design task, was to create a memory map of their collaborative design decision process, the rationale behind their problem formulations, and the justification of their particular choice among the design alternatives/solutions that were collaboratively generated (fig. 3.8).

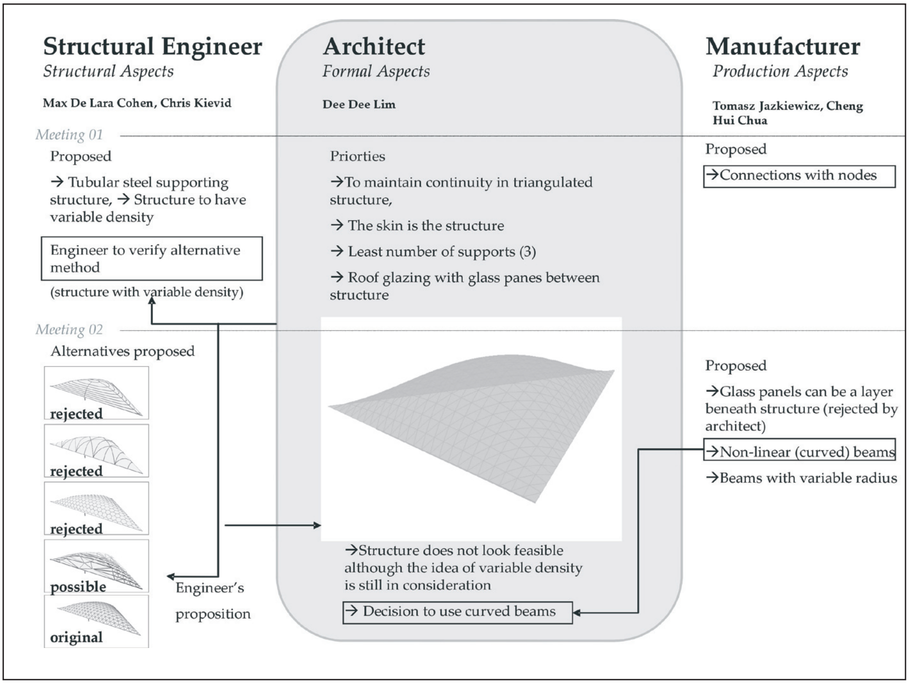


Figure 3.8: The students' representation of their collaboration process

In summary, they were required to record their design process leading to information and to track the dependencies between cross-disciplinary decisions and information in a collaborative design process. Later on, they were asked to explicate their design experiences by storing both product and process related information generated during their design process in the BLIP database by using the existing organizational structure provided by the system. They were allowed to add new features and links into the database provided that they were specific to the free-form context and at the same time generic enough to represent similar cases. The students were free to use any software at their disposal. During the workshop,the students developed various conceptual design alternatives for the downstream processes.(fig. 3.9).

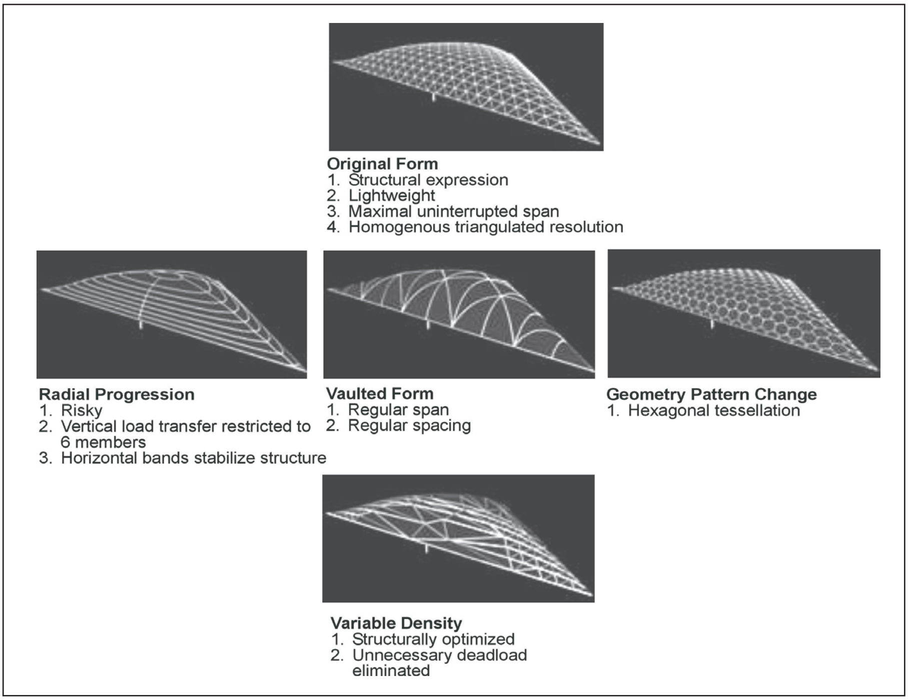


Figure 3.9: Various structural form alternatives in relation to the architectural and manufacturing constraints

3.3.3 The Second Design Workshop

The second workshop was conducted with a new group of master students with a slightly different level of design experience and familiarity with the context.

After the case study analyses and getting acquainted with the design context and terminology, the students were given a double-curved 3D geometry and were asked to develop the surface into cladding components combined with a free-form supporting structure.

Different from the first workshop, they were given two initial constraints to start with. Firstly, they were not allowed to make major changes in the given geometry. And secondly, all of the surface cladding components and the elements of the structural system should be developable. Additionally, rather than dividing the group as architect, structural engineer and the manufacturer, we defined each of their individual tasks separately so that we would not be limiting their course of action (if necessary) across the domains. Each student was given one of the following tasks:

1) division of the surface into curved, developable cladding components,

2) creating possible configurations of structural framing, composed of curved developable elements,

3) exploring available cutting and forming technologies for structural parts and components (in this case steel).

They were required to collaborate throughout the whole design process as in the first design workshop, however in this particular assignment, each student was asked to focus on his/her own individual task for the development of the alternatives for this task, and at the same time to consider the consequences of his/her decisions across other tasks.

Meetings were held between the students to mutually eachother about the progress. The conceptual design variables (formal and procedural) developed by each student were discussed and new dependencies between the tasks were discovered. In the end, the compatible design alternatives were identified, among which, one highly compatible path, satisfying all mutual constraints (the thick arrow in figure 3.10), was selected as a potential solution (fig. 3.11).

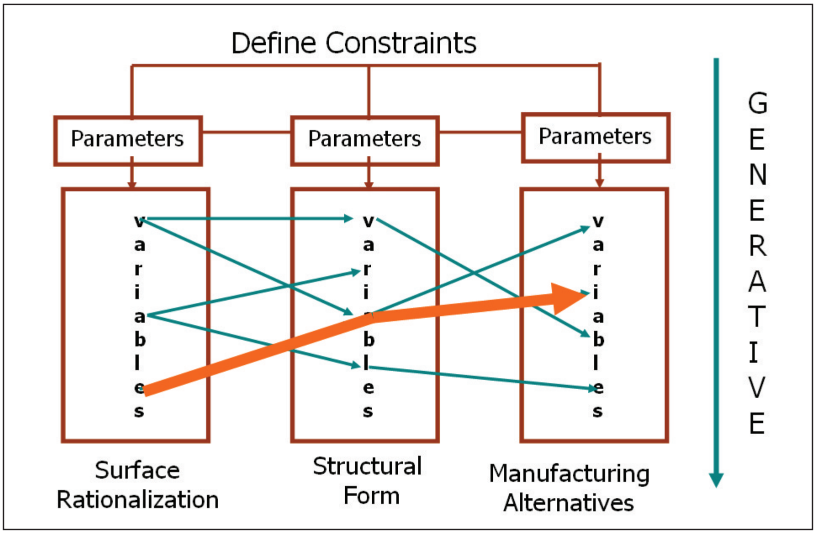


Figure 3.10: Proposed working scheme for the second workshop

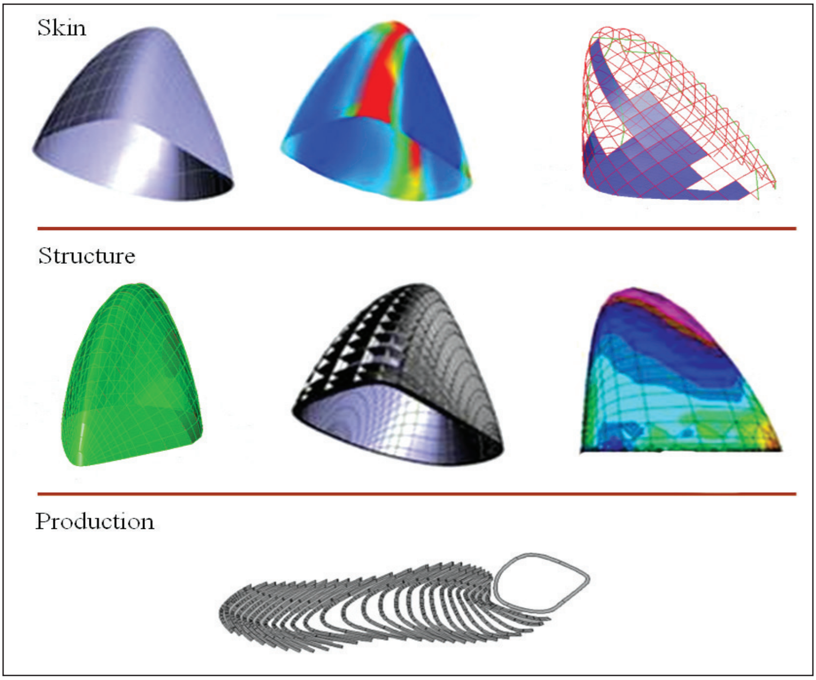


Figure 3.11 : Compatible solutions selected for the cladding patterns, the structural configuration and laser cut structural elements

The other variables, together with the knowledge they retain were stored in BLIP. The abandoned design alternatives and their partial solutions were also stored in BLIP for future reference. It has been observed that in this particular experiment the students were more innovative and creative not only in terms of the variety of design solutions, but also the methods and strategies they have invented to deal with particular constraints and dependencies between tasks (Kocaturk & Veltkamp 2005).

3.4 EVALUATION AND DISCUSSION

3.4.1 Comparing the Workshops Based on Student Performances

The student performances in the two workshops have been evaluated and compared with regard to both individual and collaborative learning experiences of the students. However, it is important to note the following changes in the set-up of the second workshop assignment, which have been observed to have direct influence on the different performances of the students.

- We did not limit the course of action of the students by defining a discipline specific role to each group (as opposed to the first workshop). Rather, we assigned them specific tasks which, by definition, required the integration of cross-disciplinary decisions.
- We gave them two specific constraints which automatically aided their problem formulation process.
- The students were not necessarily asked to develop their design alternatives together at every step of the design process, but they were rather encouraged to gather at certain intervals to discuss and compare their interim solutions.

These two changes in the workshop set-up have been observed to increase the student performances, promote beneficial cognitive processes and consequently increase their knowledge acquisition and utilization. In the first workshop, throughout their design process the students were more focused on problem solving rather than trying to identify the dependencies between concepts at a more abstract level. The only dependency type they interpreted between concepts across domains was constraints (fig. 3.12).

	Workshop 1	Workshop2
Knowledge Integration and Collaboration	Pragmatic	Explorative
Design Approach	Problem Solving	Problem Finding
	Solution Oriented	Process Oriented
	Constraints Satisfaction	Strategy/Method Development
Knowledge Generated	Specific	Generalizable

Figure 3.12: Comparison of the workshops based on student performances

Consequently, their approach to "problem solving" was mainly in the form of negotiation and compromise between the groups to satisfy those constraints. Consequently, the design alternatives were chosen according to the ease of production and realization. In this respect, their collaboration process and the way they integrated different information across disciplines were observed to be quite pragmatic. Eventually, the knowledge they created was more solution specific and they had difficulty in abstracting and generalizing the knowledge generated.

The second group, on the other hand, has been observed to score better in terms of abstract thinking and generating generalizable knowledge content which could be stored and re-used. Moreover, their creativity was oriented more towards making associations between concepts to define problems and generating alternative strategies and concepts. In this respect, while the first group generated more alternative products, the second group was more productive regarding the development of alternative strategies and approaches.

We have also observed clear differences between the two workshops regarding how collaboration took place in each. In the first workshop, the students interpreted collaborative design as an activity that was the result of a continuous attempt to develop the easiest path along a chain of constraints across interdisciplinary tasks. In the second workshop, alternatively, collaboration has been interpreted as first; to construct a shared conception of various dependency types between interdisciplinary tasks, and then; to explore these varying degrees of dependencies during their individual creative design and integrating others' viewpoints in the generation of design alternatives.

3.4.2 Generalizable Results of the Two Workshops

In both workshops, students utilized and generated different types of knowledge. These different types of knowledge were iteratively utilized and generated during both problem solving and problem formulation clarifying why and how a solution was generated in a specific way or how a problem was formulated that led to the final solution. For example, how to divide a double curved surface into individual and developable cladding components is a strategic knowledge, while the maximum thickness allowable for a steel plate in CNC cutting is a factual knowledge. Currently, different knowledge types cannot be differentiated in BLIP. Therefore, *the structuring and representation of knowledge should be enhanced in order to capture and differentiate different knowledge types that are used in problem formulations and solutions.*

It has also been observed that the current database is lacking the ability to represent varying dependency types between concepts (features). During design, various links between the same features can be created based on how the problems and solutions are formulated. These linkages reflect different viewpoints of the designers on the evolution of the artefact for the construction of a collective understanding of the domain. This collective understanding reveals one of the essential aspects of collaborative design process which is to represent and manage the interactions among the individuals' unique perspectives and viewpoints (Lue et al 2001). For example; a specific manufacturing technique will pose certain constraints on the allowable thickness and curvature of a building component. If the available manufacturing technique is influencing the decisions concerning the geometrical properties of this component, or if the desired formal qualities are influencing the choice of a specific manufacturing technique (or a combination of a few) could both lead to a creative product or a process in different ways, based on the choices made. Creativity, in this respect, may be linked to the ability of creating innovative links in both problem formulations and solutions in new and unexpected ways. Therefore, in order to support the creativity;

The organization and structuring of knowledge should be able to support the identification and capture of different links and relationships between concepts which could allow the users to modify them and apply them in new contexts.

During their design processes the students had discovered various new concepts (features) and their associated knowledge which were difficult to place under one of the 3 categories of BLIP.

These concepts have been observed to be mainly procedural and operational in nature displaying the following characteristics:

- emerged across the boundaries of the three disciplines (design, structural design and production)
- highly multi-dimensional and interactive
- facilitate the creation of new internal processes and social interactions specific to the domain
- requires the engagement of stakeholders at various levels and are highly influential for the evolution of the artefact.

Based on these findings, we conclude that the categorization of the initial framework of BLIP, based on disciplinary segregation of concepts, is not inclusive of the emerging collaborative concepts in free-form design. The initial framework proposed, focusing on 3 disciplinary aspects, proved to be useful for the novice designers to understand the emerging knowledge elements and organizational roles in comparison to an existing understanding. However, it also proved to impose a certain way of thinking, lacking the contextual understanding of the domain under study. This approach has been observed to hinder creativity in the first assignment. In the second assignment, it has been observed that defining design tasks, not specific to a certain discipline but rather specific to the context, independent of the solver, each design participant tried to develop a solution for the given situation, and develop alternatives for its execution. This approach proved to encourage collaboration, development of a shared knowledge and understanding among the design participants which also contributes to the collective creativity of the team members.

Therefore, *instead of categorizing and labelling the concepts (features) according to disciplinary classes, it has proved to be more useful to categorize them in relation to the specific problems they attempt to solve (or create), revealing the unique knowledge content of the domain*. We claim that such a categorization would also reflect the collaborative and integrative nature of the free-form design processes and could serve to construct a shared understanding of the domain knowledge.

Different than the *analysis* of designs, the actual *design* is a non-linear process of knowledge exchange whereby shared meanings are created between the members of the design team. The design workshops provided the students with an understanding of the dynamics of teamwork and group learning which generates a shared understanding and collaborative knowledge. Consequently, we distinguish collaborative knowledge from the individual creation of knowledge, which is constructed through the interaction of multiple actors, embodies the dynamic elements of knowledge that would be difficult to generate by an individual (Lee 2004). This view propogates a rather process oriented view of knowledge which is seen as a key to the generation and understanding of collaborative knowledge.

3.5 EVOLUTION OF A NEW FRAMEWORK

We conclude that in order to explicate the emerging knowledge content of free-form design, we need to focus on its creation process. Therefore, we require a more extended framework which reflects the collaborative, situated, and emergent characteristics of the domain knowledge, and which can facilitate the discovery of emergent interactions between its context specific concepts (e.g. tasks, processes). Based on the observations and findings of the previous section, the initial a priori framework have been extended and categories have been re-defined. Consequently, we have identified 5 general categories where collaboration has been observed to occur most frequently among the stakeholders and which have been identified as the main sources of the emerging knowledge associated with the change in the design pratice:

- Form finding approach and formal characteristics
- Rationalization of the Structure and the Skin
- Representation and Exchange of Design Information
- Materialization of the Supporting Structure and its Elements
- Fabrication of the Supporting Structure and the Surface Elements

The categories outline the contextual framework for our further investigation which will guide the case study analyses in the next chapter. The framework will be used to identify, compare and evaluate different design experineces in different projects, and to identify the concepts emerging under each category together with their context specific interactions. This would facilitate a deep understanding as to “how” and “why” design knowledge had developed into the final artefact.

CHAPTER 4

CASE-STUDY ANALYSES - THE ACQUISITION AND CONSTRUCTION OF DOMAIN CONCEPTS

> *We will not struggle to manage over things- we will manage within the unmanageable. We will not battle to organise the totality - we will organise within the unorganisable. We will not simply know things - but we will know of the unknowable.'*
> *(Flood 1999, p 3)*

This chapter reports on the process of developing a "knowledge framework" based on a comparative analysis of cases. We describe the acquision, analysis, conceptualization and construction of domain concepts in order to develop a *taxonomy* and a theoretical *model* which is a set of propositions expressing the relationships between these concepts. Rather than starting with a theory to be investigated, this chapter reports on the process of inducing a theory based on the comparative analysis of cases which represent the diversity and complexity of the knowledge content under study. The 5 interdisciplinary categories that have emerged in the previous chapter are used as a contextual framework for the selection and analysis of cases. The case study analyses aim to identify, explain and compare the unique ways in which different practitioners frame their design problems and the solutions, the terminologies they use to refer to specific concepts, and the tasks and procedures they follow in unique situations. Through the case studies we intend to:

- Identify the independent variables which cause the diversity in knowledge creation in free-form design
- Build a taxonomy of concepts which reflect this diversity
- Further clarify each category by grouping of concepts
- Identify the type and value of the relationships between concepts within and across categories
- Propose a structured framework of categories and concepts

4.1 CASE STUDY SET-UP AND CASE SELECTION

Case studies proved to be a helpful research method to investigate the contemporary phenomenon within its real life context "especially when boundaries between the phenomenon and context are not clearly evident" (Yin 1994, 23). A study of multiple cases have been carried out in order to cover the contextual conditions which is highly pertinent in the realm of free-form design. Following the grounded theory approach, we followed a comparative and explanatory methodology for the study of cases. In all of the cases, data is collected through a variety of methods: unstructured and semi-structured interviewing with the members of the design team, literature review, and participant observations. For the purpose of "grounded theory" building, we also included the literature as secondary sources of data collection for the cases, such as; quoted materials from interviews published in literature, field notes, and other descriptive materials concerning events, actions, settings and actors' perspectives. This triangulation across various techniques of data collection is particularly beneficial in theory generation, as it provides multiple perspectives on an issue, supplies more information on emerging concepts, allows for cross-checking, and yields stronger substantiation of constructs (Eisenhardt 1989; Glaser & Strauss 1967; Pettigrew 1990).

The selection of the cases have been guided by the contextual framework (consisting of 5 categories) which has been developed in the previous chapter, based on our initial inventory of cases and 2 design experiments. This framework helped us to focus our analysis, constraining irrelevant variation in our enquiry. Additionally, since these 5 categories covered a whole range of tasks from generation through realization, rather than focusing on the final product, we analyzed the project life-cycle in each case focusing on the processes and decisions which led to the final product.

Cases have been selected based on their high level of creativity with regard to the execution of the design process in each case by the introduction of new concepts and/or associations between existing concepts. Among a limited number of free-form design cases that have actually been realized, we further distinguished those which proved to have differences in terms of their independent variables. Independent variable is defined as the explanatory variable which cause an evident, perceptible change on the dependent variable. Therefore, the cases which showed the highest variety on the following independent variables have been given priority in our selection;

1) type of interdisciplinary organization and collaboration among the team members

2) design approach and methods

3) type and scale of the technology employed in the design process

4) scale of the project

We have selected 3 cases, each serving a specific purpose within the overall scope of enquiry. We started with the first case to fill the initial theoretical categories. Once a theoretical framework relating to the first case has been generated, additional cases are selected in order to extend and test the emerging theory by filling in categories that needed further refinement and development.

The first case is the Web-of-North-Holland (WNH), a temporary exhibition building built in Harlemermeer, in Holland, designed by the Dutch architectural firm ONL Architects. The second case is the Dynaform Pavilion, a temporary exhibition building built in Frankfurt, designed by the German architectural firm Franken Architects. The third case is the “Experience Music Project” (EMP), a museum building in Seattle, designed by the American architectural firm Gehry Technologies. These cases are not necessarily representative of an entire free-form design domain, and our aim is not to present the cases as generalizations. On the contrary, in addition to various similarities they exhibit, they also distinguish themselves with unique characteristics both on the formal and procedural levels.

The analysis is conducted based on the 5 interdisciplinary categories proposed in the previous chapter, namely;

- Form finding approach and formal characteristics
- Rationalization of the Structure and the Skin

- Representation and Exchange of Design Information
- Materialization of the Supporting Structure and its Elements
- Fabrication of the Supporting Structure and the Surface Elements

4.2 CASE STUDIES

4.2.1 Web-of-North-Holland (Oosterhuis NL)

Form Finding Approach and Formal Characteristics

The form-finding process of ONL is a hybrid process incorporating both digital and non-digital media. The complementary use of variant techniques is reflected in the design process of the project Web of North-Holland. This process starts with a free-form digital model which was initially created with computer sketches; splines and hand-drawn curves. The design was based on a topological surface model that governed the aesthetic continuity of the shape. The specific surface properties had been shaped together with milled physical models of the initial computer model and new adaptations to this model were combined with functional programme. This had facilitated further experimentation with the form. The styling requirements had been determined in a number of shaping rules for the design. The requirements of the internal programme had been incorporated to the shaping process during which the concave and convex areas on the surface and the folding lines that fade in and out of the surface had been critically monitored. Although the aesthetic properties of the final form reflects the stylistic approach of ONL, the form is not a fixed entity but is rather perceived as dynamic and responsive entity which re-generates itself in respond to the information that is embedded in the parametric model. The final form was composed of a single skin, double curved geometry which had further been smoothened in respond to materialization and performance criteria.

Rationalization of the Structure and the Skin

As described by Oosterhuis et al. (2004), the main decision at the macro level was to create a shape in which the surface and the structure would be aligned without the need for a secondary structure. For the rationalization of the surface, ONL applied a unique tessellating system, which is based on triangular grid of an icosahedron (a 20-faced polyhedron). This grid had been further refined by subdividing each of the main twenty faces into 36 smaller triangles (each edge subdivided into six edges) in respond to the allowable material sizes for each triangle for the cladding (fig. 4.1). The choice of this system had further been justified because of the regularity of connection details as well as directional uniformity it provided. After being twisted and deformed according to spatial and formal requirements, the warped icosahedron represented the initial structural model. For the rationalization of the structural form, taking vertical and horizontal slices along the irregular geometry was not considered because this would emphasize a certain directionality over the other, thus, would not conform to the architectural design intent.

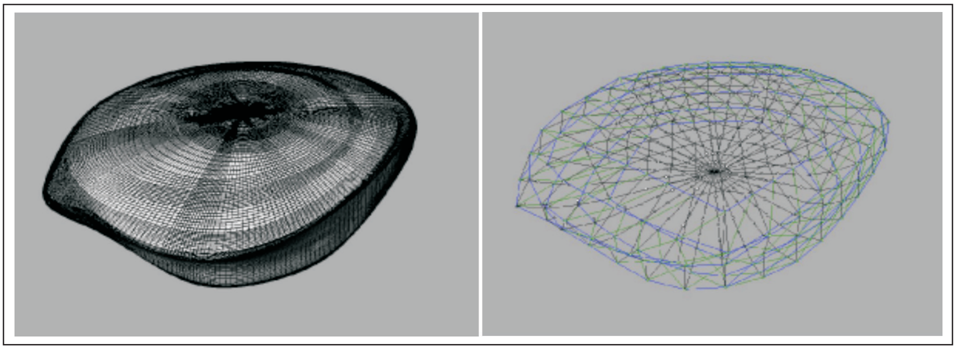


Figure 4.1: The tessellation of the NURBS surface into a triangular grid

Designing an additional supporting system to carry a fixed geometrical form was not considered either, due to the two layer construction it would require. On the contrary, the design team preferred to create a system which would integrate the structure and the skin. Thus, the main challenge for the design team was to design a structural system which could be continuous at every point and which could be adapted to any surface with complex geometry (Oosterhuis & Boer 2004). A 3D structural grid was created by mapping the icosahedron on the NURBS surface. To do this, a point map was created on the surface, each point representing a vertex of the structure, which was capable of describing the irregular (double-curved) surface. Form this point inwards, vectors were added to this structural grid (yet composed of lines) with normal lines perpendicular to the surface (fig. 4.2a). Then, the surface was offset inward of the two surface points over their respective orientations. These normal lines were combined together to form the supporting frame structure (fig. 4.2b).

