REPRESENTING INFORMATION FLOW IN BUILDING DESIGN PROCESS USING THE PARAMETER-BASED DESIGN STRUCTURE MATRIX

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By

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September, 2003

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy in Art, Design and Architecture.

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ABSTRACT

REPRESENTING INFORMATION FLOW IN BUILDING DESIGN PROCESS USING THE PARAMETER-BASED DESIGN STRUCTURE MATRIX

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Ph.D. in Art, Design, and Architecture
Supervisor: Prof. Dr. Mustafa Pultar
September, 2003

The Architecture/Engineering/Construction (AEC) industry is one of the multidisciplinary domains in which collaboration among related parties is of utmost importance. Despite the intense flow of information between design professionals, there is a lack of research to better understand and manipulate these flows. Most of the current process modeling tools in the AEC industry do not enable analyses of iterative information cycles. Moreover, these tools represent the process at high levels, thus, they are inappropriate for multi-parameter problems like building design.

With a view to alleviate these problems, this thesis introduces the use of parameter-based design structure matrix as a process modeling and system analysis tool for building design. The method reveals insights into the process structure, optimum sequence of parameter decisions, iterative cycles and concurrency in the process. A framework for parameter-based DSM applications in building design is proposed and the application of the framework is demonstrated through two case studies on real life building design problems.

Keywords: Collaborative Building Design, Design Integration, Design Management, Design Process Modeling, Information Flow, and Parameter-based Design Structure Matrix

ÖZET

YAPI TASARIM SÜREÇLERİNDE BİLGİ AKIŞLARININ PARAMETRE ESASLI TASARIM YAPISI MATRİSİ YÖNTEMİYLE MODELLENMESİ

Şule Taşlı Pektaş
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Yapı sektörü, değişik meslek gruplarının birlikte çalışmasının çok önemli olduğu disiplinler arası alanlardan biridir. Yapı tasarım sürecinde katılımcılar arası yoğun bir bilgi akışı olmasına rağmen, bu akışlar yeterince araştırılmamıştır. Yapı endüstrisinde şu anda kullanılmakta olan pek çok süreç modelleme aracı tasarımdaki döngüsel bilgi akışlarının analizine olanak vermemektedir. Ayrıca, bu araçlar tasarım sürecinin sadece üst seviyelerde modellenmesini sağlamakta, dolayısıyla yapı tasarımı gibi pek çok parametre içeren bir alanda etkinlikleri yetersiz kalmaktadır.

Bahsedilen sorunları çözmek amacıyla, bu tezde parametre esaslı tasarım yapısı matrisi yöntemi yapı tasarımı için bir sistem analizi ve süreç modellemesi aracı olarak önerilmektedir. Önerilen yöntem, tasarım sürecinin yapısı, parametre kararlarının sırası, döngüsel bilgi akışları ve eşzamanlılık konularında bilgi üretmektedir. Yöntemin yapı tasarımında kullanılması için bir çerçeve geliştirilmiş ve önerilen çerçeve iki alan çalışmasında gerçek yapı tasarımı sorunlarına uygulanmıştır.

Anahtar Kelimeler: Disiplinler arası Yapı Tasarımı, Tasarım Entegrasyonu, Tasarım Süreç Modelleri, Bilgi Akışı, ve Parametre Esaslı Tasarım Yapısı Matrisi

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The design professionals who provided input for the case studies were Kutsi Şamlı (architect), Zafer Kınacı (structural engineer), İhsan Taşeli (mechanical engineer), Nihat Akay (electrical engineer), and Atakan Ogan (OTIS). I thank them very much for their time and support. Besides information on the design processes they undertake, these professionals provided valuable comments on the application of the method in the construction industry which guided me in developing application proposals.

Finally, I would like to thank my family for their love, encouragement, and support. My husband Sait Emre Pektaş always helped and encouraged me. I am also grateful to my mother Şükran Taşlı and my father Mustafa Taşlı for their continuous support during my education.

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1. INTRODUCTION

The Architecture/Engineering/Construction (AEC) industry is one of the multidisciplinary domains in which collaboration among related parties is of utmost importance. While the knowledge needed for building processes is distributed among the different participants from diverse disciplinary backgrounds, the product of their activities, i.e. the building itself, is (or should be) highly integrated. Thus, collaboration manifests itself as an important component of project success. In a survey of AEC companies in the U.S., collaboration among parties ranked first among the many factors that affect quality in design phase (Arditi and Günaydın, 1998).

This dissertation addresses the problem of collaboration from an information flow perspective. The collaborative building design process is viewed as a series of interdependent decisions of different design professionals and it is presupposed that like other processes, it is possible and useful to build quantifiable models of building design. In this introductory chapter, the research problems and the objectives of the study are discussed and the structure of the dissertation is briefly outlined.

1.1 Problem Statement

The increasing complexity of buildings and a very competitive market place have been forcing design professionals to improve their processes in terms of time and quality. However, systematic design planning is not considered in many building projects. This is due to the common misconception of some designers that design, being a creative process, cannot be planned effectively. Even when planning is done, it is performed in an intuitive manner based on discipline specific programs, despite the fact that effective design collaboration necessitates planning the flow of interdisciplinary information. Relatively little research has been made on the management of the design process compared to production management in construction (Formoso et al., 1998).

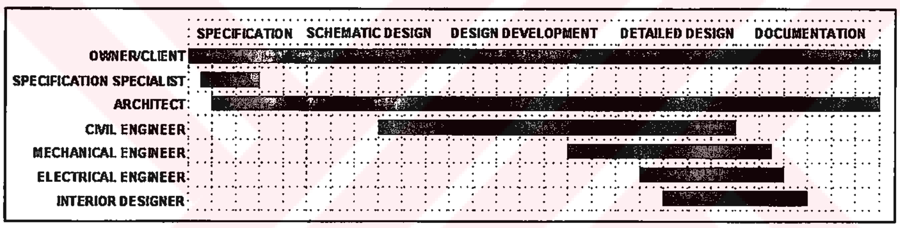


Figure 1.1: A Generalized Schema of Building Design Process (Adapted from Kalay et al., 1998)

Figure 1.1 shows a generalized schema of current building design processes. As it can be observed in the figure, architects and design engineers (structural, mechanical, and electrical engineers) constitute the two foremost groups of building professionals. The main activity of collaboration of architects and engineers in any project is evaluating and processing information and then communicating this information between various parties. Although there is an intense flow of information in building process, there is a lack of research to better understand and manipulate these flows (Eastman, 1999). Thus, in current practice, the decision-making that led to specific configurations often remains invisible. These problems are probably due to the fact that building design is a very difficult process to manage. It involves thousands of decisions with numerous interdependencies in a highly uncertain environment. A large number of personnel are included and each group has its own terminology and design methods.

Process models of design aim to capture the complexities of the design process explained above. Such models are based on the premise that although designs may be unique in different projects, the process of designing has an underlying structure which may not vary much across the projects. Although they are valuable in many aspects, existing process modeling methods in the AEC industry have considerable deficiencies. First of all, traditionally, building design has been planned by the same methods used to program construction. These techniques tend to view the design process as "document production" rather than flow of interdisciplinary information. Secondly, existing methods represent design process at high levels and thus, they are not suitable for modeling multi-parameter problems. Finally, most of the existing models are not capable of representing and managing iterations which is a main characteristic of design.

With a view to alleviate these problems, this dissertation proposes parameter-based design structure matrix (DSM) as a system analysis and process modeling method for building design. Parameter-based DSM is a structured analysis technique originally developed in the product design field. The method aims to capture dependencies between decisions on design parameters and provides means to sequence those decisions according to the dependency structure. The method has been applied previously in the automotive industry (Black et al., 1990; Cesiel, 1993; Dong, 1999), robot design (Rask and Sunnersjö qtd. in Browning, 2001), aero-engine design (Mascoli, 1999), and software development (Browning, 1998). To the best of the author's knowledge, however, this dissertation is the first study that has applied the method in building design.

In light of the discussion presented above, the research questions of this study are the following;

1. What is the information dependency pattern for design processes of architects and building design engineers?
2. Can the parameter-based design structure matrix method be utilized to analyze these processes? If so, how?

1.2 Thesis Objectives

The main goal of this dissertation is to propose an innovative process modeling method for building design process. Thus, this is a "methods" dissertation in which the desired methods are developed and/or engineered. The objectives listed below have evolved naturally in the course of the study and they shaped the structure of the thesis presented in the next section.

1. Study the different approaches to collaboration research in order to develop a valid and well-grounded research strategy for analyzing collaborative building design processes.
2. Analyze the existing process modeling methods in the AEC industry and identify advantages and disadvantages of each model.
3. Propose a new process modeling method to alleviate the shortcomings of the existing methods.
4. Develop a framework for the application of the proposed method in building design and provide means for dealing with the specific needs of the application field.
5. Demonstrate the application of the proposed method via case studies.
6. Provide guidance for further studies on the topic.

1.3 Structure of the Thesis

Further chapters of the thesis are organized as follows:

Chapter 2 discusses the recently increased interest in collaborative design research in the AEC industry and its major drivers. Three different approaches to collaborative design research are identified; namely, educational approaches, studies of communication and negotiation, and the information modeling approach. Following a discussion of each approach, an explanation is included about why an information modeling approach is taken in this dissertation.

Chapter 3 analyzes existing process modeling methods in the AEC industry and identifies their common deficiencies. With a view to alleviate the problems in the currently available methods, a three-level scheme for AEC process modeling is proposed. In this scheme, parameter-based DSM represents the lowest level process modeling method, which enables bottom-up integration of the existing models.

Chapter 4 describes the design structure matrix method. Following an explanation of how the DSM method works, four types of DSMs (component-, team-, activity-, and parameter-based DSMs) and their applications are discussed. This chapter also reviews the available DSM tools.

Chapter 5 raises the issues related to the use of parameter-based DSM in building design. First, the paradigms underlying this type of research are uncovered. Then, expected benefits of the proposed method are discussed under three headings: process improvement, process integration, and other information processing applications. Finally, a knowledge management framework for parameter-based DSM in building design is presented. The framework includes proposals on definition and classification of parameters and means for dealing with large DSMs. At the end of the chapter, visions are presented for the utilization of the method along with software.

Chapters 6 and 7 present two case studies undertaken to demonstrate the application of the method in real life building design problems. Chapter 6 studies the suspended ceiling design process for a public building project in Turkey and Chapter 7 analyzes the elevator design process in general terms. These case studies were chosen to reflect different aspects of the framework proposed in Chapter 5. Besides the insights gained into the individual design processes, some common implications were also drawn from the case studies and discussed at the end of Chapter 7.

Chapter 8 concludes the findings of the thesis. Contributions of the study and challenges of the proposed method are discussed and suggestions are made for further research.

2. COLLABORATIVE DESIGN RESEARCH IN THE CONSTRUCTION INDUSTRY

Researches on collaboration in the AEC industry have been based on a social paradigm of design defined by Mitchell (1994). According to this paradigm, design is the product of a team of professionals from different disciplines rather than a product of a single talented individual who has represented the image of designer since the Renaissance. The paradigm prioritizes the "whole" over the "parts." Mitchell presumes that designers, with the help of the ever developing communication and software technology, will come together in "virtual" design studios (or offices) to produce designs without geographical and time constraints (Mitchell, 1994). This vision has been realized to a great extent in the second half of the 1990's when collaboration research gained a momentum.

Concurrent engineering is another paradigm that has driven collaborative design research. The concept of concurrent engineering was initially proposed as a means to minimize product development time. Since then, many definitions of concurrent engineering have emerged in the literature. In general, it implies a systematic approach to the integrated and concurrent design of products and their related processes (Pena-Mora et al., 2000). Shared product knowledge and a communications architecture that will create a persistent space to support interaction among participants throughout all phases of the project are the basic notions of a concurrent engineering environment. Another important aim of concurrent engineering is to address important issues early in the project life-cycle. This necessitates involvement of all parties at a much earlier stage than would be the case in a traditional construction environment (Anumba and Duke, 2000).

Object-oriented programming and Internet technology are two emerging computing technologies that play a key role in enabling distributed and potentially concurrent collaboration for AEC projects. Object-oriented technology has been extensively used in software engineering and information management applications during the past decade. The basic idea of object-oriented programming is to combine software and data into the same object i.e. combination of the data describing the object and the operations related to it. It has enabled the definition of objects in a hierarchy so that an object can inherit the properties of its "parent" object. It is widely accepted that object-oriented programming suits the needs of building design, since it allows describing the attributes and behavior of a broad range of building objects most of which are well described by their interfaces (Sanders, 1996).

Wide-area and local area computer networks have played an important role in more effective management of information in and across various AEC offices. Until the second half of the 1990s, the use of networking technologies was limited mainly to file transfer and electronic mail. After 1995, the World Wide Web (WWW) became widely available as a graphical interface to the Internet based on a number of protocols for describing text, graphics, video, and sound data. Software used for browsing information on the WWW also became useful to view company-specific information in a secured computing network. These developments gave way to software products for Internet-based viewing and sharing of project information (Zamanian and Pittman, 1999).

Today, collaborative design studies for the AEC industry include many different approaches and an increasing amount of basic and applied research. In the framework of this dissertation, the domain of collaboration research is analyzed under three headings, namely, educational approaches, studies of communication and negotiation, and information modeling.

2.1 Definitions of the General Terms

The Oxford English Dictionary defines the word "collaborate" as "to co-operate, especially in literary, artistic or scientific work." The word is derived from the Latin words *col labore* which means to work along side one another. Collaboration can be thought of as joint problem solving. It stands for working with others toward shared goals. Compared to the similar word cooperation, collaboration implies more formal relationships, stricter planning and division of roles and full commitment to a common mission (Kvan, 2000).

Schrage explains that a "shared space" is a prerequisite for any type of collaboration. A shared space is a medium where all participants can add their notations to the shared understanding that the participants are trying to create (Schrage quoted in Schulz, 1997). According to empirical studies, shared understanding is an essential condition for team design (Valkenburg, 1998). The purpose of a shared space is not to create a presentation of some finished concept, but rather to allow the thoughts and works of participants to be understood by their partners during the process of creation (Schrage quoted in Schulz, 1997).

Communication, coordination, and negotiation are the other related terms. Communication involves the exchange of information, events and activities. Effective communication is a necessary, though not a sufficient condition to meaningful collaboration. Simply publishing information to a large group of participants does not mean that the recipients of that information are participating in the process. Communication has often been a well-known bottleneck in large-scale complex projects. Costly breakdowns in communications occur regularly even in the traditional AEC projects of physically collocated teams (Qian and Gross, 1999). Coordination involves controlling the workflow and communication process and managing various interdependencies between activities and events. It allows efficient control mechanisms to coordinate group effort (Pena-Mora et al., 2000). Finally, negotiation means compromising when design changes proposed by some team member are not agreed to by other members who find the implications of the proposed change not acceptable from their own design perspectives (Peng, 1999).

2.2 Approaches to Collaboration Research

2.2.1 Educational Approaches

Professionalism is one of the major obstacles to effective collaboration between architects and building design engineers. Professionalism is not simply a collection of knowledge and practices, but also value systems of the professionals which guide their objectives and processes. This type of socialization is largely due to the fragmented education of the design professionals. Newer educational approaches aim to address this fragmentation and to propose ways to overcome it. Some approaches claim that architects and engineers need to be educated together so they can learn how to work better together (Wheeler, 1998). However, this solution seems to be impractical due to the huge and ever growing amount of knowledge in each profession. It is more reasonable to sensitize students to the issues, objectives, and concerns of the other discipline (Taşlı, 2001a). There are several attempts to implement interdisciplinary courses for architecture and engineering students and there is evidence that such courses provide students valuable insight of the value systems used by their peers (Jackson, 1997; Chinowsky and Robinson, 1995). Pultar (1999) claims that it might be useful to give a general design education to architecture and structural engineering students for an initial period, after which, students should have the chance to choose their specialization field.

2.2.2 Studies of Communication and Negotiation

Developments in communication technologies have motivated a great amount of "technology-driven research" (Galle, 1995) in the field of computer supported collaborative work (CSCW) in the AEC industry. Internet-based technologies have formed the basis for collaboration of geographically distributed AEC teams which are often called "virtual offices." (Low and Sloan, 2001). European Commission funded projects such as EVONET (European Virtual Office Network) and RECITE (Remote Electronic Construction Industry Telematics Experiment) proved that electronic communications enable considerable increases in the operational efficiency of AEC firms (Moller, 1997).

Shared virtual reality environments utilizing VRML (Virtual Reality Modeling Language) models constitute another developing research field in computer supported communication in the AEC industry. These environments enable collaborating parties to be virtually located within a given three-dimensional environment in which they are able to interact with one another or with virtual objects that are also present in the environment. The intended aim of these environments is to create the illusion of "being there" (Caneparo, 2001; Woo et al., 2001; Lee et al., 2001; Atsuko et al., 2001).

There is also considerable interest in agent-based approaches for computer supported communication and negotiation in the AEC industry. An agent embodies particular functionality and behaves in an autonomous manner. Agents conduct tasks such as gathering information, communicating with one another as well as planning, scheduling and executing tasks. In a collaborative design context, individual agents may be responsible for either the design of subsystems, or for performing specific design tasks such as performance analysis, cost analysis, and optimization (Veeramani et al., 1998; Pena-Mora et al., 2000).

Negotiation-based approaches to design collaboration often make use of constraint satisfaction techniques to approximate the space of alternative solutions (Lottaz, 2000; Peng, 1999). Instead of negotiating over single values for parameters (which often creates artificial conflicts), constraint satisfaction techniques offer the possibility to calculate, represent, and manipulate solution spaces. The specification of project requirements using mathematical expressions makes explicit information that may be invisible at first glance. In this way, conflicts can be detected easily and causal links can be deduced from the structure of the constraint satisfaction problem (Lottaz, 2000).

2.2.3 Information Modeling Approach

Building design is largely considered as an "information processing" activity after the pioneering work of Akın (1989). The principal requirement of any project is evaluating and processing information and communicating that information between various parties. However, information related problems constitute the major cause of design failure (Baldwin et al., 1998). With a view to alleviate these problems, information modeling research has gained importance in recent years.

Following a discussion of information related problems in the AEC industry, this section introduces the information modeling approach as a means of alleviating these problems.

2.2.3.1 Information Related Problems in the Construction Industry

The main information related problems in the construction industry are summarized below.

1. Separate models of the design for each discipline and multiple views of the same objects

This is probably the most acknowledged problem in the literature, which has motivated studies on modeling interdisciplinary information. It is recognized that architects and building design engineers model buildings according to their particular points of views. Depending on the view taken, certain properties and descriptions of objects become relevant. For example, a wall may be a space division element providing privacy in architectural context and it may be load bearing or contributing to building load in structural engineering context. Both models are interdependent and they must coexist. Changes in one model inevitably affect the other one and vice versa.

2. Lack of integration between CAD tools

In the related literature, it is also well documented that there is a lack of integration between the current computer aided design (CAD) systems (Taşlı and Sagun, 2002; Stuurstraat and Tolman, 1999; Hew et al., 2001). Most of the practical and exploratory CAD tools focus on single discipline or a single task in the process. This situation is often referred in the related literature as an example of "islands of automation" in the AEC industry (Fruchter et al., 1996). Therefore, a considerable amount of research effort has been devoted to the development of systems capable of integrating a range of building design tools (Kalay et al., 1998).

3. Fragmentation of the construction industry

The AEC industry -unlike other large industries, such as the automotive, aerospace, and the electronics industries- is fragmented into numerous small organizations. Fragmentation in AEC is largely due to the growing complexity of building processes, which promotes increased professional specialization. Specialization is also reinforced by educational practices and socio-economic trends that reward excellence in ever-narrowing fields. As a result, while several related industries, such as automotive and shipbuilding manufacturing, have been relatively successful in integrating electronic information models into their operations, the construction industry continues to fail in this development. This is probably due to the fact that the larger organizations in other industries have higher profits that enable them to invest larger sums of money in technology development. Furthermore, other industries have a few key organizations that can drive a technology to suit their requirements (VTT, 2003).

4. "Document-based design" vs. "Model-based design"

Despite rapid developments in technology, the current construction project information paradigm is still primarily based on the use of traditional media such as drawings and faxes, and methods such as meetings. Consequently, all the participants in a specific project are required to convert paper-based information into electronic versions and vice-versa. This continual process of creating and translating information according to the design and presentation medium used creates several bottlenecks in the flow of information. Many researchers believe that in order for the construction industry to meet this challenge, the development of an information modeling standard that enables sharing, storing and exchanging project information electronically is essential (Tolman, 1999). In the evolving model-based paradigm, production of computable models of building objects and processes that are useful to those downstream in the process is a key aspect (Eastman, 1999).

5. Incomplete, uncertain, and untimely information

Any type of design is characterized by iteration. Incomplete, uncertain, or untimely information is likely to cause additional iterations which probably increase the duration and cost of the process. The problem of iteration is discussed at Chapter 5 in detail.

6. Lack of a shared understanding of objectives, values and processes

Shared understanding is a mutual view amongst the design participants on relevant design topics and design activities. Without this understanding, decisions will not be supported by all team members and later activities in the design process can be restricted by different views of the team members (Valkenburg, 1998). Having a common understanding of information content of design entails shared models.

7. Invisible decision making

In conventional practices, the communications between design professionals is often at such a minimal level that the documents can only provide the most basic level of information. Even when the plans reflect the design process with absolute accuracy, the decision making that led up to specific configurations remain invisible. This is a significant disadvantage when alternative solutions are searched in the process (Schulz, 1997).

8. Informal communications and lack of documentation

The successful performance of multidisciplinary projects requires enormous coordination to ensure that all parties are constantly aware of the ever-changing status of the project in an attempt to eliminate design errors. However, in current processes of the AEC professionals, communications are often informal and not documented. Thus, tracking and managing changes is a cumbersome task (Austin et al, 1994).

2.2.3.2 What is a Model?

A model can be defined as a representation of relevant characteristics of an artifact. In other words, it is a means of expressing certain characteristics of an object, system or situation that exists, existed, or might exist (Echenique qtd. in Rowe, 1991). According to the Oxford English Dictionary, a model may be defined simply as "a representation of structure." In the information modeling field, a model is used to represent the structure of information and how that information relates to other information.

Discussing models, it should always be borne in mind that no matter how much effort goes into its construction, a model can never be a perfect or complete representation of reality, because human beings do not have perfect information about the real world. Therefore, the usefulness of models should be judged not against an imaginary perfection, but in comparison with the mental and descriptive models that could be used alternatively (Forrester qtd. in Radford and Gero, 1988).

2.2.3.3 Advantages of the Information Modeling Approach

The information modeling approach is taken in this dissertation, firstly because it is widely recognized that information modeling alleviates the problems presented in 2.2.3.1. It has already become a fundamental aspect of collaboration research. In fact, an information model underlies any type of computer supported collaborative work. Rezgui et al. (1996) explain that a great deal of work has already addressed collaborative design on the implementation side. However, a model-based solution has several advantages that go beyond particular implementations. Models are independent of any particular implementation and therefore they are more likely to survive the rapid evolution of information technology. Furthermore, any model-based representation is potentially usable for other information-processing purposes.

2.2.3.4 Types of Information Models

Information models used in the AEC industry can be grouped as product models and process models. A product model is an information model that implicitly contains data regarding form (geometry and topology), function (requirements or intentions) and behavior (performance) of a product and it is able to describe the product through its life cycle. In other words, such a model provides an abstract description of facts, concepts, or instructions about a product. The role of the product model in this definition is equivalent to the role of the technical documentation in the current paper-based design and construction process (Tolman, 1999).

Since one of the most important requirements for a building product model is its capacity to allow different professionals to abstract different perspectives of the building from it (Dias, 1996), product modeling is a promising means to avoid iterations and misinterpretations from which traditional processes suffers. Moreover, it is widely accepted that a product model is a more complete and re-usable representation of a building for the whole building life cycle. Therefore, there have been many efforts to build a common product model for building design such as RATAS (Björk, 1994), COMBINE (Amor et al., 1995), COMMIT (Rezgui et al., 1996), CONCUR (Stuurstraat and Tolman, 1999), and ATLAS (Tolman, 1999).

A process model is a systematic representation of a process, which in a formal manner describes the aspects of the process that are relevant for the purpose and viewpoint of the process model (Karstila, 2000). The main purpose of process modeling is to gain knowledge of the existing process and to serve as a model for future implementation. There are three main uses of process models (Svensson et al., 1999):

1. *Process Development and Improvement:* A process model enables the capture of "as-is" information about a process. This model can then be analyzed and redeveloped as a "to-be" model that describes improvements. Some may argue that a detailed model of the existing process is unnecessary and may take a long time to do. A simple model of the existing "as-is" process followed by a more detailed future "to-be" process should be enough. However, any

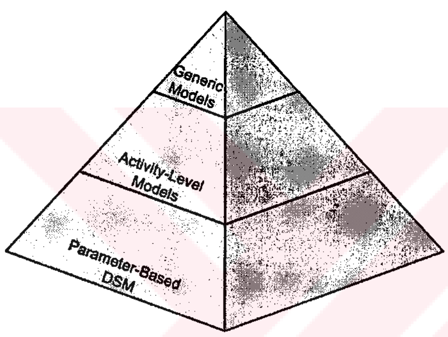
process development effort is highly unlikely to succeed without a comprehensive understanding of the existing state.

2. *Information Technology (IT) Systems Development:* Process models are used in IT development projects as a means for discovering and capturing the information content of a process and how that information is to be exchanged between participants in the process.
3. *Common Understanding of the Process:* Process models are also an important learning tool. A process model helps people visualize where they are in a process and what they need and must produce and when. In this way, it provides the basis for effective collaboration.

Although the product modeling area has been well-established and related work is more or less complete, process modeling still presents a relatively less explored research domain (Eastman, 1999). In this dissertation, the problem of collaboration in building design is studied from a process modeling perspective.

3. PROCESS MODELS OF DESIGN

The process modeling efforts in the AEC industry can be analyzed in three general groups, namely generic descriptive frameworks and formal activity models. This section identifies some shortcomings of the existing models and proposes the parameter-based DSM as the lowest level process modeling method (Figure 3.1). The analysis of the existing methods is presented in the following sections.



Modeling Level	Tools
Process	Descriptive Generic Frameworks
Activity	Formal Activity Models
Parameter	Parameter-based DSM

Figure 3.1: A Three-level Scheme for Process Modeling

3.1 Descriptive Generic Frameworks

3.1.1 Design Methods Models

Descriptive methodological and philosophical frameworks of the design process originate from the 1960's Design Methods movement. This movement claimed to bring systematic methods for designers in order to cope with the increased complexity of design process. Cross (1993) identifies two "generations" of design methods. 1960s "first generation" methods seemed simplistic and were not embraced by a large audience. The second generation design methods, which started to emerge at the early 1970s, moved away from the “omnipotence” of designers towards “satisficing” solutions and “argumentative” participatory process. These include Hubka (1982), Pahl and Beitz (1984), Cross (1989), and Pugh (1986) to name a few.

Design methods models defined design as a rational process composed of three basic steps: analysis, synthesis and evaluation. These steps were either formulated by linear flow charts, or by spiral forms representing reiterating sequence. Another of their common characteristics is that they represent the process at high levels with very little information at lower levels (Broadbent, 1988).

3.1.2 The RIBA Plan of Work

The RIBA Plan of Work (Phillips, 2001) is another generic framework which was originally published in 1963 as a standard method of operation for building construction, and is widely accepted as an operational model for the building industry in UK. The Plan of Work represents the whole building process from inception to feedback in terms of a logical sequence of work stages. According to the Plan of Work, a design project progresses from stages A to M in a linear fashion requiring the completion of one stage before proceeding to the next (Table 3.1). It is anticipated that the model will need only slight adjustments depending upon the size and complexity of the project.

Table 3.1: An Overview of the RIBA Plan of Work (Adapted from Nelson et. al., 1999)

Pre-design	A▶B
Design	▶C▶D▶E
Preparing to build	▶F▶G▶H
Construction	▶J▶K▶L
Post-Construction	▶M

Stage A: Inception
Stage B: Feasibility
Stage C: Outline Proposals
Stage D: Scheme Design
Stage E: Detail Design
Stage F: Production Info
Stage G: Bills of Quantities
Stage H: Tender Action
Stage J: Project Planning
Stage K: Operations on Site
Stage L: Completion
Stage M: Feedback

3.1.3 The Generic Design and Construction Process Protocol

The Generic Design and Construction Process Protocol (GDCPP) developed at the University of Salford is a high level map defining the process in terms of activity zones. The zones contain high-level processes spanning the duration of a project from inception to operation and maintenance. The process protocol also consists of deliverables in a form of documented project information such as stakeholder list, brief, etc. and logical dependencies between activities which are shown by interconnecting arrows.

The GDCCP breaks down the design and construction processes into eight activity zones namely, development, project, resource, design, production, facilities, health and safety, and process management, four broad stages –pre-project, pre-construction, construction, and post-construction–, and ten phases. The stage/gate approach to process management practiced in manufacturing industry was used to develop the GDCPP. From the point of view of decision making during the process, there are so-called soft gates and hard gates. Soft gates imply that decisions may be approved conditionally afterwards. On the other hand, hard gates indicate final and firm decision points whether or not to proceed to the next phase of the process. This is because late design changes often cause substantial additional costs in construction projects (Wu et al., 1998). All GDCPP process maps are publicized at a Web site hosted by the University of Salford (University of Salford, 2003).

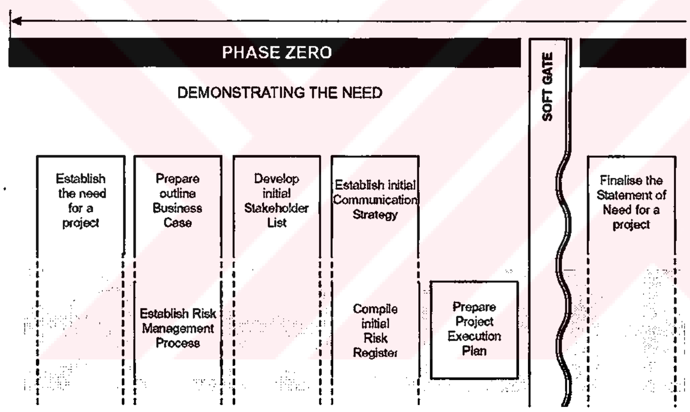


Figure 3.2: A View from GDCPP Process Map (University of Salford, 2003)

Recently, the GDCPP —in combination with Unified Modeling Language (UML) diagramming— has constituted the base of process modeling approach proposed in EU ICCI cluster project IST-2001-33022 (Wix and Katranuschkov, 2002).

Although these generic models provide a good overview of the design process, they are often too abstract to be utilized in practice. Thus, they are merely used as generic guidelines rather than effective tools for process improvement and integration.

3.2 Formal Activity Models

Engineering design and product development is the forerunner of formal design process modeling. The process modeling methods used in software development have also been shown to be valuable for other design fields (Shi and Deng, 2000). Most engineering design process models are based on the observation that design is composed of a number of tasks that have an underlying structure. This focus on underlying structure implies that the models consider the most structured parts of the design process; this enables the use of mathematical techniques. Unlike descriptive generic frameworks, formal activity level models are quantitative and graphical models that are capable of representing design processes in more detail.

This type of modeling includes network models such as the Project Evaluation and Review Technique (PERT), the Critical Path Method (CPM), Petri nets, Data flow diagrams, and the Integrated DEFinition Language 0 (IDEF0); information modeling methods such as the Entity Relationship Diagrams (ER) and Unified Modeling Language (UML); and Activity-based design structure matrix (DSM).

3.2.1 Network Models

Network models can overcome some of the drawbacks of generic models by exploiting activity relationships. Such models are based on the premise that once decomposed, the design process can be described as an interconnected network of design tasks i.e. a directed graph. A directed graph (digraph) represents the precedence relationships among tasks of a project. It consists of a set of nodes representing the design tasks and a set of directed lines connecting these nodes. The directed lines denote a dependency or a relationship between the connected tasks (Yassine et al., 1999). There are many variations of network models, but only the four basic types are discussed below.

3.2.1.1 PERT/CPM

The Project Evaluation and Review Technique (PERT) and the Critical Path Method (CPM) are based on digraphs. The PERT method is the first example of time-based process modeling. In the PERT method, three probabilistic time estimates are given to each task, reflecting the uncertainty in the duration of tasks. The CPM is a variation of the PERT method. However, the time of any task can be compressed by allocating resources. Thus, CPM assumes a time-cost tradeoff rather than the probabilistic times used in PERT. CPM diagrams also graphically show the precedence interrelationships among product activities. It is possible to develop a critical path –a sequence of activities which, if delayed, delays completion of the project– (Smith and Morrow, 1999).

There are several limitations in this type of modeling such as the following (Shi and Deng, 2000):

1. They lack the ability to model feedback and iteration in the projects, so that they cannot model projects as a dynamic decision process.
2. They deal with an activity as a non-stop process. However, in practice activities may be interrupted when required conditions cannot be met.
3. They can be time-consuming to prepare, difficult to read and to update.

Pultar (1990) has developed a progress-based scheduling technique based on progress charts and bar charts to overcome the problem of fragmentation of activities during the application of the conventional CPM to construction projects. CPM type of modeling has been used in many construction projects with varying degrees of success. However, the technique has remained to be useful for the construction phase of building process rather than the design phase.

3.2.1.2 Petri Nets

A more recent process model of design that describes information flows is a Petri net model. A Petri net is a graphical modeling tool that consists of places, transitions, and arcs (Figure 3.3). Basically, it defines transitions that are interpreted as activities, and tokens that are interpreted as resources. The idea is that resources (tokens) are used by activities (transitions), and then moved from one place to another. Input arcs connect places with transitions, while output arcs start at a transition and end at a place. A marking in a Petri net refers to a change in the state of the system. An initial state of a Petri net is called the initial marking. Transitions are only allowed to occur if they are enabled (all the preconditions for the activity are fulfilled). The concept of time can also be associated with a transition. Moreover, pre- and post-conditions can be added to a Petri net and additional attributes (colors) can be added to tokens (Karhu, 2001).

Figure 3.3 shows a process that consists of only one activity. To execute the activity, two resources have to be used. The net in Figure 3.3(a) models this process. Transition in t1 in Figure 3.3(b) is enabled because each of its input places, p1 and p2, contains a token. After the transition t1 occurs, p3 (the output place of t1) gets a token; the new marking is shown in Figure 3.3(c) (Zakarian and Kusiak, 2000).

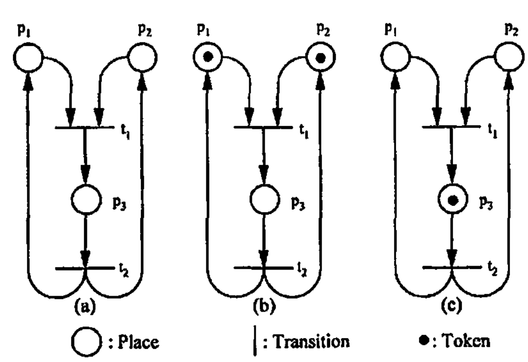


Figure 3.3: A Petri Net of an Activity that Uses Two Resources: (a) Petri Net Model (b) Initial Marking, and (c) Marking after t1 has been Occurred.

Petri nets are promising for representing systems that are concurrent, asynchronous, distributed, and parallel. The disadvantages of Petri net descriptions include the lack of decomposition and hierarchy (Karhu, 2001), and emphasis on feasibility as the output measure of interest. Additionally, there is no weighting of the transitions; all transitions are implied to be of the same importance. Furthermore, the complete structure of the project must be done in advance if the model is expected to have any useful predictive utility (Smith and Morrow, 1999).

Wakefield and Damrianant (1999) demonstrated how Petri nets, previously used for modeling computer networks and flexible manufacturing systems, can be used for modeling construction systems and processes. They claim that the graphical nature of Petri Net models makes them relatively easy to understand, to build and to communicate to others. Furthermore, the graphical Petri Net representation is readily converted into algebraic representation that facilitates analysis and numerical simulation. In fact, Petri nets are aimed more at simulation rather than static process modeling.

3.2.1.3 Data Flow Diagrams

Data flow diagramming emerged originally for software development (De Marco, 1979). A data flow diagram is constructed from four basic elements; namely, process, data or information flow, data store, and an external entity used as a source or sink of data flow. Baldwin et al.

(1999) applied these concepts to a building design process model and interpreted processes as individual design tasks, flows as design information flows, data stores as drawings etc., and external entities as clients, local authorities, etc. Abou-Zeid and Russell (qtd. in Karhu, 2001) also used data flow diagramming to study communications between participants of building design process.

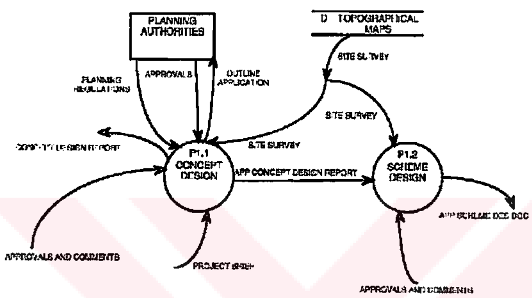


Figure 3.4: An Example Data Flow Diagram showing Concept and Scheme Design Data Flows (Baldwin et al., 1999)

The method has the capability of presenting the models in a hierarchical form through decomposition. Data flow diagrams are not concerned with how processes are performed but view systems from an information point of view. They can also represent the iterations in processes, but do not provide any means to deal with them. Moreover, the performer of a process is not modeled with this method (Karhu, 2001).

3.2.1.4 IDEF0

IDEF0 (Integrated DEFinition 0) is a graph-based technique that captures more details than other graph-based techniques by representing some of the intra-task complexity. The U.S. Air Force

Standard IDEF (U.S. Air Force, 1981) was developed from SADT (Structured Analysis and Design Technique) for process modeling in computer-integrated manufacturing and concurrent engineering. The IDEF model consists of hierarchically decomposed diagrams, along with text for each of the diagrams, and glossary of terms used in the diagrams (Smith and Morrow, 1999).

The two basic components of the IDEF diagram are a box and arrows. Boxes represent processes, while the arrows represent different interfaces such as input, output, control, and mechanism. Inputs are the data or objects that are transformed by process into output. Input arrows are associated with the left side of an IDEF0 box. Outputs are the data or objects produced by a process. Output arrows are associated with the right side of an IDEF0 box. Controls are conditions required to produce correct output. Data or objects modeled as controls may be transformed by the process, creating output. Control arrows are associated with the topside of an IDEF0 box. Mechanisms are the means used to conduct a process. Mechanism arrows are associated with the bottom side of an IDEF0 box. A generic IDEF diagram of a process is shown in Figure 3.5. In addition to the definition of the IDEF0 language, the IDEF0 methodology also prescribes procedures and techniques for developing and interpreting models, including ones for data gathering, diagram construction, review cycles and documentation (U.S. NIST, 1993).

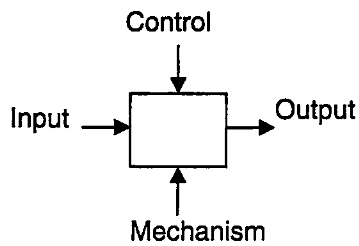


Figure 3.5: A Generic IDEF0 Diagram of an Activity (U.S. NIST, 1993)

IDEF0 is probably the most widely used formal process modeling method in the AEC industry since it was declared as the preferred notation for the creation of graphical process models for Industry Foundation Classes (IFC) specification. Studies on IDEF0-based AEC process models include but are not limited to Sanvido and Norton (1994), Karhu (2000), and Rezgui et al. (2002).

As a modeling language, IDEF0 has the following advantages:

1. It is comprehensive and expressive, capable of graphically representing a wide variety of operations to any level of detail.
2. It is a simple language, providing for rigorous and precise expression, and promoting consistency of usage and interpretation.
3. It is well-tested and proven, through many years of use in Air Force and other government development projects, and by private industry.
4. It can be generated by a variety of computer graphics tools; numerous commercial products specifically support development and analysis of IDEF0 diagrams and models.

However, like the other graph-based representations, IDEF0 also suffers from size limitations. It tends to grow rapidly for a large number of tasks and visual inspection of the information structure becomes very complex and misleading. Thus, it is more useful for high-level process representations rather than detailed processes. Moreover, process modeling techniques like SADT/IDEF0 are only well structured when the activities constitute the focus. Information, controls and mechanisms are connected to each process step but there is no way of analyzing the total information structure processed in the system. Although IDEF0 is capable of showing iterations in processes, it does not provide a means of resolving them (Svensson et al., 1999). Another limitation of the IDEF0 technique is that mainly document producing actions are captured. The technique gives weak support for modeling parallel sub-processes and for informal communication within a sub-process. Therefore, iterations between levels are difficult to analyze with IDEF0 (Malmström et al., 1999).

3.2.2 Entity-Relationship Diagrams

Information modeling methods like Entity-relationship (ER) diagrams and UML were originally developed for designing software intensive systems. ER diagrams were specifically developed to build relational databases. The method utilizes three major abstractions to describe the data; namely, entities, relationships, and attributes. The basic object that an ER model represents is an entity, which is a "thing" in the real world with an independent existence. Each entity has particular properties called attributes that describe it. A particular entity will have a value for each of its attributes. Whenever an attribute of one entity type refers to another entity type, some relationship exists. In the initial design of entity types, relationships are typically captured in the form of attributes. As the design is refined, these attributes are converted into relationships between entity types (Elmasri and Navathe, 1994).

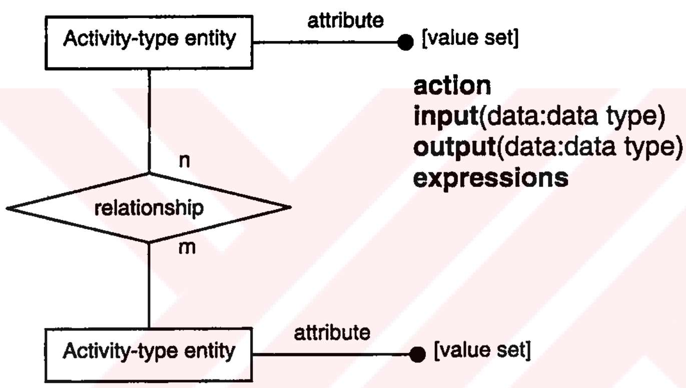


Figure 3.6: A Part of a Process Model as an Entity-Relationship Diagram (Hong and Hong, 2001)

Hong and Hong (2001) have developed an entity-relationship based process model for structural design. They claim that entity-based approach to process modeling enables them to develop integrated and uniform product and process models. The ER diagramming was also used for building a relational database for GDCPP Map Creation tool by mapping the entities and relationships as database tables (Wu et al., 1998).

Entity-relationship diagrams are beneficial for producing integrated product and process models, however, the method is more desirable for top-down design process, since it allows high level abstraction in representing design information and design activities (Hong and Hong, 2001). Svensson et al. (1999) explain that if the process modeled is a repetitive task, ER modeling can be useful, since only the type of information is relevant, regardless of what types of parts the documents are describing.

3.2.3 Unified Modeling Language

Unified Modeling Language (UML) is a standard modeling language for software development. It is a sophisticated language involving many types of diagrams; two of which are especially relevant for process modeling purposes. UML activity diagrams enable identification of communication between activities undertaken by different roles within a process. Activity diagrams address the dynamic view of a system. Use case diagrams show a set of use cases and actors and their relationships. Such diagrams address the static use case view of a system (Booch et. al., 1998). Use case diagrams of UML were recently used in OSMOS (a European Union research project) to capture the sequence of actions performed by actors in virtual construction enterprises (Rezgui et al., 2002).

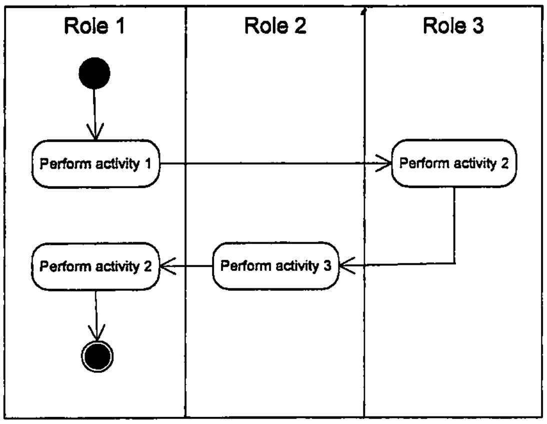


Figure 3.7: A Generic UML Activity Diagram (Booch et al., 1998)

The limitations of modeling processes with UML are as follows. First, UML is not suitable for process modeling if the purpose is to study the current state of the processes. Moreover, UML does not include any suitable technique for mid-level process modeling such as IDEF0. Therefore, it is hard to get an overview of the modeled system.

Information modeling tools like ER diagrams and UML are capable of representing dependency relationships, but they do not provide a means for analyzing the cycles in a process. Thus, their functionality as a process modeling method lies largely in IT system development rather than process integration and improvement.

3.2.4 Activity-based DSM

Activity-based DSM is a method capable of identifying and resolving iterations in a process. The details of the method and applications are discussed in the next chapter. However, a brief analysis of its advantages and disadvantages are presented below to support the conclusions made in 3.4.

The effectiveness of the activity-based DSM in sequencing activities has been shown in previous research (Austin et al., 2000); however, like the other methods reviewed in this chapter, it is too abstract to define, in detail, for complex multi-parameter problems. Furthermore, it has another considerable shortcoming; activities can be described on multiple hierarchical levels, but in an activity-based DSM, it is difficult to see at which hierarchical level each activity is described. In fact, a precise definition of activities is lacking in DSM literature. Therefore, there always seems to be a possibility of comparing activities at different levels as if they were at the same level. This problem is solved by the theoretical assumption that all activities are described at the lowest hierarchical level. However, when decomposition ends at an activity level, this assumption cannot be fully supported. At the lowest level, the design activities should be decomposed into parameter decision points.

3.3 Conventional/Empirical Methods

In the construction industry, chart-based scheduling is still the most widely used process modeling method. The milestone chart method consists of identifying the target completion date for each activity in the task outline. Bar charts (also known as Gantt charts) consist of a list of tasks along the left side of a page with horizontal bars along the right side indicating the scheduled start and finish dates for each task. Charts are easy to prepare and use, but their best applications are limited to short design projects with few participants and little interrelationship between activities since, they are incapable of representing the interrelationships.

3.4 Shortcomings of Current Building Design Process Models

Having analyzed the most widely used process modeling methods in the AEC industry, the following deficiencies are observed:

1. The complexity of design processes entails detailed analyses to gain insight into process structures. However, current process models used in the industry have a top-down approach including very little information about interrelationships at lower levels. Of course, one of the reasons why many process models fail to represent the detailed process is because of the intricacy it adds. Graphical models become so tangled as the process is represented at lower levels that the descriptiveness of the tools diminishes. The DSM method works well in such situations, since it is a compact, visual and analytically advantageous format for complex systems.

   The developments in the computer technology also support building and manipulating detailed models. When standardization efforts were begun in building product modeling in 1980s, the focus was on general systems models. As the field is more matured, the models have been refined and detailed (Tolman, 1999). Thus, it can be expected that building design process modeling would follow the same path toward comprehensive and low-level models.

2. Building design is characterized by iteration (rework). However, many process models can not represent iterative processes; even the models that are capable of identifying iterations can not resolve them (except the DSM method). In fact, systematic means for dealing with iterations are not established in the construction industry. Concurrent work is often seen as a way to reduce cycle time but, if concurrent activities are chosen arbitrarily without considering their dependencies, this can lead to abundant iteration and increased cycle time.

Thus, it can be clearly stated that there is a need for a low-level analysis tool that is capable of identifying and resolving iterations in AEC process models. As a solution to the shortcomings of the existing methods discussed in the previous section, this dissertation proposes the parameter-based DSM as the lowest level process modeling method, which enables bottom-up integration of existing process- and activity-level models.

4. DESIGN STRUCTURE MATRIX METHOD

The design structure matrix method has its roots in the 1960s, when several efforts were devoted to solving systems of equations. During the following years, developments in areas such as matrix mathematics, network diagramming and interface-to-interface (N-to-N or N^2) diagrams of systems engineering have supported such work. Donald Steward first coined the term "design structure matrix" and applied these concepts to design in 1981 (Steward, 1981). The design structure matrix method gained more credibility as a result of several researches at the Massachusetts Institute of Technology in 1990's. In recent years, DSM research has expanded to include many new areas, and a more general term, "Dependency Structure Matrix," has come to be used.

In this chapter, following an explanation of how the DSM method works, four types of DSMs and their applications are discussed. The chapter also reviews the applications of the method in the AEC industry and the available DSM tools.

4.1 Description of the Method

A design structure matrix is a matrix representation of a system or a project. The rows and columns of the symmetric matrix consist of a list of all elements of the system and matrix elements represent the corresponding dependency patterns. System components are listed in the first row and the first column of the matrix in a roughly temporal order. Off-diagonal cells indicate the dependency of one system element on another. Marks in a single row of a DSM represent the system elements whose output is required for the system element corresponding to that row. Similarly, reading down a specific column reveals which system element receives information from the system element corresponding to that column.

4.1.1 DSM Operations

The DSM method utilizes some operations to analyze information dependencies and to re-arrange system elements accordingly.

Partitioning is the process of re-ordering the DSM rows and columns so that the new arrangement does not contain iterations (i.e. the DSM is transformed into lower triangular form). For complex systems, it is often impossible to obtain a lower triangular form DSM by partitioning. In this case the aim is to move the feedback marks as close as possible to the diagonal so that fewer system elements are involved in the iteration cycle (this results in a faster development process).

Tearing is the process of choosing the set of feedback marks that if removed from the matrix will render the matrix lower triangular. The marks that are removed from the matrix are called "tears." Identifying the tears that result in a lower triangular matrix means that the set of assumptions that need to be made in order to start design process iterations. Having made these assumptions, no additional estimates need to be made. No optimal method exists for tearing, but it is recommended to use two criteria when making tearing decisions:

1. Minimal number of tears: The motivation behind this criterion is that tears represent an approximation or an initial guess to be used. Thus the number of these guesses should be reduced.
2. Confine tears to the smallest blocks along the diagonal: The motivation behind this criterion is that if there are iterations within iterations, these inner iterations are done more often. Therefore, it is desirable to confine the inner iterations to a small number of tasks.

It is desirable to have minimal number of tears and to confine tears to the smallest blocks along the diagonal in a DSM.