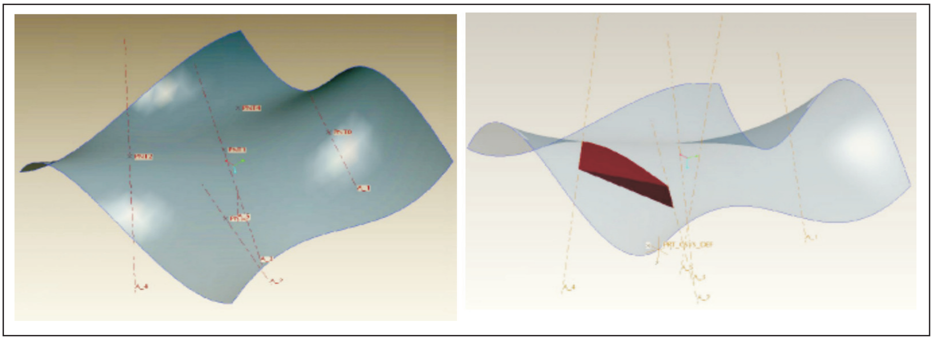


Figure 4.2: The generation of the structural frames. a) Left image showing the normal lines on the surface b) Right image showing the offsetting of the surface inward

However, when two non-parallel lines were combined, a challenge was presented. At this point, rather than combining the lines with a curved surface, a folding plate solution was preferred. The frames were at parts, simple flat plate and at some others, folded plates (fig. 4.3a). Each plate was folded over a diagonal. While the upper edge of the plate followed the exact geometry of the double-curved surface, the bottom edge was formed as a straight connection. Thus, the resulting structure was following a double-curved surface on the outside, while polygonal on the inside (fig. 4.3b).

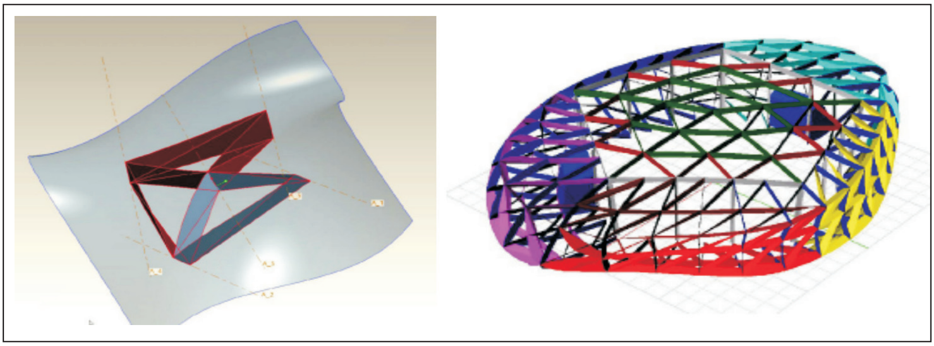


Figure 4.3: The generation of the structural frames. a) Left image showing the connection of the folded and the flat plates b) Right image showing the overall structural configuration generated by the architect

The innovation in this scheme was the orientation of the steel elements. The upper edge of each frame followed the curvature of the master form while the cross-section of each would be normal to the curvature at every point. This idea was developed as a solution to cope with the acute corners but was further developed to master the entire structural configuration.

Representation and Exchange of Design Information

After the initial shape was created as a NURBS surface, the architectural 3D data was sent to the CNC milling machine as .iges files for the solid prototyping of a foam model. After necessary modifications, the model was 3D scanned and the 3D data was updated accordingly. The master model was created in Rhinoceros which was chosen as the main design development software. The constraints from the manufacturer and the structural designers were integrated into the geometrical model parametrically within this software. For example, the changing joints at every intersection were parametrically defined in relation to its connection with the main structure. Due to the file exchange problems between the architects' and structural engineers' software, the direct digital communication of the 3D data was not possible. Therefore, the architectural office had to prepare an additional 3D model to be used in the structural engineering calculations, and which could be easily transferred to the engineering software (DIANA).

The architectural office also prepared all the digital information to be sent to the CAM process for the water jet-cutting of the steel frames and the cladding components. Before this, a mock-up model was created to confirm the exact place of each element. The architectural team wrote an autolisp to translate the three-dimensional master model to the two-dimensional drawings required for the 2D cutting of the elements. The autolisp took the elements from the 3D model, placed them on a reference plane, and flattened the elements to be cut while attaching all the relevant data associated with the element. The data for CAM process were prepared as .dxf extension files in AutoCAD. This had provided a continuous communication between the CAD and CAM software. For further communication of the design information between ONL and other design participants, an "Internet Versioning Server Software" was employed. Although the web-medium as a shared space was expected to provide ease of communication and exchange of information between the design participants, finding the right document among a database proved to be rather difficult and hard to identify. Furthermore, the documents mainly comprised of data which was lacking the necessary design knowledge

Materialization of the Supporting Structure and its Elements

The structural solution was developed as a steel frame, composed of planar elements creating triangular areas in-between. The technique that was developed by the architectural team, to generate the structural form, required variation in plate sizes. Similarly, the concept of structure was determined as every element would be differentiated according to their strength which required the thickness of the steel plates to vary. Therefore, the plate size and thickness had been crucial variables for the choice of a steel producer who would be willing to willing to vary between the given parameters. The structure as built was composed of a conventional post-and-beam steel structure, as a centrally placed pentagon form, with curved steel frames attached to this structure, radiating outwards around the circumference of the pentagon (fig. 4.4)[1] . The frames were laterally stabilized by steel plates creating an overall triangulated frame structure. Some of the plates were folded, where necessary, to comply with the original master geometry of the surface. The roof of the structure was also constructed in a similar way, the geometry of which was quite close to that of a flat roof. Since the building was originally aimed to serve as an open building - the rain could fall through - there was no need for any complicated waterproofing or insulation detailing.

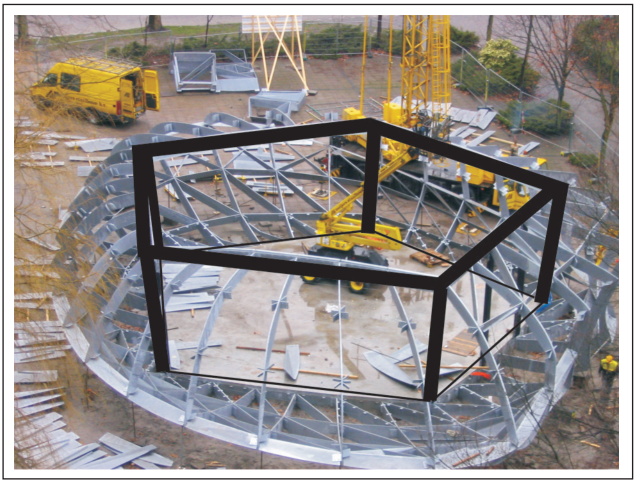


Figure 4.4: The curved steel frames attached to the inner columns

An aluminium laminate material called "hylite", produced by Corus group, was used. Hylite consists of aluminium on both sides and polyurethane in the middle. Although the material looks like aluminium, it works like a polymer in terms of flexibility and bending capacity. The material was flexible enough to get curved and fit inbetween the triangular areas of the steel structure.

---

[1] This particular picture was taken during the re-construction of the building in Delft (two years after the original building had been dismantled), to be used as a research laboratory as part of the Faculty of Architecture, at Delft University of Technology.

Although the building form was conceived and rationalized as a continuous surface, that would be supported by a continuous structure, the actual structural solution with five central columns, and the rather conventional methods of construction defied the initial tectonic quality as envisaged by the architectural office. According to the architects, this was mainly due to the lack of experience of the engineering office with no similar previous experience working with such unconventional building forms, which was also the main reason for a lack of creative collaboration between the architectural and the engineering offices.

Fabrication of the Supporting Structure and the Surface Elements

The structural steel plate elements were all CNC water-jet cut (fig. 4.5a). The frame structure was assembled in the factory to check the accuracy of the geometry and the tolerances at the joints and bolt holes (fig. 4.5b). Then it was de-assembled to be transported to the construction site in pieces.

Figure 4.5: The production of the steel frames a) Left: The CNC-cut frames b) Right: Assembling the structure in the factory

Every triangular hylite element (surface cladding) was also unfolded and water-jet cut. A company that was specialized in stretching, unstretching and unrolling flexible materials provided ONL with the software to perform this process. The claddings after being CNC-cut according to the geometry of each triangle were later cold-formed so as to fit the surface geometry and were all mounted on site. Since the corners of the claddings were bent to fit the geometry, unexpected distortions and displacements occurred at the middle part of these surfaces which caused unexpected changes in the geometry of the overall form. The information regarding the response of materials to various forming processes has proved to be essential to avoid the unexpected differences between the “designed” and the “constructed” form.

4.2.2 Experience Music Project (Gehry Technologies)

Form-Finding Approach and Formal Characteristics

Gehry's design process is based on formal investigations with sketches and craft hand-built physical models integrated with post and pre-digital adaptations. The physical models employ a variety of materials (e.g. paper, wood, plastic, metal, wax infused velvet). The firm has a specific approach to the design and production of free-form surfaces generally referred as "paper surface forms" or "sheet metal surfaces". The shapes and materials bent into these shapes may be formed without the need of stretch forming that would produce in-plane plastic deformation on the material. The surfaces created and constructed in this fashion define both the exterior and the interior surface qualities of Gehry's double-skin buildings. The surfaces of the initial models are captured in CATIA by using 3D scanning, at an early stage, in order to produce paper templates that facilitate the construction of the physical models. A final design model (more in line with the initial sketches) allows more precise structural development, as well as the development of the details relating to cladding, fenestration, material selection, etc. This hybrid process with the computer contributing to the design process models allows the precision of the digital model to be supplemented with the tactile feedback of working directly with materials. Once the final design model is complete, it is translated into a digital model through digitizing.

Rationalization of the Structure and the Skin

The rationalization of the surface geometry in Gehry's work is formulated as a constraint conditions either in the form of developable surface forms or Gaussian curvature constraints (Shelden 2002). Gehry's Bilbao Guggenheim project comprised primarily of "ruled-surfaces". This implies that structures can be framed conventionally with straight members and the skin warped to fit the design intentions. EMP's constantly changing curvature in all directions prevented this approach. The original surface of EMP (fig.4.6) was rationalized into conformance with the Gaussian curvature analysis (fig. 4.7). The analysis produced a drawing that indicates, through various colours, the extent of curvature of different areas on the surface of the building to work out the curvature problems by changing the shapes of the pieces (Linn 2000). The fully curved free-form shapes of the original design were supported as a composition of "Gaussian curvature" constrained "paper surface" forms.

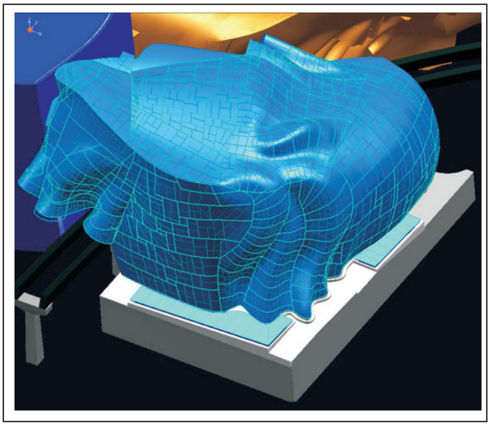


Figure 4.6: The initial surface model of one of the building blocks of EMP

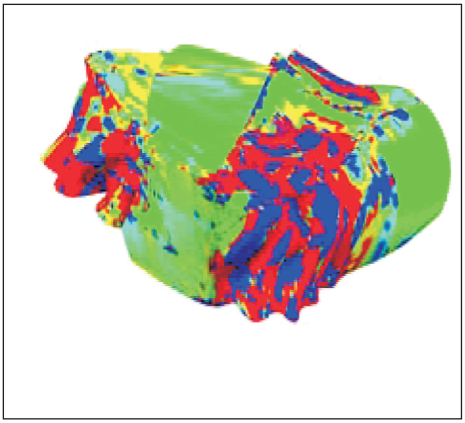


Figure 4.7: Gaussian curvature analysis applied on the surface

These constraints approximate the initial surface curvatures according to constructability constraints. For Gaussian curvature controls, a wide range of material and fabrication facts have been integrated into the allowable surface description. Continuously curving skeleton ribs were chosen as the form of the supporting structure. The geometry of each and every rib has been shaped by the architect's team which later had to be smoothed and adjusted based on what could be fabricated from a curvature standpoint (fig. 4.8). The generative studies to rationalize the surface (by dividing into pieces) attempted to optimize the layout of the face sheets on individual panels, on the basis of available material sizes (fig. 4.9).

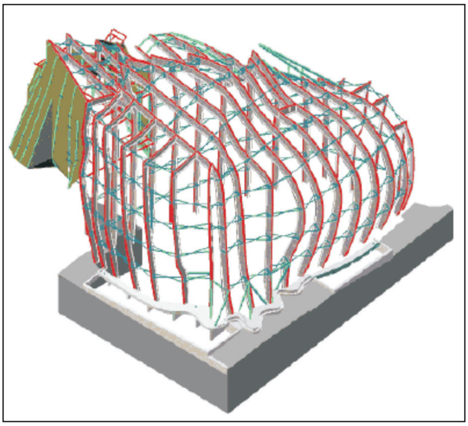


Figure 4.8: The supporting structure

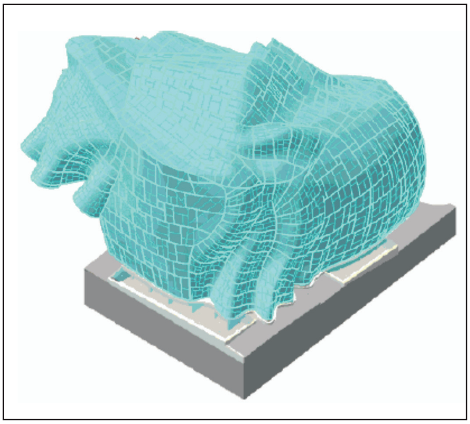


Figure 4.9: Surface subdivision

The design for the composition of the metal surface shingles in the EMP project utilized generative shape grammar algorithms. This grammar has its origins in shape grammars, a rule based system that can be used for composition. Various subdivisions were applied to the design development models. All possible sheet configurations were tested for the given panel dimensions and the material sheet size (Shelden 2002). A set of rules imposed by the fabricator on the panelling system organization was substantially extended. These additional constraints resulted in requirements that could not be addressed by a completely automated approach. Skin options had to be examined not just from a fabrication point of view but also for loading, attachment to the structure, affect on system performance, etc. The size of each individual skin, “shingle”, was determined through a program that analyzed the buckling capacity of the chosen skin material when warped in two directions. Thus, the complexity of the cladding system organization is directly related to its response to these design and performance requirements.

Representation and Exchange of Design Information

Various design process models tested the material possibilities and formal arrangements contributing to the design development which also operated as a collaborative environment facilitating interaction between the project architects, the design team and the client. The physical models had been translated into the digital medium with varying techniques. It was either the ruling lines (if the surfaces were developable), or topographical sectional contouring lines, or the points of a superimposed grid of the surface taken as reference points. Once the points, which generally describe the curves, were established in the digital model, a surface was created that tried to coincide with the points. Three digital models were produced; a surface model, describing the exterior surface, a wire-frame geometry model, usually describing the structural grid and organization, and an interior surface model. When the complexity of the free-form geometry was mathematically described, then the “rules of constructability” were introduced into forms (Shelden 2002).

The wire-frame master models formed the basis for the CATIA master model, becoming the single source of information. That information then became the database for all geometrical control on the project. It has been exchanged electronically among the project participants, ensuring continuity and facilitating communication of vital information to all the team members, including the contractors.

Materialization of the Supporting Structure and Its Elements

The structural system incorporated 240 individual curving steel beams, covered by mesh, then a 5 inch layer of shotcrete over welded wire fabric (fig. 4.10). This created a steel stiffened concrete shell. The entire structure was then coated with waterproofing membrane. An elaborate system of 5 inch diameter steel pedestals of varying lengths were attached to the ribs, to support 3000 panels of steel and aluminium skin (comprised of 21000 individually shaped shingles) and to resolve the difference in geometry between the structure and the skin (fig. 4.11).

Figure 4.10: The curving steel beams

Figure 4.11: Steel pedestals

The structural system was undertaken at a time when the material type and quality to be used for the building's skin, and the details of the cladding system had not yet been determined (Magnusson 2001). Once the cladding system was designed, its organization had to be integrated with the already designed structural system organization. The panels were connected to (and supported by) a system of segmented tubes which span between the ribs of the structural system. The structural requirements imposed numerous additional geometric rules on the layout of this tube system. At the same time, the tube layout had substantial implications on the surface pattern, changing the panel connection details at certain intervals. The major challenge of the system became fitting the system of tubes to the small interstitial space between the design surface and the already existing geometry of the structural rib and concrete shell (Magnusson 2001).

Fabrication of the Supporting Structure and the Surface Elements

CNC guided plasma cutters were used to cut the flanges of the curving structural steel members. CNC rolling machines were used to bend the flanges, and an automated trolley, which ran along the flange, welded the assembly together. Shotcrete and waterproofing were applied to reinforcing steel overlaid with stainless-steel hardware cloth. The skin was applied on-site wherever curves were extremely complex. The surface was pre-fabricated as a panellized system, rather than being constructed on-site. The panels were formed as a box configuration of planar, CNC cut fins that respond to the curvature of the CATIA surface model. Each panel was bolted to the aluminium pipe girds which were carried by a tube system (figures 4.12 and 4.13). Face sheets of the finish metal were pressed and fastened onto these fins. The software driving the CAM machines was capable of optimizing the layout of shapes on each sheet to minimize waste. The manufacturer was able to substantially automate the fabrication of metal components. An automated panel layout program (ZAPLA), written in a parametric modeller (Pro-Engineer), generated panel component geometry from the surface model and panel/face sheet boundaries provided by the architectural team. Flattened profiles for each CNC cut elements were also generated by the program.

Figure 4.12.: The panel system

Figure 4.13: The tube system supporting the skin panels

4.2.3 Dynaform (Franken Architects)

Form-Finding Approach and Formal Characteristics

Franken’s form generation process is based on constant interaction of the designer with the computer in the digital medium. The final form is a continuous double curved skin, which becomes a frozen instance of a continuous deformation process. Instead of merely creating a pre-conceived form, “the form is born through the constant interaction of designer and computer” (Franken 2002). In Dynaform project, the building form was generated by using an animation software (Maya) using force-field simulations which interactively generated the form. The architect parametrically defined the basic object, its form generating laws, specific boundary conditions and force fields that transformed the object. The software used had the ability to simulate, following physical laws, the changes in the shape of an object subjected to force-fields. The designer, in such a process, specifies the form generating rules, specific boundary conditions and forces. These forces, however, are not related to the structural performance related gravitational forces, but rather the forces created by a conceptual vehicle moving through a virtual matrix of parallel lines. Finally, A single layer skin defined the generated form – “the master geometry”.

Rationalization of the Structure and the Skin

The supporting structure was required to follow the exact geometry of the architectural form. Therefore, the structural engineers focused on two alternative approaches for the materialization of the form and for the development of the structure. First option was to design a system of linear or curvilinear structural members that would support a secondary and non structural skin. Second option was that the skin itself would be the primary load-bearing system and act as a surface structure with a shell-like behaviour.

One of the primary determinants in finding the form of the supporting structure was that the structure should follow the exact curvature of the master geometry. And at the same time, it should leave room to the architect for formal developments during the design process (Grohmann et al. 2004b). The architects and engineers jointly decided to design a series of primary steel frames. The structural frames were generated by taking 16 cross sections from the master geometry each section taken at a different angle, and each resulting in a unique shape, and each following the outline of the master geometry – dynaframes, as the primary structure (fig 4.14). The inner and the outer lines were connected at regular intervals in order that the structure could work as a Vierendeel Truss (fig. 4.15). Each of these Vierendeel frames was completely different shaped.

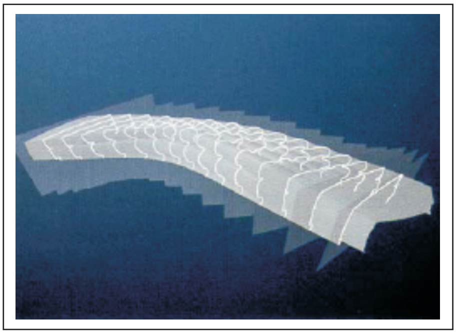


Figure 4.14: The outer lines following the master geometry

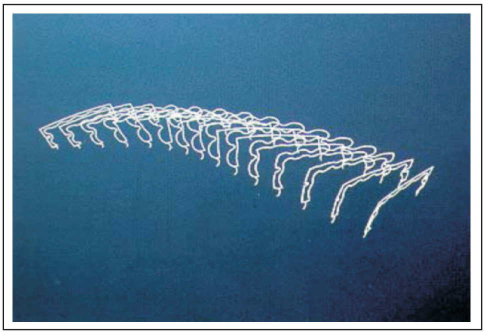


Figure 4.15 The vierendeel truss system

The surface rationalization was performed after the structural form, system and materials were already decided. The special material properties of the surface material (membrane) and its connection toh the supporting structural frames were the main determinants of the rationalization process. The decision was made to integrate the skin and the structure in a configuration where the dynaframes divided the skin into 16 segments. The division of each segment into individual fields was accomplished according to the design intentions, transportability and practicality. For each step, the peculiarities of the weave, the layout of the fabric section, and the interfacing with the support construction had to be taken into account. If double axial curves were allowed in a structure comprised of various membrane fields, each field would begin to buckle and the structure would appear bulky (Brauer 2002). Therefore, unlike other typical membranes and pre-stressed cable-nets, the membrane was decided not to have a two directional curve. And in turn, the individual membrane segments between the frames displayed an arbitrary curvature, varying from field to field.

The engineers first translated the structural form of each membrane segment into separate surfaces relatively true to architects' original form. They then divided the surface into cylindrical, conical and flat surfaces. Although the entire surface was re-constructed out of ruled surfaces, it gave the impression of a double-curved complex geometry at the macro level. This was due to the multiplicity of the geometrical forms employed.

Representation and Exchange of Design Information

The initial master geometry was a double-curved surface without thickness. Then a number of derivatives were generated from this surface to create elements suitable for building. The derivatives were rendered images, the structural engineers' calculations by FE analysis, or the two dimensional sections as CAD drawings. However, the master geometry could not be changed, only its derivatives (nth factor) could be used instead. A full-size mock-up of several structural frames had been produced enabling the design and construction team to study the required assembly time and procedures as well as to identify and resolve possible problems with regard to the connections between the components (Kloft 2005)

No existing software met all the demands of the project. While the form generation was done by MAYA, the structural engineering calculations were carried out in Ansys and R-Stab, Mechanical Desktop (a mechanical engineering add-on for AutoCAD), and Rhinoceros were used to develop the lead bearing structure. Some structural elements could only be worked out in CATIA. Separate data post-processing had to be programmed for the CNC machines that could understand the machine code. Because of the variety of the programs and operating systems, it has been decided to use an interface format – a protocol - instead of a mandatory program for all design participants. The protocol facilitated communication and data viewing for all parties involved. The interface formats were chosen as IGES for all 3D data and DWG for all drawings. A joint 3D computer model containing all necessary information for production and assembly, beam axes and profile directions had been formed during planning, and had been continuously modified and adapted to meet production requirements in consultation with the contracted firms. The files were exchanged on the internet. The complete 3D data was stored in an internet server which informed all participants by e-mail or by fax for data updates.

Materialization of the Structure and Its Elements

Due to the extremely short construction period, they decided to separate the structure and the skin by designing a primary load-bearing system of welded steel frames and a secondary pre-tensioned membrane layer. Since the structural system could not change the form, the load bearing system had been continuously altered until a suitable system was found for the master geometry. Before the structural engineers came up with a supporting structural system for the building, they performed various FE-analyses regarding the strength of complicated geometries. The initial approach was to check if the form could support itself without further elements, as in a shell system. Given the scale of the building, another structural system – ribs – were incorporated into the structure. The structure was composed of 15 unique steel frames covered by a semi-structural membrane skin. Each individual frames was made from rectangular hollow steel profiles, individually cut from plates and welded together. Each of these frames had the same width of 22 cm while their thickness varied to suit the structural requirements. Since the engineers could not optimize the structure geometrically through shape modification, high local forces and bending moments had to be accepted into the system to comply with the geometrical constraints introduced by the architect.