Banding is the addition of bands to a DSM to show independent (i.e. potentially parallel or concurrent) system elements. The collection of bands within a DSM constitutes the critical path of the system or project. Furthermore, one element within each band is often critical. Thus, fewer bands are preferred since they improve the concurrency of the system/project.

Clustering is the process of finding subsets of DSM elements (clusters) that are mutually exclusive or minimally interacting subsets. In other words, clusters absorb most, if not all, of the interactions internally and the interactions between separate clusters is eliminated or at least minimized (DSM MIT, 2003).

4.1.2 A Simple DSM Example

The use of a DSM can be best explained via an example. The following is a simple example, showing a DSM for a familiar process, putting on socks and shoes (Figure 4.1). This example is adapted from Denker et al. (1999). In the figure, the marks below the diagonal imply, for instance, that "get socks" must precede "put on socks," and "get shoes" must precede "put on shoes" and "inspect shoes." The mark above the diagonal indicates that, once shoes have been inspected, they may be found wanting (e.g. too dirty or the wrong color for the clothes), requiring an iteration, "get (new) shoes."

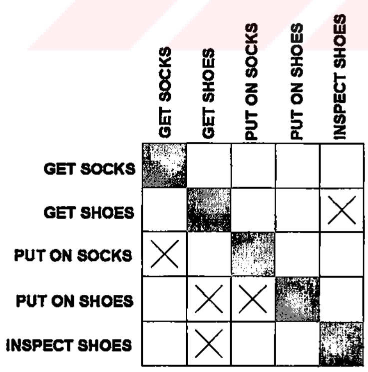


Figure 4.1: The Initial DSM of the Process

Now, the goal in DSM analysis is to resequence the activities so as to minimize iterations and their scope. Since the activities "get shoes" and "inspect shoes" are coupled, there is no way to reorder the rows (and columns) of the DSM to get all the marks below the diagonal. Then, the aim is to move the above diagonal marks as close to the diagonal as possible, minimizing the scope of iteration. In Figure 4.1, it is shown that once we “get shoes,” we go ahead and “put on socks” and “put on shoes” before we “inspect shoes.” If we move the inspection step upstream, as in Figure 4.2, we minimize the impact of a need to “get (new) shoes.”

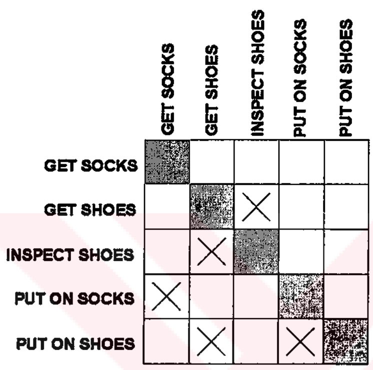


Figure 4.2: The Partitioned DSM

The banded DSM indicates which activities can be accomplished in parallel without causing additional iteration. For example, Figure 4.3 shows that “get socks” and “get shoes” can be done simultaneously, as can “inspect shoes” and “put on socks.”

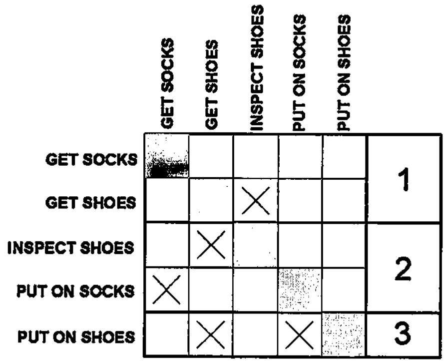


Figure 4.3: The Banded DSM

If an assumption can be accurately made about the dependency shown with an arrow in Figure 4.4 (a), this mark can be torn. The resulting matrix is shown in Figure 4.4 (b).

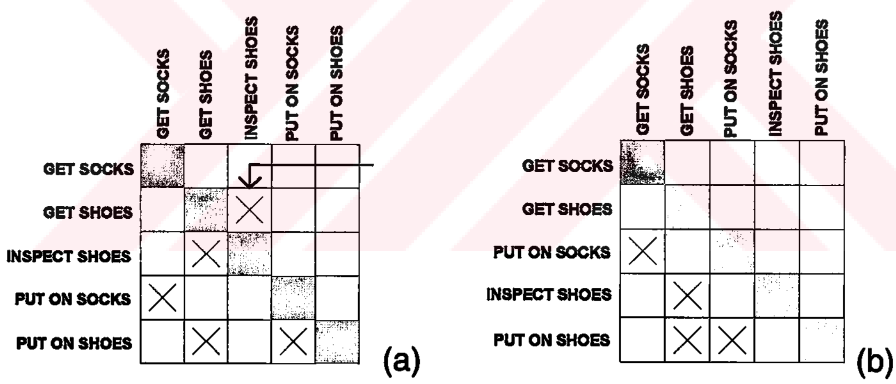


Figure 4.4: Tearing the DSM (a) Tear Decision (b) Torn DSM

4.1.3 Building and Using a DSM

The construction of a DSM requires extensive knowledge of the system to be modeled. Besides the formal knowledge manifested in design documents, the DSM method aims also to capture informal knowledge held by the professionals. Therefore, in the initial stages, it may be difficult to produce a useful DSM. However, once an initial DSM model is built, it can serve as a platform for continued organizational learning and process improvement.

The steps of DSM development are summarized below.

1. *Determine list of system elements.*

   This is conducted by examining design documents and interviewing design professionals. The system under study is decomposed into elements. The decomposition can be hierarchical or non-hierarchical (network type). In the hierarchical decomposition the system decomposed into sub-systems, modules, and then into other smaller components. In the network type, hierarchy is not evident.

2. *Determine inputs, outputs, strengths of interaction, etc.*

   Related attributes of the system elements are identified by asking the design professionals.

3. *Build a DSM.*

   When the system elements and their interactions are defined, they are listed in the DSM as row and column labels in the same order. In the sequence-based DSM types this order corresponds to the sequence of tasks.

4. *Manipulate DSM to rearrange the process.*

   Through DSM operations, the DSM is analyzed. Collected information can also be used for simulation purposes.

4.2 DSM Types and Applications

There are two main categories of DSM; namely, static and time-based. Static DSMs represent existing system elements simultaneously, such as components of a product architecture or groups in an organization. Static DSMs are usually analyzed with clustering algorithms. In time-based DSMs, the ordering of the rows and columns indicates a flow through time; upstream elements of a process precede downstream elements, and terms like "feedforward" and "feedback" become meaningful when referring to interfaces. Time-based DSMs are typically analyzed using partitioning algorithms (Browning, 2001). This taxonomy of different DSM types is shown in Figure 4.5.

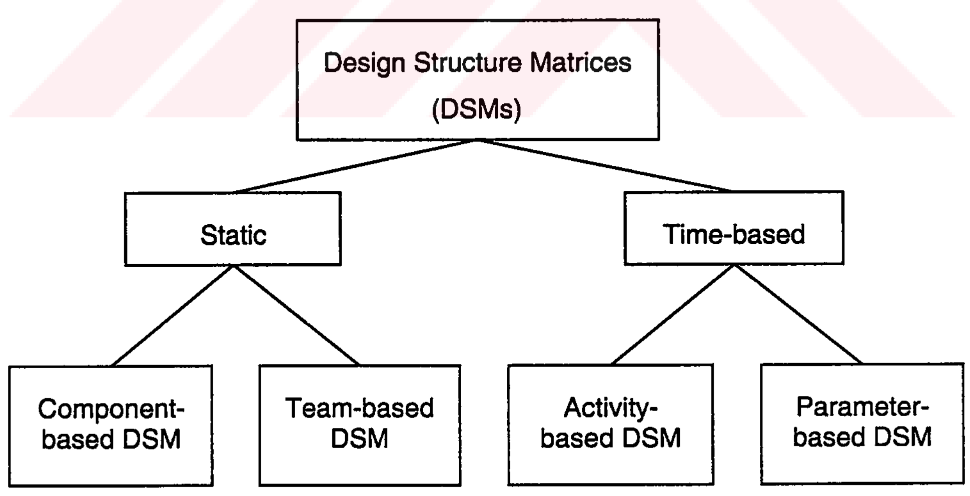


Figure 4.5: DSM Taxonomy (Adapted from Browning, 2001)

4.2.1 Component-based DSM

System engineering efforts in product development involve three general steps.

1. Decompose the system into its elements
2. Understand and document the interactions between the elements
3. Analyze potential reintegration of elements via clustering.

Every complex system development project includes these steps, although they are not always approached systematically. A component-based DSM is a systematic approach for product architecture integration (Browning, 1998).

A component-based DSM documents the interactions between the component elements in a complex system. This type of DSM has been utilized by Pimmler and Eppinger (qtd. in Browning, 2001) to reveal and explore alternative architectures for an automobile climate control system at Ford Motor Company. Different types of interactions can be displayed in a component-based DSM according to project type (Table 4.1).

Table 4.1: A Taxonomy of System Element Interactions (Pimmler and Eppinger qtd. in Browning, 2001)

Spatial	needs for adjacency or orientation between two elements
Energy	needs for energy transfer/exchange between two elements
Information	needs for data exchange between two elements
Material	needs for material exchange between two elements

After developing a taxonomy for interactions, an optional quantification scheme helps weight them relative to each other (Table 4.2). Marks in the DSM are replaced by a number (an integer -2, -1, 0, 1, or 2). Weighting information can be obtained by reviewing architectural diagrams and system schematics. Further classification comes from interviewing engineers and domain experts.

Table 4.2 Example of a Spatial Interaction Quantification Scheme (Pimmler and Eppinger qtd. in Browning, 2001)

Required	+2	Physical adjacency is necessary for functionality.
Desired	+1	Physical adjacency is beneficial, but not necessary for functionality.
Indifferent	0	Physical adjacency does not affect functionality.
Undesired	-1	Physical adjacency causes negative effects but does not prevent functionality.
Detrimental	-2	Physical adjacency must be prevented to achieve functionality.

The goal of matrix analysis in a component-based DSM is to cluster the elements into subsystems. This facilitates the determination of the organizational structure of system development. Integration analysis with a DSM promotes architectural innovation by demonstrating the rationale behind architecting decisions.

4.2.2 Team-based DSM

Team-based DSM is used for modeling organization structure based on information flow between people and/or groups. A team-based DSM is constructed by identifying the required communication flows and representing them as connections between organizational entities in the matrix. The aim of the analysis is to cluster teams into groups where interactions are most frequent. The analysis facilitates understanding the critical interfaces between groups and developing integrative mechanisms.

Information flow between teams can be characterized in several ways. A taxonomy for information flows in a team-based DSM is presented below.

Table 4.3 A Taxonomy for Information Flows in a Team-based DSM (DSM MIT, 2003)

Level of Detail	Sparse (documents, computer networks) to rich (models, face-to-face)
Frequency	Low (one-shot, batch) to high (piece-by-piece, on line, intensive)
Direction	One-way (monologue) to two-way (dialog)
Timing	Early (preliminary, begins the process) to late (completed work, ends the process)

The team-based DSM is an effective tool for modeling organizational elements and their relationships. The DSM provides a platform for communicating about alternative organizational structures and perspectives. One limitation of the method is that a single team-based DSM shows interactions between teams at a given point in time. Showing dynamic relationships may require multiple DSMs. Eppinger (2001) have proposed a team-based DSM to analyze a hierarchical, team-based organization for automobile engine development.

4.2.3 Activity-based DSM

The activity-based DSM method assumes that each task in a process can be modeled as an information processing activity, using and creating information. The output information from one activity becomes the input information to another activity. Activities are indicated in the rows and columns, in roughly a chronological order. Matrix elements indicate the existence and direction of information flow from one activity to another. Reading across a row, a dependency mark reveals the flows to that element from the column activities. Reading down a column reveals the output information flows from the activity represented by that column to other activities. Thus, the marks to the right of the diagonal in a single row reveal a feedback from a later activity to an earlier one that causes iteration in the design process. By re-arranging the position of activities, unintentional iterations can be avoided and an optimum sequence may be obtained.

Activity-based DSMs provide process visibility, highlight feedbacks and iterations and improve concurrency. Designing a design process according to the information flows rather than to the interactions between traditional activities can also eliminate nonvalue-added activities, facilitating for “lean” processes. However, This type of DSM has some limitations besides the lack of hierarchy of activities that mentioned in the previous chapter. First, a single DSM shows only a single process flow; it does not show all possible flow paths (Larson and

Kusiak, 1996). While the DSM can be augmented with additional symbols to represent contingent information flow (e.g. "+" instead of "X") analysis and improvement of a large process with many possible flow paths becomes intractable without simulation. Second, the DSM does not explicitly show overlapping activities. A Gantt chart remains one of the best representations of activity concurrency (Browning, 2001).

This type of DSM is probably the most exploited DSM type among the others. Krishnan (1993) has worked on sequencing and overlapping activities in product development via DSM to improve design processes in the automotive and the electronics industry. Eppinger et al. (1994) have used activity-based DSM to model processes of a major semiconductor company (Intel Co.). Browning (1998) has applied DSM techniques in developing lean design strategies for aerospace industry. Ulrich and Eppinger (1999a) have modeled a critical portion of the development process with activity-based DSM at FIAT automobile company. Ulrich and Eppinger (1999b) have also utilized the technique at Kodak to model cartridge development processes. Rogers and Salas (1999) have applied activity-based DSM at NASA for sequencing and monitoring design processes. Tang et al. (2000) have devised an algorithm of recognizing the coupled activities in a process to increase concurrency of designs and illustrated the framework with a die design example. English et al. (2001) have developed a method for identifying the strength of couplings in multidisciplinary design process in mechanical and aerospace engineering. Cronemyr et al. (2001) have used the DSM method to simulate the impact of improvements to the engineering design process. Chen et al. (2003) have incorporated activity-based DSM with timing for project scheduling.

4.2.4 Parameter-based DSM

In chapter 3, it was concluded that there is a need for a building design process modeling tool which is capable of representing iterations and detailed processes. The use of parameter-based DSM is proposed here for this purpose. Parameter-based DSMs are developed on the premise that bottom-up analysis of design processes based on low-level activities can reveal better insights into design process structure.

A parameter-based DSM is a square matrix, which defines the structure of parameter decisions. A parameter is a physical property whose value determines a characteristic or behavior of a system component and parameter decisions correspond to the lowest level activities in a design process. Thus, the level of analysis constitutes a main difference between activity- and parameter-based DSMs.

Activity- and parameter-based DSMs also differ in the scope of their representations. While an activity-based DSM includes reviews, tests, and analyses, parameter-based DSM documents the physical and rational relationships between the parameters that determine design. In other words, a parameter-based DSM describes design processes close to the product architecture. This is an advantageous property since high-level processes sometimes contain unnecessary activities and some high-level activities produce unnecessary outputs. Building a process up through the integration of low-level activities and deliverables, which are known to be required because of their closeness to the design at a parameter level, can help identify irrelevant activities and outputs in the process. Other benefits of using parameter-based DSMs are explained in the next chapter in building design context.

The application of parameter-based DSM analysis is described below via a simplified example. The example illustrates relationships between parameters affecting plenum depth for a suspended ceiling design. The table below shows seven parameters defined for this problem. The predecessors and owners of the parameters are also listed.

Table 4.4: List of Parameters, Their Predecessor(s) and Owner(s) for Suspended Ceiling Design

Parameter	Description	Predecessor(s)	Owner(s)
A	Floor Area	-	Architect
B	Floor to Ceiling Height	A, G	Architect
C	Beam Depth	A, E	Structural Engineer
D	Air Duct Depth	A	Mechanical Engineer
E	Air Duct-Beam Integration Scheme	C, D	Architect, Structural Engineer, Mechanical Engineer
F	Lighting Fixture Depth	A	Architect
G	Plenum Depth	C, D, E, F	Architect

The initial DSM produced according to this table is shown in Figure 4.6 (a). The parameters are listed in the first row and first column of the matrix in a roughly chronological order of design decisions. Reading across a row shows input resources; reading down a column shows output sinks. For example, the marks in row E denote that parameter E requires information from parameters C and D. If the parameter decisions were made in the order of A through G, it would be desirable for all information required by each parameter to have been already generated by a predecessor parameter decision. It can be seen in Figure 4.6 (a) that this is not the case for some of the parameters. Parameter B, for example, requires information from parameter A and G. However, information from the parameter G has not been made available. Thus, an assumption needs to be made about the value of parameter G. If the sequence of parameters were changed to have a lower triangular matrix form, with all the marks below the diagonal, an optimum sequence for parameter decisions could be realized. This reordering is achieved via some partitioning algorithms; the resulting matrix is shown in Figure 4.6 (b). As can be seen in the figure, the assumptions have not been removed totally, since there is a two-way dependency or coupling between parameters C and E. Complex processes like building design include many such problems and the method helps in identifying information cycles and minimizing their scope.

	A	B	C	D	E	F	G
A	1						
B	X	2					X
C	X		3		X		
D	X			4			
E			X	X	5		
F	X					6	
G			X	X	X	X	7

(a)

	A	D	F	C	E	G	B
A	1						
D	X	4					
F	X		6				
C	X			3	X		
E		X		X	5		
G		X	X	X	X	7	
B	X					X	2

(b)

Figure 4.6: A Parameter-based DSM Example (a) The Initial Matrix (b) The Partitioned Matrix

Black et al. (1990) have applied parameter-based DSM method to automobile brake system design. This work enabled designers to investigate the best initial points for iterated design and helped the company develop a systematic approach to low-level design process planning. Cesiel (1993) documents a similar application where designed experiments were used to study the parameter-based design options. Dong (1999) has analyzed the design processes of various parts of a car using parameter-based DSM. Rask and Sunnersjö (qtd. in Browning, 2001) have used the method to describe the relationship between design variables of a robot arm and its housing. Previously, design parameters were separated into two, coupled “meta-activities”: “design arm housing” and “design arm.” The DSM model was used to sequence and integrate the low level activities in a new way. The method has also been used at Boeing Company to plan the development of a multivariable wing analysis tool. Listing subroutines of the new tool, which were once individual analysis tools, as rows in the DSM and noting their necessary data exchanges as interfaces, the designer prescribed an efficient process for wing design procedures (Browning, 1998). Mascoli (1999) has applied DSM as a tool to organize design parameters at the conceptual design phase of aero-engine development. The analysis enabled understanding the relationships between design parameters and which interactions occur within a specific component, and which interactions cross the component boundaries.

4.2.5 Variations on the Basic DSM Method

Since its initiation in 1980s, DSM research has widened its scope and several variations of the basic DSM method have emerged. In fact, the method is versatile enough to be adapted to the needs of different types of analyses. Some modified DSM models are discussed below.

Numerical DSMs have been developed to quantify interactions. In binary DSM notation (0/1, or X marks) only the absence or existence of a dependency between different system elements can be shown. However, numerical DSMs can contain a multitude of attributes that provide more detailed information on the relationships between the different system elements. These include the following;

1. Level numbers: They indicate the order in which the feedback marks should be torn. The mark with the highest level number will be torn first and the matrix is partitioned again. This process is repeated until all feedback marks disappear. Level numbers range from 1 to 9 depending on the designers judgement of where a good estimate for a missing information piece can be made (Steward, 1981).

2. Importance ratings: A scale can be constructed to differentiate between different importance levels of the X marks (For example 1: high importance, 2: medium importance 3: low importance). In this approach, low importance marks are first torn and then the medium and high in a process similar to the level numbers method explained above.
3. Dependency Strength: This is a measure of dependency strength on scale (For example, 1: minimum dependency, 2: medium dependency, and 3: maximum dependency). The matrix is partitioned by minimizing the sum of the dependency strengths above the diagonal.
4. Volume of Information Transferred: An actual measure of the volume of the information exchanged (measured in bits) may be utilized in a DSM. Partitioning of such a DSM would require a minimization of the cumulative volume of the feedback information.
5. Variability of Information Exchanged: A variability measure can be devised to reflect the uncertainty in the information exchanged between system elements. This measure can be the statistical variance of outputs for that task accumulated from previous executions of the task (or a similar one). However, if there is a lack of such historical data, a subjective measure can be devised to reflect this variability in task outputs (Yassine et al., 1999).
6. Probability of Repetition: This number reflects the probability of one activity causing rework in another. Upper-diagonal elements

represent the probability of having to loop back (i.e. iteration) to earlier activities after a downstream activity was performed. Partitioning algorithms can be devised to order the tasks in this DSM such that the probability of iteration or the project duration is minimized (Smith and Eppinger, 1993).

7. Impact strength: This can be visualized as the fraction of the original work that has to be repeated if an iteration occurs Browning (1998). This measure is usually utilized in conjunction with the probability of repetition measure, above, to simulate the effect of iterations on project duration.

Browning (1998) has demonstrated that a DSM-based model of a process could be used to quantify a process configuration's expected cost and duration via simulation. It is assumed that cost and duration are largely a function of the number of iterations required in the process execution and the scope or impact of those iterations. Since iterations may or may not occur depending on a variety of variables, this model treats iterations stochastically, with a probability of occurrence depending on the particular package of information initiating rework. Thus, this approach requires a DSM model and some additional data such as cost and duration estimates, learning curve, probability of a typical change in the data causing rework, and the impact of that rework if it occurs.

Besides adding extra attributes to DSM analysis, modifying the content of DSM elements has also been used to create variations to basic DSM. Hamer et al. (1999) have studied document interdependencies on the design phase of one-of-a kind delivery process using a DSM that does not conform to established component-, team-, activity-, and parameter-based DSM classification. In the proposed method, each row and column represented one document class and the rows and columns were ordered identically. Reading across a row lists all the information which is needed as an input to produce the document class in question. Reading down a column outlines all the document classes that use the document class in question (column) as input information. Unlike a complete DSM analysis, the study did not aim at optimizing the sequence in which the documents are produced, since the main aim of the analysis was to obtain a picture of the document level interdependencies.

Lockledge and Salustri (2001) have developed "The Design Process Matrix" to model how functional systems relate to one another and to physical components. The model is very similar to conventional DSMs, but the authors used columns in the matrix for major components, and rows for major functional systems and subsystems. Thus, elements of the matrix represent interactions between a functional system and a component. Like the document example mentioned above, the aim in this study was not to prescribe a single process for engine design, but to provide a map of the existing process.

4.2.6 DSM Applications in the Construction Industry

DSM methods are mainly used in product engineering to optimize product design processes. However, there are a few DSM applications in the construction industry. DSM has been applied in building research by Loughborough University and VTT (National Research Organization) in Finland. The research team at the Loughborough University has developed a DSM-based design planning technique called Analytical Design Planning Technique (ADePT). This research has led to many publications (Austin et. al., 2000; Baldwin et. al., 1999; Austin et. al., 1999; Baldwin et. al., 1998) and the team won the 'Achievement through Innovation' award at the 1999 Quality in Construction Awards. Currently, they are extending this research under the “Integrated Collaborative Design” project.

ADePT research began in early 1990s in order to define and represent the work involved and the information flowing in a multidisciplinary building design project and to develop a technique to schedule the design phase more efficiently. The study combined two structured analysis techniques, namely data flow diagrams and design structure matrix.

In ADePT, information flows between design activities are first modeled via data flow diagrams. In the next step of the technique, DSM analysis is used to achieve an optimum sequence of design tasks. In the earlier versions of the model a binary information dependency scale was used. In the later versions, the researchers proposed a three-point scale, "A" being the most critical information and "C" being the least. Information classifications were made on the basis of three factors: strength of dependency of the task on the information, sensitivity of the task to slight changes in the information, and the ease with which the information can be estimated. As the task is increasingly dependent and sensitive and less estimable, the criticality of the information flow increases (Austin et al., 2000).

The ADePT design process model originated from a simple design example of a plant room consisting of 17 tasks across civil engineering, mechanical engineering, structural engineering, and electrical engineering disciplines (Austin et al., 1994). The research team has since elaborated the model to include 600 design tasks and 4600 information requirements (Austin et al., 2000). Recently, Salford and Loughborough Universities, in conjunction with some industrial collaborators, have produced The Generic Design and Construction Protocol which aims to be a description of the entire project process. The protocol combines Salford's Construction Process Protocol with ADePT (Macmillan et al., 2001; Austin et al., 2002).

Huovila and Seren (1998) have studied the applicability of DSM in understanding customer needs and in planning the building design process. The authors have proposed integrative use of activity-based

DSM with Quality Function Deployment (QFD) matrix. QFD is a team decision-making tool used to achieve a common understanding of design objectives and selected design solutions. In such a matrix, properties of design are entered as columns and requirements are entered as rows. The relationships between properties and requirements are entered at the intersection cells in a numerical scale (e.g. how important a specific property in satisfying a customer requirement? 3: high, 2: medium, 1: low). A weight (importance) factor is assigned to each customer requirement. The customers' requirement priorities and their perception of the performance of the existing products are also entered in the matrix. Using all the data how specific designs satisfy customer requirements are calculated and different configurations are compared. The authors claim that the use of both tools facilitates for a customer-oriented and efficient design process.

Austin et al. (2001) have utilized DSM technique to map conceptual building design activities in an experimental workshop. The workshop aimed to test the applicability and validity of a preliminary model of the conceptual design phase. The workshop involved 15 participants divided into three groups. Two of the teams were designated as test groups and the third as the control group. The two test groups were provided with a copy of the preliminary conceptual design framework. One team was given the option to follow it while the other team was asked to follow it. The two teams were then introduced to the brief and told to begin the exercise. The third team was asked to solve the design problem without the framework model. An activity-based DSM was produced to map the processes of the each team and the performances of the groups were compared accordingly.

4.3 DSM Tools

DSM tools can be obtained either as standalone programs or as Web-based tools.

4.3.1 Standalone Programs

PSM 32 (Problem Solving Matrix) is a commercial DSM program developed by the Problematics firm. PSM 32 is capable of producing numerical DSMs, and performing analyses such as partitioning and banding. It also provides simplistic tearing advice (Problematics, 2003).

Acclaro Designer is team collaboration software solution permitting the construction and analysis of multi-level hierarchical design matrices. Acclaro Designer adopts the axiomatic design approach to the construction of conceptual and functionally decomposed designs. Projects in the program can also be exported to Microsoft Project. Acclaro Sync. software supports the synchronization of Microsoft Project schedules to changing design matrices (Axiomatic Design Inc., 2003).

DeMAID/GA (Design Manager's Aid for Intelligent Decomposition with a Genetic Algorithm) is a knowledge-based software tool for ordering the sequence of design processes and identifying a possible multilevel structure for a design cycle. It has been developed at the NASA Langley Research Center. DeMAID displays the processes in a Design Structure Matrix format. A genetic algorithm (GA) capability was added to the latest version of DeMAID to examine a large number of orderings of processes in an iterative subcycle and optimize the ordering based on cost, time, and iteration requirements.

DeMAID was developed as a standalone program, but it has been integrated with a Web-based system for easy monitoring of project flow. A main project web page has been developed with links to the process web pages created by project team members. The project Web pages describe various processes of the project, such as disciplinary analyses and optimization. The program generates an HTML file for use with a web browser, allowing engineers to monitor the project flow. The HTML file is automatically reloaded every few seconds to display the current status of the DSM Web page and uses different colors to indicate the current status of each process and coupling (Rogers and Salas, 1999).

4.3.2 Web-based Tools

Sabbaghian and Eppinger (1998) have proposed a Web-based tool to enable rapid collection, continuous update and structured display of organizational and task interaction in large projects. The program uses a distributed data collection system involving a model coordinator and many participants. The Web interface allows the model coordinator to select a task for decomposition and assign another individual to model this lower level DSM. The system then automatically generates an e-mail to the target individual requesting his/her cooperation in modeling activity. The system utilizes a multi-tiered DSM configuration to present collected data.

WeB-DSM is a commercial system analysis and project management tool developed by Decision Sciences Inc. The system shows near-real time Web-based status of all events in a process, incorporates rework estimates, and optimizes the sequencing of activities via partitioning. It also has links to Microsoft Project and Microsoft Outlook Business Contacts (Decision Sciences Inc., 2002).

PlanWeaver is a Web-based software application for optimizing building design activities developed by Biw Technologies Ltd. It is based on ADePT technique discussed above. PlanWeaver contains a generic model of building design process at activity level. This model can be tailored to the design team's specifications. The final model is optimized through partitioning and delivered as a project program by linking the DSM to a project programming software application such as MS Project, Primavera or PowerProject. This project program can then be reviewed. If changes are needed, the matrix can be manipulated either directly or via the project planning software package.

5. PARAMETER-BASED DSM FOR BUILDING DESIGN

This chapter presents the proposals for the use of the parameter-based DSM in building design. After a discussion of the underlying paradigms, expected benefits of the method are envisaged. Finally, a knowledge management framework is proposed for the application of the method.

5.1 Underlying Paradigms

The use of parameter-based DSM in building design is based on a systematic approach to design. This endeavor has been motivated by two design paradigms, namely, design methods research tradition and lean design approach which are briefly discussed below.

5.1.1 Design Methods Research Tradition

The design methods research tradition dates back to 1960s when new mathematical techniques and computing were all available to the design theorists in highly developed forms. The design methods approach emerged from these sources as a discipline in its own right. In this research tradition, several techniques and theories have been borrowed from operations research such as matrix analysis, linear programming, network analysis, Monte Carlo method, value analysis, decision theory and theory of games. A number of graphic techniques have also been developed such as interaction chart and connections diagram (Broadbent, 1988).

The design methods movement initiated the idea that human affairs may have a mathematical structure (Atkin, 1974). This idea motivated many researches, for example, Baykan and Pultar (1995) have analyzed the structure of space-activity relationships in houses using the notion of a simplicial complex defined by a relationship between two sets. The recognition that the design process has an underlying structure was also rooted in this movement. One of the pioneers of design methods movement, John Chris Jones, explained in his famous book *Design Methods: Seeds of Human Futures* (1970) that the main challenges for a design manager are the following:

1. Identifying and reviewing critical decisions.
2. Relating the costs of research and design to the penalties for taking wrong decisions.
3. Matching design activities to the persons who are expected to carry them out.
4. Identifying usable sources of information.
5. Exploring the interdependency of processes.

Thus, the design methods research tradition constitutes one of the underlying paradigms of parameter-based DSM research in building design.

5.1.2 Lean Design

The major aim of lean production is to eliminate waste in production processes. Lean production was developed by a Toyota team, led by Ohno in the late 1980s. The term "lean" was coined in 1991 by the research team working on international auto production to reflect both the waste reduction nature of the Toyota production system and to contrast it with craft and mass forms of production (Howell, 1999). Lean philosophy has later expanded into many other fields. In 1993, the U.S Air Force and the Massachusetts Institute of Technology established a research organization named the Lean Aerospace Initiative (LAI). The initiative defines the term lean as "adding value by eliminating waste, being responsive to change, focusing on quality, and enhancing the effectiveness of the workforce." (LAI, 2002). In 1997, the Lean Construction Institute (LCI) was founded to extend lean design and production philosophy to the construction industry. The institute is a non-profit association supporting lean research in construction and it disseminates knowledge through its publications and annual conferences (LCI, 2002).

Gregory Howell, the director of the LCI, explains that the first goal of lean construction is to fully understand the underlying "physics" of processes, the effects of dependence and variation. He also comments that these physical issues are ignored in current practice which tends to focus on more human issues such as teamwork, communication and commercial contracts. In current practice for example, a delay is often attributed to one or more participants being morally deficient. However, lean design theory claims that such delays may be due to the combined effects of dependence and variation in a long period (Howell, 1999).

Lean design groups advocate the use of design structure matrix based methods, because they suit well the aims of lean philosophy. Like the lean design approach, the design structure matrix method aims to understand the underlying dependence structure in processes and to ultimately eliminate waste (or non-value adding components) from the process.

5.2 Expected Benefits

Browning (1998) explains that DSMs are especially useful when several participants must coordinate actions and/or information, because they provide a medium whereby the groups can visualize and explore how they must function together to achieve overall goals. Such is the condition in the collaboration of architects and engineers in building design.

The author of this dissertation believes that the main power of the parameter-based DSM lies in its capability to be used both as a system analysis and a project management tool. Most of the process modeling methods used in building design have been borrowed from the manufacturing industry and these models tend to view design process as "document production." Even the structured techniques adapted to building design, for example ADePT (Austin et al., 2002), take only the document producing activities in consideration for modeling. However, it is more advantageous to view design as making decisions rather than creating documents or following schedules. Being close both to product and process architectures, parameters are the core concepts of designing.

Within this perspective, expected benefits of the proposed method are discussed below under three headings: process improvement, process integration, and other information processing applications.

5.2.1 Process Improvement

5.2.1.1 Iteration Management

Design iteration implies rework or refinement, returning to previously made decisions to account for changes (Browning, 1998). Iteration occurs in all design projects; however, it is rarely discussed in design literature. Although understanding and controlling the nature of iteration is very important to improve design processes, there are no formal or detailed descriptions of where and how iteration occurs.

Iteration is typically necessary for two reasons; an unexpected failure of a design to meet established criteria, and an expected response to information which was generated after the previous iteration was completed. The former is called unexpected iteration and the latter is called expected iteration. Failure to converge to design specifications can require unexpected iteration. Such insufficiency in the design is more likely to occur when requirements and objectives are unstable or prone to change. Unexpected iterations also arise from new information arriving late in the process (caused by out of sequence activities, mistakes, etc.). Expected iteration usually results from downstream activities (particularly verification and validation activities) revealing aspects of upstream activities that must be reworked. Typically, some of the design decisions are made even though the information needed to complete them fully is not known. As this input information becomes available, the tasks are repeated and the product comes closer to meeting the design specification.

Rework can also be generated by changes in the information provided to and received from concurrent or interdependent (coupled) activities. Also, when downstream or coupled activities create rework for upstream activities, the resulting changes may cause second order rework for interim activities (those between the upstream and downstream activities directly involved in the iteration). Both types of iteration are common in the design process (Smith and Eppinger, 1993).

Browning's (1998) "intentional" and "unintentional" categories of iteration address the same two types of iteration. Clausing (qtd. in Browning 1998) similarly proposes the categories "creative iteration" and "disciplined iteration" as intentional and "dysfunctional iteration" as unintentional. Ballard (2000) proposes a distinction between positive vs. negative iteration in design. He claims that positive iteration is essential for generating value in design processes. However, not all iteration generates value. Negative iteration that can be eliminated without value loss is waste. Ballard explains that research should be made on reducing negative iteration and on generating value through promoting positive iteration.

Although iteration management is very important for conducting efficient processes, it is a difficult task. Browning (1998) explains that the first step towards reducing design cycle time lies in minimizing unintentional iterations. This necessitates ensuring that the right information is available at the right time in the process. The next step towards accelerating the design cycle involves two basic options for managing intentional iterations:

1. Faster iterations.
2. Fewer iterations.

Faster iterations can be achieved by improved coordination e.g. CAD systems that accelerate individual activities, improved intragroup coordination for teams assigned to individual activities, increased co-location of those executing highly coupled activities, concurrent engineering, integration of engineering analysis tools used for different purposes, and removal of extraneous activities from the process. Previous studies by Eisenhardt and Tabrizi, and Gebala and Eppinger (both qtd. in

Browning, 1998) found that additional faster iterations are significantly correlated with faster design development. Fewer iterations result from improving the structure of design processes e.g. activity decoupling and improved activity sequencing. However, fewer iterations can mean lower design performance. They make sense if each one is of sufficient productivity to ensure acceptable output. Faster iterations are advantageous only if each activity can be accelerated while continuing to produce satisfactory outputs (Browning, 1998).

There are a number of techniques for managing iterations such as the design structure matrix, team problem solving, cross functional teams, shared range of acceptable solutions, shared incomplete information, reduced batch sizes, team pull scheduling, concurrent design, deferred commitment, least commitment, set-based vs. point-based design, and overdesign (Ballard, 2000). Except the design structure matrix method, all of those techniques take a "communication and negotiation" approach. They basically aim to improve communication among the participants and to approximate the possible range of design solutions. However, the design structure matrix is a structured approach, which aims to provide explicit definitions of iterations in order to deal with them accordingly.

Rouibah and Caskey (2003) define four aspects of an effective design change management system:

1. Tracking the iteration's impact on the system elements.

2. Identifying the people to be informed.
3. Determining a reasonable sequence for informing the people identified.
4. Executing an order of activities with the participation of all persons involved or affected by the change.

A parameter-based DSM gives an overview of the existing relations between decisions; thus it can be effectively used as a tool to control the change propagation. When a parameter value is changed, it is very easy to extract the affected parameters using the dependency network. During collaborative design, as different design participants decide on parameter values, capturing the relationship between parameters consequently specifies the relationship between the decision-makers. Who should be informed about a change and the sequence of actions that should be taken can also be easily determined using the tool. As a result, a parameter-based DSM is an effective change management tool according to the criteria proposed by Rouibah and Caskey (2003).

5.2.1.2 Common Understanding of a Process

In Chapter 2, it was pointed out that a shared understanding of design process is an essential component of effective collaboration and having a common understanding of information content of design entails shared models. A DSM is a useful tool for opening the process to its participants and facilitating a common understanding.

A parameter-based DSM may provide insights into the following system properties.

1. *Information ownership (who produces a particular piece of information).*

   Designers may not be aware of what information they hold and what information they owe to others. DSM can be an efficient learning tool to discover previously unknown patterns of organizational architecture.

2. *The pattern of information dependency.*

   The DSM method is based on the premise that there is an underlying structure of design decisions. Due to the complexity and collaborative nature of design process, the pattern of information dependencies may not be easily discovered. A DSM opens up the information dependency patterns to the participants.

3. *The optimum sequence of parameter decision points.*

   In conventional practice, the sequence of design decisions is often based on intuition and professional experience of designers. There is no established method in the industry for examining the appropriateness of decision sequences. Besides its use as a descriptive tool, a parameter-based DSM can also be used to provide the optimum sequence of parameter decisions.

4. *Critical parameters that cause large iteration cycles.*

   Decisions on some parameters affect a large number of parameters in building design. Consequently, the changes in those parameters are more likely to cause larger iteration cycles. A parameter-based DSM is very useful for identifying such parameters, called "critical" parameters.

5. *Schedule of assumptions to be made in the process.*

   In building design, several assumptions are made when related information is not available. These assumptions are reviewed at some point in the process in order to validate them. What assumptions have been made and when they are to be reviewed are important for process success. DSM makes these assumptions explicit. It identifies when assumptions should be made and how they affect the overall process.

5.2.1.3 Concurrent Engineering

Concurrent engineering is increasingly becoming an area of interest in building design management. From the DSM point of view, moving marks above the diagonal closer to the diagonal enhances concurrent engineering by minimizing the scope and duration of the potential iteration. However, integrating important design decisions into the earlier phases, which is another aim of concurrent engineering, also results in increased amount of coupling and lengthened design time.

Concurrent work is often seen as a way to reduce cycle time but, if concurrent activities are chosen arbitrarily without considering their dependencies, this can lead to abundant iteration and increased cycle time. Research has shown that there is an optimum amount of activity overlapping beyond which additional is not useful (Krishnan et al., 1993). DSM analysis can help to determine that optimum point.

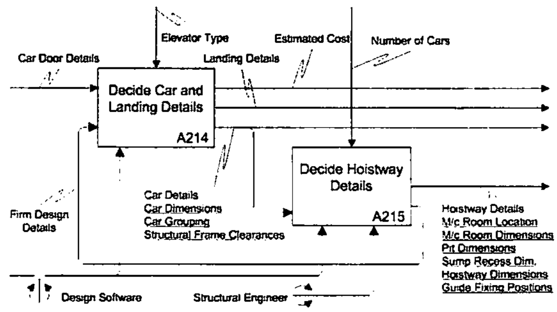
5.2.2 Process Integration

The situation of building design process modeling is similar to that of building product modeling approximately a decade ago. There are several attempts from different sources, but the existing models tend to be incompatible and fragmented. This fragmentation has recently forced, for example, European Commission research bodies to propose integration projects. ICCI (Innovation, coordination, transfer and deployment through networked Cooperation in the Construction Industry -IST-2001-33022) is a clustered project that aims to establish such a common platform for integration ideas (Rezgui and Zarli, 2001).

Besides its usage as a process improvement tool, parameter-based DSM can also be used as a process integration tool. Browning (2002) claims that parameter-based DSMs are truly integrative applications and a combinational use of top-down and bottom-up techniques in process modeling may reveal valuable insights into the process structure. A discussion on how parameter-based DSM can be used to integrate an activity-based model is presented below.

Any activity-level process model includes two general components; namely, process elements (activities) and deliverable elements. Deliverables are inputs and outputs exchanged by process elements. In order to truly integrate a group of activities (rather than merely aggregate them) the flow of deliverables among them must be well-defined. In existing tools, the modeling process starts at a high-level definition and it is decomposed as needed. In these approaches, there is no way of going backward i.e. using the deliverables as building blocks and integrating the model in a bottom-up manner. Therefore, the accuracy of deliverable flows is always questionable. A parameter-based DSM, however, can be used as a bottom-up integrative tool. In the example below, parameter-based DSM is used to integrate two activities modeled with IDEF0 (Taşlı Pektaş, 2003a).

In IDEF0 notation, deliverables are information pieces since the method focuses on representing a process from the viewpoint of information within it, rather than of its sub processes. Two activities of elevator design process and the deliverables (parameter decisions) for each activity are defined in the example below (Figure 5.1). The diagram shows that there is a coupling between activities A214 and A215. However, the structure of this cycle, namely which parameter decisions are dependent on each other, is not clear (Figure 5.1a).



(a)

		1	2
Decide Car and Landing Details	1	1	X
Decide Hoistway Details	2	X	2

(b)

Figure 5.1: Two Coupled Activities of Elevator Design Process (a) IDEF0 Model (b) Activity-based DSM

The representation of the same relationships in an activity-based DSM (Figure 5.1b) does not lend itself to further analysis either. In order to analyze the situation in detail, a parameter-based DSM can be produced (Figure 5.2a). The Parameter-based DSM shows the information flows (dependencies) between the parameter decision points in two activities and works as a detailed process map. When the DSM is partitioned, the optimum sequence of the decisions is obtained (Figure 5.2b). Although iteration can not be removed from the process totally, its scope is minimized.

		1	2	3	4	5	6	7	8	9
Car Dimensions	1	1							X	
Car Grouping	2	X	2							
Structural Frame Clearances	3			3						
Machine Room Location	4				4					
Machine Room Dimensions	5	X	X			5				
Pit Dimensions	6	X					6		X	
Sump Recess Dimensions	7	X						7	X	
Hoistway Dimensions	8	X	X	X					8	
Guide Fixing Positions	9	X							X	9

(a)

		3	4	1	2	8	5	6	7	9
Structural Frame Clearances	3	3								
Machine Room Location	4		4							
Car Dimensions	1			1		X				
Car Grouping	2			X	2					
Hoistway Dimensions	8	X		X	X	8				
Machine Room Dimensions	5			X	X		5			
Pit Dimensions	6			X		X		6		
Sump Recess Dimensions	7			X		X			7	
Guide Fixing Positions	9			X		X				9

(b)

Figure 5.2: Two Coupled Activities of Elevator Design Process (a) Initial Parameter-based DSM (b) Partitioned DSM

This example, although simple, illustrates the integrative use of parameter-based DSM with IDEF0. Examinations with other process modeling tools need further research.

5.2.3 Other Information Processing Applications

Parameters are increasingly becoming a center of attention in CAD (Computer Aided Design) tools. The early geometry-based models have been replaced by object-oriented information rich models (Rotheroe, 2002; Rundell, 2002). Wittenoom (1998) claims that "parametrics," i.e. building models on parameters as the basic components, will shape the future developments in information modeling field in the AEC industry. Similarly, Rouibah and Caskey (2003) identify an emerging "parameter-based concurrent engineering" paradigm in engineering design where parameter decisions are considered as the basis of the process.

Although representing parameter values in CAD models are studied extensively, the interactions between parameter decisions is a neglected issue. This dissertation suggests that explicit definition of parameters and characteristics of information flows between them may be helpful for the development of information processing applications that model components of a system with their interfaces. Previous examples of the use of parameter-based DSM in software development support this view (Browning, 1998).

5.3 A Knowledge Management Framework for Parameter-based DSM

Due to the inherent complexity of building systems, providing a knowledge management framework is an important issue for building information models. This dissertation takes a system analysis approach to deal with knowledge management problems in the proposed method.

A system is an assemblage of components formed to serve specific functions and subject to constraints. Thus, a system comprises some essential and interrelated components. Each component contributes to the performance of the system in serving the specified functions and the performances of components affect each other. A building is a good example for a system according to this definition; since, it comprises many essential components designed to meet certain needs. Moreover, the parts of a building must be fully compatible and are highly interdependent.

In systems analysis, a system is first resolved into its basic components. Then, it is investigated in order to determine the nature, interaction and performance of the components or of the systems as a whole. Components of a system may also be grouped; such groups are called subsystems. A complex system can be resolved into many types and sizes of subsystems. For example, it is possible to separate previously defined subsystems into further subsystems or to recombine parts taken from each subsystem into a new subsystem. Hence, a system can be analyzed in many different ways (Merrit and Ambrose, 1990).

This section of the dissertation aims to provide a knowledge management framework for parameter-based DSM applications in building design. An earlier version of this framework has also been published elsewhere (Taşlı Pektaş, 2003b). First, the assumptions and scope of the proposed model are put forward. Second, the need for explicit definition of parameters is addressed and the Industry Foundation Classes (IFCs) are proposed as a solution. Third, some classification schemes for design parameters, based on different views of parameter-based design, are developed. Fourth, means for dealing with large DSMs are discussed. Fifth, the complementary use of IDEF0 and DSM is proposed and finally, visions are presented for the utilization of the tool as software.

5.3.1 Assumptions and Scope of the Proposed Model

Design activity can be defined as a hierarchical decision making process (Demirkan, 1998). The proposed parameter-based model of design process is based on an understanding of the design process as a series of decisions on parameter values. Oxford English Dictionary defines the word "parameter" as "something that decides or limits the way in which something can be done." This definition implies that parameters should be conceived in a network. In his study, Dong (1999) has given a loose definition of engineering design parameters as "a collection of items that engineers have to consider in order to deliver a quality product." In CAD literature the term "parameter" is often used as a synonym to "attribute" which stands for a quality or a feature. This dissertation takes a more focused approach and defines a parameter as a physical property whose value determines a characteristic or behavior of a system component.

It is assumed that architects have a priority in deciding initial parameter values regarding the sizes and layout of building components in response to client's needs. This coincides with an architect's commonly accepted role as lead consultant and design leader. It is the responsibility of architect to produce preliminary designs of architectural systems. These systems overlap with many other systems belonging to the domain of other design professionals. In the model, it is also assumed that building design engineers' responsibility is to provide expert advice to verify related aspects of architect's design.

In real life projects, it is not so rare that another participant (client, stakeholders, etc.) interferes with the decision processes of design professionals. Such interferences are not included in the model, since they are often biased and unstructured. Thus, it can be expected that they would not add much to the existing framework.

5.3.2 The Need for Explicit Definition of Parameters and Industry Foundation Classes

One limitation of the use of the parameter-based DSM is that the parameters must be explicitly defined. However, for building design this is usually the case as product architectures and their associated parametric descriptions are relatively formalized via generic frameworks such as Industry Foundation Classes (IFCs). The development of the IFCs is a main standardization effort for the representation of AEC knowledge by the International Alliance for Interoperability (IAI). IAI is a non-profit organization comprised of about 600 member companies working to define and implement a "common language" for integration of project information that is valid for the life cycle of a project. Through the definition of IFCs, IAI aims –using an object-oriented approach– to provide a common model to which all applications can interface (Liebich and Wix, 2003).

In order to develop the IFC specification, it is essential to have a common view of building data that can be shared by the AEC community and software development professionals. This common view is known as the IFC object model, defined using a top-down approach. By starting with a very general view of the of the AEC industry, an overall model of a building can be defined suitable for software applications. The IFC development process involves the following components (VTT, 2003):

- **Usage Scenarios** are written descriptions of the processes that users perform, such as how a design engineer makes a traffic analysis for an elevator system. These usage scenarios capture the decisions and information that are used during each step of the process.
- **Process Diagrams** are visual representations of the process that is being defined. A process diagram is a diagrammatic representation of a usage scenario. IDEF0 is the recommended diagramming method for IFC development.
- **Classes** are object-oriented programming components used to define objects. They are designed to support the needs of the process and include concise definitions of the AEC data objects. For example, elevator parts like car, landing, and hoistway may represent a class (Figure 5.3).

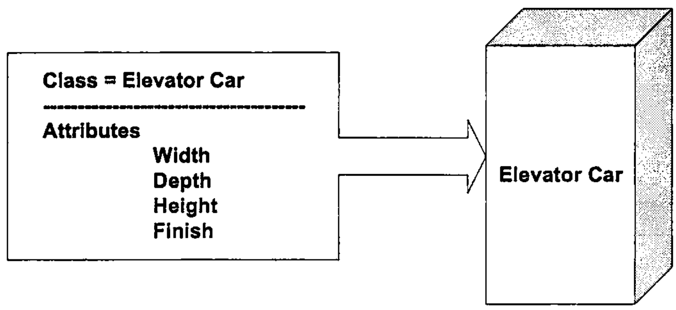


Figure 5.3: Elevator Car Class and its Attributes in the IFC System

- **Attributes (or Parameters)** are information about the class or its interface and are added to fully define an AEC object. Length, width, height, and location are some typical attributes of AEC objects.

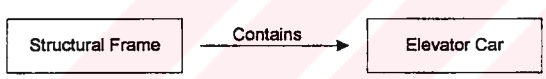


Figure 5.4: An IFC Relationship Diagram of Elevator Car and its Frame

- **Relationships** occur between classes. For example, an elevator car has a relationship to its structural frame. A structural frame contains a car and reciprocally a car is contained by a structural frame (Figure 5.4).
- **Interfaces** are used to provide access to the object. IFC interfaces are designed to support the AEC processes, and enable software vendors to implement IFC based objects. For example, an elevator

object must support a variety of AEC disciplines and include interfaces for traffic analysis, structural consideration, costing, etc.