The main frames were coupled in longitudinal direction by tubes for the longitudinal stabilization of the building. They were arranged along the folding lines of the building skin. Because the outer skin was derived from a bundle of tubes this surface was curved in one direction only. With a span of more than 8 m it was a challenging task to find a way to span the membrane in only one direction without sagging. Several test assemblies had to be done to find the optimum combination between the appropriate compensation and pre-stressing. Special attention had to be given to the detailing of the connection between the membrane and the steel frames.

Fabrication of the Supporting Structure and the Surface Elements

The steel members for the frames were flame cut from flat steel frames (fig. 4.16), then bent into shape and welded together (fig. 4.17).

Figure 4.16: Sheet steel cut with flame cutters

Figure 4.17: Steel plates welded together to form the vierendeel truss

The main challenge for the contractor was to maintain the tight tolerances while translating the 3D data into a built form. The flanges were all rectangular cut and had to be rolled according to the curvature of the top and bottom outlines of the boxes. More than 30.000 individual pieces were cut using computer-driven-plasma-cutters (Seele 2002). Due to the size limits of the cutting machines, individual pieces were welded by hand with tight tolerances.

In order to give the desired uni-axial curved affect to the membrane surface, an opaque PVC-polyester fabric had been pre-stressed in the warp direction between the steel frames, avoiding any stress areas in the weft direction (fig. 4.18) (Wilhelm 2002). This would avoid any curvatures running in the opposite direction. The individual membrane sections were tied to the load bearing frames with girds, each with a movable joint allowing moment-free connection at the membrane edge. The mechanical characteristics of the membrane were determined by simulating various load situations. Both mock-up tests and these analyses served as a basis for the calculation of the cutting patterns for the fabric.

Figure 4.18: PVC-membrane pre-stressed between the steel frames

4.3 THE IMPLICATIONS OF THE SOCIO-ORGANIZATIONAL CONTEXT AND TYPES OF COLLABORATION

As has been observed in the case studies, digital design strategies are based on dependencies between the generative design and the actual production processes. While the design does not require to be controlled entirely from the top down and making does not necessarily proceed sequentially from the bottom up (Kieran & Timberlake 2004). The expert knowledge and experience of all relevant disciplines can be used as a collective source of inspiration and input which can be exchanged throughout the entire life cycle of a project. While it is true that the design phase precedes and informs the construction, it is the later phases that inform the design phase concerning what it can and ought to do. The input received from fellow collaborators may trigger new, innovative solutions, or combinations not seen earlier. In this form, collaboration becomes an instrument for creation of new knowledge (Kalay 2004).

The evolution of the final artefact and the creation of new concepts and links between them in each project have been observed to be highly influenced by the following factors;

- socio-organizational structure and the varying degrees of collaboration among the stakeholders
- design approach of the architectural team
- technical availabilities
- budget of the project
- experience/familiarity of the stakeholders with the design context.

Among these, the "collaboration type" and "the experience/familiarity" of the design team with the design context have been posited to have a direct impact on creativity, collaborative knowledge generation and the evolution of the final artefact.

The collaboration between the project participants may take many forms, at different stages of the design and realization process. The design and realization (although in a cyclical loop mutually informing one another) may be at two separate ends in terms of knowledge integration. The realization of a product after the form is fixed, and the necessary processes to realize this product requires different type/degree of collaboration than a design approach in which realization knowledge is embedded early in the form generation. Similarly, the involvement of the domain holders during the earlier stages of the design process, and how the information within and across domains are integrated into the design process varies. The degree of this integration resulting in the creative act can be directly linked to, among others, the earlier experiences of the stakeholders in similar projects, the contractual relationships (assigning strict roles to the stakeholders), and the availability of common data exchange platforms. The following section will evaluate the different forms of knowledge integration and collaboration in each of the project and the degree to which the team members in each project contributed to the artefact evolution and knowledge generation.

WNH

ONL's approach is based on sharing and integrating interdisciplinary knowledge early in the form generation and development process which is orchestrated by the architectural office. However, such integration, in the Web-of-North-Holland project, has been mainly based on social interaction rather than a digital platform. The incompatibility of the software between the architectural and the engineering office, the lack of experience of the engineering firm in such projects, and the traditional contractual relationships which limited the responsibilities of the project participants had a direct negative influence on the knowledge integration and on the design process including the final form. The contribution of the structural engineering firm in the generation of the structural form was limited to providing information on the minimum thickness of the planar steel frames and the cross-sectional length of frames at the nodal intersections. This information was integrated into the parametric design model manually by the architectural firm, as performance parameters, which contributed to the evolution of the final model based on the given criteria. In contrast to the engineering consultants, the architect and the steel manufacturer had a notable collaboration concerning both the decision process, 3D-2D data flow, and the final production process. The manufacturer had a direct influence on the evolution of the final building form.

EMP

Gehry's design aesthetic tends to favour innovation of fabrication over that of engineering (Shelden 2002). These intentions have resulted in unusual contractual relations with the fabricator in which the fabricators work directly with the architect and the engineers of the design team, and are directly involved in the design development phase where they assist the creative act. Another indispensable requirement of these contractual agreements is that both the fabricators and the engineers should have the necessary skills and expertise to operate CATIA and to deal with the 3D CAD models. When this could not be possible, as occurred in many previous projects of the firm, extra construction administration roles were left to the architect's team. In EMP project, the fabricator was not only responsible for the generation but also for the execution of the building skin. Zahner's firm designed and installed the skin as a design-build contractor, worked in close collaboration with Wallace Engineering, to create the metal panel details, while developing software that would use CATIA's digital model of the building's surface to drive CNC (computer numerically controlled) machines to manufacture the metal panels. In the same project, engineers' contribution to the creative act, however, was less clear and minimal. In Gehry's work process, the main role of the engineers is to provide flexibility to the architects to make the necessary geometrical changes on both the interior and the exterior forms of the building. Such a role definition for engineers is apparent on the tectonic qualities of many buildings designed by Gehry. The EMP project is yet another example where the main role of the structural system is to support the expressive forms of the interior and the exterior surfaces.

Dynaform

In Dynaform project, the digital workflow redefined not only the working method of the planning team but also gave new roles to both the architect and the engineers. The architects from ABB/Bernhard Franken and the engineers from Bollinger+Grohmann worked as a team from the very beginning. Although there was no special contractual arrangement between Franken and Bollinger-Grohmann and they were both traditionally contracted by the client, the high level of trust between both companies allowed the desired collaboration with shared responsibilities starting from the early stages of the design process. Because of the variety of the programs and operating systems, an interface format was used. The protocol facilitated communication and data viewing for all parties involved. A joint 3D computer model was constructed during planning, and continuously modified and adapted to meet the production demands in consultation with the contracted firms. By collecting constant feedback from the construction firms, all relevant information was gathered at Bollinger+Grohmann, as the main orchestrator of the project information. Following the demands of the structural calculations, the engineers converted the 3D model of the architects into an extensively developed spatial construction model containing all necessary information for production and assembly. It also contained information about material strengths, and in agreement with the architect, the formal and economical smoothing of the surface contours. The initial shape generated and fixed by the architect had been a challenging task for the engineering and the production teams to be creative in their solutions in support of the architectural design idea. In this project, although the contribution of the engineers and manufacturers were minimal to the evolution of the architectural form, the realization of this challenging form could not be possible without the successful collaboration between all the parties involved in the design and production processes.

4.4 DATA ANALYSIS, CODING AND THEORY BUILDING

This section will give an account of how the data collected throughout the case-studies have been analysed and conceptualized. The theory is built with actual incidents and activities as observed during case studies; referred as the "raw data". The raw data is extracted and analyzed as the potential indicators of the specific knowledge elements of free-form design. The raw data are then given conceptual labels, in other words: they are conceptualized (coded) into "concepts" which are used as the basic units of our comparative analysis. These concepts are clustered into conceptual sub-categories under each main category, which define the context of our focus. For the ease of representation, the main categories are labelled into the following terms, as will be consistently used in the following sections:

- *DESIGN INTENTIONS* - Form finding approach and formal characteristics
- *REPRESENTATION* - Representation and Exchange of Design Information
- *MATERIALIZATION* - Materialization of the Supporting Structure and its Elements
- *RATIONALIZATION* - Rationalization of the Structure and the Skin
- *FABRICATION* - Fabrication of the Supporting Structure and Surface Elements

The data to be collected has been identified according to the degree that it indicates a specific formal and/or procedural concepts of the free-form design domain. As for the number of data to code, they are collected both for existence and for the frequency of occurrence. In data collection, the decision with regard to how to distinguish the concepts (level of generalization) becomes crucial. The level of generalization is the decision concerning whether to code the data exactly as they appear, or to record them in different forms. The concepts (variables) are labeled according to the common terminology used by interviewees (practitioners) in their perception of the phenomenon, with an attempt to best represent the context to which they apply. In this way, the theory building could be based on the free-form design context and could fulfil the following criteria for a grounded theory: generality, relevance, fit (valid), and modifiability (control) (Glaser & Strauss 1967).

1. Generality entails that the theory is applicable in a variety of contexts
2. Relevance entails that the theory be comprehensible to all involved in the area of study

3. Fit entails that the theory fits the substantive data.
4. Modifiability entails that the theory anticipates possible confounding variables that may be brought up by challengers to the theory, thus it should be modifiable.

The coding of the data into “concepts” was conducted with an attempt to make the concept explicit, and then to generalize it according to its frequency of occurrence in other cases. For example, although the “hylite” was used only for the WNH project, it has been identified and collected as a valuable data for it has specifically been produced to form into complex shapes. Additionally, the response of the material to “cold-forming” technique is observed to represent a crucial and generalizable knowledge content with the potential to be used in different free-form design contexts. Consequently, the concepts arising under each category have been selected and identified not only based on their individual meaning but also with regard to their interactions with other concepts. Furthermore, the concepts which proved to share the same meaning have been coded into one single concept to represent the similar content.

It is also important to note that the collection, coding and analysis of data have been an iterative and comparative process in order to test and extend the provisional concepts which have been generated throughout the whole study. The next section will provide an account of this comparative analysis during the acquisition and construction of a body of concepts across 3 cases.

4.4.1 Acquisition/Construction of Concepts Through Content Analysis

The main method used for the acquisition and construction of concepts was the manual coding of documents and transcripts to obtain the words and word-phrase clusters for further analysis and comparison. The coding has been conducted parallel to a horizontal and vertical analysis of cases. With horizontal analysis, the concepts and their interactions with other concepts have been identified within the specific context of each case. In addition to this, the vertical analysis facilitated a comparative study of these concepts across cases – in different contexts of use – in order the understand the hierarchical relationships between concepts at different levels of generality. The following section exemplifies the coding process and the horizontal analysis of a partial transcript given for each case.

The following figures (fig. 4.19, fig. 4.20, fig. 4.21) depict a partial transcript analysis of the WNH (fig. 4.22), EMP (fig. 4.23), and Dynaform (fig. 4.24) projects. Each text depicts how the concepts were interconnected either to formulate or to solve a problem during the design process. In each text, the words and phrases are either clustered into one concept (terms in parenthesis) or, alternatively, are taken as they appear within the text (highlighted text) in accordance with their meaning within the specificity of each context. What each concept refers to (e.g., method, a process, a task) and its frequency of occurrence in other cases are the two determining factors for the labelling (coding) - the level of generalization used to identify the concept. For example, "the aligning of the surface and structure" is a concept which is a decision concerning the *Rationalization* of the structure and the skin.

The decision to integrate or separate the skin has been frequently encountered during the case studies which signifies the possibility of a generic decision process in Free-Form design. Therefore, it is generalized into a more general concept. On the other hand, 'hylite' refers to a specific material which is defined as a concept under the *Materialization* category, and is taken directly from the text as it appears, most likely as an instance of a larger group of concepts. The degree to which each concept may be generalized and labelled in a larger context have become more clear after the cross-case comparison and, accordingly, the comparative levelling of the concepts, which will be described later in the "vertical analysis" section.

The main decision at the macro level was to create a shape in which the **surface and the structure would be aligned (SKIN/STRUCTURE INTEGRATED)** without the need for a secondary structure…………. The final form was composed of a **single skin**, **double curved geometry** which had further been smoothened in respond to **materialization** and performance criteria………. For the rationalization of the surface, ONL applied a unique **tessellating** system, which is based on **triangular grid (TRIANGULATION)** of an icosahedron (a 20-faced polyhedron)………. A 3D structural grid was created by mapping the icosahedron on the **NURBS** surface……….The choice of this system had further been justified because of the **regularity of connection** details as well as **directional uniformity** it provided……….When **two non-parallel lines which are not in the same plane were combined (DEVELOPABILITY)**, a challenge was presented. At this point rather than combining the lines with a curved surface, a **folding plate** solution was preferred….Every triangular **hylite** element (surface cladding) was also **unfolded** and **water-jet cut**…. Since the corners of the **claddings were bent (COLD FORMING)** manually to fit the geometry, unexpected distortions and displacements occurred at the middle part of these surfaces which caused unexpected changes in the geometry of the overall form.

Figure 4.19: Extraction of domain concepts (WNH)

The firm has a specific approach to the design and production of free-form surfaces generally referred as "**paper surface forms**"………. The shapes and materials bent into these shapes **may be formed without the need of stretch forming (DEVELOPABILITY)** ……….. The surfaces created and constructed in this fashion define both the exterior and interior surface qualities of Gehry's **double-skin** buildings **(MULTI-LAYER SKIN)**………. The surfaces of the initial models are captured in CATIA by using **3D scanning**, at an early stage………. The original surface of EMP was rationalized into conformance with the **Gaussian curvature analysis**………. The fully curved free-form shapes of the original design were supported as a composition of Gaussian curvature constrained paper surface forms………..The generative studies **to rationalize the surface (SURFACE RATIONALIZATION)** attempted to optimize the layout of the face sheets on individual panels, on the basis of available **material sizes**. Skin options had to be examined not just from a fabrication point of view but also for loading, attachment to the **structure (STRUCTURAL SYSTEM)**, affect on system performance, etc……….. **CNC guided plasma cutters (CNC-CUTTING)** were used to cut the flanges of the curving structural steel members. **Shotcrete** and waterproofing were applied to reinforcing steel overlaid with stainless-steel hardware cloth.

Figure 4.20: Extraction of domain concepts (EMP)

The final form is a **continuous double curved skin (FORMAL INTENTIONS)**, which becomes **a frozen instance of a continuous deformation process (DIGITAL MODELLING)**. The **supporting structure (STRUCTURAL SYSTEM)** was required to follow the exact geometry of the architectural form……….. The structural frames were generated **by taking 16 cross sections from the master geometry (SECTIONAL CONTOURING)** each section taken at a different angle, and each resulting in a unique shape, and each following the outline of the master geometry……….. The special **material properties** of the surface material (membrane) and its connection with the supporting structural frames were the main determinants of the **surface rationalization (CLADDING ORGANIZATION)**……….. The engineers translated the structural form of each membrane segment into separate **cylindrical, conical and flat surfaces (RULED SURFACES)**……….. A full-size **mock-up (PHYSICAL MOCK-UP)** of several structural frames had been produced. enabling the design and construction team to identify and resolve possible problems with the **connections between the components**. The flanges were all rectangular cut **(CROSS-SECTION)** and had to be **rolled (COLD-FORMING)** according to the curvature of the top and bottom outlines of the boxes and the individual pieces were cut using **computer-driven-plasma-cutters (CNC-CUTTING)**

Figure 4.21: Extraction of domain concepts (Dynaform)

4.4.2 Meta-Analysis

In each of the three cases analyzed, the overall design process displays a continuous negotiation and reconciliation between multiple perspectives utilizing multiple terminologies expressing the needs of a multi-disciplinary team. We created a meta-analytic schedule, which is a cross-case summary table in which the rows are case studies and the columns are the variables identified each category. The purpose of meta-analysis is to allow us to use the summary of case studies to make theoretical generalizations. Table 4.1 shows the collected concepts (variables) from each case after a comparative study.

	RATIONALIZATION	MATERIALIZATION	REPRESENTATION	FABRICATION	DESIGN INTENTIONS
EMP	Gaussian Analysis Curvature Constraints Surface Sub-Divisions Surface Pattern Framing	Composite Action Sheet Metal Concrete Shell Geometry of Skin Geometry of Structure	Surface Model 3D Scanning Point Data Paper Surfaces Master Model Parametric Modeller	Shotcrete Spraying Plasma Cutter CNC cutting Forming Process	Paper Surfaces Multi-Layer Skin Physical Models Exterior/ Interior Surfaces
WNH	Triangulation Skin-Structure Integrated Tessellating Sectional Contouring Irregular Cladding Division	Planar Elements Frame action 3D Structural Grid Primary Structure Hylite Triangulated Frame Structure	Developability NURBS Unfolding 3D Scanning File Exchange Protocol Mock-up Model	Unfolding Water-jet Cutting Solid Prototyping Cold-Forming CAM Processes	Directional Uniformity Single Layer Skin Parametric Modelling Hand-Drawn Curves Double-Curved Directional Uniformity
DYNA-FORM	Skin-Structure Integrated Irregular Subdivision Curvilinear Structural Members	Steel Thickness Vierendeel Truss Semi-Structural Membrane Varying Thickness	Ruled Surfaces Wireframe Model Master Model Full-Size Mock-up Interface Format	CNC cutting Manual Forming Machine Code Fabrication Tolerances	Fixed Form Digital Modelling Parametric Design Single Curved

Table 4.1 A summary of the case studies with extracted concepts[2]

---

[2] The table is indicative rather than final. New concepts have been re-generated and re-named recursively, by continuous comparisons between higher and lower levels concepts extracted across the categories.

Categories consist of similar concepts that have similar properties. Properties are characteristics that are common to all the concepts in a category. This has been followed by a vertical and horizontal analysis across the columns and the rows of the meta-analytic table.

4.4.3 Horizontal Analysis

The horizontal analysis serves to formalize and compare the strategic and situational interrelatedness of the concepts within and across categories for each of the 3 projects studied. Horizontal study is conducted to analyze the interactions of context specific design concepts and the emerging links between them, which are identified as the main sources of emerging design knowledge. This will facilitate a deeper understanding of how concepts are linked at different levels of abstraction; how strong these links are; how do the value, strength and direction of these links vary. The horizontal study is conducted parallel to the vertical study to improve the terminology and sub-category descriptions under each category. While the content analysis aims to extract the concept vocabulary of the domain in each case, the horizontal analysis aims to understand the value, strength and direction of the links between the concepts in each project. The horizontal analysis is directly taken from the content of the text and is graphically illustrated for each case separately, as shown in the figures below (fig. 4.22, fig. 4.23, fig. 4.24).

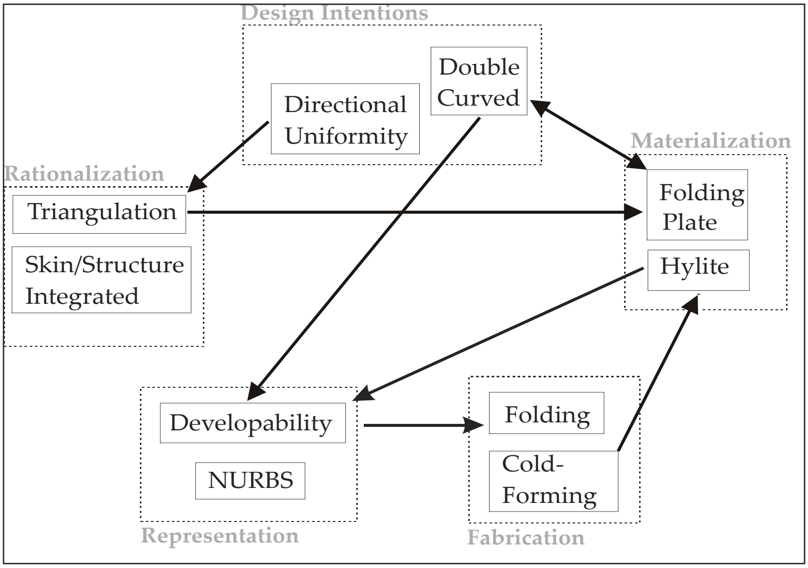


Figure 4.22: Horizontal Analysis for WNH showing the interactions of the concepts across categories

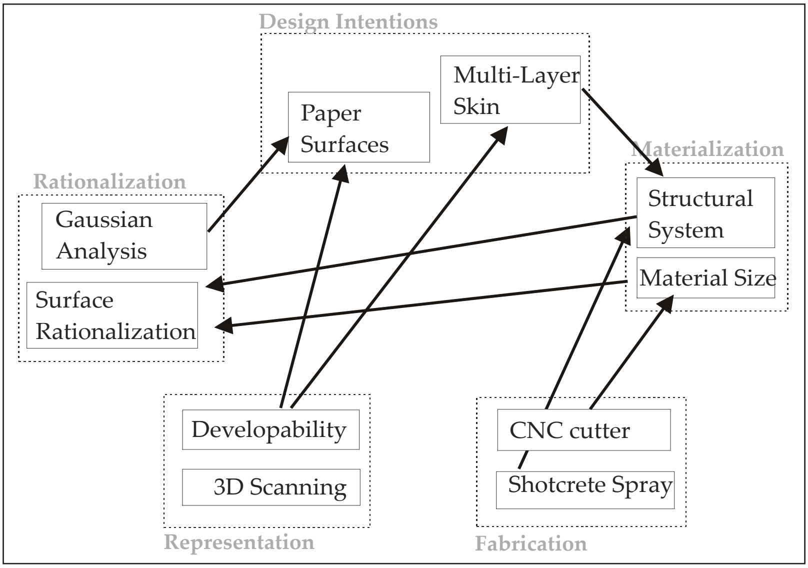


Figure 4.23: Horizontal Analysis for EMP showing the interactions of the concepts across categories

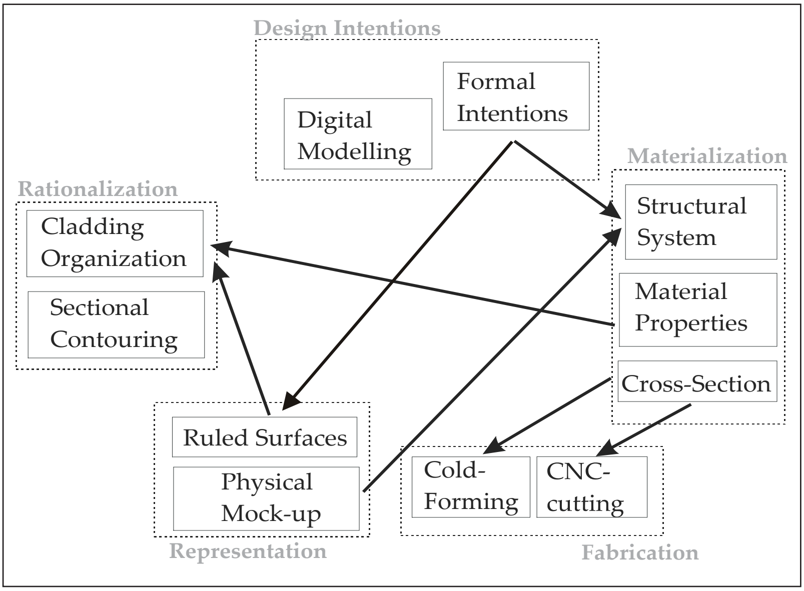


Figure 4.24: Horizontal Analysis for Dynaform showing the interactions of the concepts across categories

Following the commonly accepted notion that there is never a complete representation of the design problem in the head of the designers (Lawson 1980), in the horizontal study, we focused more on the local and non-sequential network of links in different design situations in each case. As has been observed from the case studies, each category comprises of a sequence of concepts (strategies, solutions, techniques, methods) specific to each project and their associations. While the clustering of these concepts under the 5 main categories help to understand the purpose of each concept within its context, showing the associations (or links) between them try to explicate the unique ways in which different practitioners frame the design problems and the solutions they bring to unique situations. The defining characteristic of these design problems is that they are highly interdependent. Following the definition of Lawson (1980), it is the very interrelatedness of these factors that is the essence of design problems rather than the isolated factors themselves. According to Eastman (2001), a better understanding of the process of structuring problems allow further insight into our understanding of the design processes followed by designers. We define these problem structures as the ways in which various concepts interacted in each project studied.

It has been observed that the concept and their association with (an) other concept(s) accommodate different knowledge types of the free-form design domain. For example, “cold-forming”, or “Gaussian analysis” provide the declarative and procedural knowledge elements of the domain what has been called as “knowing that” and “knowing how”, which are also referred as process or task knowledge. Declarative knowledge comprises facts people know (what). Procedural knowledge comprises the skills people know how to perform (how) (Anderson 1985). According to the Jong and Ferguson-Hessler (1986), an effective knowledge repertoire for solving problems in semantically rich domains also contains strategic and situational knowledge in addition to procedural and declarative knowledge (how and why) (Jong & Ferguson-Hessler 1986).

The links between concepts also comprise strategic and situational knowledge elements. Situational knowledge is necessary to recognize problems in a particular domain, and is important for the selection of the relevant declarative and procedural knowledge in memory. Strategic knowledge is a more general knowledge type. It refers to knowledge of processes that are planful, and consciously chosen to facilitate the acquisition and utilization of knowledge (Christiaans 1992). Thus, in order to understand the knowledge embedded in the tacit experiences of these projects, we need to look into the ways how the knowledge was created.

For example, in EMP, while the division of the surface into individual cladding components (surface rationalization which was later defined as cladding organization) has been determined by the available sheet-metal sizes and the constraints coming from the fabricator. This way, a link is created between the cladding organization (Rationalization) and material properties (Materialization) which reflects the approach of the design team, affects the choices made, and the evolution of the final artefact. Alternatively, the organization of the cladding components could have been determined solely by aesthetic criteria. In a similar example, the membrane surface in Dynaform project is represented by ruled surfaces for the ease of constructability. The use of a variety of ruled surfaces is justified to create an impression of a double-curved overall surface to comply with the formal intentions (Design Intentions) of the architect, as well as providing ease of constructability.

Another distinguishing factor between the creation of these associations is that different associations may be generated between the two same concepts by any member of the design team. For example, while the cladding organization in EMP is conducted by the architectural team, the same process becomes the task of the engineering team in Dynaform project reflecting the viewpoint of the collaborating members of the design team in problem formulation which affects generation of solutions in relation to the way the problems were formulated. Thus, understanding the viewpoints of the people in the collaboration - whose personal focus based on their disciplinary background might influence their decision process and choices - is essential for the understanding of how the form evolved into its final shape.

While, certain relationships are emphasized more in one project, others become less important or are ignored as the design process progresses. With every project, new relationships may be introduced, either empirically or through the introduction of new facts and relations that had been previously suppressed. Furthermore, these links may change both in meaning and form with regard to how they are associated and according to the viewpoint of the project participant (across disciplines) who creates this association. The change in meaning relates to the dependency relation types (e.g. constraint, influence, inspiration) between different aspects, whereas, the change in form relates to the change in the direction of dependencies (e.g. bi-directional, mono-directional). An additional observation concerning the dependencies between concepts is that they can be linked at any phase of the design process even though they belong to different phases of design. For example, constructability criteria can influence the form generation at the very early stages of the design process.

4.4.4 Vertical Analysis

Vertical analysis aims to cluster these concepts into sub-categories in a hierarchical organization. The concepts extracted and collected during content analysis for each case are compared with the other concepts across cases. According to this comparative analysis, they are further classified according to their degree of generality. This further classification is to understand to what extent each concept is generic (applies across many situations) or specific (applies to one of few situations). The decision concerning the levels in the hierarchy for each concept is decided according to the attributes of each concept which determines if a concept inherits generic attributes or if it is a mere instance of its class. For example, “hylite” is an instance of a whole range of materials that might be used as a cladding element in free-form design, therefore takes place under material, which is under the “material level” (other levels are the “main structure” and “element” levels) under the main category: Materialization. On the other hand, “framing strategy” represents a more generic concept, which is placed at a higher level in the hierarchy, under the *Rationalization* category (Table 4.2).

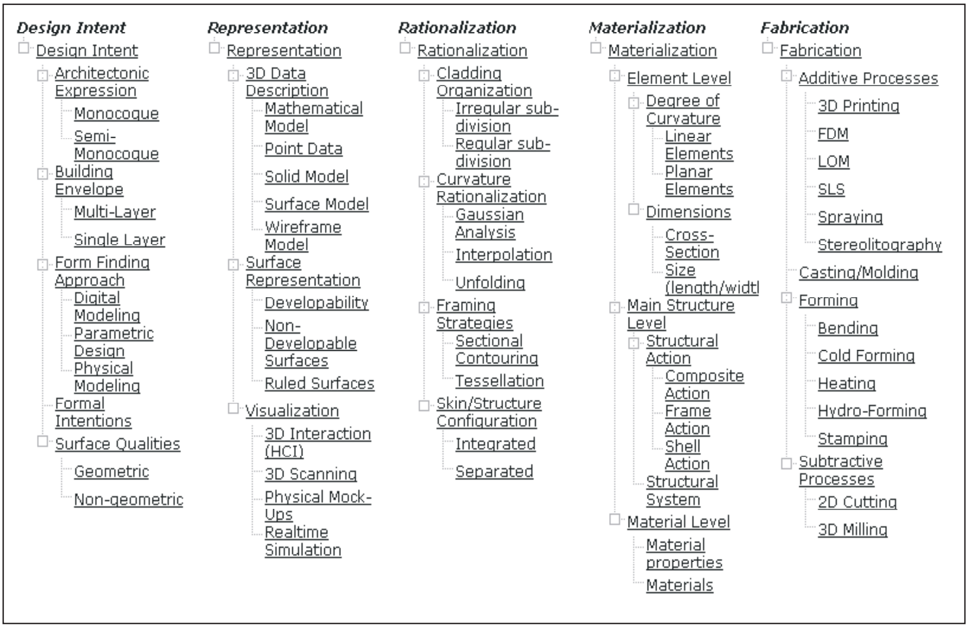
3rd Degree	2nd Degree	1st Degree	Main Category
NURBS	Surface Model	3D Data Description	Representation
	Developability	Surface Representation	Representation
	3D Scanning	Visualization	Representation
	Ruled Surfaces	Surface Representation	Representation
	Wireframe Model	3D Data Description	Representation
	Physical Mock-up	Visualization	Representation
Triangulation	Tessellation	Framing Strategy	Rationalization
	Gaussian Analysis	Curvature Rationalization	Rationalization
	Sectional Contouring	Framing Strategy	Rationalization
	Skin-Structure Integrated	Skin-Structure Configuration	Rationalization
	Irregular Sub-Division	Cladding Organization	Rationalization
Frame Action	Structural Action	Main Structure	Materialization
Hylite	Materials	Material level	Materialization

3rd Degree	2nd Degree	1st Degree	Main Category
Composite Action	Structural Action	Main Structure level	Materialization
Sheet Metal	Materials	Material Level	Materialization
Membrane	Materials	Material Level	Materialization
Steel-Thickness	Dimensions	Element Level	Materialization
Water-jet Cutting	2D Cutting	Subtractive Process	Fabrication
Folding	Bending	Forming	Fabrication
	Shotcrete Spraying	Casting/Molding	Fabrication
Plasma Cutter	2D Cutting	Subtractive process	Fabrication
Manual Forming	Cold-Forming	Forming	Fabrication
CNC-cutting	2D Cutting	Subtractive Process	Fabrication
	Single Layer Skin	Building Envelope	Design Intentions
	Directional Uniformity	Formal Intentions	Design Intentions
Paper Surface	Geometric	Surface Qualities	Design Intentions
	Multi-Layer Skin	Building Envelope	Design Intentions
	Physical Modelling	Form Finding Approach	Design Intentions
	Skin-Structure Separated	Formal Intentions	Design Intentions
	Digital Modelling	Form-Finding Approach	Design Intentions

Table 4.2: Hierarchical ordering and levelling of data within the categories

Some concepts are directly taken from the data collected during the case studies, while some others (especially the ones at higher levels in the hierarchy such as; visualization or element level) are generated as generalizations. These generalizations are based on an iterative process of comparisons between the concepts across cases, such that they could be applicable to other cases. The generalizations are also based on an anticipation of possible new data that might be brought under these generalizations.

The terminology used to label a concept, its level in the hierarchy, the degree of abstraction and the generation of appropriate generalizations are determined in a continuous comparison of cases. Similarly, each concept is identified according to the category it falls under and accroding to its semantic relations with other concepts in the hierarchy. This has led to the the evolution of a *taxonomy of free-form design*. The taxonomy is defined as an explicit conceptualization (Gruber 1993) of a domain, and a representational vocabulary of the domain knowledge (Chandrasekaran, Josephson et al. 1999). For the purpose of this research, the taxonomy is understood as the essential concepts representing the semantics of the free-form design domain. We will use this taxonomy as a hierarchical concept vocabulary (fig. 4.25) and to define a framework to organize the knowledge content of free-form design.



Design Intent

- Design Intent
  - Architectonic Expression
    - Monocoque
    - Semi-Monocoque
  - Building Envelope
    - Multi-Layer
    - Single Layer
  - Form Finding Approach
    - Digital Modeling
    - Parametric Design
    - Physical Modeling
  - Formal Intentions
  - Surface Qualities
    - Geometric
    - Non-geometric

Representation

- Representation
  - 3D Data Description
    - Mathematical Model
    - Point Data
    - Solid Model
    - Surface Model
    - Wireframe Model
  - Surface Representation
    - Developability
    - Non-Developable Surfaces
    - Ruled Surfaces
  - Visualization
    - 3D Interaction (HCI)
    - 3D Scanning
    - Physical Mock-Ups
    - Realtime Simulation

Rationalization

- Rationalization
  - Cladding Organization
    - Irregular sub-division
    - Regular sub-division
  - Curvature Rationalization
    - Gaussian Analysis
    - Interpolation
    - Unfolding
  - Framing Strategies
    - Sectional Contouring
    - Tessellation
  - Skin/Structure Configuration
    - Integrated
    - Separated

Materialization

- Materialization
  - Element Level
    - Degree of Curvature
      - Linear Elements
      - Planar Elements
    - Dimensions
      - Cross-Section
      - Size (length/widtl
  - Main Structure Level
    - Structural Action
      - Composite Action
      - Frame Action
      - Shell Action
    - Structural System
  - Material Level
    - Material properties
    - Materials

Fabrication

- Fabrication
  - Additive Processes
    - 3D Printing
    - FDM
    - LOM
    - SLS
    - Spraying
    - Stereolitography
  - Casting/Molding
  - Forming
    - Bending
    - Cold Forming
    - Heating
    - Hydro-Forming
    - Stamping
  - Subtractive Processes
    - 2D Cutting
    - 3D Milling

Figure 4.25: The Taxonomy - hierarchical concept vocabulary of free-form design[3]

---

[3] It should also be noted that in addition to the concepts extracted from the cases studied, we also referred to various literature (e.g. quoted materials from interviews, field notes) to check the consistency of the evolving vocabulary..

The taxonomy of concepts do not not include specific instances but rather comprises generic domain concepts as have been observed in the episodes of free-form design practice. Therefore, it is intended to be general enough to accommodate other cases, but at the same time specific enough to address to the knowledge content of free-form design domain.

4.5 THE EVOLUTION OF A KNOWLEDGE FRAMEWORK

Within the taxomony, we recognize two sets of relationships between concepts with regard to the knowledge content they represent (fig. 4.26). One is the hierarchical relationships between the concepts in each category, providing an outline of the tasks and processes of the domain under study. The second relationship is the associations between the concepts within and across categories. Accordingly, both the concepts and the links between them can be considered as the variables that vary in each case and that can be used to explain the unique ways in which in which designers frame the design problems and the solutions they bring to unique situations.

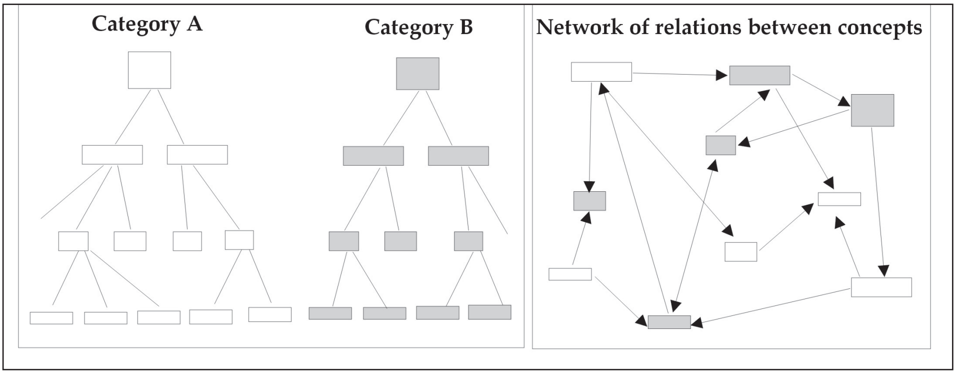


Figure 4.26: The types of relationships defined by the knowledge framework. Left: Hierarchical relationships between concepts under each category. Right: A network of relationships between concepts within and across categories

As has been reported earlier in the *horizontal study* section, the concept and their association with (an) other concept(s) accommodate different knowledge types. While some concepts and their links refer to the declarative and procedural knowledge - also referred as process or task knowledge - some others are identified as situated and strategic knowledge elements which may vary from one project to the next. Similarly, the links between these concepts may also change in meaning and form. It has also been observed that new concepts are generated within the practice with the emergene of new techniques and methods in respond to the specific needs of the designers. Therefore, rather than a static and formal description of the domain concepts, we propose to extend our taxonomy with the *theoretical model* developed throughout the horizontal analysis of the cases earlier in this chapter. This *theoretical model* consists of a set of propositions expressing the relationships between the concepts of the domain and knowledge construction. Thus, we propose a *knowledge framework* which consists of both the formal and theoretical descriptions of the domain semantics. A *knowledge framework* further clarifies the knowledge structure of the domain, links the structuring of knowledge with its uniqe content, facilitates the assimilation of new concepts into the existing structure, and allows its users to share and extend their knowledge with others. Consequently, it provides the means for the users to explicate their knowledge and supports the individual and collective construction of knowledge.

As for the knowledge content it intends to support, we claim that the knowledge content of free-form design, comprising of different types of knowledge, can be explained either as an instance of each concept, or as an instance of the interconnection between two or more concepts in this framework. Therefore, the framework should also allow extension with the introduction of new concepts and links which we define as knowledge construction.

4.6 SUMMARY OF FINDINGS

The comparative analyses of case studies have contributed to the understanding of the different dimensions of knowledge and the factors contributing to its complexity. This chapter gave an account of how the data collected throughout case-study analysis have been analyzed and conceptualized in order to develop a *taxonomy* and a *knowledge framework.* A *knowledge framework* is composed of a set of concepts, principles, processes related to free-form design which can be used as a reference model to frame, evaluate, construct and share design experiences. Therefore, the knowledge framework builds upon the taxonomy by also integrating the types, characteristics of the domain knowledge and the ways it is generated by the designers. We can summarize these characteristics as follows:

- In order to understand the knowledge embedded in the tacit experiences of designers, we need to look into the ways how the knowledge was created and how problems are formulated.
- Both the concepts and the links between them are the elements of the domain knowledge as well as the value, strength and direction of these links.

- There are certain processes which are performed by different stakeholders in different projects. Accordinly, the links that are created between the concepts in each project reflects a certain bias which may affect the evolution of the artefact.
- Understanding the viewpoints of the people in the collaboration - whose personal focus based on their disciplinary background might influence their decision process and choices - is essential for the understanding of how the form evolved into its final shape.
- The links between concepts should be able to explicate the unique ways in which different practitioners frame the design problems and the solutions they bring to unique situations.
- The links may change both in meaning and form with regard to how they are associated and according to the viewpoint of the project participant (across disciplines) who creates this association. The change in meaning relates to the dependency relation types (e.g. constraint, influence, inspiration) between different aspects, whereas, the change in form relates to the change in the direction of dependencies (e.g. bi-directional, mono-directional).
- Concepts may be linked at any phase of the design process at any degree of generality. For example, constructability criteria can influence the form generation at the very early stages of the design process, while it can also be left to the final phases.

Based on the findings of this chapter, the next chapter will describe the development and implementation of a web-based system. The system is based on the model developed in this chapter and intends to support knowledge needs of designers by facilitating knowledge capture, construction, sharing and re-use.

We conclude that in order to provide effective support, the system should display the following features:

- The system should reflect the domain knowledge not only with the content of knowledge it stores, but also with the dynamic associations (links) it provides among knowledge elements.
- The system should be able to accommodate different types of knowledge; such as declarative, procedural, specific, and factual, by facilitating the means to distinguish them during the construction and acquisition of knowledge

- The system should refer to the domain terminology (taxonomy of concepts) and facilitate its extensibility with the addition of new information.
- The system should be able to accommodate both specific and general domain knowledge elements while allowing the user to distinguish them during knowledge construction and re-use.
- The system must be able to facilitate knowledge capture from differing sources and viewpoints and must be capable of representing the evolution of knowledge through the design activity.

CHAPTER 5

THE DEVELOPMENT OF A WEB-BASED SYSTEM (InDeS) TO SUPPORT COLLABORATIVE KNOWLEDGE CONSTRUCTION

The massive amount of information associated with the design and construction demands of complexly shaped buildings demand explicit knowledge about the way various information pieces relate to one another, to be able to achieve an intelligent use of those resources throughout the design process. This gives rise to a strong need for computational support systems that help not only to retrieve information but also explain the relationships between elements of information (Bar-On & Oxman 2002). This chapter presents the development of a web-based system (InDeS) to support collaborative knowledge construction, sharing and re-use. A prototype has been developed by implementing the *knowledge framework* into an existing database structure (Infobase) and by adding supplementary functionalities to its representational structure for efficient access to the related knowledge content. Using the characteristics of the domain content identified earlier, the prototype aims to provide a flexible and extensible structure for the organization and representation of the domain knowledge. While doing so, it tries to answer to the following questions:

- How can the *knowledge framework* accommodate change, incorporate different design experiences and new information?
- How can it evolve by the actual creators of the knowledge themselves, thus contributing to a collective and collaborative creation of knowledge?

- How can this facilitate knowledge transfer between designers within and across disciplines?

Finally the prototype is evaluated according to the factors which would inlfuence its effectiveness and further improvement with regard to user profiles in varying collaborative contexts.

5.1 A REVIEW OF INTELLIGENT SUPPORT FOR DESIGN

AI in design includes modelling of designer activity, the representation of designer knowledge, and the construction of systems that produce designs or systems to assist designers (Brown 1992). Various techniques are used to model both the knowledge and activities which let researchers classify design problems in computable forms, making the underlying structure apparent. Through such explication, it is often possible to understand the task domain and the conceptual knowledge required to understand and solve design problems. However, the complexity of the design process demands richness of reasoning that often contrasts with the highly simplified and restricted computational approaches. Thus, this complexity often makes it necessary to integrate complementary techniques in order to develop effective heuristics for realistic, complex design problems.

Knowledge Based Systems rely on the extraction of generalizable and useful characteristics of the information and its classification in a manner that is retrievable as well as applicable in similar future design situations. Knowledge based methods developed by a number of researchers are capable of modelling many aspects of the design problems that are relevant to the design at different stages of the design process. These systems address different aspects of the knowledge requirements at different stages during the design process. The use of databases of known design solutions has become a very common approach. These databases have the flexibility to store vast amount of data relating to many aspects of the design domain of the interest to the designer. Tang (1997) reviews various approaches to knowledge-based design systems and claims that most tools available cannot satisfactorily adapt to new contexts or acquire new knowledge. Partial remedy to these drawbacks lies in the case-based design (CBD) paradigm. Watson and Perera (1997) shows that CBD systems may facilitate not only analogous thinking and experience based knowledge but also are able to learn by introducing new cases into knowledge repositories. Case based reasoning is a general paradigm for problem solving based on the recall and reuse of specific experiences. It presents a model for the acquisition, organization, and reuse of specific design knowledge.

This involves retrieving relevant cases, referring to the solution of a previous case, and storing newly generated design case for future use (Rosenman & Gero 1994). There is a wide range of applications that have implemented case-based reasoning, each trying to resolve theoretical issues through their implementation.

5.1.1 Distinguishing Design Systems and Positioning InDeS

Knowledge representation is considered as a prior condition to the development of knowledge support tools (Brodie et al. 1984). Both case-based, knowledge-based, expert and similar other systems rely on the explicit symbolic representation of knowledge. These systems have mainly gone in two parallel directions in the support they provide for designers. First, is the "automated design systems"; also called intelligent CAD (MacCallum 1990), whose aim is full or partial automation of the design process; while the role of the human designer is to give the initial requirements, evaluate solutions and build prototypes. The second is the "design support systems" that aimes at assisting human designers in their tasks by recalling past cases (Watson & Perera 1997), critiquing and navigating (Fischer 1992), reasoning and consistency maintenance (Smithers et al. 1990; Tang 1997). A design knowledge support system, unlike a CAD system, does not actually design anything, instead, it attempts to support the designer during the exploration of possible designs that could eventually help them to reflect on their design decisions, become familiar with the problem structures and possible solutions, and to share their design knowledge. While the fomer approach provides a design memory with facilities that automatically retrieve or adapt previous cases, the latter provides a memory for indexing and retrieval of previous cases. In both approaches there is a strong need to develop a formal representation of the design experiences.

In the following sections, we will report on the development of a web-based system (InDeS) which is based on the general principles of design support systems. The extent of knowledge we intend to represent covers a broad spectrum of information necessary for the overall design and realization process, facilitating the exploration of collaborative knowledge in free-form design. It is anticipated that through communication and collaboration domain knowledge could be shared by all participants of the design team and contribute to the collective creation of collaborative knowledge.

For the purpose of this thesis, it is important to note the differences between knowledge, data and information. Knowledge is commonly distinguished from data and information. Data represent observations or facts out of context, and therefore not directly meaningful. Information results from placing data within some meaningful context. Knowledge is the meaningfully organized accumulation of information through experience, communication or inference (Zack 1999).

5.1.2 Highlighting General Features of Design Support Systems

Various approaches and systems have been reviewed in the general domain of architectural design which provide knowledge support in the design process. Analogies between design systems can be based on various criteria. The identified similarities help us to highlight those features of design support systems that have a high degree of generality and can be applied to many systems.

Cognitive approaches for modelling design knowledge affect the structuring of knowledge in the memory. As for the memory organization (structure and organization of knowledge), the cognitive model of CBD claims that knowledge resides in memory both as specific events (cases) and as generalizations (Heylighen & Neuckermans 2001). Specific events are the knowledge embedded in specific cases, whereas generalizations refer to the abstracted concepts of the domain under study.

Indexing is crucial in determining how the system will be used, how the cases will be retrieved, and provides a reasoning process to use the knowledge in the system by remembering the cases with common attributes to assist the user in comparing those cases with the problem at hand.

The organizational structure of the memory contributes to the capability of accessing relevant knowledge (R. E. Oxman & Oxman 1990). Accordingly, a common issue in organizing design cases is the need to predetermine the features (abstract concepts) to serve as indices for efficient access to cases (Maher & Garza 1997). In Archie-II[1] , the stories (cases) and guidelines (abstract concepts) are linked by two different set of indices, one, to identify the stories, and the other, to direct the users' attention to the related material (Domeshek & Kolodner 1992).

---

[1] Archie-II is a CBD aid for architects developed at the AI lab of Georgia Tech's College of Computing in collaboration with the members of Tech's College of Architecture. Archie-II supports architects during the early conceptual stage of public building design by providing them interesting design cases. The system focuses on case-representation and retrieval.

A slightly different approach to memory organization is adopted in PRECEDENTS[2], where stories are organized by an Issue-Concept-Form formalism, which are high level concepts to serve to organize specific events (R.E. Oxman 1994). In this system, the memory structure is an associative network of stories related to these high-level concepts, resulting in a semantic net which provides the basis for indexing. Instead of indexing the complete designs, every design story is indexed independently.

Representation of a specific case knowledge is an other important issue. In the systems reviewed, it has been observed that case-knowledge is represented either as complete representation of the entire case or in the form of knowledge chunks (also called design stories) comprising graphical, textual or numerical information.

The memory organization is highly dependent on the decision of representation. This will effect how different cases will be linked to one another as well as how the generalizations about these cases will be associated. Memory organization will also affect the retrieval of domain specific knowledge. For example, in typological models, instances and higher level generalizations are linked hierarchically from general (type) to specific (case), whereas, in precedent-based systems, they are linked cross-contextually which enables access to the generalized knowledge in a conceptual network.

The identification of the relevant features for the system is to a greater degree dependent on the knowledge content and will certainly affect the structure and organization of the memory and the representation scheme in relation to the context that is represented. In addition to the underlying cognitive model employed in various systems, the following aspects are what distinguishes each one of these systems:

- The scope and the domain
- The content and the context
- The design stages addressed
- Knowledge encoding strategies

---

[2] PRECEDENTS is a CBD aid for architecture developed by Rivka and Robert Oxman in Technion University in Israel. The design task PRECEDENTS concentrates on is the spatial organization of museums in the early conceptual stage of the design process. The focus of the system is case-representation, specifically, the representation of the conceptual knowledge embedded within past designs, making it fit to be researched and browsed within a computerized library of precedents.

In the following sections, how these variables are constructed and defined for the implementation of InDeS will be explained and discussed.