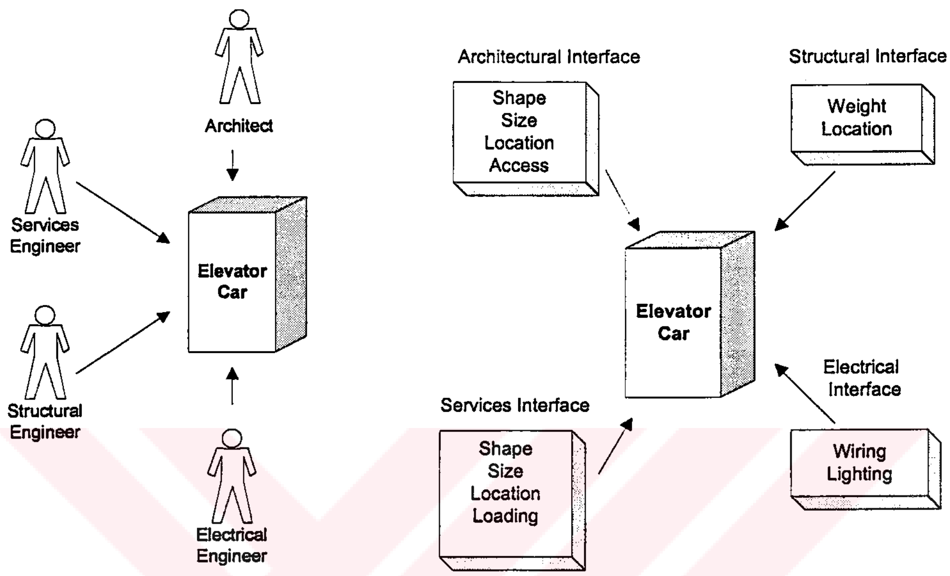


Figure 5.5: The Interfaces of Elevator Car Class in the IFC System

Being a widely accepted standardization effort, IFC development shapes the future of building information modeling. Therefore, future parameter-based models of design process should be integrated with IFCs. Usage scenarios and activity diagrams of IFCs can be effectively used as reference top-level process definitions which guide the development of DSMs. Attribute definitions of IFC classes can be used to define and classify the parameters. The case study on elevator design in Chapter 7 demonstrates how IFCs and parameter-based DSM can be integrated.

5.3.3 Classification of Parameters

This dissertation identifies four different views to analyze a parameter-based design. First of all, parameters are characteristics or attributes of products, so their relationship with product architecture is of concern. Secondly, parameter-decisions are the lowest-level components of a process —a view which is often emphasized in this dissertation—, thus, the place of parameter decisions in whole process architecture is interesting to study. Thirdly, in building design, parameter decisions are often made in a distributed environment by different design professionals; then, the information ownership issues (role view) arise. Finally, the definition of "parameter" devised in this dissertation conceptualizes parameters in close relation to performance requirements that they satisfy. Therefore, the analyses of relationships between parameter decisions and performance requirements deserve attention (Figure 5.6).

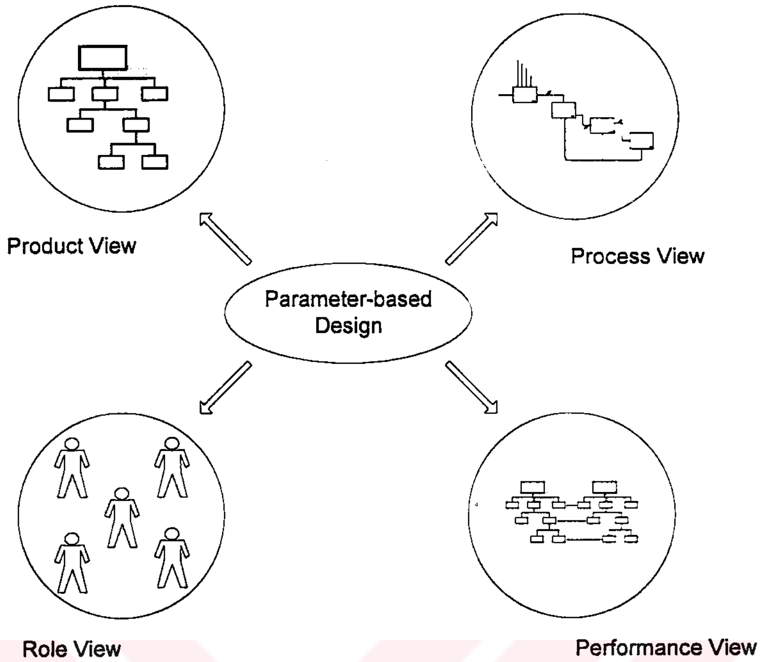


Figure 5.6: Four different Views of Parameter-based Design

Developing a classification scheme and representing it in a DSM increase the descriptiveness of the tool. In parameter-based DSM applications in building design, parameters can be categorized in four ways according to the views adapted:

1. Classification according to the building parts that a parameter belongs to.
2. Classification according to the parent activities.
3. Classification according to the "owner" of a parameter.
4. Classification according to the information content of a parameter (or an information flow).

The details of these four schemes are discussed below.

5.3.3.1 Classification According to Building Parts

In a DSM, systems are usually defined in relation to the parts of the design object. Parameters belonging to different building parts may be shown in different colors in a parameter-based DSM for building design. In this way, the information flows or dependencies among building systems and subsystems can be easily understood. UNIFORMAT II (Charette and Marshall, 1999) can be used as the base for classification of building parts.

UNIFORMAT II is an elemental classification system that has been widely accepted as an American Society for Testing and Materials (ASTM) standard. The format is mainly used for cost estimating and building specifications. Elements are major components, common to most buildings which usually perform a given function regardless of the design specification, construction method, or materials used. Examples of such elements are foundations, exterior walls, sprinkler systems, and lighting. The classification consists of three levels; namely, major group elements, group elements, and individual elements (For a detailed list, see Appendix A.1).

Elemental formats were developed in countries other than the U.S. prior to UNIFORMAT. The Canadian Institute of Quantity Surveyors (CIQS) classification and the Royal Institute of Chartered Surveyors (RICS) classification of the United Kingdom are the most widely used ones in countries which have a classification system for building parts. The need for a universal elemental system has encouraged the International Council for Building Research Studies and Documentation (CIB) and the Construction Economics European Committee (CEEC) to establish an elemental format to collect costs for international exchange. A major objective of the CEEC format is to make it compatible with the existing formats of as many European countries as possible. However, the CEEC format has not been widely adopted (Charette and Marshall, 1999).

UNIFORMAT is a preferable classification system for the purposes of this dissertation due to the following reasons:

1. Its framework is hierarchical to allow aggregation and summarization at different levels.
2. Its framework accommodates unlisted items based on the judgment of building professionals.
3. Included items have high frequency of occurrence.
4. Included items are distinctive.
5. It can be applied to any building type, although it has been designed for commercial buildings.
6. It separates the classification of building elements from the classification of building related site work.

Moreover, UNIFORMAT relates to other widely used classifications such as CIQS and RICS.

5.3.3.2 Classification According to Parent Activities

Some process modeling tools like IDEF0 incorporate a hierarchical organization. In such tools, it is possible to view the model at different resolutions and to track relationships between different levels.

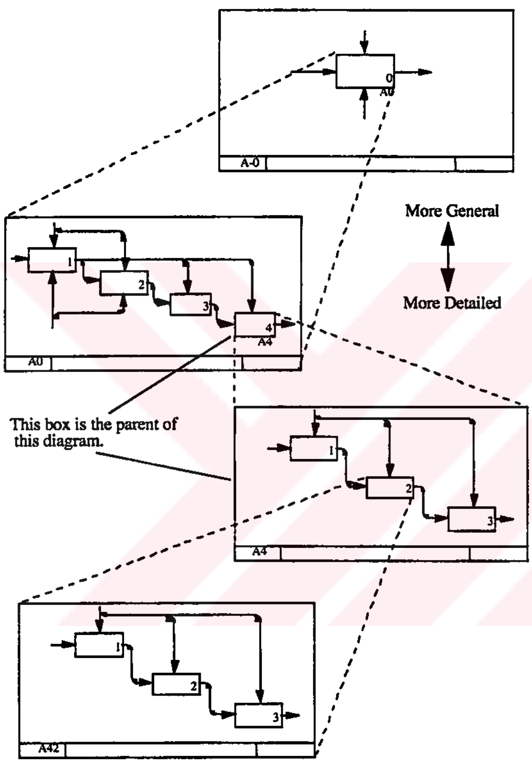


Figure 5.7: The Hierarchical Organization of IDEF0 Modeling (U.S. NIST, 1993)

However, one of the limitations of the DSM method is that it does not include a hierarchy of elements. This dissertation suggests that representing the relationships between parameters and high-level activities may provide better insight into the process structure and also facilitate for process integration. Therefore, in a parameter-based DSM, parameters can be categorized according to the activities that produce them. Parameters belonging to different activities can be shown in different colors in a DSM. In this way, the initial matrix can be used as a process map, which shows the detailed flows between the activities.

5.3.3.3 Classification According to Information Ownership

An "owner" of a parameter is a design professional who produces a value for that parameter during the process. This ownership definition refers to "information ownership" rather than "authority ownership." The latter one means having an authority to make a decision on the final value of a parameter and is widely used in project management applications. However, the information ownership definition proposed in this dissertation has a broader scope including verification processes. Therefore, a parameter may have more than one owner in the model. In the following case studies, the owners of the parameters are captured and displayed in the information database (See Chapters 6 and 7).

5.3.3.4 Classification According to Information Content

Parameters are often addressed in design literature with reference to the requirements that they are expected to satisfy. For example, a recent but widely recognized design theory developed by Suh (1998) specifies that all designs can be represented in four domains:

1. Customer Domain: Specifying the customer needs, expectations, design specifications, etc.
2. Functional Domain: Specifying the functional requirements which will satisfy the functional requirements
3. Design Domain: Specifying the physical design parameters which satisfy the functional requirements
4. Process Domain: Which allocates the processes required to achieve the design parameters, i.e. realize product (Suh, 1998).

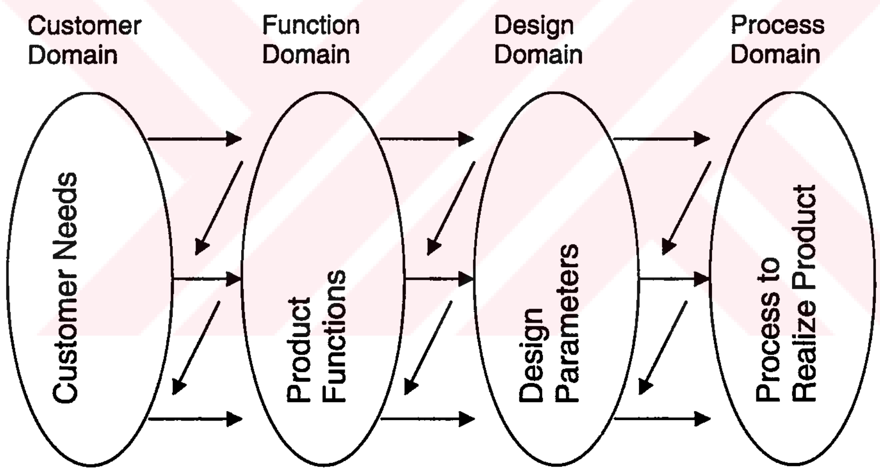


Figure 5.8: The Four Domains of Suh's Axiomatic Design Theory

Although axiomatic design theory has been developed and applied in product design, it seems to be valid for building design as well regarding the similar nature of design processes. Just like product design, building design also starts from the clients' wishes which are often stated in nontechnical terms. Furthermore, some of the requirements may be covert, or vaguely stated. The architect must identify and convert these requirements to more technically specific functional requirements. These are also called “design constraints” in the related literature. The actual design parameters that satisfy each of the functional requirements lie in the design domain (Figure 5.9).

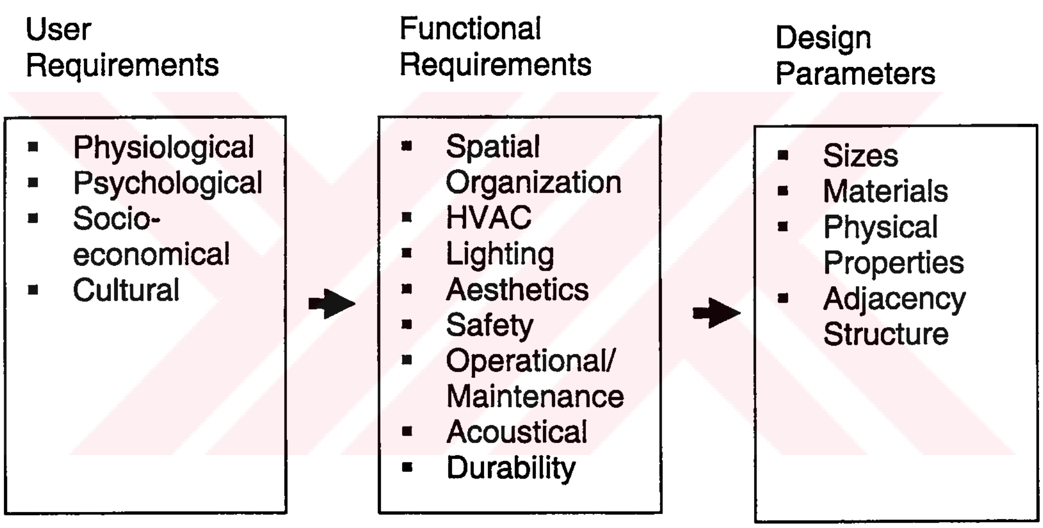


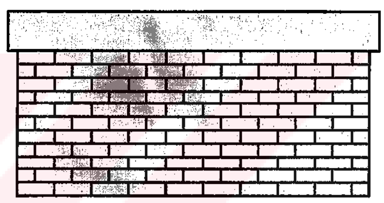
Figure 5.9: Suh’s Domains Adapted to Building Design

Within this perspective, building design parameters can be categorized into two according to their information content.

1. Spatial parameters: size, shape, location, layout, arrangement
2. Performance parameters: the properties of objects directly related to satisfying some functional requirements.

These definitions are consistent with the terms "design parameters" (physical parameters) and "performance parameters" used by Clarkson and Hamilton (2000) and "explicit attributes" (design parameters) and implicit attributes (performance parameters) used by McMahon and Xianyi (qtd. in Clarkson and Hamilton, 2000). The two different parameter types in building design are illustrated through the exterior wall example shown in Figure 5.10.

SPATIAL/GEOMETRICAL PARAMETERS
Shape
Size (width, depth, height, area)
Location
Layout



Exterior Wall

PERFORMANCE PARAMETERS	
Performance requirement	**Related Performance parameter**
Resist climatic conditions	Thermal transmittance
Keep out intruders	Intrusion resistance
Present a decent face to world	Appearance
Structurally sound	Structural parameters (Load resistance, Allowable deformation, etc.)
Normal wear and tear	Durability parameters (Service life, resistance to temperature changes, etc.)
Provide privacy	Transparency/opaqueness

Figure 5.10: Different Parameters of an Exterior Wall

Although it is possible to reflect this classification scheme in a DSM, a more useful application would be to include performance requirements in the DSM and to denote the performance requirements that parameters serve. Spatial parameters often serve more than one requirement. The information flows can also be categorized according to the performance requirements. This provides insights into how requirements drive the solution of a specific design problem.

The basic performance requirement groups in building design are listed below.

- Spatial Organization
- HVAC
- Lighting
- Acoustics
- Aesthetics/Appearance
- Hygiene
- Safety
- Operational/Maintenance
- Durability

However, the analyses can be based on more detailed forms of these basic groups. For example, spatial organization requirement can be decomposed into requirements such as spatial fit, functional zoning, privacy, proximity, continuity, etc. For more information, one may examine the list of performance factors that are proposed by the U.S. Construction Specifications Institute (CSI) (Appendix A.2).

5.3.4 Dealing with Large DSM Models

One of the challenging problems in DSM models is presenting complex systems with many interacting elements in the DSM format. When constructing models comprised of hundreds of elements, the intuitiveness provided by the DSM representation diminishes. It becomes increasingly difficult to identify the relationships in a very large matrix so that the method loses its advantage of simplicity.

DSMs with fewer than ten elements can often be analyzed via visual inspection and manual manipulation. 50-100 element DSMs are legible on a standard page. In order to decrease the complexity of larger DSMs and to make them easier to review, one can aggregate some design parameters under a generic name so that a series of DSMs with different "resolutions" can be obtained. Of course, aggregation requires choices about how to integrate elements to represent them as a single element with minimal loss of information in the model (Browning, 2001).

In fact, the size of the DSM is dependent on the size of the design problem. The experience of the author in building DSMs suggests that it is advisable to define the problem in a manageable size for a parameter-based DSM. Since such DSMs are low-level analysis tools that promote a bottom-up approach, even a small design problem may consist of many parameters. The previously produced parameter-based DSMs support this view. The majority of them focuses on a specific design problem and includes 40-100 parameters. These include Dong's (1999) Vehicle Door design and Throttle Body Design DSMs, Mascoli's (1999) Aero Engine Design DSM, and Black's (1990) Brake System Design DSM, to name a few.

Grose (qtd. in Sabbaghian and Eppinger, 1998) developed a method called multi-tiered DSM to structure a large DSM into a hierarchy of smaller DSMs. Grose developed this method for activity-based DSM modeling in which initial highest level activities are further decomposed into a set of sub-activities forming a series of level 2 DSMs. In this structure there are three possible forms of information exchange:

1. Internal interaction: This refers to information being exchanged within a single matrix represented by marked cells within each matrix.
2. External interaction: This consists of information being exchanged between two or more matrices.
3. Boundary interaction: This is the information exchange occurring at the boundaries of the model with entities outside the project such as customers, suppliers, etc.

Although the method seems to be useful for activity-based DSMs, it can not be used for parameter-based DSMs that already include the undividable components of a process.

In this dissertation, it is proposed that parameter-based DSMs can be produced at two levels as the following to manage the size and legibility of the matrices.

1. Single subsystem (Assembly) level: The matrix contains the parameter relationships in a single subsystem.
2. System interfaces to a subsystem: The matrix contains the parameter relationships between different subsystems.

This grouping also enables the modeler to compare assembly and system level DSMs and to comment on the design process.

5.3.5 Complementary Use of IDEF0 and DSM

The author's interest in IDEF0 (U.S. NIST, 1993) models resulted from practical concerns while developing DSMs for the case studies. Developing a DSM may be a difficult task because as the number of elements increase, the points of interactions increase geometrically. Therefore, individuals may have difficulty in building DSMs with more than ten elements (Browning, 2001). In that case, it is often useful to use another complementary technique to ease the modeling process. Malmström et al. (1999) mention the complementary roles of IDEF0 and DSM for the modeling of information management processes and claim that useful insights can be reached with additional work by using both techniques.

The IDEF0 technique is suitable for the purposes of this dissertation, since in this method, a process is represented from the viewpoint of information within it, rather than of its sub processes. Moreover, IDEF0 diagrams do not describe how a task should be done; they only represent what is necessary to perform that task and what is transformed into. Since it is a top-down analysis tool, the top parts can be read to obtain an overview of the system and if more detail is required, the lower levels can be studied. Thus, having some IDEF0 models of the system before building low-level parameter-based DSMs helps to monitor the consistency of the DSM and to represent where parameters take place in a hierarchy of process diagrams.

However, due to the graphical nature of the method, in IDEF0 models it is difficult to decide, at a glance, where some of the data has originated. This disadvantage is outweighed by using the two techniques together; since DSM provides a compact and analytically advantageous format for description.

5.3.6 Implications for Implementation Using Information Technology

Considering the large number of parameters in building design, it is envisaged that the method should be utilized along with a software tool. This necessitates production of generic parameter-based models and is important for enabling widespread application of the method. Internet-based project management tools (sometimes called "project extranets") have been increasingly used in the last decade. The improvements in bandwidth and network security have been the major drivers of this development. Sharing information through project-specific secure Web pages seems to be the focus of further developments in project management field. Thus, it is proposed that parameter-based DSM can be implemented as this type of software.

Figure 5.11 shows an implementation model for parameter-based DSM in building design. In the model, parameter data is stored in an object-oriented database. The data may be generic or project specific. At the start of the project, the project manager (often the architect) copies the generic model and then edits it through the user interface to make it appropriate for the new project. This functionality is important for building design, because unlike other products, buildings have a "one-of-a-kind" nature.

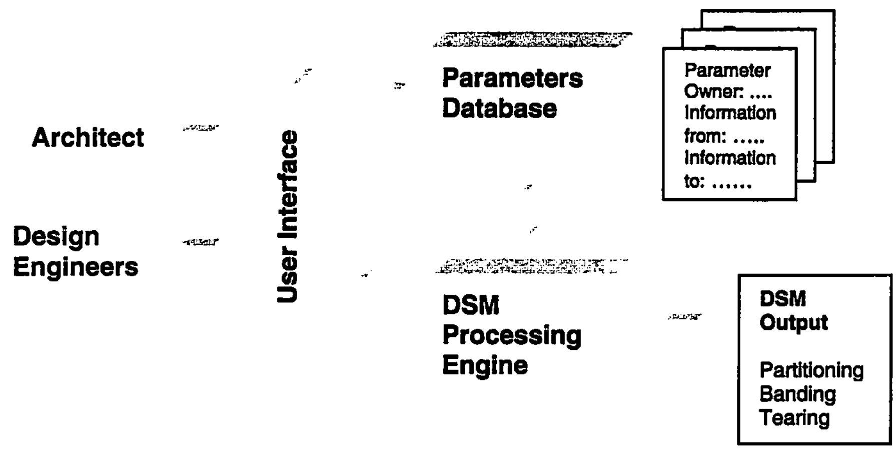


Figure 5.11: The Proposed Implementation Model

Each parameter object contains three attributes: owner of the parameter, provider parameters (which parameters provide information to that parameter), and recipient parameters (which parameters receive information from that parameter). The DSM processing engine performs analyses of partitioning, banding, and tearing and produces a DSM output. A detailed usage scenario for the tool is presented below (Figure 5.12).

A project manager logs in to the project web page and chooses a design task among a list of pre-defined tasks (for example, elevator design). A generic DSM model is available in the program for each task. The project manager imports the related generic model to the web page to create a project-specific model. Using the modification procedures such as adding and/or deleting parameters and their dependencies, the generic model is adapted to the project. For this purpose, the project manager also assigns roles to designers such as structural engineer, mechanical engineer etc. to the design task. The model is checked out by these multiple designers; however, each actor can only edit the section of the model to which their responsibility has been assigned. When the modified dependencies relate to parameters outside the users' domain, the user at this stage have to communicate to the project manager to make the proposed change. The final matrix is optimized by the project manager via partitioning. Durations may be added to the tasks and the optimum schedule of the process is notified to all roles. If a change occurs while conducting the processes, the model check out is repeated. At this stage, the DSM helps identify the affected parameters and manage change in processes.

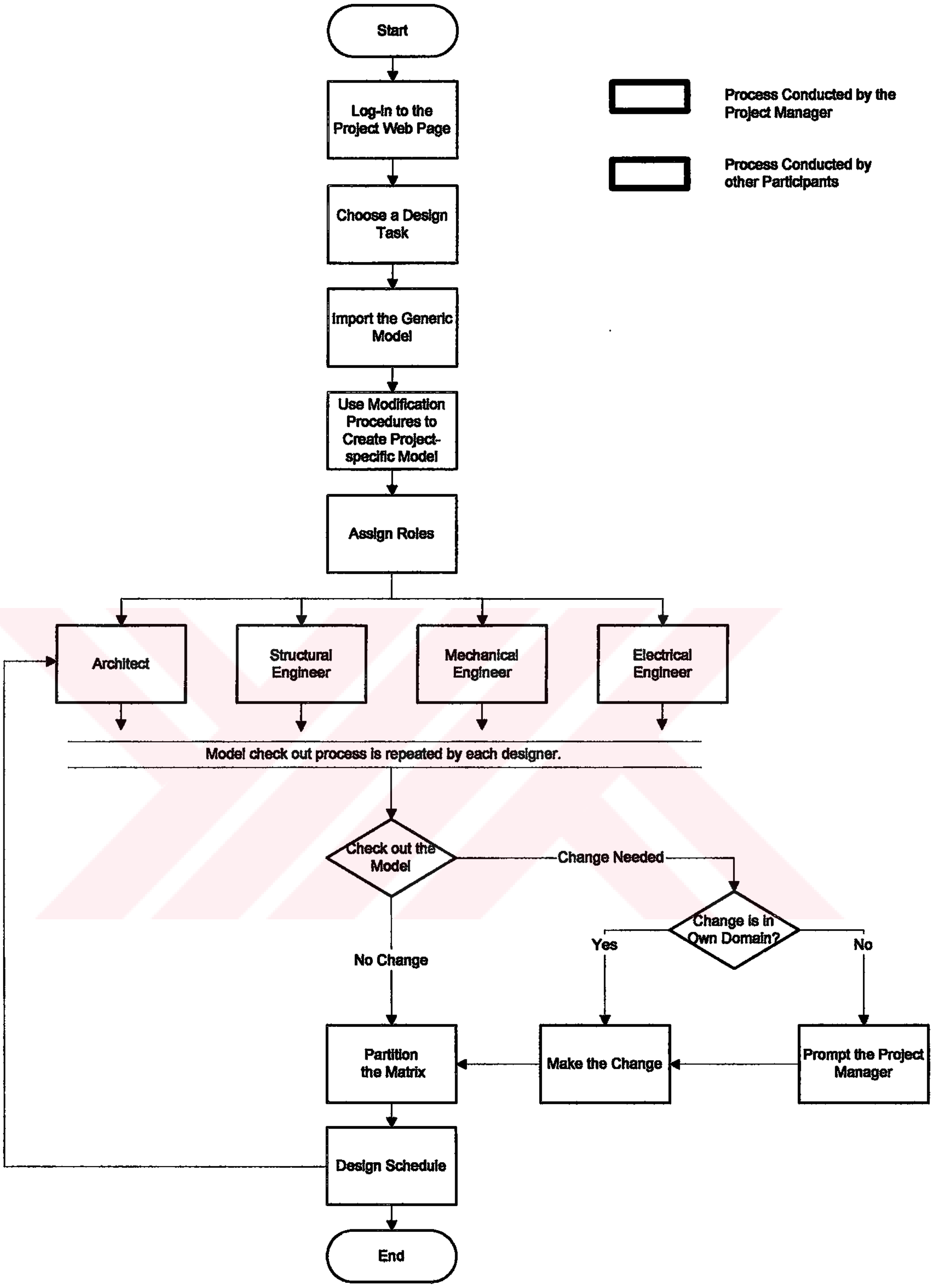


Figure 5.12: A Workflow Proposal for a Project Management System Utilizing the Parameter-based DSM

6. CASE STUDY 1: SUSPENDED CEILING DESIGN

6.1 Introduction to the Case Studies

The research questions of this dissertation posed in Chapter 1 have been the following:

1. What is the information dependency pattern for design processes of architects and building design engineers?
2. Can the parameter-based design structure matrix method be utilized to analyze these processes? If so, how?