5.2 THE METHODOLOGICAL FRAMEWORK

The underlying cognitive model of InDeS is based on the knowledge framework developed earlier, as well as the theoretical standpoint adopted in this research. According to this standpoint, design is perceived not only as an information processing activity, nor solely a problem solving activity (which are the main foci of knowledge-based and case-based systems, respectively), but rather a combination of both. Furthermore, a very important aspect of the design process, especially in free-form design domain where very little knowledge is present for the designers, is understanding the problem structures of the domain. Accordingly, supporting the designers not only in presenting earlier solutions to problems, but also providing them with the problem structures inherent in those solutions has become an important requirement for the system.

Another important requirement that influenced the functionality of the system was the extent to which it could reflect designers' actions and behaviours during design. It is commonly known that architects do not consider the different aspects of a design separately, but always in relation to other issues (Lawson 1997). When creating a curved surface element, for example, the materialization aspects of the form can not be separated from how that form will be produced in relation to its overall architectonic effect. Lawson (1997) states that all different considerations run through the head of designers simultaneously and they concurrently jump from one design aspect to another. Accordingly, the system, while supporting the designers at the early stages of design process, aims at providing information about the various stages of a project life-cycle. It is claimed that making evaluative material available to architects early in the design process can make them more aware of the downstream implications of their decisions. Consequently, it has been decided to organize the memory of InDeS in such a way that information pieces from the different stages of a design process can be related at various levels of detail. This could aslo allow the explication of problem structures in a multi-disciplinary context. The main objectives for the implementation of InDeS can be summarized as follows:

- Providing a conceptual understanding of the free-form design domain by clarifying problem structures in a multi-disciplinary framework.

- A dynamic knowledge source which supports knowledge capture, knowledge creation, re-use and sharing;
- Reflects human actions in design processes and can accommodate multiple views of knowledge

5.2.1 Knowledge Content: Type, Quantity and Acquisition Method

The determination of what design knowledge must be captured in free-form design must be preceded by an understanding of knowledge needs of the domain. Facing a new design problem, experienced designers do not design strictly by abstract design principles, nor do they exhaustively search a space of previous design cases. They refer both to previous experiences and to general domain knowledge. In order to support this process, the system should strive to record significant and meaningful concepts, categories, and definitions, (declarative knowledge), processes, actions and sequences of events (procedural knowledge), rationale for actions or conclusions (explanatory knowledge), circumstances and intentions (strategic and situational knowledge) within the domain of free-form design.

In the system described, these different knowledge types are fit into a context that could facilitate access to the three different forms of knowledge that designers use during a design process; general domain knowledge (about the high-level concepts of the domain), specific domain knowledge (about the different states of the domain concepts and their variables) and specific case knowledge (about specific experiences in specific situations). InDeS proposes a representational scheme which integrates all three, which are stored as “documents” in the system in various formats, such as text files, drawings, photographs, etc. The documents contain chunks of knowledge and are differentiated according to the context of use and the type of knowledge they contain. Instead of dealing with the entire design problem or process at once, the system is designed to focus on smaller pieces of information. Therefore, the content of the documents should focus on this aspect by decomposing knowledge into relevant information pieces that can also be used in the indexing of these documents for ease of access to their knowledge content.

The elementary tasks associated with the representation of documents are the content and the structure of the knowledge representation. The content needs to be identified in terms of what is in a document in order to reason about its applicability in a new design situation. If the repository is conceived as a “knowledge platform”, then many different views of the content may be derived from a particular repository structure (Zack 1999). Therefore, it is helpful to provide a memory structure to define the contexts for interpreting the accumulated content. The structure refers to determining an appropriate structure of encoding design knowledge in a document. The content and the structure of a document determine how knowledge can be represented so as to maximize its usefulness for the user.

5.2.2 Knowledge Context

During the design process, the architect has to investigate, evaluate, and process a massive amount of cross-disciplinary information. In order to succeed, an understanding of the contexts in relation to the knowledge ingredients (content) is required. This refers to binding the pieces of information into some logical, contextual structure in order to provide answers on a general level to evolve a conceptual understanding of the domain under study. Consequently, the system should be designed not only for information retrieval but should also be able to reveal the relations among the categories of information (Bar-On & Oxman 2002) according to the way in which information is used and manipulated by human designers.

The context for the system is created with regard to the contextual framework that was formulated earlier in chapter 3, and further developed in chapter 4. The framework provides a decomposition of particular design phases to structure the focus of our investigation. The decomposition is based on a categorization of 5 generic design phases in the domain of free-form design, with a particular focus on the design of the building skin(s) and the supporting structure. These phases are generalized as follows:

- DESIGN INTENT - specification of the formal qualities and design approach,
- REPRESENTATION - representation and description of the design object for subsequent phases
- RATIONALIZATION - division of the of the free-form surface into rational cladding components combined with a supporting structure
- FABRICATION - selection of the fabrication processes, tools, techniques and strategies
- MATERIALIZATION – decisions concerning the formal and behavioural properties of the structural system, the elements and the choice of materials.

These 5 categories provide the context where the design system operates. These are the recognized categories of various design stages relevant to both design and realization processes, drawing the architects' attention to all life-cycle implications of their design early in the design process. The categories are characterized by the type of problems and solutions they generate during the life-cycle of a project. As design is often approached as a decomposition problem, hierarchies are often used for guiding the decomposition process. For each category, multi-level sub-categories are identified (see chapter 4). The sub-categories are hierarchically organized as generic classes of features which form the basic vocabulary of concepts that need to be tackled under each category; referring to tasks, procedural or formal decisions, strategies, etc. The features, at the higher levels of hierarchy, are context independent, such as; "surface representation", "framing strategies", and "architectonic expression". At the lower-levels, they start to define more specific and context dependent concepts, methods, tasks or product features, such as; "gaussian analysis", "developablity", and "sectional contouring". The documents are connected to these features, that are meaningful for the design team who will share knowledge, providing access paths to documents.

5.3 MEMORY ORGANIZATION AND REPRESENTATION

Memory organization refers to the way documents are organized for access during retrieval. If the memory does not contain many documents, then the memory organization is usually a list of pointers to the cases. The memory structure of InDeS is composed of two layers. 1) concept layer 2) Information layer.

Concept layer consists of a hierarchical tree structure of concepts which is the main representation scheme of the system (fig. 5.1). The scheme consists of 5 generic classes of design phases with their associated features and sub-features representing a class of information elements hierarchically organized from more generic to more specific concepts. Information layer consists of documents that are connected to these *features* and to the *links* between the features.

The representational media that was used for the system is an extension of the database model developed for the InfoBase project[3], which has been previously

---

[3] The database model is derived from the ICTO-InfoBase project which has been developed by the Design Informatics Department of the Faculty of Architecture, at Delft University of Technology. The project, led by Dr. Rudi Stouffs, concerns the development and implementation of a multi-media learning environment that supports the students in exchanging and managing information in group work. It also serves as a digital media library for collections of student works (Stouffs et al. 2004).

developed as a flexible representation framework that offers support for various information structures in different situations (Stouffs et al. 2003). InDeS had been developed by providing a context to this representational framework. This has been achieved by adding a hierarchically organized vocabulary of features and additional functionalities for efficient access to the related knowledge content.

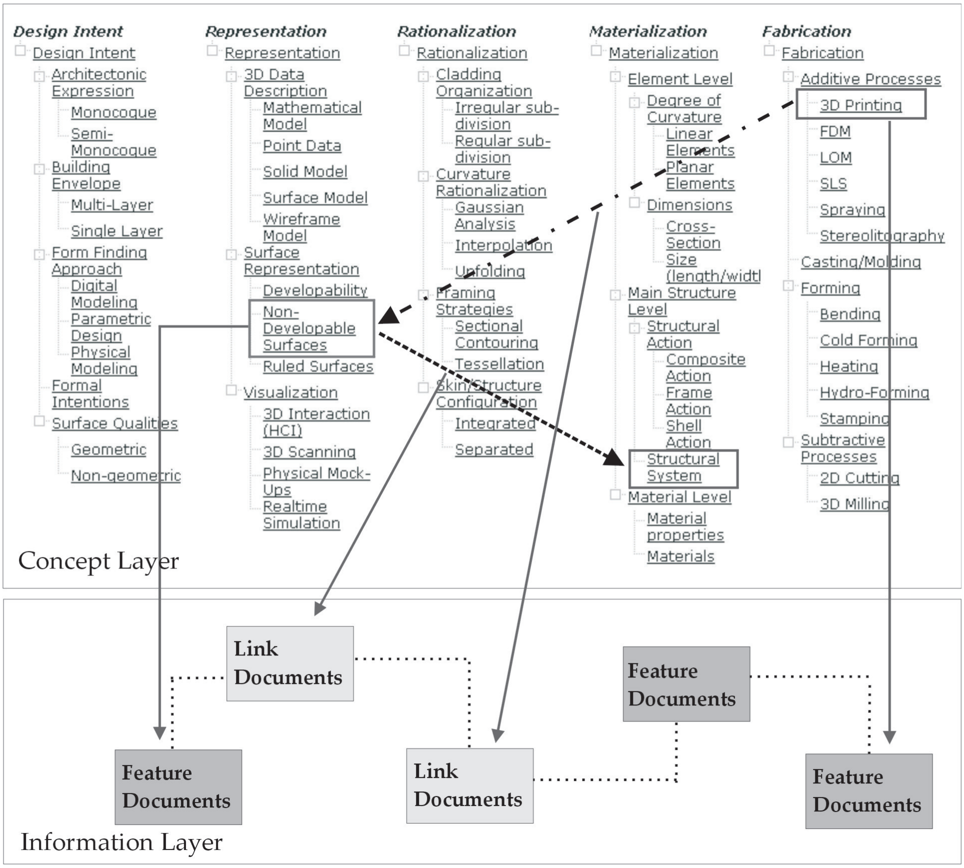


Figure 5.1: The connection between the Information and Concept Layers

5.3.1 Document Types in Relation to Features

Documents contain either domain knowledge (specific or general) or decomposed specific case knowledge in the form of knowledge or information chunks. Two document types are distinguished according to the number of features they are associated with, and according to the type of knowledge they provide. Feature documents associated with only one feature, and provide general and/or specific domain knowledge about different ways that feature has been interpreted and used in a precedent situation. For example a feature document connected to “Non-developable surfaces” feature may contain specific or general information on the characteristics of non-developable surfaces, or may exemplify a method that was used to identify non-developable surface parts on a building model. Many documents can be connected to the same feature.

Link documents are associated with two or more features at any level in the hierarchy, within the same category or across categories. They are created by linking two or more features and may provide both specific domain knowledge and/or specific case knowledge about how two or more features have been associated in a specific context. Link documents create conceptual associations between features. These associations define the problem structures within the domain which may reflect not only the objective side of a design situation but also may mirror the subjective preferences of the designer related to his/her own methodology. The link between the features fit the knowledge into a meaningful context. The links are augmented with distinct relationship types (e.g. constrained by, inspired by, dependent on, influenced by, defined by) mimicking the ways how different pieces of information can be brought together by different designers in different design situations.

The system also allows the users to define new generic relationship types during document entry. These relationships are not only distinct in meaning but also in form (e.g. mono-directional, bi-directional, non-directional). Such differentiation of linkages represent the different viewpoints of the actors in the design team and further helps to explicate how the problems were structured by the designers that led to a specific solution. These solutions may be concrete or strategic, in either case, providing tactical and conceptual support to the users.

The linkages are an other important aspect of cognition in design thinking. In associative reasoning, knowledge elements (features) are linked on the basis of these conceptual relationships. It is important to note that, features under each category are intrinsically linked while cross-categorical links between the features can only be created with document entry. This means, no links or associations exist between the features by default. They are expected to be created and constructed in time by the users of the system.

5.3.2 Document Descriptions for Data Entry and Retrieval

A common issue in organizing the documents is the need to predetermine indices for efficient access to the documents. A common way of storing documents is by attribute-value pairs. This allows the document to be self-defining and incremental. An attribute (or property) identifies the attribute's value to a user. Associated with an attribute is a type (part of its meaning). In the system described, the documents are structured and identified according to their attribute types and values, and by the features they are associated with, each distinguished with a unique document ID. The types of documents are further distinguished by the number of features listed in their document descriptions, in other words, by the number of features they connect (fig. 5.2).

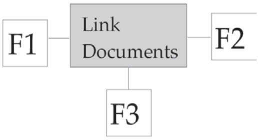
Document Type	Relations with Features	Attribute types	Knowledge type
Feature Document		features, keywords, project, architect	"what" and "how" knowledge, general domain knowledge, specific domain knowledge
Link Documents (connecting two features)		features, keyword, project, architect, link type, link direction	"how" and "why" knowledge, specific domain knowledge, case specific knowledge, knowledge about problems, and solutions
Link Documents (connecting more than two features)		features, keywords, project, architect, link type	"how" and "why" knowledge, specific domain knowledge, case specific knowledge, knowledge about problems, and solutions

Figure 5.2: Comparisons between different document types according to the features they link, the attributes and the knowledge content

For example, a feature document is associated with only one feature, while a link document is associated with two or more features. Consequently, features are cross-referenced via link document descriptions, creating a network of features which provide the means to navigate within the system by their associative connections. Searching within the documents is also possible via the descriptions of their particular attributes. While all documents have four searchable attributes (feature, project name, keyword, architect), an additional search function is provided for link documents via their link types.

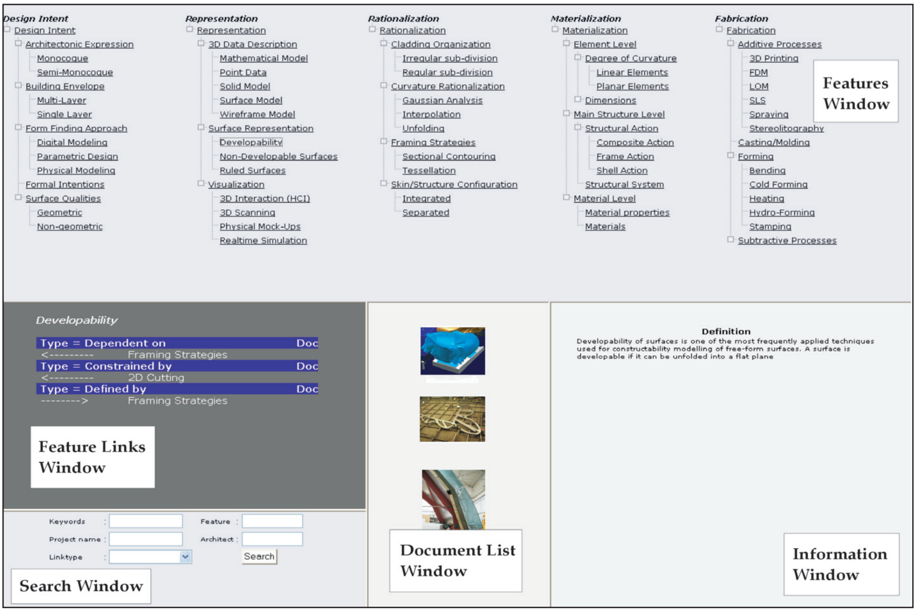
Link documents connecting only two features have an additional attribute called the *link direction*, which is not yet a searchable attribute in the current prototype. Non-searchable document attributes comprise of *comment, author,* and *document type* which are listed in the *Information Window* during document retrieval for review purposes. All of these attributes can be defined by the user during document entry

5.4 USER INTERFACE

The system is designed for both reviewing and browsing through information as well as adding new information into the system. The user interface is designed to address these two purposes with separate interfaces. One is the “browsing and search” interface. The other is the “data entry and editing” interface which allows the construction and extension of new knowledge into the system. The former is updated automatically according to the changes and additions in the latter.

5.4.1 Browsing and Search Interface

Since the core aim of InDeS is to allow cross-contextual exploration of features (information units) within the domain, the *browsing and search interface* is optimised on this aspect. At any time, the screen layout provides feedback to the user about which feature she/he is exploring (or searching) and its links with other features while providing options for the user to choose between in-depth or in-breadth exploration and/or search. The knowledge support system has a five-section structure (fig. 5.3): (a) *Features Window*, (b) *Feature Links Window*, (c) *Document List window*, (d) *Information Window*, (e) *Search Window*.



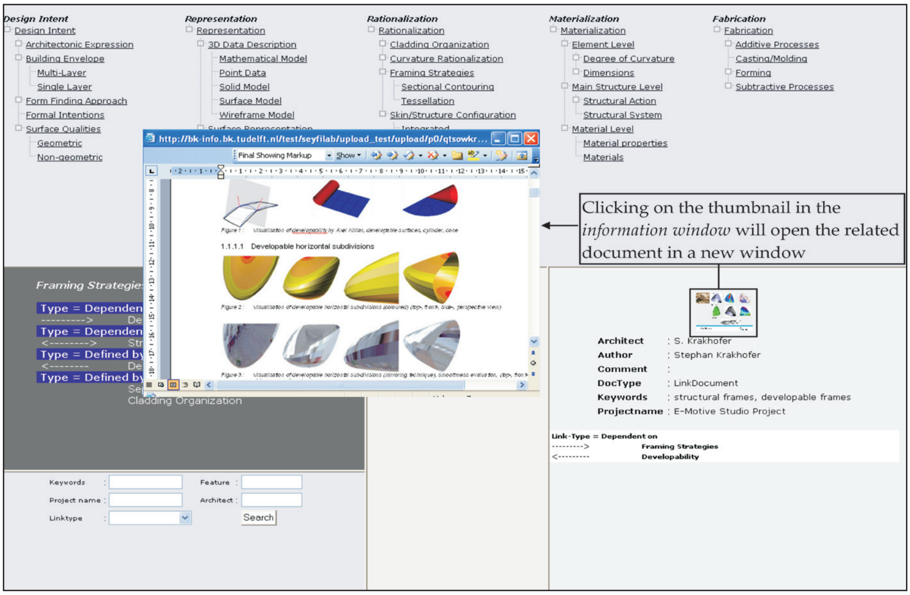
Definition

Developability of surfaces is one of the most frequently applied techniques used for constructability modelling of free-form surfaces. A surface is developable if it can be unfolded into a flat plane

Figure 5.3: A Snapshot of the Interface

At the core of the system is the *Features Window* which gives an overview of all the predefined features, currently present in the system, within a hierarchical structure. This window is also the starting point of the exploration process activated by clicking on one of the features. In this case, the selected feature will be highlighted and displayed in the *Feature Links Window*, together with the features that are linked to the selected feature. It is important to note that the display of other features in this window is only possible if there are documents already stored in the system which is the only way to create links between features together with their link types and link directions (if applicable). Access to these documents are provided in the same window.

Selecting a feature will display a list of feature documents, if there are any stored in the system, in the *Document List Window*. At the same time, description of the selected feature will appear in the *Information Window*, providing a short explanation of its focus. Suc a description becomes necessary due to the fact that the features are generalized abstractions of the content they represent, thus, the users who are not familiar with these abstractions may derive different meanings than what has originally been intended. The content of the *Document List Window* and *Information Window* will be automaticall updated according to the steps that the user takes, based on the preferred path of search to retrieve a specific information. For example, if the user clicks on one of the associated features in the *Features Window*, both the feature document list (in the *Document List Window*), and the content of the *Information Window* will be updated automatically according to the new selection. If the user clicks on one of the "doc" buttons in the *Feature Link Window*, then the *Document List Window* will display the selected link document. Clicking on the thumbnail of the document in this window will display a list of the document's attributes in the *Information Window* (fig. 5.4). Clicking on the document thumbnail will then open the document in a new window.



Clicking on the thumbnail in the *information window* will open the related document in a new window

Architect : S. Krakhofer
Author : Stephan Krakhofer
Comment :
DocType : LinkDocument
Keywords : structural frames, developable frames
Projectname : E-Motive Studio Project

Link-Type = Dependent on
---------> Framing Strategies
<--------- Developability

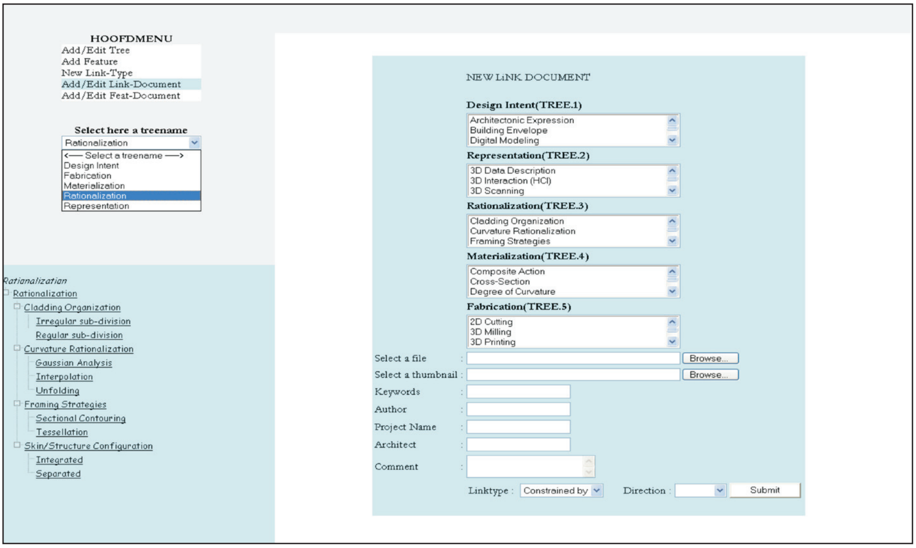
Figure 5.4: A snapshot of the"browsing and search" interface displaying an open document window and its attributes in the *Information Window*

While the *Features Window* is the starting point of the exploration process, the *Search Window* can be considered as the starting point for a more specific search which addresses primarily to a more experienced group of users who are already familiar with the system, or who are more specific in their inquiry. In general, three basic cognitive classes of browsing activity are identified (Carmel et al. 1992): (1) search-oriented browsing (scanning and reviewing of information in the context of a fixed task), (2) review-browsing (scanning and reviewing of information without a fixed goal), and (3) scan-browsing (scanning - without reviewing - of interesting information). One or all of these activities can take place at the same time depending on the type of information the user is looking for or depending on the purpose of his/her enquiry. For more information on the *browsing and search interface*, see the related section in the appendix.

5.4.2 Data Entry and Editing

The *data entry and editing* interface allows designers to add and edit information within the system with certain restrictions. It also allows customization of the hierarchical feature lists (as displayed in the *browsing and search interface*) according to the specific knowledge needs of the design team. As shown in Figure 5.5, the main menu provides the users with commands to:

- add a new hierarchical tree list (a new category and its associated features)
- edit the names and definitions of existing features
- add new features in the existing hierarchical list
- move an existing features to a different place in the hierarchical tree list within and across categories
- add new link types
- add new documents (feature and link documents) and their relevant attributes



Select here a treename: Rationalization

Linktype : Constrained by

Figure 5.5: A snapshot of the *data entry and editing* interface

Saved additions and modifications will automatically be updated in the *browsing and search* interface. For more information on the *data entry and editing* interface, see the related section in the appendix.

5.5 AN EXEMPLARY BROWSING ACTIVITY

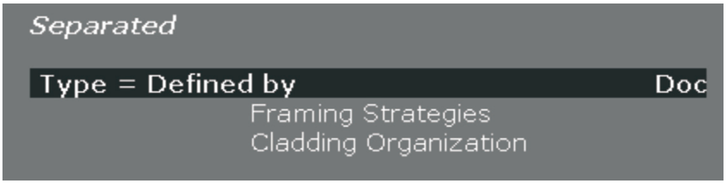
During the early phases of a project (form generation and development), designers face a number of problems such as interpreting a design specification, and developing set of alternatives schemes for it. We take the exemplary design case of a free-form roof structure covering an area of 50x50m. We assume that the designer has already created a preliminary free-form geometry according to his own design and aesthetic criteria, and looking for alternative supporting structures for this geometry. At this stage, one possible scenario of starting to browse through the system might be to search for alternative ways of "integrating the building's skin with its structure". The user, then, might browse through the Feature Window and select the Skin/Structure Configuration feature under the *Rationalization* category. (fig. 5.6). This will automatically list all related sub-features in a tree-hierarchy which provides the users with generic approaches of relating the skin to the structure in the free-form design domain.

Rationalization

- Cladding Organization
  - Irregular sub-division
  - Regular sub-division
- Curvature Rationalization
  - Gaussian Analysis
  - Interpolation
  - Unfolding
- Framing Strategies
  - Sectional Contouring
  - Tessellation
- Skin/Structure Configuration
  - Integrated
  - Separated

Figure 5.6: The hierarchical tree structure of the *Rationalization* category

Assuming that the user selected the "Separated" sub-feature, then he/she will be offered a few alternative browsing paths. In the first option, she/he may review the feature documents that provide the user with both general and specific information on the methodological and typological approaches in which the structure and skin were separated in precedent designs. As a second option, the user may browse through other features in the same category, to have an overview of the other processes, strategies, or tasks (*features*) of importance by scanning through the feature definitions and their related documents. Or, she/he might review the *Features Link Window* to see the other features associated with the selected *feature* via the link documents (fig. 5.7).



Separated

Type = Defined by Doc

Framing Strategies

Cladding Organization

Figure 5.7: A Snapshot of *Features Link Window* **displaying 2 features linked to the selected feature**

By clicking on the "doc" button, and by opening the related document, the user will retrieve further information (e.g. graphical, textual, numerical) on how those *features* were brought together during in problem formalization and solution in a specific design situation. Switching to another feature is also possible in the *Feature Link Window* which will automatically update the interface and list the relevant information for the new selection. For example clicking on "framing strategies" in the previous figure (fig. 5.7) will update the *Features Link Window* accordingly, as shown in the figure below (fig. 5.8), displaying how the "framing strategy" feature has earlier been associated with other features by document entry, together with their related link types and directions.

Framing Strategies

Type = Dependent on Doc

---------> Developability

Type = Dependent on Doc

<--------> Structural System

Type = Defined by Doc

<-------- Developability

Type = Defined by Doc

Separated

Cladding Organization

Figure 5.8: The Features associated with the selected feature are displayed together with their link types and directions, providing access to each link document

The user may continue his browsing either by viewing the content of the related feature and link documents (in-depth browsing - content specific) and/or by switching between the features (in-breadth browsing – context specific). In either case, the user will have an overall idea of how the information pieces are related to one another at different levels of detail, and will have a conceptual understanding of the domain within the context of focus. Different documents may be entered into the system exemplify how a feature is associated with (an) other feature(s) in a specific design situation, providing further information about the reasoning process and the viewpoint of the designer linking his/her problem formulation to the solutions generated. Currently there are five default link types within the system (constrained by, defined by, dependent on, inspired by, influenced by) which have been specified during the testing of the prototype by using additional design cases from the free-form design domain. The system is designed to allow the specification of new link types during document entry.

The system intends to support knowledge construction at any stage during the design process. As the design progresses, the designer learns more about possible problem and solution structures as new aspects of the situation becomes apparent and inconsistencies inherent in the formulation of the problem are revealed. Thus, during the design process, the designer often develops a better understanding of the particular problem they are working on. As a result, with new insights into the problem, a new view is formed, and the problem and solution are redefined. This process of exploration and redefinition continues. This learning process may often result in new requirements being incorporated into the design specification, or may end up with the introduction of new information into the design knowledge base. This new information refers to either a new solution to a common problem, or a new problem definition by introducing new relationships between existing features, either empirically or through the introduction of facts and relations that had previously been suppressed. The system allows a flexible and extensible framework for adding new features, link types, and documents as well as editing existing features and their definitions. However, how the knowledge content stored in the system will be used in the context of a new design situation, how it will be adapted and modified in a new context is totally up to the user.

5.6 VALIDATION AND DISCUSSION

Validation is the process of checking if the research results satisfy certain criteria. The validation criteria, in this research, are determined according to the initial objectives of the research in addition to the requirements that have evolved throughout the research process. These requirements mainly focus on the "intended use", "intended users" and the "intended contexts" of the theoretical and practical outputs of this research. In the following sections, we are going to validate and evaluate the research outputs based on these initial criteria in accordance with the general criteria for grounded theory research (Glaser & Strauss 1967):

1. the theory should fit the substantive data (fit)
2. the theory is applicable in a variety of contexts (generality)
3. the theory should be comprehensible to all involved in the area of study (relevance)
4. the theory should anticipate possible confounding variables that may be brought up by the challengers to the theory; thus it should be modifiable (modifiability)

5.6.1 Testing the Knowledge Framework

Both the knowledge framework and the web-based system are developed specifically for the free-form design context in support of the theories developed throughout the research. While the framework propose a model to analyze and structure new information in order to be able to build a relational structure of the knowledge content, the web-based system implements this model into a working prototype to construct and share knowledge. Accordingly, our verification in this section, rather concentrates on the consistency and completeness of the knowledge framework and its representation in a web-based system. Using the knowledge framework, we have conducted an analysis of the design process of a test case - Kunsthaus in Graz, designed by Peter Cook - based on a textual description of the design process by the structural engineers of the project. The aim of this analysis was

- to verify whether the knowledge framework and the web-based system can be generalized to analyze and capture the knowledge content of a different project
- whether the analysis can capture information on the design problems of the domain in relation to the solutions generated
- whether we can represent this knowledge by distinguishing the views of the design team members (their problem formulation)

The text is analyzed in order to extract the keywords that match the generic concepts (features) of the knowledge framework and their semantic relationships. The following figure illustrates this initial analysis (fig. 5.9).

> The master model is of importance for the structural engineers as well. Due to the not to be modified outer form it is necessary to proceed from the outside to the inside when creating a structural system. To benefit from shell action that the form provides may eliminate the need for additional structural items that are not part of the original design.After a preselection of possible surface and cladding materials, their available dimensions turned out to be the limiting factor for the spacing of the primary structure. .A good deal of the cooperation of architects and engineers was required by the synchronization of the outside façade pattern with the steel structure below. Again the internal structure became determined by the outside geometry since each of the six fixation pins around a standard façade panel had to be positioned on a steel member of the structure below. The position of the diagonals had to be adjusted to the façade pattern making the creation of the master model difficult and time consuming. Once the geometries of the triangulated structure and the rectangular façade have been adjusted to each other, the outside façade could be developed independently which turned out to be a time saving issue.To produce the 1200 individual panels, the heat soaked raw material was laid over a CNC milled positive form block of polyurethane foam and carefully cooled. The formed panel was trimmed and drilled by the CNC machine still lying on its form that served as a jig. The form block was then milled down to the following curvature, which made the production sequence a matter of volume optimization.

Figure 5.9: The analysis of the textual description of the project by the engineers (Grohmann et al. 2004a)

Thereafter, the semantic relations between these features are identified with reference to the hypothetical relationship types proposed earlier. The semantic relations can be further represented according to the viewpoint of the engineers in their problem formulation or the generation of the solution. In other words, how the engineers associated the concepts to one another, which is hidden in the meaning of their description, could be extracted according to the type and the direction of the association, which can be stored in the system based at this level of specificity (fig. 5.10). If the extracted keywords are an instance of an existing feature in the system, or is a new generic feature is a decision to be made by the users. Similarly, as the knowledge content increases, the frequency of occurrence of similar instances may require the specification of a new generic feature. This brings about the question of how to maintain and expand the framework.

The analysis of Kunsthaus project is conducted by the author of this research to show the applicability of the framework in another context. However, in order to verify the relevance of the system for the potential users within the field and to

Keywords	Features Matched/Linked	Linke Type	Link Direction	Problem Formulation	Solution
fixed form	formal intentions	dependent on	↑	●	●
design of structural system	structural system				
cladding materials	materials	constrained by	│	●	
dimensions	size				
spacing the structure	tessellation				
internal structure	framing strategy	dependent on	↕	●	●
outside geometry	cladding organization				
framing strategy	framing strategy	defined by	↓		●
façade pattern	cladding organization				
triangulation	framing strategy		│		●
rectangular façade	cladding organization				
outside façade	multi- layer (building envelope)				

Figure 5.10: The extraction of concepts and their relationships according to the type and the direction of the association

get feedback on its representational scheme, we have conducted a semi-structured interview with both expert and novice designers. Majority of designers interviewed over the hierarchical categorization have found it useful due to the ease of access it provides to the context of focus, and due to the degree of specificity it allows for data entry and retrieval. While the generalizations and abstractions were found quite understandable by both expert and novice designers, creating new abstractions (features) during knowledge entry have been viewed as likely to cause confusion especially among the novice designers, for mainly two reasons. First was about how to decide what knowledge or information could be worthy to store, and secondly, how to find the right abstractions to represent the knowledge content. Although these two reasons are not directly related to the functionality of the system, it gives an indication of how users with different experience levels can make use of the system; either by focusing on data entry or retrieval, or both. Experienced designers expressed different and varying opinions concerning whether certain features should rather be located uner a different category. For example, while one group perceived “developability” as a feature of “Fabrication” aspect (rather than its current place under “Representation”), another group found it more relevant that it has been listed under its current category. As a similar example, although the function of the buildings were out of the scope of the system, one designer sugested to add “building function” as a generic feature of “Design Intent”, which, in his own design approach, has considerable metaphorical influences on the curves of his buildings. These examples have proved the necessity to allow users to customize the location of features and to add new features into the system relevant to their own perception and design approach. The current prototype allows such customization and the construction of a situated view of knowledge as observed or created by the users of the system.

5.6.2 Validity of the Knowledge Framework

The research developed a grounded theory of how to understand the knowledge elements and their interrelationships within the emerging free-form design practice, which led to the evolution of a knowledge framework. The knowledge framework is empirically valid because the theory-building process has been intimately tied to the episodes of design practice (Eisenhardt 1989). There is a controversial belief claiming that building a theory from a limited number of cases is susceptible to researchers’ preconceptions. However, Eisenhardt (1989) argues persuasively that the opposite is true. He explains that the iterative comparison across projects, strategies, methods, evidence, and literature that characterizes such research leads to a constant juxtaposition of conflicting realities [that] tends to “unfreeze” thinking, and so the process has the potential to generate theory with less researcher bias than theory built from incremental studies. Following this argument, Guba (1990) points out that when the reality is constructed through the identification of multiple and contradicting constructions and their critical comparison, it improves the grounds for making informed choices between constructions.

The knowledge framework developed here meets the criteria of practical applicability proposed by Glaser and Strauss (1967). First of all, the concepts and relations posited as central are intimately related to (because derived from) the real practice of design (fit). Secondly, the knowledge framework is sufficiently general to be applicable to a range of situations in the context of free-form design and at the same time specific enough to capture the contextual dimensions of the domain under study, as has been shown in the case analysis above (generality). Thirdly, it is readily understandable by practitioners, and provides useful guidance (relevance). And finally, it is flexible to accommodate contradictory design approaches and provides an extensible structure that would allow maintenance and revision (modifiability).

5.6.3 Discussion on the Applicability of the System in Various Contexts

InDeS is one of the various possible prototype implementations of a design support system facilitating knowledge construction, sharing and re-use in design. The contribution of this prototype lies in the fact that it is a first step towards a concrete support for designers in free-form design which provides them with a situated and interdisciplinary view of design knowledge in their knowledge acquisition and utilization. The final prototype is not a “complete system” and therefore has not yet been tested in different, real-life design settings. The results of such a test could only be realistic and valid after a long period of use which would go far beyond the time limits and focus of this research. In the domain of free-form design, with such situated and interdisciplinary view of knowledge, the success and efficiency of InDeS, or any other system, would naturally be dependent on its ability to adapt the changing contexts and the varying profiles of users it intends to support. Therefore, a system which is based on knowledge construction, sharing and re-use in an interdisciplinary and dynamic context should also be evaluated according to the degree to which it serves this purpose in varying contexts. The varying contexts of use refers to the transfer of knowledge among users both horizontally and vertically. Horizontal transfer takes place among users with different disciplinary backgrounds or functional responsibilities, while vertical transfer takes place between users within the same discipline with different experience levels, or different functional responsibilites. In the context of free-form design, the experience level cannot be measured only by the years of experience in practice. The familiarity with the design context would also play a crucial role in such measure. Such a discussion becomes even more crucial given the fact that the system is intended to grow with user participation and their reflection on design processes.

In the following sections, the applicability of InDeS in various contexts are discussed, observations and suggestions are made for its further improvement specific to each context of use. These recommendations and observations can be generalized to guide the future development of similar systems and collaborative design support tools in design. The discussion in the following section is mainly based on personal observations, literature, semi-structured interviews with expert designers and lwith master's level students at Delft University of Technology who were asked individually to contribute to the evaluation.

Between an Architectural and an Engineering Office

In this potential context of use, in order to achieve an efficient use of the system, it is imperative that the engineering and the architectural office already have some degree of experience in free-form design context or at least have collaborated earlier. This would help the members of each office to get acquainted with the culture, values and terminologies employed by the other firm. This would also facilitate a familiarity with the context of the system and its vocabulary. It has been suggested by the majority of the interviewees that the system would be most beneficial, if both offices collaborate and work together on several projects to be able to build a reliable knowledge source. Such a repertoire could be built by contributions from both offices. An effective use of the system, as suggested by the interviewees, would be to use the system as "an integrative platform" to organize the multi-disciplinary decisions taken during the meetings between the two offices. The strategic solutions decided jointly by the both groups could then be entered in the system. In this context, efficiency of the system is expected to increase in time with more and collective document entry which would facilitate communication, coordination and understanding over a large amount of complex information that needs to be shared, managed and exchanged.

A possible difficulty would be the interpretation of the terminology within the system, especially during new feature and link document entry with new dependency types. For example, a new feature and its associated document added by the engineering firm needs to be described clearly such that it can be understood in the same way by the members of the design firm. Another key issue may arise when each of the parties wish to aggregate and classify concepts in a different way (e.g. under a different category). As long as what is intended with every feature is clear, this does not cast a problem with regard to its association with other features since the semantic links between the features are created independent of the category under which they appear in the interface. Another possible future improvement for the system could be to allow each party to view the same content simultaneously in a different and customized hierarchical list according to their preferred choice of categorization.

A common concern for all the interviewees was the issue of intellectual property. Although the architectural office and the engineering firm might be collaborating on the same project, they would not necessarily prefer to share all the knowledge generated throughout the project. At this point, they might need to run the system at two different modes, one for internal use, focusing more on the discipline specific features, and another one for external and collaborative use. Such a functionality is currently not present, but can be integrated in the future.

In an Architectural Office

A potential context intended for the system is an architectural design office, composed of designers with varying experience levels and functional responsibilites. In this context, the most distinctive contribution of the system would be facilitating knowledge transfer between the experienced and the novice designers within the office. While the novice designers could benefit by learning from the design strategies, especially regarding the ways how the experienced members of the design team formulate problems, the experienced designers could benefit from the explicit representation of their throughts under such dynamic knowledge structure. Learning from earlier experiences is not yet supported in the architectural design offices. The existing support mainly focuses on the management processes, and the earlier project experiences exist mainly in the head of the designers and in the form of "project documents" with redundant textual and graphical data. The explication of these experiences could contribute to the collective knowledge construction for the members of the design office and to the transfer of knowledge from experienced to the novice designers. In this way, the contribution of InDeS to "design learning" is expected to increase sequentially. According to Seger (1994), implicit learning requires a large number of instances. Accordingly, the efficiency of the system is expected to increase, especially for the novice designers, with more documents entry and with the collective review of these documents during staff meetings. The learning process that InDeS aims to facilitate consists of the three key behaviours of expert designers; outlined by Akin (1990) as the necessary conditions for design expertise:

1. recognition of creative solutions,
2. problem structuring in a way that facilitates creative discovery,
3. formulation of heuristic procedures that translate passive knowledge into active exploration.

The Manufacturers' Contribution

The knowledge modelling effort in this thesis is originally intended to address primarily to "designers" that are responsible for the form generation and form development process. While such creative involvement early in the design process has generally been attributed mainly to architects and engineers, this study revealed the fact that, in the context of free-form design, the creative contribution of the manufacturers early in the design and decision making process are equally crucial. The necessity of integrating manufacturing knowledge early in the design process is not a new concept in the history of architecture. Such an integration has generally been quite straightforward for conventional and orthogonal buildings which relied mainly on industrial mass production. However, in the context of free-form design, each building is unique and each project demands a new manufacturing process necessitating a close cooperation between the architects and the partnering fabricators. According to Shelden "the true sources of innovation - and the parties ultimately responsible for execution of this innovation - are the fabricators themselves". And he continues by stating that "this expertise is best included in the design process during the design development and decision making, before the contract documents have been completed" (Shelden 2002, p. 41).

Therefore, the experience arising from such collaborative effort have become one of the essential sources of knowledge input for InDeS. The results of the interviews with the experienced designers also support this proposition since the majority of the expert designers stated that manufacturing innovations of other(s') projects would be one of the primary reasons for them to use InDeS. However, it is anticipated that, initially, the knowledge coming from the manufacturer would still require to be elicited and documented by the members of the design team. Such anticipation arises due to the rather conservative nature of the conventional contractual agreements within the building industry in which the direct contribution of the manufacturers to the decision making process is implicitly inhibited. That is one of the reasons why unconventional contractual solutions are being sought on a project basis in the free-form design practice. InDeS aims to provide a medium where the design knowledge generated in collaboration with the manufacturers can also be documented and shared.

The Educational Context

Although InDeS has not yet been applied in a design studio context, in education, its analytical knowledge framework has been utilized in the context of a technical workshop where students were taught the basic knowledge about the tasks and cross-disciplinary interactions of free-form design processes. The analytical and integrative framework proved to be useful in the sense that it gave the students the basic skills to critically compare different designs. Moreover, it assisted the students in providing a conceptual understanding of the free-form design domain and its context specific problem structures. We have observed differences in the ways how each students applied these newly gained skills in their own projects, and the degree to which these skills could be applied according to project characteristics. One student, out of three, was designing a free-form building. She was observed to use the framework more successfully to synthesise various interdisciplinary factors in her design. The other two students, who worked with more orthogonal forms, were not as successful in their synthesis of interdisciplinary information. Although it is difficult to generalize this observation without further experimentation in different contexts, it gives the indication that the analytical knowledge framework of InDeS, in its present form, is likely to be more effective in the specific context of free-form design education.

5.6.4 General Remarks on Maintenance and Extensibility

Knowledge capture should not be treated as a one-time-only process creating a static knowledge structure, as such a structure will, at times, contain errors and eventually go out of date. Therefore, such systems should be dynamically designed with ease of revision and maintenance. However, whether such maintenance should be carried out separately or simultaneously during the design process, and the person(s) who would be the responsible for such maintenance become crucial concerns with regard to the efficient use of the system. In any context, the knowledge capture is best practised by the internal users, rather than outside knowledge experts. Capturing knowledge in real-time also has the advantage that knowledge can be made available soon after creation. This improves the communication within the design team. The decisions can be based on the latest information available. This is important particularly if these decisions require trade-offs between different aspects of design. The designers interviewed had all agreed on the increasing efficiency of the system with real-time maintenance but not on conducting such maintenance by all designers within the office. Common concerns for expert designers had been observed. First concern was the allocation of resources and time for such maintenance. Second concern was the reluctance to share all the knowledge with all the members of the design team who could eventually leave the firm with all the critical knowledge that the office possesses. The second concern proves to be more critical in the free-form design context, in which almost all solutions are customized, and the success of design teams develop parallel to the technological and strategic competency of these solutions in a wider market.

The contribution of InDeS to design innovation and creativity is expected to increase if and when it is used by highly collaborative and multi-disciplinary teams. Multi-disciplinary teams tend to be more creative because they interact to share knowledge across disciplinary boundaries, and exploit inter-disciplinary communication, transfer, reasoning, and insights (Sonnenwald 1996). The relevance of such a contribution is supported by the results of a research conducted on the innovative and creative practices (Petre 2004). According to this research, innovation tends to emerge at the 'edges', at the boundaries between domains. A similar definition of creativity, by Langrish (cited in Petre 2004, p.479), is that it consists of a new combination of existing ideas which are present in different people, and achieving creativity requires some kind of interaction to produce the combination.

Issues of update, maintenance, lack of enthusiasm to invest on long term gain, staff costs, and concerns related to intellectual property, have been identified as decisive factors inhibiting the effective use and the applicability of the system in the practice context as was originally intended.

It is anticipated that the immediate application of InDeS in an educational context, as a teaching and learning environment would be more realistic and effective than its immediate use in practice. This anticipation is, firstly, based on the fact that the control, update and maintenance of the knowledge content between the instructor and the student is an easier task compared to the hierarchical and organizational complexities of the design practice. And secondly, the system would require some degree of customization for each design/engineering firm as well as an adjustment time for the users to get familiar with the terminology of the system. Due to both reasons, it is likely to take a longer time to see the the actual contribution of the system in practice.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

As its central theme, this thesis stressed the need for a critical understanding of the structure and the state of the knowledge that has emerged with the new digital approaches in free-from design in architecture. And as an ultimate goal, it attempted to conceptualize the free-form design domain in order to understand and identify the knowledge content it entails specific to its unique context.

This research contributes to this goal by the development of a "knowledge framework" comprising of both the formal and theoretical descriptions of the domain semantics. A knowledge framework further clarifies the knowledge structure of the domain, links the structuring of knowledge with its unique content, facilitates the assimilation of new concepts into the existing structure, and allows its users to share and extend their knowledge with others. The proposed framework has been developed into a web-based system which provides the means to explicate, and to support the individual and collective construction of domain knowledge. The web-based system is developed as a prototype with the potential to be developed into a design support system. It can be more directly used in education as a transferable, teachable body of structured knowledge generating a grounded understanding of the changes in architectural design practice.

The free-form design has been described as a new design domain in architecture, which has been identified not only with its expressive formal characteristics, but also with its unique material and mental creation processes. These processes are identified as highly dynamic and interdisciplinary, challenging the established concepts and understandings while facilitating the emergence of a new body of design knowledge. This emergence is observed to originate due to the three distinct characteristics of the free-from design practice.

- The extensive use of digital technologies in design generation, representation and production processes
- Complex formal and tectonic characteristics of the artefacts produced
- New forms of communications and role divisions between the stakeholders during the life-cycle of the projects.

However, the possibilities that are offered with the digital tools and technologies also come with certain limitations. For example, although mass customization allows geometric differentiation departing from systematic building strategies, the designers still need to bring a certain degree of geometrical regularity to these complex geometries, while combining traditional and advanced computer-based manufacturing and construction practices with regard to certain quality and cost constraints. In the case studies we presented, we have observed several differences in the ways and extent to which designers incorporate these digital and traditional tools and technologies into their working processes. Similarly, how the design and implementation processes are structured and conducted vary from one practice to the next which have immediate consequences on the formal qualities of the final artefact.

6.1 MAIN FINDINGS

The design experiments have contributed to an understanding of the radical differences between collaborative and individual creation of knowledge. The highly non-linear process of knowledge exchange between stakeholders facilitate the creation of shared meanings between the members of the design team. The resulting knowledge is defined as collaborative, which is constructed through the interaction of multiple actors, and embodies the dynamic elements of knowledge that would be difficult to generate by an individual. This view contradicts with the product oriented view of knowledge, propagating a rather process oriented view, which we claim is the key to the understanding of collaborative design and its associated knowledge.

An initial analysis of the knowledge content and the design experiments revealed that the free-form domain tasks and processes are highly multidisciplinary and require the engagement of various stakeholders at various levels starting from the very early stages of a design process. Therefore, it has proved to be more useful to categorize the domain concepts in relation to the specific stages they address according to the specific problems they attempt to solve (or create), rather than who solves or performs them.

We have identified 5 general categories where collaboration has been observed to occur most frequently among the stakeholders and which have been identified as the main sources of the emerging knowledge in free-form design.

- Form finding approach and formal characteristics
- Rationalization of the Structure and the Skin
- Representation and Exchange of Design Information
- Materialization of the Supporting Structure and its Elements
- Fabrication of the Supporting Structure and the Surface Elements

The categories have drawn the contextual framework for our further investigation and have guided the case analyses. The framework has been used to identify, compare and evaluate the knowledge content of three cases (WNH by Kas Oosterhuis, EMP by Frank Gehry, and Dynaform by Bernhard Franken). A comparative analysis of case studies have contributed to the understanding of the different dimensions of knowledge and the factors contributing to its complexity. A horizontal study for each case have facilitated a grounded understanding of how domain concepts are linked within and across categories at different levels of abstraction; how strong these links are; how do the value, strength and direction of these links vary; "how" and "why" the artifact have evolved into its final form. Parallel to this, a vertical study has been conducted in order to cluster the extracted concepts into sub-categories in a hierarchical organization, which has led to the development of a taxonomy of concepts.

Rather than a static and formal description of the domain concepts, we proposed to extend our taxonomy with a theoretical model which has been developed after a thorough analysis of cases. We then defined a "knowledge framework" by integrating the formal and the theoretical model. The knowledge framework consists of the following propositions expressing the characteristics of the domain knowledge and its construction:

- In order to understand the knowledge embedded in the tacit experiences of the designers we need to look into the ways how the knowledge was created.
- Two sets of relationships are recognized between concepts which require different representations with regard to the knowledge content they comprise. One is the hierarchical relationships between the concepts in each category, providing an outline of the tasks and processes of the domain under study. The second relationship is the associations between the concepts within and across categories. Accordingly, both the concepts and the links between them can be considered as variable of knowledge and can be used to explain the unique ways in which designers frame the design problems and the solutions they bring to unique situations.
- Both the concepts and the links between them comprise of knowledge elements which can be distinguished by the value, strength and directions of these links.
- Different types of knowledge can be explained either as an instance of each concept, or as an instance of the inter-connection between two or more concepts
- The same tasks can be performed by a different stakeholder in each project. Accordingly, the links that are created between concepts would reflect a certain bias with regard to the responsibility of the stakeholder who performs the task. Accordingly, the links would reflect the viewpoints of the stakeholders. Understanding these viewpoints is essential for the understanding of how the artefact evolved into its final form.
- The links between concepts should be able to explicate the unique ways in which different practitioners frame the design problems and the solutions they bring to unique situations.
- The links may change both in meaning and form with regard to how they are associated and according to the viewpoint of the project participant (across disciplines) who creates this association. The change in meaning relates to the dependency relation types (e.g. constraint, influence, inspiration) between different concepts, whereas, the change in form relates to the change in the direction of dependencies (e.g. bi-directional, mono-directional).
- Concepts may be linked at any phase of the design process at any degree of generality. For example, constructability criteria can influence the form

generation at the very early stages of the design process, while it can also be left to the final phases.