In order to explore these questions, two case studies have been designed.

The main objective of these case studies is to apply the proposed method to real life building design problems to represent information dependency pattern of decisions. Aiming to be innovative in design process modeling, the case studies tend to be exploratory and qualitative and they are expected to guide future research.

The scope and content of the two case studies were designed to reflect different aspects of the framework proposed in Chapter 5. The first case study is based on an analysis of suspended ceiling design process for a public building in Turkey. The DSM analysis for this case aims to capture the information flows in a specific design configuration. The second case study, which analyzes elevator design, however, does not focus on a specific configuration. Both of these approaches have been validated in previous DSM researches (Browning, 1998).

Besides the approach to the analysis, the characteristics of the designs are also different in the two case studies. Suspended ceiling design is one of the tasks of a whole building design process in which several subsystems interact with each other. A suspended ceiling system includes a space called plenum formed to conceal structural members, lighting fixtures, diffusers, and air ducts. The integration of these components constitutes the major problem in design. The situation is complicated by the fact that the elements influencing suspended ceiling are in the domains of different building professionals; structural members being designed by structural engineers, diffusers and air ducts by mechanical engineers, and lighting fixtures by electrical engineers. Therefore, the effective design of a suspended ceiling necessitates coordination of these design participants.

Elevator design process involves the intense collaboration of the same design professionals (architect, structural engineer, mechanical engineer, and electrical engineer) as well. Compared to suspended ceiling design, however, it is a more self-contained problem. Unlike a suspended ceiling which is basically an interface problem, an elevator is a well-defined complex system in itself. These different characteristics of two design processes were reflected in the DSM analyses. In the first case study, the

DSMs were produced at two levels: assembly and system interface. The assembly level DSM represents the information flows between the parameters that belong to suspended ceiling parts. The system level DSM shows the information flows between the suspended ceiling system and other systems related to suspended ceiling. Due to the different character of elevator design, this bi-partite approach was not taken in the second case study. Moreover, in the suspended ceiling design case, performance requirements were also included in the analysis in order to compare how they drive design at the two levels of analysis (assembly and system interface levels), which is not the case in the elevator study.

In each case study, a different parameter classification system was used. In the suspended ceiling study, the parameters were classified according to the physical system architecture which enabled mappings between performance requirements and building parts. Similar mappings have been previously made by Mascoli (1999) and Dong (1999). In the elevator design study, however, parameters were categorized according to the activities that produce them (parent activities). In this way, the DSMs were used as process maps which showed detailed flows between the activities. Rask and Sunnersjö (qtd. in Browning, 2001) have provided a simplistic example for such a use of a parameter-based DSM.

Another aspect of difference between the case studies is the way parameters were defined in each study. While in the elevator study parameters were defined according to the IFCs, this was not possible for the suspended ceiling study; since, IFC definitions currently do not include necessary parameters for suspended ceiling integration. However, the importance of coordination of interdisciplinary information in suspended ceiling design has recently forced IAI to develop a ceiling plenum coordination project. The project aims to develop a tool that can check for conflicts in suspended ceiling design according to explicit rules. The proposed project will develop such explicit rules and other requirements that plenum coordination imposes on the IFC project model. In the project description sheet, it is explained that the most difficult part of the project will be the initial establishment of the rules, but rules developed in the project will serve as basis for customization of future and more specific project rules (IAI North America, 2003). It is hoped that the analyses made in this dissertation may facilitate for such integration efforts.

Having highlighted the different aspects of the two case studies, the rest of this chapter discusses the suspended ceiling design case study. Following a description of the system architecture, the suspended ceiling design process is briefly outlined. Finally, the research procedure and the results are discussed.

6.2 Suspended Ceiling System Architecture

A suspended ceiling is a ceiling type which is not directly fixed to the floor or roof structure above it but, as its name implies, is suspended by means of metal hangers and channels. This type of system is most commonly used in public buildings and is rarely applied in residential buildings. Suspended ceilings are available as either complete proprietary systems including services fittings (e.g. lighting fixtures and air diffusers), or as separate components from different sources. The former type, called "integrated ceilings," is not widely used in Turkey.

In general, there are two types of suspended ceilings: exposed grid and concealed grid. In the exposed grid type, suspended ceiling panels are laid in a grid of steel or aluminum sections. In the concealed grid type, a grid of main beams and tee sections is located into kerfs in the edges of the panels. Several combinations of these two types are possible such as exposed linear grid type in which exposed grid members are used to support the ends of rectangular panels, while the long edges are supported by concealed grid members.

This dissertation analyzes suspended ceiling design using a system view of suspended ceiling. According to this view, the basic components of a suspended ceiling system are panels, main runners and cross-tees, plenum, hangers, and wall angles. The collection of these members constitutes the suspended ceiling assembly (Figures 6.1 and 6.2).

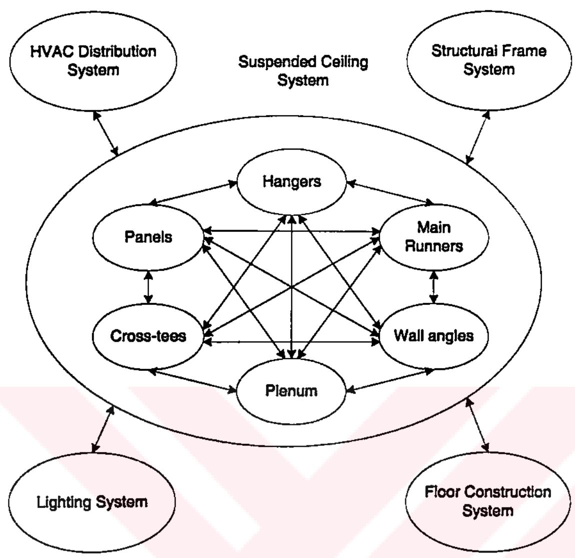


Figure 6.1: A System Design View of Suspended Ceiling

A suspended ceiling panel is a form of a prefabricated ceiling element used with exposed suspension systems. The term "suspended ceiling tile" is usually applied to the same type of ceiling elements used with concealed or semi-exposed systems. Edge and joint details of panels must be compatible with the selected suspended ceiling type and the structural system. Several other properties of panels such as humidity-, sag-, and fire-resistance as well as acoustical and thermal properties should be considered while selecting them.

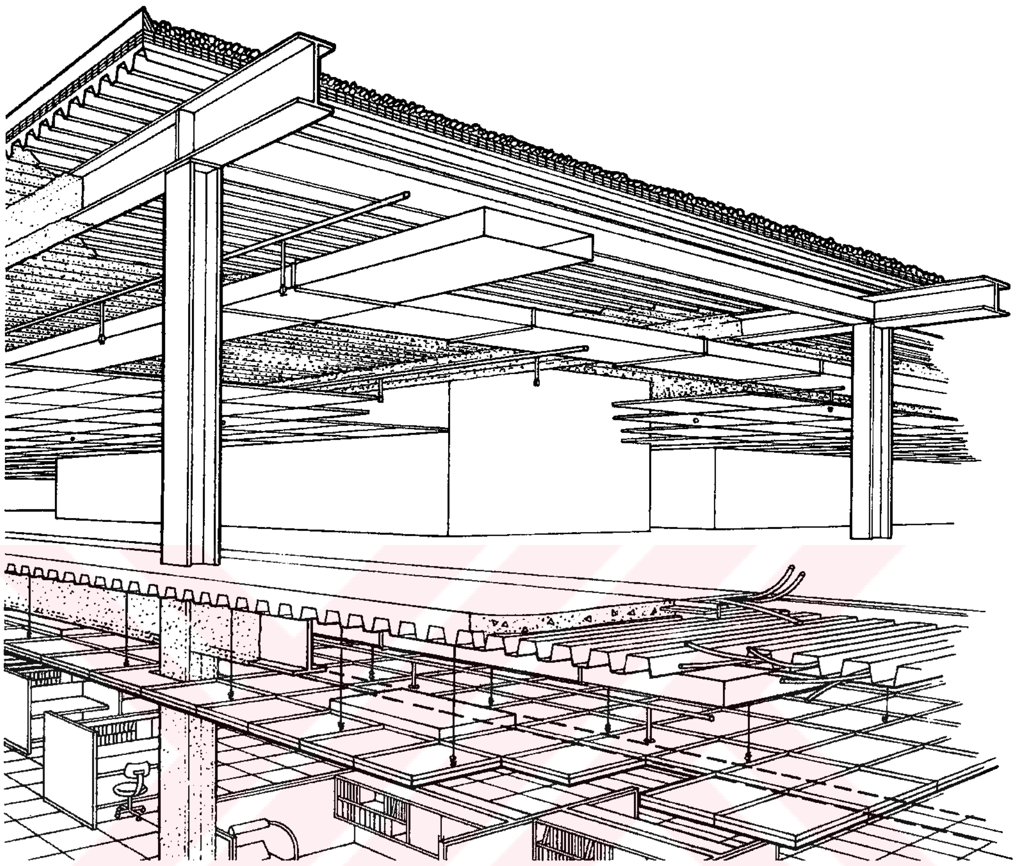


Figure 6.2: A Detail from A Suspended Ceiling System (Rush, 1986)

Main runners are the load-bearing parts of the suspended ceiling structural grid which are suspended from floor or roof structure. Cross tees are run between the main runners to provide additional support. Flat or T splines may also be used along with main runners and cross tees. The dimensions of these structural elements are critical for structural stability of the suspended ceiling. For most suspended ceilings, there is an option for supporting integrated fittings (lighting fixtures, air diffusers, etc.) via the suspension system. Fittings supported in this way must be compatible with the ceiling system in terms of size, weight, and edge details.

A suspended ceiling plenum is the space between the suspended ceiling and roof or floor structure above. This space normally accommodates a number of services such as HVAC equipment, lighting fixtures, sprinkler systems, etc. The depth of plenum is a critical parameter to consider since it determines the available space for included services and directly affects floor-to-ceiling height.

Hangers are metal elements with adjustment clips which are used to connect suspended ceiling structure to the building structure. The spacing of hangers is critical for the structural stability of the system. Wall angles are metal L sections which are used to connect panels to the surrounding walls. Their design should be compatible with the rest of the suspension system.

6.3 Suspended Ceiling Design Process

Insights into the suspended ceiling design process were gained through the interviews conducted as a part of the case study. The process is summarized below in order to provide a background for the detailed models presented in the next section.

Suspended ceiling design process begins with a feasibility study, which involves the client and the architect. If a suspended ceiling is required, the next step is its design. Although suspended ceilings are constructed late in construction phase, their designs should be undertaken in an early design stage, since they affect several other building systems.

The earliest consideration in suspended ceiling design is plenum depth. This decision necessitates information on required depths for HVAC and lighting equipment; and structural members. Plenum depth should not only be sufficient for services and equipment, but also allow enough extra clearance for access panels to be lifted out. Structural element connection details and HVAC and superstructure integration scheme are layout considerations that affect plenum depth. There may be several options for connecting structural members. For example, structural steel beams and girders may be connected either by framing beams into girders or in a two-layered system. The former scheme minimizes plenum depth and some mechanical services can pass through the holes cut into the beam webs, but large lines may have to be accumulated in the space below. The two-layer system increases plenum depth considerably, but provides more space for services. Similarly, HVAC and superstructure integration scheme may adopt either a layered or a shared approach. The former requires more plenum depth; however, it is more flexible. The latter may save considerable space in the plenum, but it brings strict dimensional constraints to the integrated systems. Girders or beams may be slightly oversized to allow for penetration of ducts through them.

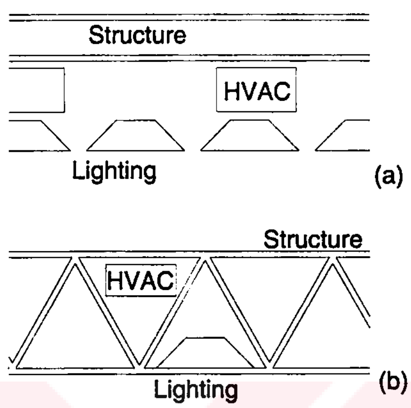


Figure 6.3: Layered (a) and Shared (b) Schemes for Integration of Structure, HVAC and Lighting Systems (Adapted from Bovill, 1991)

Having decided an initial value for plenum depth, the architect determines the structural grid of the suspended ceiling. Chosen suspended ceiling type and dimensions of the total ceiling area are the factors that are influential on this layout. Panels are also chosen by the architect according to the performance criteria. There are many parameters related to panels which are probably the most important part of suspended ceiling in creating the "atmosphere" of the interior.

Cross sections of the structural members of suspended ceiling (main runners and cross tees) are chosen as to be compatible with imposed loads and panel properties. Hanger spacings are also determined according to the loads imposed on the system. Obstructions to hanger positions should be anticipated to enable solutions to be adopted. Services in the plenum should be set out with sufficient accuracy to ensure that the integrated fittings they serve will be correctly positioned relative to the suspension grid and the panels.

Suspended ceiling manufacturers often provide several combinations of suspended ceiling components and the architect chooses a specific configuration which best satisfies the project's needs. Thus, suspended ceiling, at the assembly level, is often a "kit-of-the-parts" type design.

6.4 Analyzing Suspended Ceiling Design Process with DSM

6.4.1 Research Setting

This research was carried out in the architectural design department of TEPE Construction Company and in the offices of their engineering collaborators. Tepe Group Companies began operations in Ankara in 1969, and the companies are still fully owned by Bilkent Holding which belongs to Bilkent University. Today the Tepe Group provides total services from project development to turnkey project turnover. This approach is realized by full integration of its various companies which deal with such areas as infrastructure, construction, construction materials, doors, frames, kitchens and furniture. The engineering collaborators are privately owned firms leaded by a chief engineer. Design staff employed at these offices includes approximately 4-5 people in each office (including the draftsmen). Thus, the collaboration between TEPE and its engineering collaborators is an example of a distributed collaboration of small design teams, which constitutes the most widespread model in the Turkish AEC industry.

The suspended ceiling case study took five months between September 2002 and January 2003. The chief architect of the architectural design department of TEPE, and three engineering collaborators (one structural engineer, one mechanical engineer, and one electrical engineer), whose names are mentioned in the "Acknowledgement" section, provided supports and inputs for this research.

6.4.2 The Project

As mentioned in the beginning of this chapter, this research studies suspended ceiling design process in a specific project. The analyzed project is the Turkish customhouse complex situated at the Turkey – Iran border, being built on the E-23 highway next to Gürbulak village in Ağrı. The project was developed as a result of the government's decision to demolish the existing customs building which had failed to respond to the emerging needs and to build a new, functional and prestigious customhouse complex. The reason for choosing this project as the subject of the case study was that this building had been the most recent design project completed by TEPE Construction Co. when the study was being undertaken. Thus, it was expected that tracking the information flows in the process would be easier.

The complex consists of eight individual buildings; namely, customs directorate and passengers' hall, TIR customs office, customs inspection hall, 2 social buildings, customs management hall, warehouse, entrance and exit control units. The architectural and engineering systems of all the buildings in the complex are similar to each other; therefore, the analysis of a single building would be sufficient for the purposes of this dissertation. The TIR customs office building is chosen as the focus of the research, because the participants reported that this building truly reflects the whole design process.

The TIR customs office building is a two-story building with a basement floor. The building serves TIR drivers and contains two main functions. One part of the ground floor is allocated to the customs offices such as registration, entry-exit approvals, accountant's office, management offices, and computer hall. The other part of the ground floor is designed for recreational facilities and it includes a waiting hall surrounded by duty free shops and a restaurant. There are medical and management offices in the first floor. The building has a structural steel frame system. The bi-partite nature of the building is also reflected in the structural system so that there is an expansion joint separating the building into two parts (Figure 6.4).

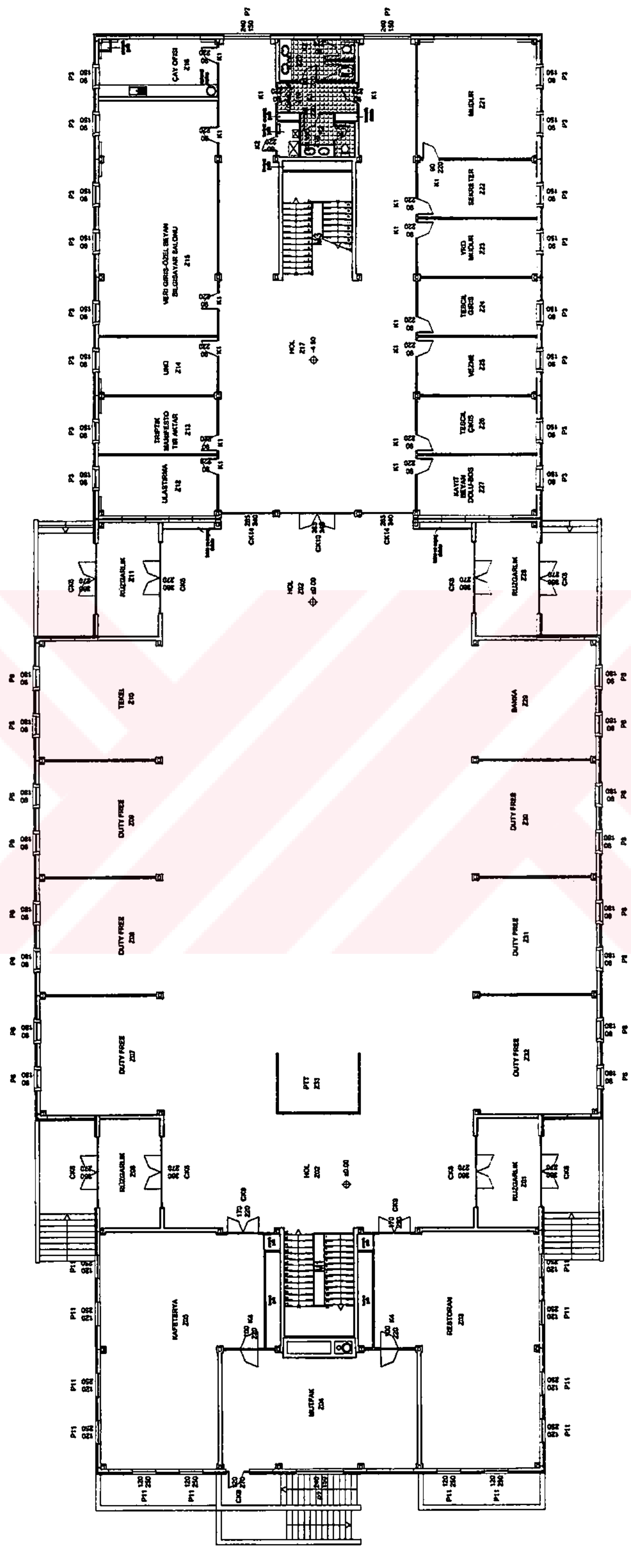


Figure 6.4: Ground Floor Plan of Gürbulak Customs Building (Courtesy of TEPE Construction Co., 2002)

Having briefly explained the project, a few aspects of the overall design process is discussed below. Following the RIBA's *The Architect's Plan of Work* (Phillips, 2001) the design process of the building can be divided into four phases.

Table 6.1: An Outline of the Design Process

Design Phase	**Produced Documents**	**Decisions**
Outline proposals	Sketches	Commence development of strategic brief into full project brief, decisions on the system selections, early schemes for space organization, cost estimations
Detailed proposals	1:200 plans, sections, and elevations	Complete development of the project brief, preparation of detailed space organization scheme
Final proposals	1:100 plans, sections, and elevations, 1:50 partial plans	Preparation of final proposals for the project sufficient for coordination of all components and elements of the project
Production information	1:20 Systems details Point details when necessary	Preparation of production information in sufficient detail to enable tenders to be obtained for the construction of the project

The whole design process took 2 months and the personnel who worked on the project were the following;

Architectural design: 4 people

Structural design: 4 people

Mechanical design: 4 people

Electrical design: 3 people

Infrastructure design: 2 people

At the beginning of the case study, the building was analyzed as a whole and the aim was to identify the problem areas in the building's design in terms of the collaboration of the participants. During the early interviews, suspended ceiling design revealed itself as a specific design problem that deserved further attention. The air ducts used in the HVAC system of the building were sufficiently large to require strategic care in their placement. The main supply and return ducts were run in the plenum above the main corridors of the building because additional ceiling space was available and the corridors provided a natural path of easy access to the all building spaces but how the HVAC distribution system was integrated with the structural system and hidden in the plenum constituted an important building systems integration problem. Therefore, the author focused on analyzing suspended ceiling design with parameter-based DSM.

6.4.3 Objectives of the Analysis

The objectives of the analyses were to:

1. Identify and document important relations specific to suspended ceiling assembly and its interfaces including structural frame system, floor system, HVAC system, and lighting system.
2. Study information flow and coupling in suspended ceiling design.
3. Identify critical parameters that cause large iteration cycles.

4. Identify assumptions made in the process.
5. Show knowledge ownership.
6. Define performance requirements for suspended ceiling design and demonstrate how requirements drive design.
7. Compare assembly level DSM with system level DSM in terms of dependency intensity, amount and scope of iterative loops and percentage of information flow contents regarding performance requirements.

6.4.4 The Procedure

The procedure that was followed in this part of dissertation research consists of the following steps:

1. Choose a particular design problem; define the system and its scope.
2. Interview designers to define the elements involved in the system and the interactions between them.
3. Produce IDEF0 diagrams to outline the processes graphically.
4. Build an information database to record the interactions.
5. Show the information database to the designers and make revisions if necessary.
6. Construct and analyze the matrix and comment on the design process.
7. Evaluate the results.

6.4.4.1 The Design Configuration

The suspended ceiling system studied is comprised of six major parts; namely, main runners, cross tees, panels, hangers, wall angles and plenum. Galvanized steel main runners are suspended from the above structure at 120 cm. intervals. Cross tees run between the main runners to provide places for 60x60 cm. mineral fiber panels. The panels have square edges and the suspension system is an exposed grid type. Lighting fixtures are typical parabolume fluorescent type (60x120 cm.) to be installed flush with the suspended ceiling. Air diffusers are square (60x60 cm.) multi-cone units that are also flush with the suspended ceiling.

6.4.4.2 Data Collection

DSM analysis of processes requires collection of the data through inspection of design documents and interviews with designers. This is often an iterative and time-consuming process. The collected data, their classification, and interdependencies should be checked with the information sources.

The author interviewed the architect, the structural engineer, the mechanical engineer and the electrical engineer of the project. In the first interviews, she explained the aim and the procedure of the study; then, showed DSMs and explained how they work. The early interviews were open-ended type and recorded by the author. Besides these interviews, the brief, the drawings, and the manufacturers' information were examined. The author identified the initial set of system elements based on initial interviews and design documents. After the set of system elements were defined, the first draft of the DSMs was built.

In the second phase of the data collection process, the author showed the DSMs to the participants and received their comments. The initial DSMs were modified according to the feedbacks from the designers. The data collection process was difficult because of the following reasons:

1. Even experienced design professionals like the architect and the engineers whom the author interviewed had not systematically thought about all aspects of the design. The participants responded to the interviews very positively, because these interviews made them think from a systems point of view.
2. In the previous DSM examples from product and machinery design field, the researchers had benefited significantly from the documentation of the participating design organizations. In this study, such documentation was very limited, if it existed at all. This probably points out a difficulty of the building design industry in terms of documenting and guiding processes.

Other observations made about the data collection process are as follows:

1. The data collection process for DSM building was iterative. Deeper understanding of the system usually resulted in modification of the

parameter relationships. However, once an initial model was produced, it constituted the base for further development.

2. The interviews were just as important as reading design documents, because all the knowledge was not well captured by design documents. A large amount of it existed in the designers' heads. Interviews seem to be a good means to extract this knowledge.
3. A confusion about the "really-followed" and "should-be followed" processes occurred during the data collection. The respondents sometimes tended to describe the process that they thought of as an ideal one. In these cases, the author explained to the participants that the aim of the study is to model the process as it occurred.
4. The author introduced both IDEF0 and DSM models to the participants. The participants understood the IDEF0 notation easier than that of DSM. This suggests that the DSM method may be difficult to comprehend for the uninitiated.

6.4.4.3 The IDEF0 Models

Before building DSMs, the author produced IDEF0 models of the suspended ceiling design process. While producing the diagrams, the framework proposed in the U.S. NIST (National Institute of Standards) IDEF0 Standard (U.S. NIST, 1993) was used. Microsoft Visio Professional Edition was used as the graphical modeling tool. First, an A0 context diagram was produced for suspended ceiling life cycle (Figures 6.5, 6.6 and 6.7), and then the model was detailed to reflect the design process

(Figure 6.8). Context diagrams of system interfaces were also constructed (Figure 6.9). These documents guided the DSM building process in the later phases

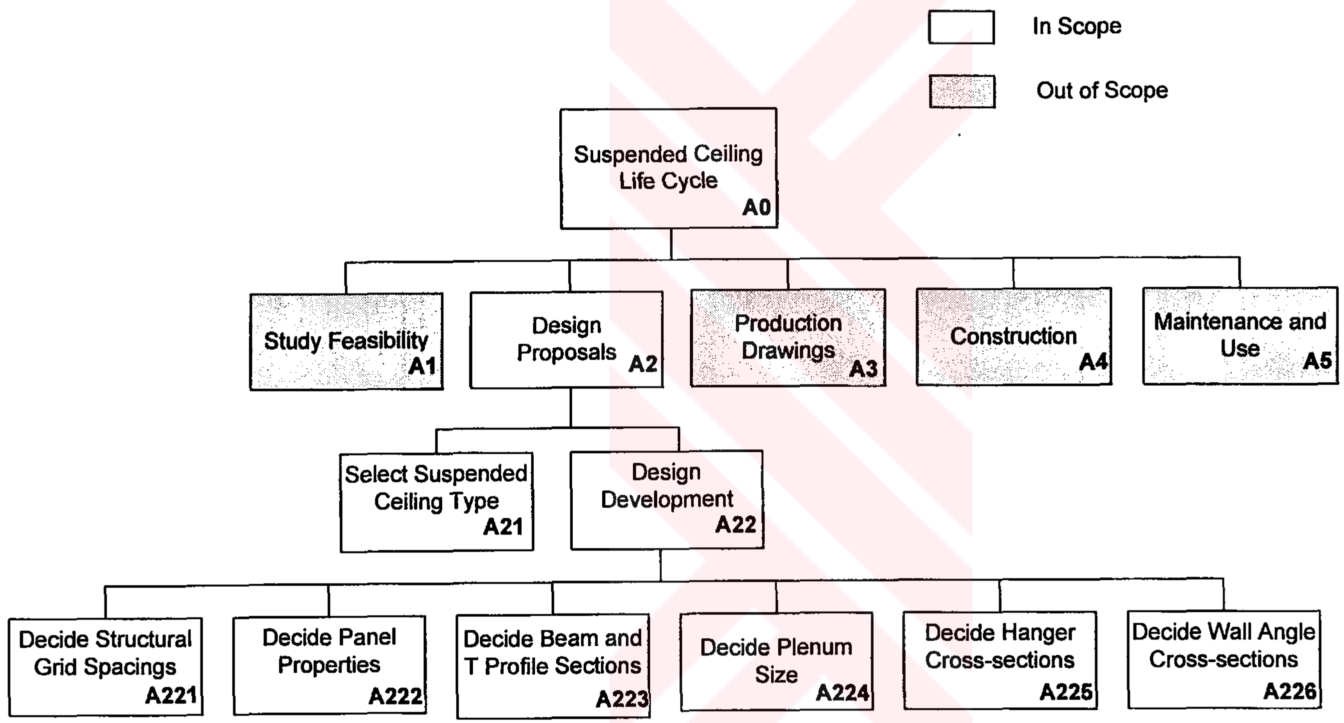


Figure 6.5: The Scope of the Suspended Ceiling Design Model

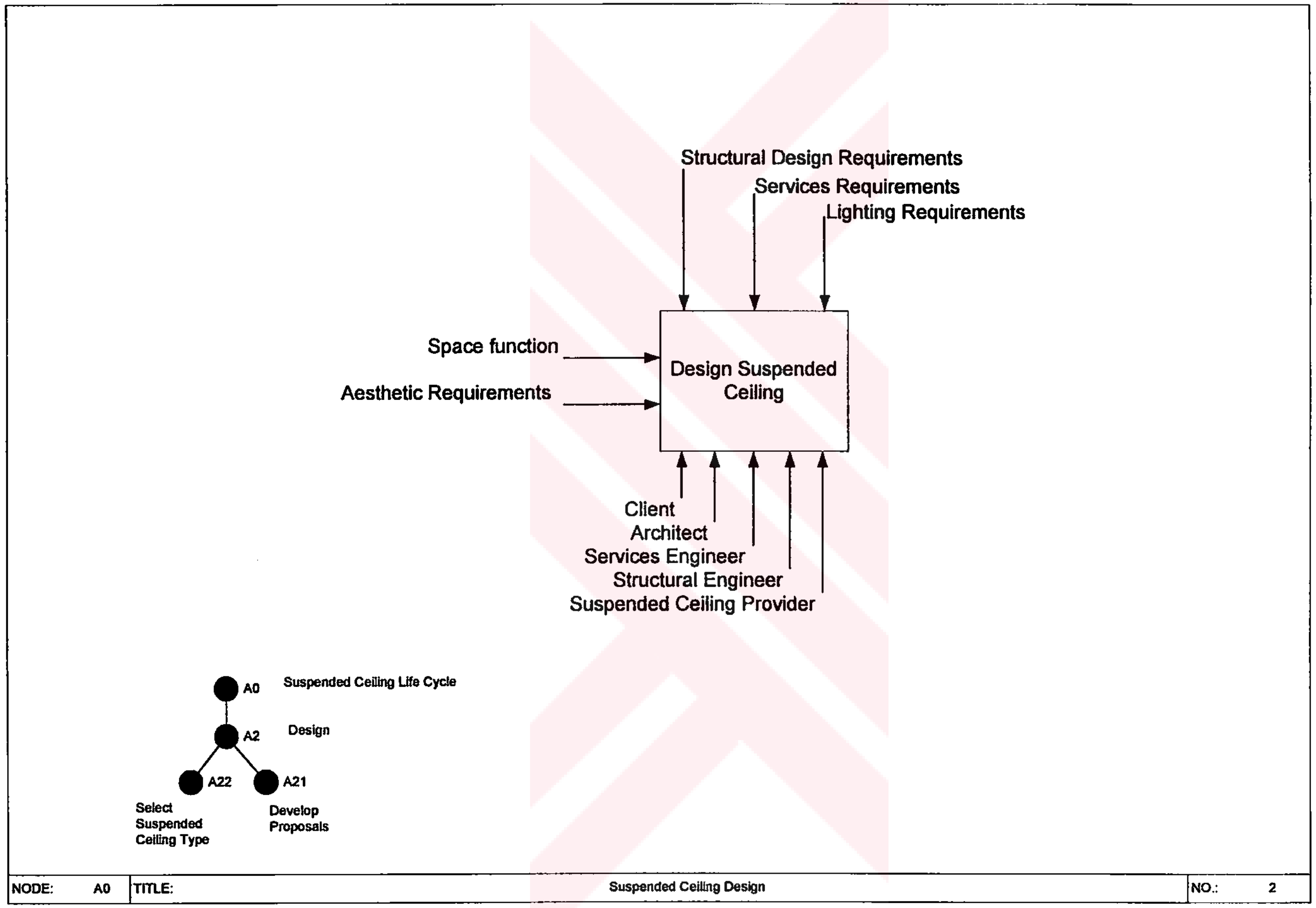


Figure 6.6: The Context Diagram of Suspended Ceiling Design

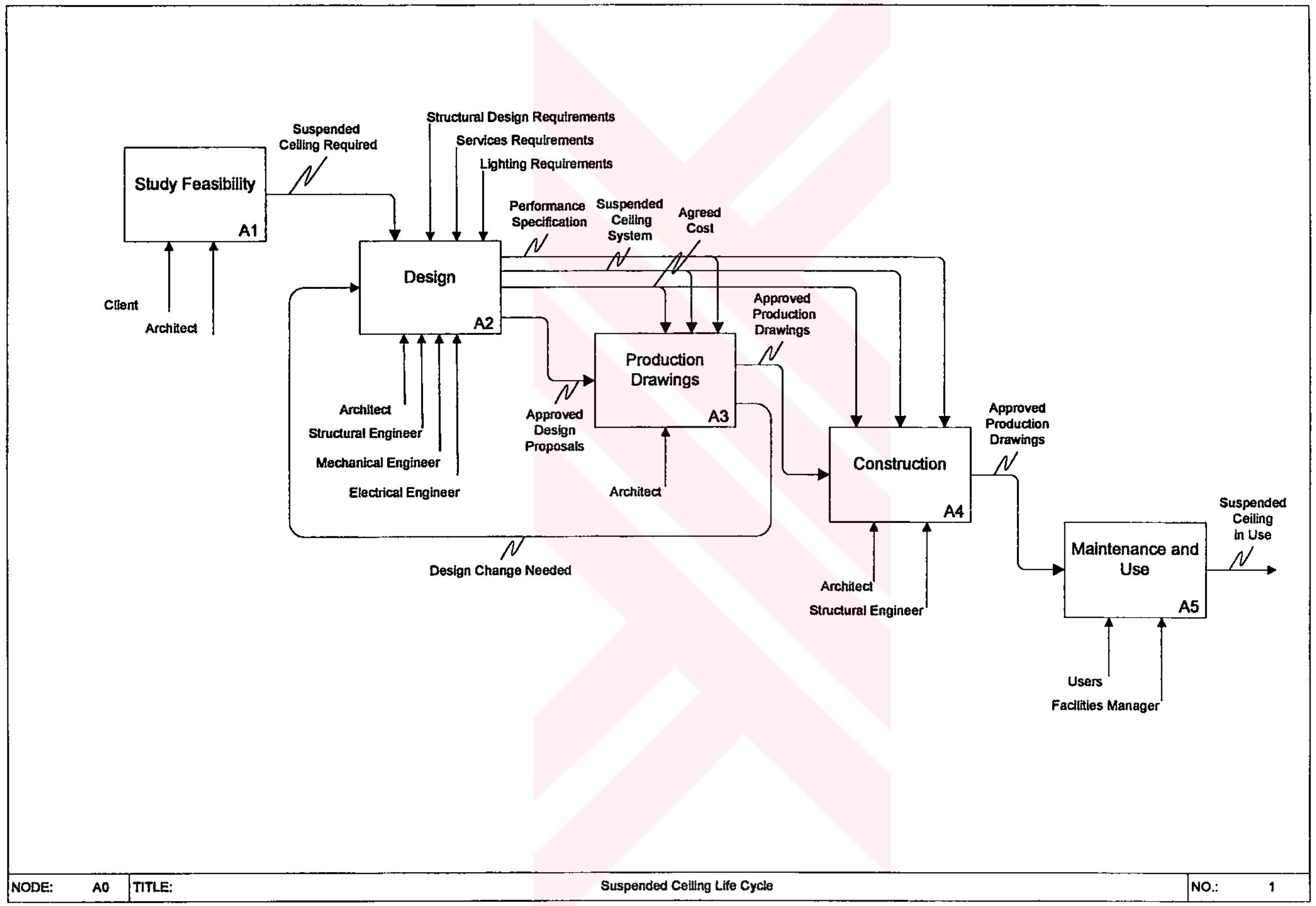


Figure 6.7: An IDEF0 Model of Suspended Ceiling Lifecycle

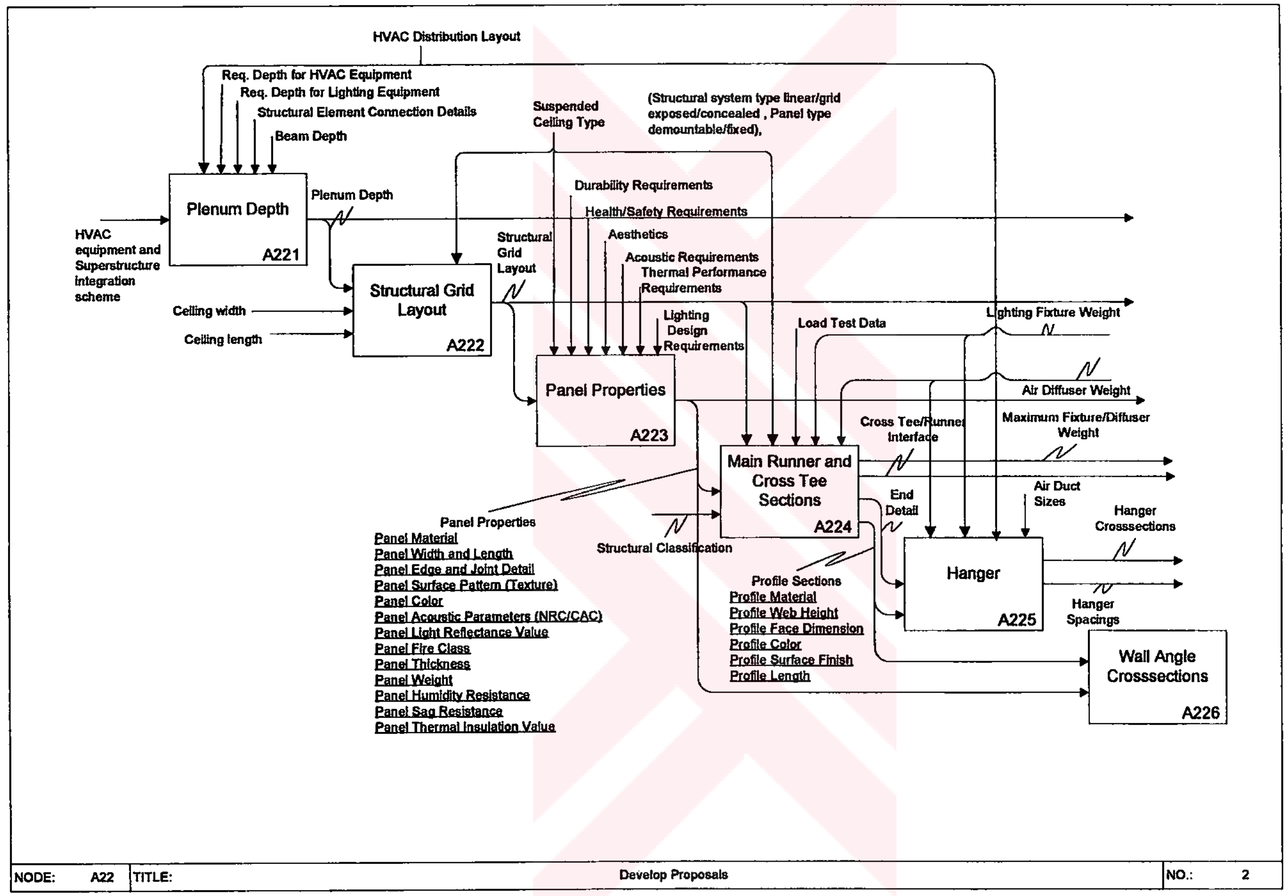


Figure 6.8: An IDEF0 Model of Suspended Ceiling Design

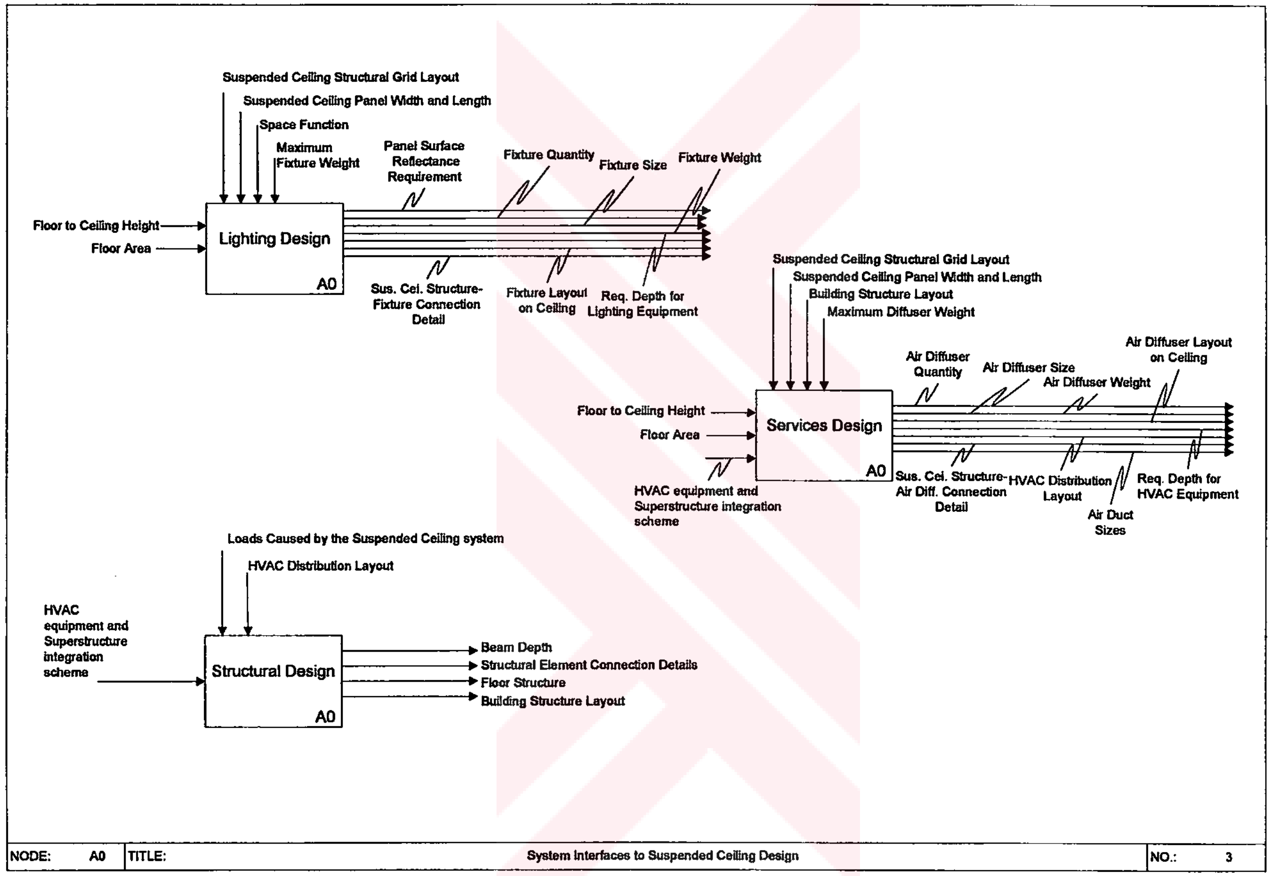


Figure 6.9: An IDEF0 Model of Suspended Ceiling System Interfaces

6.4.4.4 The Information Database

Although there are several commercial DSM tools, the case studies undertaken in this dissertation utilized Microsoft EXCEL for data processing, because EXCEL is a widely known application and it is very suitable for recording, sorting, and manipulating data as well as performing calculations. Moreover, the program development tool of EXCEL (Microsoft Visual Basic) is versatile enough to devise functionalities in DSMs according to the framework proposed in this thesis.

The collected information in the case study was stored in a Microsoft EXCEL database. All system elements are listed in the System Description sheet. Parameter description consists of a name and a code for each parameter. The "Owner" column shows who produces a value for a specific parameter during the process.

The system elements contain not only physical components in the system, but also performance requirements. The reason to include the performance requirements in the DSM is to see how the requirements drive suspended ceiling design, and to compare assembly- and system-level design from this point of view.

An example from a system description sheet is shown in Figure 6.10.

Number of Parameters in the System	43			
Parameter Description	Code	Owner		Legend
Floor Area	1	A		A: Architect
Building Structure Layout	2	S		S: Structural Engineer
Beam Depth	3	S		M: Mechanical Engineer
Floor Structure	4	S		E: Electrical Engineer
Suspended Ceiling Type	5	A		
HVAC Equipment and Superstructure Inte	6	M		
HVAC Distribution Layout	7	M		build unpartitioned matrix
Required Depth for HVAC Equipment	8	M		
Required Depth for Lighting Equipment	9	A, E		
Structural Element Connection Details	10	S		
Plenum Depth	11	A, S, M, E		
Suspended Ceiling Structural Grid Layout	12	A, S		

Figure 6.10: An Example System Description Sheet

In the parameter relations sheet (Figure 6.11), the system element that provides information is listed in the "From" column. The system element that receives information is listed in the "To" column. The "Content of Information Flow" column records the reason of information exchange in terms of performance requirements i.e. shows performance requirements that are satisfied by a specific flow of information between two parameters.

From	To	Content of Information Flow
Floor Area	Air Duct Width and Length	Thermal Performance
Floor to Ceiling Height	Lighting Fixture Quantity	Lighting Performance
Lighting Fixture Weight	Main Runner and Cross Tee Face Dimension	Structural Safety
Air Diffuser Weight	Main Runner and Cross Tee Face Dimension	Structural Safety
Lighting Fixture Layout	Air Diffuser Layout	Aesthetics/Appearance
Space Function	HVAC Distribution Layout	Operational/Maintenance Performance
Space Function	Services Equipment Maintenance Req.	Privacy
Required Depth for HVAC Equipment	Plenum Depth	Spatial Fit
Required Depth for Lighting Equipment	Plenum Depth	Spatial Fit
Structural Element Connection Details	Plenum Depth	Spatial Fit
Beam Depth	Plenum Depth	Spatial Fit

Figure 6.11: An Example Parameter Relations Sheet

Detailed descriptions of the suspended ceiling parameters can be examined in Appendix B.1.

6.4.4.5 Production of the Matrix and Analyses

Using a Microsoft EXCEL Visual Basic program developed by Qi Dong (1999) and modified by Sait Emre Pektaş, DSMs were produced automatically according to the recorded data. The produced DSMs are of basic binary type in which a number (1) shows the existence of an information flow. It may be thought that numerical DSMs described in Chapter 3 would include more in-depth information. However, Browning (1998) explains that numerical DSMs should be based on initially developed basic DSMs and that attempts toward developing numerical DSMs in the absence of any base binary DSM often result in superficial outputs. Thus, it was expected that binary DSMs would be more appropriate in this dissertation, since there was no available base DSM that could be used.

Two DSMs were produced for suspended ceiling design. The system level DSM (Figure 6.12) shows the information flows between the suspended ceiling system and four other systems (HVAC distribution system, structural frame system, lighting system, and floor construction system). The assembly level DSM (Figure 6.13) shows the information flows between the parameters that belong to suspended ceiling parts (main runners and cross tees, panels, plenum, hangers, and wall angles). Partitioning (Figures 6.14 and 6.15) and banding (Figures 6.16 and 6.17) were made to identify couplings and independent (concurrent) parameter decisions in the process. The results of the analyses are presented below.