Based on these findings, we have concluded that any computational system with an aim to support to the acquisition, constructing and transfer of knowledge should display the following features:

- The system should reflect the domain knowledge not only with the content of knowledge it stores, but also with the dynamic associations (links) it provides among knowledge elements.
- The system should be able to accommodate different types of knowledge; such as declarative, procedural, specific, and factual, by facilitating the means to distinguish them during the construction and acquisition of knowledge
- The system should refer to the domain terminology (taxonomy of concepts) and facilitate its extensibility with the addition of new information.
- The system should be able to accommodate both specific and general domain knowledge elements while allowing the user to distinguish them during knowledge construction and re-use.
- The system must be able to facilitate knowledge capture from differing sources and viewpoints and must be capable of representing the evolution of knowledge through the design activity.

Based on these descriptions, we have developed a web-based system (InDeS) to support collaborative knowledge construction, sharing and re-use. Thus, we have developed and implemented a grounded theory of how to understand and explicate the knowledge elements and their interrelationships within the emerging free-form design domain.

6.2 VALIDITY

The proposed knowledge framework is empirically valid because the theory-building process has been intimately tied to the episodes of design practice. It also meets the criteria of practical applicability proposed by Glaser and Strauss (1967). First of all, the concepts and relations posited as central are intimately related to (because derived from) the real practice of design. Secondly, the knowledge framework is sufficiently general to be applicable to a range of situations in the context of free-form design, and at the same time it is specific enough to capture the contextual dimensions of the domain under study, which has been tested at the end of chapter 5. Thirdly, it is readily understandable by practitioners, and provides useful guidance for the conceptualization of free-form design domain. And finally, it is flexible to accommodate contradictory design approaches and provides an extendable structure that allows maintenance and revision.

6.3 APPLICABILITY OF THE SYSTEM

The web-based system developed (InDeS) is only a working prototype and has not yet been tested in practice. However, any system which intends to support collaborative knowledge construction should be assessed with regard to the degree to which it serves this purpose in varying contexts. It is common knowledge that the user profiles and their contexts are influential in the effective use of any system. Such a discussion becomes even more crucial given the fact that the system is intended to grow with user participation and reflection on design processes. The applicability of InDeS in various contexts have been discussed, observations and suggestions have been made for its further improvement specific to each potential context of use. The assessment is based on participant and personal observations, semi structured interviews and literature in the field, and can be summarized as follows:

If the system is used between an architectural and an engineering office;

- The system would be most beneficial, if the offices already have some degree of collaboration.
- An efficient use of the system would be as “an integrative framework” to facilitate communication, coordination and understanding over a large amount of complex information.
- A common concern was if the members of each office wish to aggregate and classify concepts in a different way (e.g. under a different category). As long as the descriptions of the associated features are clear, this would not cast any problems since the semantic links between the features are created independent of the category under which they appear in the interface.
- Another concern for the practitioners have been the issue of intellectual property and who owns the rights of the knowledge that is entered in the system.

If the system is used between the designers of an architectural office;

- the most distinctive contribution of the system would be facilitating knowledge transfer between the experienced and the novice designers within the office.

While the novice designers could benefit by learning from the design strategies, especially regarding the ways how the experienced members of the design team formulate problems, the experienced designers could benefit from the explicit representation of their thoughts under such dynamic knowledge structure.

- The contribution of InDeS to “design learning” is expected to increase sequentially with more document entry into the system.

The designers interviewed had all agreed on the increasing efficiency of the system with real-time maintenance but not on conducting such maintenance by all designers within the office. Issue of update, maintenance, lack of enthusiasm to invest on long term gain, staff costs, and concerns related to intellectual property, have been identified as decisive factors inhibiting the effective use and the applicability of the system in the practice context as was originally intended.

It is anticipated that the immediate application of InDeS in an educational context, as a teaching and learning environment would be more realistic and effective than its immediate use in practice. This anticipation is, firstly, based on the fact that the control, update and maintenance of the knowledge content between the instructor and the student is an easier task compared to the hierarchical and organizational complexities of the design practice. And secondly, the system would require some degree of customization for each design/engineering firm as well as an adjustment time for the users to get familiar with the terminology of the system. Due to both reasons, it is likely to take a longer time to see the actual contribution of the system in practice.

6.4 MAIN CONTRIBUTIONS OF THE RESEARCH

This research contributes to knowledge in the field of free-form design in digital architecture. The following are the theoretical and applicative contributions of this research:;

- introduction of a taxonomy – a hierarchically organized multidisciplinary vocabulary of free-form design.
- development of a theoretical model – a set of propositions expressing the relationships between the domain concepts.
- extraction of concepts, principles and experientially verified relationships useful for explaining the free-form design processes and products.

- development of a "knowledge framework" for the representation and conceptual modelling of knowledge in an interdisciplinary context.
- development of a web-based environment to support collaborative knowledge construction
- analysis of the free-form design, engineering and manufacturing practices with regard to the evolving interdisciplinary design culture and values.

6.4.1 General Contribution to Design Practice

This research tried to frame the ways in which practitioners frame problems and roles. By describing and analysing precedents, we have built a repertoire of concepts which characterize the domain. By providing practitioners with some insight into the context, structure, and process of free-form design, the framework serves as a basis from which the designers can assess and manage a complex design situation. The process of recognition and restructuring helps the practitioners to be aware and criticize their own tacit frames. It is also anticipated that the research results will help the engineers and architects to enter a different way of seeing design problems from the viewpoint of another discipline, which could enrich their collaborative process. Yet, as Schodek (1994) argues, "good design will not result simply because we have a structured framework for the design process in a computer based model that sounds reasonable, and a database that supports this process". The critical contribution of the design support system (InDeS) to design practice is not to support designers immediately in their design process, but rather, its transformation of the understanding of design practice in particular. Obviously, this awareness that the system creates is anticipated to be more effective, rather than the ability to model what is in a designer's mind.

6.4.2 General Contribution to Design Research

This research aims to contribute to the existing research in the fields of collaborative knowledge construction, and architectural design research in general. It is anticipated that our grounded theory approach, taking into account the contextual and processual elements of knowledge, will largely contribute to the understanding of collaborative knowledge in design. In this research, we focused on the socially constructed nature of knowledge, where the meanings were derived through social interactions which is in contrast to mechanistic, object oriented and rational views of knowledge. In this research, design knowledge is viewed as a collaborative and social construct dealt with and modified by people through interpretation and social experience. We also distinguished "communication of design information" from "design collaboration" and identified collaboration as a tool for the generation of a new body of knowledge.

Additionally, the research generated a grounded understanding of the changes associated with the applications of digital technologies in all phases of design, which contributes to the architectural design research in general. Through the analysis of digital free-form design, the research defines a state of transformation for the design practice at large.

6.4.3 General Contribution to Design Education

The representation of knowledge presented in this research forms a transferable, teachable body of knowledge, which is anticipated to contribute to the education of new generation of architects. Understanding the structure and the state of knowledge is the first foundation to establish specific teaching objectives in free-form design and in design education. One of the objectives of the teaching method applied throughout the research is the involvement of the students in creating knowledge. This approach does not only motivate the students in their effort, but also provides them with a conceptual understanding of the design processes in general. This approach challenges the common product oriented approach in architectural design education where students are implicitly guided and taught with an understanding that design knowledge is actually encoded within the geometric artefacts of design (Mitchell 1990). Design studio should not be a medium where the students merely learn to master various CAD software, but they certainly require an understanding of the general principles that are necessary to experience, produce and analyze free-form architecture with all of its complexities.

6.5 RECOMMENDATIONS FOR FUTURE WORK

While more empirical work is necessary to elaborate and verify the framework, it is believed that a useful starting point has been made. Empirical validation and elaboration of the concepts in other settings are clearly needed. In this research, the theoretical framework was generated by examining the limited number of cases in free-form design practice, albeit in depth. More empirical grounding and comparisons will sharpen and enrich the concepts developed here and yield more complex understanding of the phenomenon. First, it is necessary to investigate different contextual factors. We concentrated mainly on the technological and socio-organizational factors that affect the knowledge content, its acquisition and utilization. More contextual factors (e.g. cost, environment, company size and culture) need to be examined to ascertain whether the proposed concepts and framework are relevant in other situations.

It is also necessary to test the system in the context of design practice, in complex projects involving multiple disciplines. This would also ascertain the level and degree of customization that would be required in each context. It is important to test the crucial balance between the degree of customization that should be allowed within the system, and the degree of modification that would turn the system into a different tool than was originally intended. How and to what extent this could be preserved is crucial. In the practice context, an important future improvement within the system would require the inclusion of import and export facilities from/to CAD and CAE tools for instant data entry and retrieval of a specific phase and state of an earlier project. Both engineering and architectural firms keep a record of various versions of their drawings at different stages of the project each of which has its associated knowledge and relevant representations in graphical, textual or any other relevant form. Allowing the transfer and organization of these documents by the system would facilitate the capture and re-use of the abandoned partial information of past designs.

It is possible that by extending the dimensions and contextual factors, a more finely-regulated classification system will be needed, for example, to distinguish between the levels of detail in the definition of abstractions (features). This would require a more elaborated search and retrieval mechanism for the system proposed. Similarly, the links and associations between the features could be assigned weights for conflicting and multiple dependency situations. Integrating these into the system would eventually require much more sophisticated programming skills and techniques.

REFERENCES

1. Akin, O. (1990) 'Necessary conditions for design expertise and creativity', *Design Studies,* vol. 11, no. 2, pp. 107-113.

2. Akin, Ö. (1986) *Psychology of architectural design*, Pion, London.

3. Alexander, C. (1964) *Notes on the synthesis of form*, Harvard University Press, Cambridge,.

4. Anderson, J. R. (1985) *Cognitive psychology and its implications,* 2nd edn, W.H. Freeman, New York.

5. Andia, A. (2002) 'Reconstructing the effects of computers on practice and education during the past three decades', *Journal of Architectural Education,* vol. 56, no. 2, pp. 7-13.

6. Arciszewski, T., Michalski, R. S. & Wnek, J. (1994) 'Machine learning in engineering design: A constructive induction approach', in *Proceedings Of The 1995 Nsf Design And Manufacturing Grantees Conference*, pp. 7-8.

7. Bandini, M. (1997) 'The Conditions of Criticism', in MD Pollak (ed.), *The education of the architect : historiography, urbanism, and the growth of architectural knowledge*, MIT Press, Cambridge, Mass., pp. 425-437.

8. Barnes, L. B., Christensen, C. R. & Hansen, A. J. (1994) *Teaching and the case method : text, cases, and readings,* 3rd edn, Harvard Business School Press, Boston, Mass.

9. Bar-On, D. & Oxman, R. E. (2002) 'Context over content: ICPD, a conceptual schema for the building technology domain', *Automation in Construction,* vol. 11, no. 4, p. 467.

10. Baron, J. B. & Steinberg, R. J. (eds.) (1987) *Teaching Thinking Skills:Theories and Practice*, Freeman, New York.

11. Baynes, K. (1969) *Attitudes in design education*, Lund Humphries, London,.

12. Benne, B. (2004) 'Techno-Organizational Models to Support Construction Industry Work Processes', PhD Thesis, University of California, Berkeley, USA.

13. Boland, R. J. (1985) 'Phenomenology: A Preferred Approach to Research on information Systems', in E Mumford, R Hirschheim, G Fitzgerald & T Wood-Harper (eds), *Research Methods in Information Systems*, North Holland, New York, pp. 193-201.

14. Bollinger, K. & Grohmann, M. (2004) *Workflow architecture - engineering*, Birkhauser, Basel.

15. Boulding, K. E. (1956) *The Image: Knowledge in Life and Society*, Ann harbor: University of Michigan Press.
16. Brauer, G. (2002) *Dynaform + cube : Architecture as brand communication*, Birkhäuser, Basel.
17. Broadbent, G. (1973) *Design in architecture*, John Wiley & Sons, London, New York.
18. Brodie, M. L., Mylopoulos, J. & Schmidt, J. W. (1984) *On conceptual modelling : perspectives from artificial intelligence, databases, and programming languages*, Springer-Verlag, New York.
19. Bronowski, J. (1978) *The origins of knowledge and imagination*, Yale University Press, New Haven.
20. Brown, D. C. (1992) 'Design', in S SHapiro (ed.), *The encyclopedia of Artificial Intelligence*, 2nd edition edn, John Wiley & Sons, New York, pp. 331-339.
21. Brown, D. C. & Birmingham, W. P. (1997) 'Understanding the nature of design', *Expert, IEEE [see also IEEE Intelligent Systems and Their Applications]*, vol. 12, no. 2, p. 14.
22. Burry, M., Coulson, J., Preston, J. & Rutherford, E. (2001) 'Computer-aided design decision support: interfacing knowledge and information', *Automation in Construction*, vol. 10, no. 2, p. 203.
23. Carmel, E., Crawford, S. & Chen, H. (1992) 'Browsing in Hypertext: A Cognitive Study.' *IEEE Transactions on Systems, Man and Cybernetics*, vol. 22, no. 5, pp. 865-884.
24. Carrara, G. & Kalay, Y. E. (1994) *Knowledge-based computer-aided architectural design*, Elsevier, Amsterdam.
25. Carrara, G., Kalay, Y. E. & Novembri, G. (1992) 'Multi-modal representation of design knowledge', *Automation in Construction*, vol. 1, no. 2, pp. 111-121.
26. Chandrasekaran, B., Josephson, J. R. & Benjamins, V. R. (1998) 'The Ontology of Tasks and Methods', *Paper presented at the 11th Knowledge Acquisition for KBS Workshop*, Canada.
27. Chang, K. E., Sung, Y. T. & Chen, I. D. (2002) 'The effect of concept mapping to enhance text comprehension and summarization', *Journal of Experimental Education*, vol. 71, no. 1, pp. 5-23.
28. Chang, K. E., Sung, Y. T. & Lee, C. L. (2003) 'Web-based collaborative inquiry learning', *Journal Of Computer Assisted Learning*, vol. 19, no. 1, pp. 56-69.
29. Chaszar, A. (2003) 'Blurring the lines - An exploration of current CAD/CAM techniques', *Architectural Design*, no. 161, pp. 111-117.
30. Cheng, N. Y.-w. (2003) 'Approaches to design collaboration research', *Automation in Construction*, vol. 12, no. 6, pp. 715-723.
31. Christiaans, h. (1992) *Creativity in Design, The Role of Domain Knowledge in Designing*, Lemma, Utrecht.

32. Cross, N. (1982) ‘Designerly Ways of Knowing’, *Design Studies,* vol. 3, no. 4, pp. 221-227.

33. Cross, N., Christiaans, H. & Dorst, K. (1996) *Analysing design activity*, Wiley, Chichester ; New York.

34. Cuff, D. (1991) *Architecture: the story of practice*, MIT Press, Cambridge.

35. de Vries, A. E. (1994) ‘Structuring information for design problem solving’, PhD Thesis, Eindhoven University.

36. Dohmann, F. (1999) ‘Introduction to the process of hydroforming’, *Hydroforming of Tubes, Extrusions, and Sheet Metals, Proceedings of the International Conference on Hydroforming*, ed. K Siegert.

37. Domeshek, E. A. & Kolodner, J. L. (1992) ‘A Case-Based Design Aid for Architecture’, in JS Gero (ed.), *Artificial Intelligence in Design*, Kluwer Academic, Dordrecht, pp. 497-516.

38. Dorf, R. C. & Kusiak, A. (1994) *Handbook of design, manufacturing and automation*, Wiley, New York.

39. Duffy, A. H. B. (1997) ‘The “What”and “How” of learning in design’, *Expert, IEEE [see also IEEE Intelligent Systems and Their Applications],* vol. 12, no. 3, p. 71.

40. Duffy, S. M. & Duffy, A. H. B. (1996) ‘Sharing the Learning Activity Using Intelligent CAD’, *Artificial Intelligence for Engineering Design Analysis and Manufacturing (AIEDAM),* vol. 10, no. 2, pp. 83-100.

41. Dzbor, M. (October 1999) *Knowledge Intensive Design Support: An enquiry into the role of ontologies and analogous thinking in the design support. Technical Report.*, The Open University.

42. Eastman, C. M., McCracken, W. M. & Newstetter, W. C. (2001) *Design knowing and learning cognition in design education*, Elsevier, Amsterdam.

43. Edelson, D. C., Gordin, D. N. & Pea, R. D. (1999) ‘Addressing the challenges of inquiry-based learning through technology and curriculum design’, *Journal Of The Learning Sciences,* vol. 8, no. 3-4, pp. 391-450.

44. Eisenhardt, K. M. (1989) ‘Building Theories from Case-Study Research’, *Academy of Management Review,* vol. 14, no. 4, pp. 532-550.

45. Evbuomwan, N. F. O., Sivaloganathan, S. & Jebb, A. (1996) ‘A survey of design philosophies, models, methods and systems’, *Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture,* vol. 210, no. 4, pp. 301-320.

46. Fischer, G. (1992) ‘Domain-Oriented Design Environments’, *Proceedings of the 7th Knowledge-Based Software Engineering Conference* IEEE Computer Society.

47. Flood, R. L. (1999) *Rethinking the Fifth Discipline*, Routledge, London.

48. Frampton, K. (2001) ‘Technoscience and environmental culture: A provisional critique’, *Journal of Architectural Education,* vol. 54, no. 3, pp. 123-129.

49. Franken, B. (2002) ‘Form Follows Force: The Form Finding Process for the Dynaform’, in G Brauer (ed.), *Dynaform + cube : Architecture as brand communication*, Birkhäuser, Basel, pp. 59-73.

50. Friedman, K. (2003) ‘Theory construction in design research:criteria: approaches and methods’, *Design Studies* vol. 24, no. 6, pp. 507-522.

51. Gero, J. S. & Maher, M. L. (eds.) (1993) *Modelling creativity and knowledge-based creative design*, L. Erlbaum, Hillsdale, NJ.

52. Glaser, B. G. & Strauss, A. L. (1967) *The discovery of grounded theory; strategies for qualitative research*, Aldine Pub. Co., Chicago.

53. Glazer, B. & Strauss, A. (1967) *The Discovery of Grounded Theory*, Aldine, Chicago.

54. Grohmann, M., Bollinger, K. & Michel, M. (2004) ‘Kunsthaus Graz - Design and Construction’, *Proceedings of the International Symposium on Shell and Spatial Structures - from Models to Realization*, ed. R Motro, Montpellier.

55. Grohmann, M., Bollinger, K. & Michel, M. (2004) ‘Spatial Structures for Fair Events’, *Proceedings of the International Symposium on Shell and Spatial Structures - from Models to Realization*, ed. R Motro, Montpellier.

56. Groot, A. D. (1972) *Methodology*, Mouton & Co., The Hague & Paris.

57. Gruber, T. R. (1993) ‘A Translation approach to Portable Ontology Specifications’, *Knowledge Acquisition,* vol. 5, no. 2, pp. 199-221.

58. Guba, E. G. (ed.) (1990) *The Paradigm dialog,* Sage Publications, California.

59. Hales, C. (1987) ‘Analysis of the Engineering Design Process in An Industrial Context’, Cambridge University, United Kingdom.

60. Heylighen, A. & Neuckermans, H. (2001) ‘A case base of Case-Based Design tools for architecture ’, *Computer-Aided Design,* vol. Volume 33, no. Issue 14.

61. Hoinkes, R. M. (1996) ‘Visualizing Design Processes for Knowledge Mapping’, Doctor of Design Thesis, Harvard Graduate School of Design. Retrieved April 8, 2003, from Harvard University Digital Theses.

62. Hubka, V. & Eder, W. E. (1988) *Theory of technical systems : a total concept theory for engineering design*, Springer-Verlag, Berlin ; New York.

63. Ibrahim, M. & Krawczyk, R. (2003) ‘The Level of Knowledge of CAD Objects within the Building Information Model’, *Proceedings of the 2003 Annual Conference of the Association for Computer Aided Design In Architecture*, ed. K Klinger, Indianapolis, CA, USA. Retrieved August 20, 2005, from CUMINCAD Online database.

64. Jehng, J. C. J. (1997) ‘The psycho-social processes and cognitive effects of peer-based collaborative interactions with computers’, *Journal Of Educational Computing Research,* vol. 17, no. 1, pp. 19-46.

65. Jong, T. d. & Ferguson-Hessler, M. G. M. (1986) ‘Cognitive Structures of Good and Poor Novice Problem Solvers in Physics’, *Journal of Educational psychology,* vol. 78, no. 2, pp. 279-288.

66. Kalay, Y. E. (1999) ' The Future of CAAD: From Computer-aided Design to Computer-aided Collaboration', *Proceedings of the International Conference on Computer Aided Architectural Design Futures*, Atlanta, pp. 14-30.

67. Kalay, Y. E. (2004) *Architecture's new media : principles, theories, and methods of computer-aided design*, MIT Press, Cambridge, Mass.

68. Kalay, Y. E., Khemlani, L. & Choi, J. W. (1998) 'An integrated model to support distributed collaborative design of buildings', *Automation in Construction*, vol. 7, no. 2-3, p. 177.

69. Kangassalo, H. (1990) *Information modelling and knowledge bases*, IOS Press, Washington, DC.

70. Karacapilidis, N., Adamides, E. & Evangelou, C. (2005) 'A computerized knowledge management system for the manufacturing strategy process', *Computers in Industry,* vol. In Press, Corrected Proof.

71. Kieran, S. & Timberlake, J. (2004) *Refabricating architecture : how manufacturing methodologies are poised to transform building construction*, McGraw-Hill, New York.

72. Kipnis, J. (1993) 'Towards a New Architecture', in G Lynn (ed.), *Folding in Architecture*, AD Profile no:172, pp. 40-49.

73. Klinger, K. R. (2001) 'Making Digital Architecture: Historical, Formal, and Structural Implications of Computer Controlled Fabrication and Expressive Form', *Proceedings of the nineteenth ECAADE Conference on Education and Architectural IT Curricula*, Helsinki. Retrieved January 15, 2003, from Online database.

74. Kloft, H. (2005) 'Non-Standard Structural Design for Non-Standard Architecture', in B Kolarevic & AM Malkawi (eds), *Performative Architecture:Beyond Instrumentality*, Spon Press, New York.

75. Kocaturk, T. & Tuncer, B. (2004) 'Modeling Collaborative Conceptual Design in the Digital Age', *Third International Workshop on Construction Information Technology in Education*, ed. A Dikbas, ITU Press, Istanbul, Turkey, pp. 149-163.

76. Kocaturk, T., Tuncer, B. & Veltkamp, M. (2003) 'Exploration of Interrelationships Between Digital Design and Production Processes of Free-Form Complex Surfaces in a Web-based Database', *Digital Design: Research and Practice, Proceedings of the 10th International Conference on Computer Aided Architectural Design Futures*, eds. M-L. Chiu, J-Y Tsou, T. Kvan, M Morozumi & T-S Jeng, Kluwer Academic, Dordrecht, The Netherlands, pp. 445-454.

77. Kocaturk, T. & Veltkamp, M. (2005) 'Interdisciplinary Knowledge Modeling for Free-Form Design – An Educational Experiment', *Computer Aided Architecture Design Futures*, eds. B Martens & A Brown, Kluwer Acedemic, Dordrecht, pp. 465-474.

78. Kolarevic, B. (2001) 'Digital Fabrication: Manufacturing Architecture in the Information Age', *Architectural Information Management - Proceedings of the 19th eCAADe conference*, ed. H Penttilä, Espoo, Helsinki.

79. Kolarevic, B. (ed.) (2003) *Architecture in the digital age : design and manufacturing*, Spon Press, New York, NY.

80. Kolarevic, B. & Malkawi, A. (2005) *Performative architecture : beyond instrumentality*, Spon Press, New York.

81. Kolb, D. A. (1984) *Experiential learning : experience as the source of learning and development*, Prentice-Hall, Englewood Cliffs, N.J.

82. Kolodner, J. L. (1993) *Case-based reasoning*, Morgan Kaufmann Publishers, San Mateo, CA.

83. Konda, S., Monarch, I., Sargent, P. & Subrahmanian, E. (1992) 'Shared Memory in Design: A Unifying Theme for Research and Practice', *Research in Engineering Design,* vol. 4, no. 1, pp. 23-42.

84. Kvan, T. & Candy, L. (2000) 'Designing collaborative environments for strategic knowledge in design', *Knowledge-Based Systems,* vol. 13, no. 6, pp. 429-438.

85. Kwinter, S., Wigley, M., Mertins, D. & Kipnis, J. (eds.) (2004) *Phylogenesis foa's ark: foreign office architects*, Aktar, Barcelona.

86. Lakkala, M., Lallimo, J. & Hakkarainen, K. (2005) 'Teachers' pedagogical designs for technology-supported collective inquiry: A national case study', *Computers & Education,* vol. 45, no. 3, p. 337.

87. Landsdown, J. (1986) 'Requirements for Knowledge Based Systems in Design', *Proceedings of the Computer-Aided Architectural Design Futures*, ed. A Pipes, London: Butterworths, Delft, The Netherlands, pp. 120-128.

88. Lawson, B. (1980) *How Designers Think*, Architectural Press; Eastview Editions, N.J.

89. Lawson, B. (1997) *How designers think : the design process demystified,* Completely rev. 3rd edn, Architectural Press, Oxford ; Boston.

90. Laxton, M. (1969) 'Design Education in Practice', in K.Baynes (ed.), *Attitudes in Design Education*, Lund Humphries, London.

91. Lindsey, B. & Gehry, F. O. (2001) *Digital Gehry : material resistance/digital construction*, Birkhäuser, Basel ; Boston.

92. Linn, C. (2000) 'Creating Sleek Metal Skins for Buildings', *Architectural Record*, October 2000, pp. 173-178.

93. Logan, B. S. (1985) 'Representing the Structure of Design Problems', *Proceedings of the Computer-Aided Architectural Design Futures*, ed. A Pipes, London: Butterworths, pp. 158-170.

94. Love, T. (2002) 'Constructing a coherent cross-disciplinary body of theory about designing and designs: some philosophical issues', *Design Studies,* vol. 23, no. 3, p. 345.

95. Lu, S. C.-Y. & Udwadia, F. (2000) *Conflict Management in Collaborative Engineering Design*, Online Research Report, University of Southern California, School of Engineering, November 2000.

96. Lynn, G. (1999) *Animate Form*, Princeton Architectural Press, New York.

97. MacCallum, K. J. (1990) 'Does Intelligent CAD exist?' *Artificial Intelligence in Engineering*, vol. 5, no. 2, pp. 55-64.

98. Magnusson, J. D. (2001) 'Experience Music Project', *Modern Steel Construction*, June 2001. Retrieved April 12, 2004, from Moder Steel Construction Online database.

99. Maher, M. L., Balachandran, M. & Zhang, D. M. (1995) *Case-Based Reasoning in Design*, Lawrence Erlbaum Associates, Hillsdale, N.J.

100. Maher, M. L. & Garza, A. G. D. S. (1997) 'AI in Design: Case-Based Reasoning in Design', *IEEE Expert: Intelligent Systems and Their Applications* vol. 12, no. 2, pp. 34-41.

101. March, S. T. & Smith, G. F. (1995) 'Design and Natural-Science Research on Information Technology', *Decision Support Systems*, vol. 15, no. 4, pp. 251-266.

102. Martin, P. Y. & Turner, B. A. (1986) 'Grounded Theory and Organizational Research', *Journal of Applied Behavioral Science*, vol. 22, no. 2, pp. 141-157.

103. Minsky, M. L. (1968) *Semantic information processing*, MIT Press, Cambridge, Mass.

104. Minsky, M. L. (1975) 'A Framework for Representing Knowledge', in PH Winston & B Horn (eds), *The Psychology of Computer Vision*, McGraw-Hill, New York, pp. vi, 282 p.

105. Mitchell, W. J. (1990) *The logic of architecture : design, computation, and cognition*, MIT Press, Cambridge, Mass.

106. Mitchell, W. J. (2001) 'Roll Over Euclid: How Frank Gehry Designs Buildings', in JF Ragheb (ed.), *Frank Gehry, Architect*, New York: Guggenheim Museum Publications, pp. 352-363.

107. Mitchell, W. J. & McCullough, M. (1991) *Digital design media : a handbook for architects and design professionals*, Van Nostrand Reinhold, New York.

108. Mulet, E. & Vidal, R. (2005) 'Functional requirements for computer-based design support systems, derived from experimental studies', *Knowledge-Based Systems*, vol. In Press, Corrected Proof.

109. Norberg-Schulz, C. (1966) *Intentions in architecture*, M.I.T. Press, Cambridge, Massachusetts.

110. Novak, J. D. (1990) 'Concept Mapping - A Useful Tool For Science-Education', *Journal Of Research In Science Teaching*, vol. 27, no. 10, pp. 937-949.

111. Novitski, B.-J. (1987) 'Integrating computers into the architectural curriculum : ACADIA '87 Workshop proceedings, October 30-November 1, 1987, School of Design, North Carolina State University, Raleigh, North Carolina 27695', ACADIA, [S.l.], p. 208 p.

112. Oosterhuis, K. (2002) *Architecture Goes Wild*, NAI Publishers, Rotterdam.

113. Oosterhuis, K. & Boer, S. (2004) 'Architectural Parametric Design and Mass Customization', *Proceedings of The 5th European Conference on Product And Process Modelling In the Building And Construction Industry – ECPPM 2004*, eds. A Dikbas & R Scherer, Istanbul.

114. Orlikowski, W. J. (1993) 'Case Tools as Organizational-Change - Investigating Incremental and Radical Changes in Systems-Development', *Mis Quarterly,* vol. 17, no. 3, pp. 309-340.

115. O'Sullivan, B. (2002) *Constraint-aided conceptual design*, Professional Engineering, London.

116. Oxman, R. E. (1994) 'Precedents in design: a computational model for the organization of precedent knowledge', *Design Studies,* vol. 15, no. 2, pp. 141-157.

117. Oxman, R. E. (1995) 'Viewpoint Observing the observers: research issues in analysing design activity', *Design Studies,* vol. 16, no. 2, p. 275.

118. Oxman, R. E. (1999) 'Educating the designerly thinker', *Design Studies,* vol. 20, no. 2, pp. 105-122.

119. Oxman, R. E. (2001) 'The Mind in Design - A Conceptual Framework for Cognition in Design Education', in CM Eastman, WM McCracken & WC Newstetter (eds), *Design knowing and learning : cognition in design education*, 1st edn, Elsevier Science B.V., Amsterdam ; New York, pp. 105-122.

120. Oxman, R. E. (2004) 'Think-maps: teaching design thinking in design education', *Design Studies,* vol. 25, no. 1, pp. 63-91.

121. Oxman, R. E. (2006) 'Theory and design in the first digital age', *Design Studies,* vol. 27, no. 3, pp. 229-265.

122. Oxman, R. E. & Oxman, R. (1990) 'Computability of Architectural Knowledge', in M McCullough, WJ Mitchell & P Purcell (eds), *The Electronic design studio : architectural knowledge and media in the computer era*, MIT Press, Cambridge, Mass., pp. 171-187.

123. Oxman, R. E. & Oxman, R. (1994) 'Case-based design: cognitive models for case libraries', in G Carrara & YE Kalay (eds), *Knowledge-based computer-aided architectural design*, Elsevier, Amsterdam ; New York, pp. 45-68.

124. 'Peter B. Lewis Building, Case Western Reserve'(2002), *Modern Steel Construction*, June 2002. Retrieved March 12, 2003, from Modern Steel Construction Online database.

125. Parsaye, K. (1989) *Intelligent databases : object-oriented, deductive hypermedia technologies*, Wiley, New York.

126. Petre, M. (2004) 'How expert engineering teams use disciplines of innovation', *Design Studies Expertise in Design,* vol. 25, no. 5, pp. 477-493.

127. Petrovic, I. K. (1994) ‘On Some Issues of Development of Computer-Aided Architectural Design Systems’, in G Carrara & YE Kalay (eds), *Knowledge-Based Computer-Aided Architectural Design*, Elsevier, Amsterdam.

128. Pettigrew, A. M. (1990) ‘Longitudinal Field Research on Change: Theory and Practice’, *Organization Science,* vol. 1, no. 3, pp. 267-292.

129. Piaget, J. (1971) *Psychology and epistemology*, Grossman, New York,.

130. Quillian, M. R. (1968) ‘Semantic Memory’, in M Minsky (ed.), *Semantic Information Processing*, MIT Press, Cambridge, USA.

131. Rada, R. (1991) *Hypertext: From Text to Expertext*, University Press, Cambridge.

132. Restrepo, J. & Christiaans, H. (2003) ‘Problem Structuring and Information Access in Design’, *Proceedings of the 6th Design Thinking Research Symposium on Expertise in Design*, eds. N Cross & E Edmonds, Sydney, Australia.

133. Reymen, I. M. M. J. (2001) ‘Improving Design Processes through Structured Reflection: A Domain-independent Approach’, PhD Thesis. Retrieved December 15, 2003, from Eindhoven University of Technology.

134. Rezgui, Y. (2002) ‘Review of information and the state of the art of knowledge management practices in the construction industry’, *The Knowledge Engineering Review,* vol. 16, no. 03, pp. 241-254.

135. Richards, D. & Simoff, S. J. (2001) ‘Design ontology in context -- a situated cognition approach to conceptual modelling’, *Artificial Intelligence in Engineering,* vol. 15, no. 2, pp. 121-136.

136. Rosenman, M. A. & Gero, J. S. (1994) ‘The What, the How, and the Why in Design’, *Applied Artificial Intelligence,* vol. 8, no. 2, pp. 199-218.

137. Rotheroe, K. C. (2000) ‘The Computer-Aided Design and Manufacture of Complexly-Shaped Metal Architectural Frame Structures’, PhD Thesis, Harvard University, USA. Retrieved April 15, 2003, from Harvard University Digital Theses.

138. Rotheroe, K. C. (2001) ‘Manufacturing FreeForm Architecture’, in M Bechthold, K Griggs, D Schodek & M Steinberg (eds), *New Technologies in Architecture I - Digital Design and Manufacturing Techniques*, Harvard Design School: Technology Report Series 2001-1, Cambridge

139. Ruby, A. (2001) ‘Architecture in the Age of Digital Productability’, in P Cachola Schmal (ed.), *Digitalreal : Blobmeister - first built projects* Birkhäuser Verlag, Basel ; Boston, pp. 206-213.

140. Schodek, D. L. (1994) ‘Critical issues in automation based creative design education’, in A Tzonis & I White (eds), *Automation based creative design : research and perspectives*, Elsevier Science B.V., Amsterdam, pp. 447-458.

141. Schodek, D. L., Bechthold, M., Griggs, J. K., Kao, K. & Steinberg, M. (2005) *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design*, John Wiley & Sons, NJ.

142. Schön, D. A. (1983) *The reflective practitioner : how professionals think in action*, Basic Books, New York.

143. Seele, G. (2002) 'Contemporary Filigree Spatial Structures - A Global Challenge', in G Brauer (ed.), *Dynaform + cube : Architecture as brand communication*, Birkhäuser, Basel, pp. 105-120.

144. Seger, C. A. (1994) 'Implicit Learning', *Pshychological Bulletin,* vol. 115, no. 2, pp. 163-196.

145. Shelden, D. R. (2002) 'Digital surface representation and the constructibility of Gehry's architecture', PhD Thesis, Massachusetts Institute of Technology. Retrieved April 20, 2005, from Massachusetts Institute of Technology Digital Theses.

146. Smithers, T., Conkie, A. & Doheny, J. (1990) 'Design as Intelligent Behaviour: an AI in Design Research Programme', *Artificial Intelligence in Engineering,* vol. 5, no. 2, pp. 78-109.

147. Sonnenwald, D. H. (1996) 'Communication roles that support collaboration during the design process', *Design Studies,* vol. 17, no. 3, pp. 277-301.

148. Stouffs, R., Kooistra, J. & Tuncer, B. (2004) 'Metadata as a means for correspondence on digital media ', *ITcon,* vol. 9, no. Special issue Digital Media Libraries, pp. 129-142.

. 149. Stouffs, R., Tuncer, B. & Sariyildiz, I. S. (2003) 'InfoBase: a multimedia learning environment to support group work and discourse', *System-based Vision for Strategic and Creative Design*, ed. F Bontempi, A.A. Balkema, Lisse, The Netherlands, pp. 1751-1756.

150. Strauss, A. & Corbin, J. (1994) 'Grounded Theory methodology: An overview', in N Denzin, K. and Lincoln, Y.,S. (ed.), *Handbook of Qualitative Research*, Sage Publications, London.

151. Tang, M. X. (1997) 'A Knowledge-Based Architecture for Intelligent Design Support', *Knowledge Engineering Review,* vol. 12, no. 4, pp. 387-406.

152. Tang, M. X. (2001) 'Inductive learning techniques in design process -- A design concept learning system', *Integrated Computer-Aided Engineering,* vol. 8, no. 2, pp. 171-186.

153. Tang, M. X. & Frazer, J. (2001) 'A representation of context for computer supported collaborative design', *Automation in Construction,* vol. 10, no. 6, p. 715.

154. Tuncer, B., Stouffs, R. & Sariyildiz, I. S. (2001) '(Re)presentation of architectural analyses - Two prototype applications', in *Computer Aided Architectural Design Futures 2001, Proceedings*, pp. 495-505.

155. Tuncer, B., Stouffs, R. & Sariyildiz, I. S. (2002) 'Document decomposition by content as a means for structuring building project information', *Construction Innovation,* vol. 2, no. 4, pp. 229-248.

156. Tzonis, A. & White, I. (eds.) (1994) *Automation based creative design : research and perspectives*, Elsevier Science B.V., Amsterdam.

157. Van Berkel, B. & Bos, C. (1999) *Move*, Architectura & Natura, Amsterdam.

158. Van der Vegte, W. F., Pulles, J. P. W. & Vergeest, J. S. M. (2001) 'Towards computer-supported inclusion and integration of life cycle processes in product conceptualization based on the process tree', *Automation in Construction,* vol. 10, no. 6, p. 731.

159. Watson, I. & Perera, S. (1997) 'Case-Based Design: A Review and Analysis of Building Design Applications', *Artificial Intelligence for Engineering, Design, Analysis and Manufacturing,* vol. 11, pp. 59-87.

160. Wilhelm, V. (2002) 'Membrane Engineering - Why Form and Construction are Co-Dependent', in G.Brauer (ed.), *Dynaform + cube : Architecture as brand communication*, Birkhäuser, Basel, pp. 137-146.

161. Yin, R. K. (1994) *Case study research : design and methods,* 2nd edn, Sage Publications, Thousand Oaks, CA.

162. Zack, M. (1999) 'Managing Codified Knowledge', *Sloan Management Review,* vol. 40, no. 4, pp. 45-58.

163. Zellner, P. (ed.) (1999) *Hybrid Space: New Forms in Digital Architecture*, Thames and Hudson, London.

164. Zha, X. F. & Du, H. (2005) 'Knowledge-intensive collaborative design modeling and support: Part II: System implementation and application', *Computers in Industry,* vol. In Press, Corrected Proof.

FIGURE SOURCES:

Figure 2.1	Image courtesy of Bollinger& Grohmann
Figure 2.2	www.franken-architekten.de
Figure 3.8	Image courtesy of Chris Kievid, Tomasz Jazkiewiez, Max De Lara Cohen, Cheng Hui Chua, Dee Dee Lim
Figure 3.9	Image courtesy of Chris Kievid
Figure 3.11	Image courtesy of Stephan Krakhofer
Figure 4.1	Image courtesy of Oosterhuis NL
Figure 4.2	Image courtesy of Oosterhuis NL
Figure 4.3	Image courtesy of Oosterhuis NL
Figure 4.5	Image courtesy of Oosterhuis NL
Figure 4.6	www.archmcgill.ca/prof/sijpkes
Figure 4.7	Image courtesy of Gehry Technologies
Figure 4.8	Image courtesy of Gehry Technologies
Figure 4.9	Image courtesy of Gehry Technologies
Figure 4.10	Image courtesy of Hoffman Construction
Figure 4.11	Image courtesy of Hoffman Construction
Figure 4.12	www.emplive.org
Figure 4.13	Image courtesy of Hoffman Construction
Figure 4.14	Image courtesy of Bollinger&Grohmann
Figure 4.15	Image courtesy of Bollinger&Grohmann
Figure 4.16	Image courtesy of Bollinger&Grohmann
Figure 4.17	Image courtesy of Bollinger&Grohmann
Figure 4.18	Image courtesy of Bollinger&Grohmann

SAMENVATTING

Dit onderzoek behandelt het opkomende domein van free-form design. In het onderzoek wordt getracht de kennis en kenmerken van free-form design expliciet te maken door een systematische verkenning van de praktijk van free-form design. Free-form design laat zich niet simpelweg kenmerken door louter formele complexiteit, maar dient eerder in zijn totaliteit begrepen te worden, met zijn eigen unieke methodologie, en technologische en theoretische inhoud. Hiermee is free form design representatief voor de toenemende invloed van digitale technologieën op architectonisch ontwerpen en productie. Vanuit deze vooronderstellingen zien we dat de kennis van het nieuwe domein gekenmerkt wordt door het veelvuldig gebruik van digitale tools en technologieën, formele en procedurele complexiteiten, pluralistische ontwerp methodologieën en de unieke interactievormen die nodig zijn in verscheidene disciplines.

De studie naar een nieuw en evolutionair domein van ontwerpen is een uitdagende taak die een kritische strategie behoeft, waarbinnen rekening gehouden wordt met mogelijke tegenstellingen tussen bestaande opvattingen over - en nieuw ontstane kenmerken van ontwerpen. Er is evenwel een kritieke balans te vinden in het spanningsveld tussen enerzijds de mate waarin reeds verankerde vooronderstellingen onze queeste kunnen beïnvloeden en anderzijds de mate waarin ontvankelijkheid en openheid voor nieuwe concepten betracht moeten worden. Deze nieuwe concepten vormen een uitdaging voor bestaande opvattingen over ontwerpen en kennis van ontwerpen. De hiervoor beschreven kritieke balans vormt het uitgangspunt voor dit onderzoek en heeft tot de volgende onderzoeksvraag geleid: “hoe kunnen we het domein van free-form design conceptualiseren om het kennisdomein dat het met zich meebrengt te identificeren en tevens te begrijpen in relatie tot de unieke context?”

Elke poging om deze vraag te beantwoorden roept in de eerste plaats om een nadere bepaling van de kernthema’s die het nieuwe domein doen verschillen van conventioneel ontwerpen:

1. De mate waarin digitale technologieën geïntegreerd worden in de ontwerp- en productieprocessen

2. Opkomende formeel/tectonische kwaliteiten en variëteiten.
3. De veranderende socio-organisatorische rollen en veranwoordelijkheden van deelnemers.

Doordat met elk thema nieuwe concepten, werkprocessen en vaardigheden geïntroduceerd worden in free-form design, vervagen de harde grenzen tussen de werkprocessen van de verschillende disciplines. Verder zullen verschillende interactietypes bij deze thema's tot nieuwe afhankelijkheidsrelaties leiden tussen ontwerptaken binnen en tussen disciplines, die bijdragen aan de evolutie van de uiteindelijke artefact. In zo'n kader wordt samenwerking een instrument voor de creatie van gemeenschappelijke kennis. Deze gemeenschappelijke kennis zullen we expliciet moeten maken om de nieuwe inhoudelijke kennis van het domein te kunnen beschrijven. Voor het doel van dit onderzoek worden de interdisciplinaire processen geïdentificeerd met een specifieke focus op de werkprocessen van drie disciplines, architectonisch ontwerpen, draagconstructief ontwerpen en fabricage. Hierbij wordt gelet op de mate waarin zij elkaar wederzijds beïnvloeden en bijdragen aan de inhoud van het nieuwe kennisdomein.

Om tot een context gebaseerde en proces georiënteerde beschrijving en verklaring van het te bestuderen domein te komen is als methodologische insteek gekozen voor een grounded theory benadering en case study analyses. Daarbij wordt parallel aan de kennisontwikkeling een theorie ontwikkeld op basis van de analyse van voorbeelden uit de ontwerppraktijk. De theorie beschrijft en verklaart de free form design processen. Op deze manier wordt rekening gehouden met de verschillende manieren, waarop ontwerp problemen worden waargenomen en geformuleerd door leden van ontwerp teams.

Het onderzoek stelt een taxonomie voor – een representatieve, hiërarchisch georganiseerd vocabulaire van de domeinconcepten – die voorziet in een gedeelde structuur en een set van beschrijvende termen. Parallel hieraan is een theoretisch model ontwikkeld, dat bestaat uit een set van stellingen, waarmee de relaties tussen deze concepten worden vastgelegd. Dit heeft geleid tot het definiëren van een 'kennis raamwerk' dat is samengesteld uit een verzameling concepten, principes en experimenteel bepaalde relaties waarmee de processen van free-form design kunnen worden verklaard. Het kennis raamwerk is bedoeld om als een referentie model gebruikt worden om de ervaringen met het ontwerpen en hun verwante onwerpkennis in te kaderen en te evalueren. Niettemin kan zo'n raamwerk nooit compleet zijn, gegeven de voortdurende ontwikkeling van nieuwe concepten, methoden en technologieën in ontwerpen. Het bovenstaande heeft geleid tot de volgende, definitieve onderzoeksvragen:

- Hoe kan zo’n model omgaan met verandering en een plaats bieden aan verschillende ervaringen met ontwerpen en nieuwe informatie?
- Hoe kan het model zich ontwikkelen door de bijdrage van de producenten van de kennis zelf, waardoor er een bijdrage geleverd wordt aan een collaboratieve creatie van kennis?
- Hoe kan dit een kennistransfer faciliteren tussen ontwerpers binnen en tussen verschillende disciplines?

De antwoorden op deze vragen worden gezocht door het ontwikkelen van een praktische toepassing in de vorm van een web-based systeem dat ontwikkeld is door de kenniscontext (de voorgestelde taxonomie) in een bestaande database (InfoBase) te integreren en door supplementaire functionaliteiten aan zijn representationele structuur toe te voegen voor een efficiënte toegang tot het gerelateerde kennisdomein. Een lange termijn doelstelling en motivatie voor de ontwikkeling van dit prototype was het ondersteunen van het collectief genereren en de transfer van kennis van free-form design, waaraan nieuwe kennis kan worden toegevoegd en opgehaald worden door verschillende gebruikers. In dit systeem is de kennisgroei intrinsiek afhankelijk van de gebruikersparticipatie. Daarom richt het onderzoek zich ook meer op het ontwikkelen van een prototype dan op een compleet systeem met alle functionaliteiten. Door het gebruik van de eerder beschreven eigenschappen van het kennisdomein, biedt het prototype een flexibele en uitbreidbare structuur voor de organisatie en representatie van de gesituationeerde en collaboratieve kenniselementen.

Uiteindelijk wordt het prototype geëvalueerd aan de hand van de factoren die van invloed zouden kunnen zijn op de effectiviteit, toepasbaarheid en de verdere ontwikkeling in verschillende collaboratieve contexten. Op die manier vindt de evaluatie plaats aan de hand van verschillende gebruikersprofielen binnen en tussen verschillende disciplines. Het belang van zo’n evaluatie neemt alleen maar toe, gegeven de omstandigheid dat het systeem bedoeld is om te groeien door gebruikersparticipatie en hun gedachtegang over ontwerpprocessen.

De uitkomsten van dit onderzoek met hun toepassingsmogelijkheden zijn als volgt:

1. Een taxonomie (een representatieve, hiërarchisch georganiseerd vocabulaire van free-form design). Door de kennis expliciet vast te leggen die ontwerpers gebruiken om hun taken te vervullen, kunnen we hun methoden bestuderen en mogelijk verbeteren.

2. Een kenniskader (formele en theoretische representatie van het domein gebonden conceptuele kader). De representatie van kennis vormt een overdraagbare kennis, geschikt voor onderwijs. Hierdoor wordt een bijdrage geleverd aan de opleiding van nieuwe generaties van architecten.
3. Een prototype(een web-based omgeving die de opbouw, het delen en het hergebruik van collaboratieve kennis ondersteunt). Modelvorming van kennis in een vorm die vertaalbaar is naar computers, vormt de basis voor de ontwikkeling van ontwerp ondersteunende instrumenten met betrekking tot het specifieke kennisdomein en de kennisbehoefte van de ontwerpers.

ABOUT THE AUTHOR

Tuba Kocatürk was born on March 15, 1975, in Mersin, Turkey. In 1996 she obtained her Bachelor's degree in Architecture at the Faculty of Architecture, Middle East Technical University, Ankara, Turkey. After a three year post-graduate research, she received her Master's degree in Building Science from the same university. She worked as an architect in addition to her teaching and research activities at Middle East Technical University between 1997-2001.

In 2001, She has joined the Structural design chair together with BLOB and Hyperbody research groups at the Faculty of Architecture, Delft University of Technology, the Netherlands, as a PhD researcher and a teaching assistant. In 2003, she conducted part of her research as a research fellow at Harvard University, Center for Design Informatics, Cambridge, USA.

Since February 2006, she is working as an Assistant Professor at the School of Construction and Property Management, at the School of Construction and Property Management, Salford University, Manchester, UK. She is the co-founder and co-chair of the Free-Form Design Sub-working Group within the Structural Morphology Group of the International Association for Shell and Spatial Structures (IASS). Her main research interests are digital design tools and processes, IT in construction, cognitive models in digital design education and design information management. She has given various lectures and workshops at international levels on collaborative knowledge modelling in digital free-form design.