Performance Requirements
System Level Parameter
HVAC Distribution System
Structural Frame System
Lighting System
Floor Construction System
Suspended Ceiling System

		Thermal Performance	Lighting Performance	Structural Safety	Aesthetics/Appearance	Operational/Maintenance Performance	Spatial Fit	Privacy	Services Equipment Maintenance Req.	Space Function	Floor Area	Building Structure Layout	Beam Depth	Floor Structure	Suspended Ceiling Type	HVAC Distribution Layout	Air Diffuser Quantity	Air Duct Width and Length	Required Depth for HVAC Equipment	Required Depth for Lighting Equipment	Structural Element Connection Details	HVAC Equipment and Superstructure Integration Scheme	Plenum Depth	Floor to Ceiling Height	Suspended Ceiling Structural Grid Layout	Panel Width and Length	Panel Edge and Joint Detail	Panel Weight	Lighting Fixture Quantity	Lighting Fixture Width and Length	Lighting Fixture Layout	Lighting Fixture Weight	Air Diffuser Layout	Air Diffuser Width and Length	Air Diffuser Weight	Load Test Data	Main Runner and Cross Tee Web Height	Main Runner and Cross Tee Face Dimension	Maximum Lighting Fixture Weight	Maximum Air Diffuser Weight	Main Runner and Cross Tee Weight	Suspended Ceiling Structure-Lighting Fixture Connection Det	Suspended Ceiling Structure-Air Diffuser Connection Detail	Hanger Spacings
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
Thermal Performance	1	1																																										
Lighting Performance	2		2																																									
Structural Safety	3			3																																								
Aesthetics/Appearance	4				4																																							
Operational/Maintenance Performance	5					5																																						
Spatial Fit	6						6																																					
Privacy	7							7																																				
Services Equipment Maintenance Req.	8					1			8	1																																		
Space Function	9	1	1			1	1	1		9																																		
Floor Area	10						1			1	10	1																																
Building Structure Layout	11			1						1	1	11																																
Beam Depth	12			1								1	12			1						1																						
Floor Structure	13			1							1	1		13														1				1			1						1			
Suspended Ceiling Type	14				1	1	1		1	1	1				14	1																												
HVAC Distribution Layout	15	1					1			1	1	1				15	1					1		1									1											
Air Diffuser Quantity	16	1								1	1						16							1																				
Air Duct Width and Length	17	1					1				1						1	17																										
Required Depth for HVAC Equipment	18						1									1		1	18																									
Required Depth for Lighting Equipment	19						1													19										1														
Structural Element Connection Details	20			1									1								20		1																					
HVAC Equipment and Superstructure Integration Scheme	21						1						1			1		1	1		1	21	1																					
Plenum Depth	22						1						1			1			1	1	1	1	22																					
Floor to Ceiling Height	23						1					1	1			1			1	1	1	1	1	23																				
Suspended Ceiling Structural Grid Layout	24			1			1				1				1										24																			
Panel Width and Length	25						1																		1	25																		
Panel Edge and Joint Detail	26				1		1		1						1												26																	
Panel Weight	27			1																						1		27																
Lighting Fixture Quantity	28		1							1	1													1					28															
Lighting Fixture Width and Length	29		1																							1				29														
Lighting Fixture Layout	30		1		1					1	1													1	1				1		30		1											
Lighting Fixture Weight	31			1																												31							1					
Air Diffuser Layout	32	1									1														1						1		32											
Air Diffuser Width and Length	33	1									1															1								33										
Air Diffuser Weight	34			1																															34					1				
Load Test Data	35			1																								1				1			1	35								
Main Runner and Cross Tee Web Height	36			1			1								1												1	1				1			1	1	36							
Main Runner and Cross Tee Face Dimension	37			1			1								1												1	1				1			1	1		37						
Maximum Lighting Fixture Weight	38			1																					1					1							1	1	38					1
Maximum Air Diffuser Weight	39			1																					1									1			1	1		39				1
Main Runner and Cross Tee Weight	40			1											1																						1	1			40			
Suspended Ceiling Structure-Lighting Fixture Connection Detail	41			1			1																														1	1				41		
Suspended Ceiling Structure-Air Diffuser Connection Detail	42			1			1																														1	1					42	
Hanger Spacings	43			1												1		1							1											1								43

Figure 6.12: Initial Parameter-based DSM of Suspended Ceiling Design at System Level

- Performance Requirements
- System Level Parameters
- Plenum
- Panels
- Main Runners and Cross Tees
- Hangers
- Wall Angles

		Thermal Performance	Acoustical Performance	Lighting Performance	Structural Safety	Fire Safety	Hygiene	Aesthetics/Appearance	Operational/Maintenance Performance	Durability	Spatial Fit	Suspended Ceiling Type	Plenum Depth	Suspended Ceiling Structural Grid Layout	Panel Humidity Resistance	Panel Sag Resistance	Panel Antimicrobial Treatment	Panel Acoustics NRC	Panel Acoustics CAC	Panel Thermal Insulation Value	Panel Fire Resistance	Panel Material	Panel Width and Length	Panel Edge and Joint Detail	Panel Surface Reflectance Requirement	Panel Surface Pattern	Panel Thickness	Panel Weight	Panel Color	Main Runner and Cross Tee Color	Main Runner and Cross Tee Structural Classificatio	Load Test Data	Main Runner and Cross Tee Web Height	Main Runner and Cross Tee Face Dimension	Main Runner and Cross Tee Weight	Main Runner and Cross Tee Surface Finish	Main Runner and Cross Tee Profile Length	Main Runner and Cross Tee Interface	Main Runner and Cross Tee End Detail	Hanger Crosssections	Hanger Spacings	Wall Angle Crosssections
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Thermal Performance	1	1																																								
Acoustical Performance	2		2																																							
Lighting Performance	3			3																																						
Structural Safety	4				4																																					
Fire Safety	5					5																																				
Hygiene	6						6																																			
Aesthetics/Appearance	7							7																																		
Operational/Maintenance Performance	8								8																																	
Durability	9									9																																
Spatial Fit	10										10																															
Suspended Ceiling Type	11							1	1		1	11																														
Plenum Depth	12								1		1	1	12																													
Suspended Ceiling Structural Grid Layout	13				1			1			1	1		13																												
Panel Humidity Resistance	14									1					14																											
Panel Sag Resistance	15									1						15																										
Panel Antimicrobial Treatment	16						1										16																									
Panel Acoustics NRC	17		1															17																								
Panel Acoustics CAC	18		1																18																							
Panel Thermal Insulation Value	19	1																		19																						
Panel Fire Resistance	20					1															20																					
Panel Material	21	1	1	1		1	1	1	1	1					1	1	1	1	1	1	1	21																				
Panel Width and Length	22										1			1									22																			
Panel Edge and Joint Detail	23							1	1		1	1												23																		
Panel Surface Reflectance	24			1																					24																	
Panel Surface Pattern	25							1																	1	25																
Panel Thickness	26										1	1										1					26															
Panel Weight	27				1																	1	1				1	27														
Panel Color	28			1				1																					28	1												
Main Runner and Cross Tee Color	29			1				1																					1	29												
Main Runner and Cross Tee Structural Classification	30				1																										30											
Load Test Data	31				1																							1			1	31										
Main Runner and Cross Tee Web Height	32				1						1	1															1				1	1	32									
Main Runner and Cross Tee *Face Dimension*	33				1						1	1												1				1			1	1		33								
Main Runner and Cross Tee Weight	34				1							1																					1	1	34							
Main Runner and *Cross Tee Surface Finish*	35			1				1		1																										35						
Main Runner and Cross Tee Profile Length	36										1																										36					
Main Runner and *Cross Tee Interface*	37							1																									1	1				37				
Main Runner and Cross Tee End Detail	38				1						1																												38	1		
Hanger Crosssections	39				1																											1							1	39		
Hanger Spacings	40				1									1																		1									40	
Wall Angle Crosssections	41				1			1			1																1							1		1						41

Figure 6.13: Initial Parameter-based DSM of Suspended Ceiling Design at Assembly Level

- Performance Requirements
- System Level Parameter
- HVAC Distribution System
- Structural Frame System
- Lighting System
- Floor Construction System
- Suspended Ceiling System

		Thermal Performance	Lighting Performance	Structural Safety	Aesthetics/Appearance	Operational/Maintenance Performance	Spatial Fit	Privacy	Space Function	Services Equipment Maintenance Req.	Floor Area	Building Structure Layout	Beam Depth	Suspended Ceiling Type	HVAC Distribution Layout	Air Diffuser Quantity	Air Duct Width and Length	Required Depth for HVAC Equipment	Required Depth for Lighting Equipment	Structural Element Connection Details	HVAC Equipment and Superstructure Integration Scheme	Plenum Depth	Floor to Ceiling Height	Suspended Ceiling Structural Grid Layout	Panel Width and Length	Lighting Fixture Quantity	Lighting Fixture Width and Length	Lighting Fixture Layout	Air Diffuser Layout	Panel Edge and Joint Detail	Panel Weight	Air Diffuser Width and Length	Lighting Fixture Weight	Air Diffuser Weight	Load Test Data	Main Runner and Cross Tee Web Height	Main Runner and Cross Tee Face Dimension	Maximum Lighting Fixture Weight	Maximum Air Diffuser Weight	Hanger Spacings	Main Runner and Cross Tee Weight	Suspended Ceiling Structure-Lighting Fixture Connection Det	Suspended Ceiling Structure-Air Diffuser Connection Detail	Floor Structure
		1	2	3	4	5	6	7	9	8	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25	28	29	30	32	26	27	33	31	34	35	36	37	38	39	43	40	41	42	13
Thermal Performance	1	1																																										
Lighting Performance	2		2																																									
Structural Safety	3			3																																								
Aesthetics/Appearance	4				4																																							
Operational/Maintenance Performance	5					5																																						
Spatial Fit	6						6																																					
Privacy	7							7																																				
Space Function	9	1	1			1	1	1	9																																			
Services Equipment Maintenance Req.	8					1			1	8																																		
Floor Area	10						1		1		10	1																																
Building Structure Layout	11			1					1		1	11																																
Beam Depth	12			1								1	12		1						1																							
Suspended Ceiling Type	14				1	1	1		1	1	1			14	1																													
HVAC Distribution Layout	15	1					1		1		1	1			15	1					1		1						1															
Air Diffuser Quantity	16	1							1		1					16							1																					
Air Duct Width and Length	17	1					1				1					1	17																											
Required Depth for HVAC Equipment	18						1								1		1	18																										
Required Depth for Lighting Equipment	19						1												19								1																	
Structural Element Connection Details	20			1									1							20		1																						
HVAC Equipment and Superstructure Integration Scheme	21						1						1		1		1	1		1	21	1																						
Plenum Depth	22						1						1		1			1	1	1	1	22																						
Floor to Ceiling Height	23						1					1	1		1			1	1	1	1	1	23																					
Suspended Ceiling Structural Grid Layout	24			1			1				1			1										24																				
Panel Width and Length	25						1																	1	25																			
Lighting Fixture Quantity	28		1						1		1												1			28																		
Lighting Fixture Width and Length	29		1																						1		29																	
Lighting Fixture Layout	30		1		1				1		1												1	1		1		30	1															
Air Diffuser Layout	32	1									1													1				1	32															
Panel Edge and Joint Detail	26				1		1			1				1																26														
Panel Weight	27			1																					1						27													
Air Diffuser Width and Length	33	1									1														1							33												
Lighting Fixture Weight	31			1																													31					1						
Air Diffuser Weight	34			1																														34					1					
Load Test Data	35			1																											1		1	1	35									
Main Runner and Cross Tee Web Height	36			1			1							1																1	1		1	1	1	36								
Main Runner and Cross Tee Face Dimension	37			1			1							1																1	1		1	1	1		37							
Maximum Lighting Fixture Weight	38			1																				1			1									1	1	38		1				
Maximum Air Diffuser Weight	39			1																				1								1				1	1		39	1				
Hanger Spacings	43			1											1		1							1											1					43				
Main Runner and Cross Tee Weight	40			1										1																						1	1				40			
Suspended Ceiling Structure-Lighting Fixture Connection Detail	41			1			1																													1	1					41		
Suspended Ceiling Structure-Air Diffuser Connection Detail	42			1			1																													1	1						42	
Floor Structure	13			1							1	1																			1		1	1							1			13

Figure 6.14: Partitioned Parameter-based DSM of Suspended Ceiling Design at System Level

- Performance Requirements
- System Level Parameters
- Plenum
- Panels
- Main Runners and Cross Tees
- Hangers
- Wall Angles

		Thermal Performance	Acoustical Performance	Lighting Performance	Structural Safety	Fire Safety	Hygiene	Aesthetics/Appearance	Operational/Maintenance Performance	Durability	Spatial Fit	Suspended Ceiling Type	Plenum Depth	Suspended Ceiling Structural Grid Layout	Panel Humidity Resistance	Panel Sag Resistance	Panel Antimicrobial Treatment	Panel Acoustics NRC	Panel Acoustics CAC	Panel Thermal Insulation Value	Panel Fire Resistance	Panel Material	Panel Width and Length	Panel Edge and Joint Detail	Panel Surface Reflectance Requirement	Panel Surface Pattern	Panel Thickness	Panel Weight	Panel Color	Main Runner and Cross Tee Color	Main Runner and Cross Tee Structural Classificatio	Load Test Data	Main Runner and Cross Tee Web Height	Main Runner and Cross Tee Face Dimension	Main Runner and Cross Tee Weight	Main Runner and Cross Tee Surface Finish	Main Runner and Cross Tee Profile Length	Main Runner and Cross Tee Interface	Main Runner and Cross Tee End Detail	Hanger Crosssections	Hanger Spacings	Wall Angle Crosssections
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Thermal Performance	1	1																																								
Acoustical Performance	2		2																																							
Lighting Performance	3			3																																						
Structural Safety	4				4																																					
Fire Safety	5					5																																				
Hygiene	6						6																																			
Aesthetics/Appearance	7							7																																		
Operational/Maintenance Performance	8								8																																	
Durability	9									9																																
Spatial Fit	10										10																															
Suspended Ceiling Type	11							1	1		1	11																														
Plenum Depth	12								1		1	1	12																													
Suspended Ceiling Structural Grid Layout	13				1			1			1	1		13																												
Panel Humidity Resistance	14									1					14																											
Panel Sag Resistance	15									1						15																										
Panel Antimicrobial Treatment	16						1										16																									
Panel Acoustics NRC	17		1															17																								
Panel Acoustics CAC	18		1																18																							
Panel Thermal Insulation Value	19	1																		19																						
Panel Fire Resistance	20					1															20																					
Panel Material	21	1	1	1		1	1	1	1	1					1	1	1	1	1	1	1	21																				
Panel Width and Length	22										1			1									22																			
Panel Edge and Joint Detail	23							1	1		1	1												23																		
Panel Surface Reflectance	24			1																					24																	
Panel Surface Pattern	25							1																	1	25																
Panel Thickness	26										1	1										1					26															
Panel Weight	27				1																	1	1				1	27														
Panel Color	28			1				1																					28	1												
Main Runner and Cross Tee Color	29			1				1																					1	29												
Main Runner and Cross Tee Structural Classification	30				1																										30											
Load Test Data	31				1																							1			1	31										
Main Runner and Cross Tee Web Height	32				1						1	1															1				1	1	32									
Main Runner and Cross Tee Face Dimension	33				1						1	1												1				1			1	1		33								
Main Runner and Cross Tee Weight	34				1							1																					1	1	34							
Main Runner and Cross Tee Surface Finish	35			1				1		1																										35						
Main Runner and Cross Tee Profile Length	36										1																										36					
Main Runner and Cross Tee Interface	37							1																									1	1				37				
Main Runner and Cross Tee End Detail	38				1						1																												38	1		
Hanger Crosssections	39				1																											1							1	39		
Hanger Spacings	40				1									1																		1									40	
Wall Angle Crosssections	41				1			1			1																1							1		1						41

Figure 6.15: Partitioned Parameter-based DSM of Suspended Ceiling Design at Assembly Level

		Thermal Performance	Lighting Performance	Structural Safety	Aesthetics/Appearance	Operational/Maintenance Performance	Spatial Fit	Privacy	Space Function	Services Equipment Maintenance Req.	Floor Area	Building Structure Layout	Beam Depth	Suspended Ceiling Type	HVAC Distribution Layout	Air Diffuser Quantity	Air Duct Width and Length	Required Depth for HVAC Equipment	Required Depth for Lighting Equipment	Structural Element Connection Details	HVAC Equipment and Superstructure Integration Scheme	Plenum Depth	Floor to Ceiling Height	Suspended Ceiling Structural Grid Layout	Panel Width and Length	Lighting Fixture Quantity	Lighting Fixture Width and Length	Lighting Fixture Layout	Air Diffuser Layout	Panel Edge and Joint Detail	Panel Weight	Air Diffuser Width and Length	Lighting Fixture Weight	Air Diffuser Weight	Load Test Data	Main Runner and Cross Tee Web Height	Main Runner and Cross Tee Face Dimension	Maximum Lighting Fixture Weight	Maximum Air Diffuser Weight	Hanger Spacings	Main Runner and Cross Tee Weight	Suspended Ceiling Structure-Lighting Fixture Connection De	Suspended Ceiling Structure-Air Diffuser Connection Detail	Floor Structure
		1	2	3	4	5	6	7	9	8	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25	28	29	30	32	26	27	33	31	34	35	36	37	38	39	43	40	41	42	13
Thermal Performance	1	1																																										
Lighting Performance	2		2																																									
Structural Safety	3			3																																								
Aesthetics/Appearance	4				4																																							
Operational/Maintenance Performance	5					5																																						
Spatial Fit	6						6																																					
Privacy	7							7																																				
Space Function	**9**	1	1			1	1	1	9																																			
Services Equipment Maintenance Req.	8					1			1	8																																		
Floor Area	10						1		1		10	1																																
Building Structure Layout	**11**			1					1		1	11																																
Beam Depth	12			1								1	12		1						1																							
Suspended Ceiling Type	14				1	1	1		1	1	1			14	1																													
HVAC Distribution Layout	15	1					1		1		1	1			15	1					1		1						1															
Air Diffuser Quantity	16	1							1		1					16							1																					
Air Duct Width and Length	**17**	1					1				1					1	17																											
Required Depth for HVAC Equipment	18						1								1		1	18																										
Required Depth for Lighting Equipment	19						1												19								1																	
Structural Element Connection Details	20			1									1							20		1																						
HVAC Equipment and Superstructure Integration Scheme	**21**						1						1		1		1	1		1	21	1																						
Plenum Depth	22						1						1		1			1	1	1	1	22																						
Floor to Ceiling Height	**23**						1					1	1		1			1	1	1	1	1	23																					
Suspended Ceiling Structural Grid Layout	**24**			1			1				1			1										24																				
Panel Width and Length	25						1																	1	25																			
Lighting Fixture Quantity	28		1						1		1												1			28																		
Lighting Fixture Width and Length	**29**		1																						1		29																	
Lighting Fixture Layout	**30**		1		1				1		1												1	1		1		30	1															
Air Diffuser Layout	32	1									1													1				1	32															
Panel Edge and Joint Detail	26				1		1			1				1																26														
Panel Weight	27			1																					1						27													
Air Diffuser Width and Length	33	1									1														1							33												
Lighting Fixture Weight	31			1																													31					1						
Air Diffuser Weight	34			1																														34					1					
Load Test Data	**35**			1																											1		1	1	35									
Main Runner and Cross Tee Web Height	36			1			1							1																1	1		1	1	1	36								
Main Runner and Cross Tee Face Dimension	37			1			1							1																1	1		1	1	1		37							
Maximum Lighting Fixture Weight	**38**			1																				1			1									1	1	38		1				
Maximum Air Diffuser Weight	**39**			1																				1								1				1	1		39	1				
Hanger Spacings	**43**			1											1		1							1											1					43				
Main Runner and Cross Tee Weight	**40**			1										1																						1	1				40			
Suspended Ceiling Structure-Lighting Fixture Connection Detail	**41**			1			1																													1	1					41		
Suspended Ceiling Structure-Air Diffuser Connection Detail	**42**			1			1																													1	1						42	
Floor Structure	13			1							1	1																			1		1	1							1			13

Figure 6.16: Banded Parameter-based DSM of Suspended Ceiling Design at System Level

		Thermal Performance	Acoustical Performance	Lighting Performance	Structural Safety	Fire Safety	Hygiene	Aesthetics/Appearance	Operational/Maintenance Performance	Durability	Spatial Fit	**Suspended Ceiling Type**	Plenum Depth	Suspended Ceiling Structural Grid Layout	Panel Humidity Resistance	Panel Sag Resistance	Panel Antimicrobial Treatment	Panel Acoustics NRC	Panel Acoustics CAC	Panel Thermal Insulation Value	Panel Fire Resistance	Panel Material	Panel Width and Length	Panel Edge and Joint Detail	Panel Surface Reflectance Requirement	Panel Surface Pattern	Panel Thickness	Panel Weight	Panel Color	Main Runner and Cross Tee Color	Main Runner and Cross Tee Structural Classificatio	Load Test Data	Main Runner and Cross Tee Web Height	Main Runner and Cross Tee Face Dimension	Main Runner and Cross Tee Weight	Main Runner and Cross Tee Surface Finish	Main Runner and Cross Tee Profile Length	Main Runner and Cross Tee Interface	Main Runner and Cross Tee End Detail	Hanger Crosssections	Hanger Spacings	Wall Angle Crosssections
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Thermal Performance	1	1																																								
Acoustical Performance	2		2																																							
Lighting Performance	3			3																																						
Structural Safety	4				4																																					
Fire Safety	5					5																																				
Hygiene	6						6																																			
Aesthetics/Appearance	7							7																																		
Operational/Maintenance Performance	8								8																																	
Durability	9									9																																
Spatial Fit	10										10																															
Suspended Ceiling Type	**11**							1	1		1	11																														
Plenum Depth	12								1		1	1	12																													
Suspended Ceiling Structural Grid Layout	13				1			1			1	1		13																												
Panel Humidity Resistance	14									1					14																											
Panel Sag Resistance	15									1						15																										
Panel Antimicrobial Treatment	16						1										16																									
Panel Acoustics NRC	17		1															17																								
Panel Acoustics CAC	18		1																18																							
Panel Thermal Insulation Value	19	1																		19																						
Panel Fire Resistance	20					1															20																					
Panel Material	**21**	1	1	1		1	1	1	1	1					1	1	1	1	1	1	1	21																				
Panel Width and Length	**22**										1			1									22																			
Panel Edge and Joint Detail	**23**							1	1		1	1												23																		
Panel Surface Reflectance	**24**			1																					24																	
Panel Surface Pattern	25							1																	1	25																
Panel Thickness	26										1	1										1					26															
Panel Weight	**27**				1																	1	1				1	27														
Panel Color	**28**			1				1																					28	1												
Main Runner and Cross Tee Color	29			1				1																					1	29												
Main Runner and Cross Tee Structural Classification	30				1																										30											
Load Test Data	**31**				1																							1			1	31										
Main Runner and Cross Tee Web Height	32				1						1	1															1				1	1	32									
Main Runner and Cross Tee Face Dimension	33				1						1	1												1				1			1	1		33								
Main Runner and Cross Tee Weight	**34**				1							1																					1	1	34							
Main Runner and Cross Tee Surface Finish	**35**			1				1		1																										35						
Main Runner and Cross Tee Profile Length	**36**										1																										36					
Main Runner and Cross Tee Interface	**37**							1																									1	1				37				
Main Runner and Cross Tee End Detail	**38**				1						1																												38	1		
Hanger Crosssections	39				1																											1							1	39		
Hanger Spacings	40				1									1																		1									40	
Wall Angle Crosssections	41				1			1			1																1							1		1						41

Figure 6.17: Banded Parameter-based DSM of Suspended Ceiling Design at Assembly Level

6.5 Results and Discussion

6.5.1 Observations on Suspended Ceiling System

Interface Design

The suspended ceiling system interface DSM includes 6 iteration cycles (Figure 6.14). These comprise two groups with overlapping cycles in each. HVAC distribution system, structural frame system, and lighting system play a major role in these iterations. The floor structure system does not cause any iteration.

The main critical elements (the elements which cause large cycles) in the first iteration group are beam depth, HVAC distribution layout, air diffuser quantity, required depth for lighting equipment, structural element connection details, HVAC equipment and superstructure integration scheme, plenum depth, floor to ceiling height, lighting fixture width and length, and air diffuser layout. The main critical elements in the second iteration group are weights and maximum weights of lighting fixtures and air diffusers, and hanger spacings.

Beam depth is a critical parameter since it is sensitive to two downstream parameter decisions: HVAC distribution layout and HVAC and superstructure integration scheme. In the actual design process, the largest beams had been used at the periphery of the building to save space in the plenum where HVAC ducts would pass. However, the beams also had been needed to be slightly oversized in order to allow some of ducts pass through them.

Changes in HVAC distribution layout may create costly changes in design; since this directly affects two high level decisions in two systems (beam depth in structural frame system and suspended ceiling type in suspended ceiling system). Such a loop can be avoided by correct assumptions about floor to ceiling height, air diffuser quantity, air diffuser layout, and HVAC and superstructure integration scheme at the beginning of the process. The sizes of HVAC equipment may also cause rework in plenum depth decision. In the case study, it was reported that nearly at the end of the actual design process, the mechanical engineer had requested a change in plenum depth due to a change in HVAC equipment sizes and this had caused a conflict among the participants.

Structural element connection detail is critical in determining the plenum depth. As explained in the beginning of this chapter, generally there are two schemes of connecting the structural elements, namely, web-to-web and layered. In the Gürbulak case, structural members had been connected web-to-web to save space in the plenum.

HVAC equipment and superstructure integration scheme is another parameter that should be carefully considered in early stages of design process, since it affects two system level upstream decisions: HVAC distribution layout and beam depth. This parameter refers to the decision about how structural members and HVAC ducts interact in the plenum. Several different schemes may be applied; for example, main ducts can run parallel to the structural members, they can be placed below, or they can pass through the structure where necessary. No matter which scheme is chosen, the decision should be based on coordination of HVAC, structural and architectural designs.

While the first group of overlapping cycles represents many problematic situations in suspended ceiling design, the second group (beginning with lighting fixture weight and ending with hanger spacings) is based on a single problem: carrying lighting fixtures and air diffusers by the suspended ceiling structure. The load carrying capacity of suspended ceiling structure system puts limitations on lighting fixture and air diffuser weights. If the weights of these elements exceed the allowed limits they should be carried independently by additional hangers.

When the initial and partitioned matrices of suspended ceiling design at system level are compared, it is observed that in the parameter list of the initial system interface matrix, there are large monochrome bands (Figures 6.12 and 6.14). However, in the partitioned matrix such large bands are broken. Since each color shows a system which is in the domain of a different design professional, the large bands in the initial DSM suggest that decisions related to building systems are made sequentially without considering interdisciplinary information. The partitioned DSM, thus, recommends closer communication and collaboration among the designers and presents a more concurrent process.

In the partitioned matrix, except a few changes in the sequence of parameters, the order of parameter decisions almost remained the same, while there are large cycles. This implies that those cycles are inevitable in the process. The partitioned DSM helps in identifying the information cycles which are inevitable in the process due to the couplings.

6.5.2 Observations on Suspended Ceiling Assembly Design

Unlike the system level design which is a truly interdisciplinary endeavor, the assembly level design is in the domain of a single design professional: the architect. This task involves selecting the suspended ceiling members (usually from a pre-defined list of available options) and configuring a system accordingly. Thus, suspended ceiling design at the assembly level is not problematic. The partitioned DSM contains only two very small cycles and no critical elements. Since there are no strict constraints on the order of decisions (there are no two-way dependencies), many optional paths may be taken in the design. Experimenting with "what-if" scenarios using the "Manual Sequence" tool of the DSM software helps in identifying those paths.

6.5.3 A Comparison between the Assembly Level DSM and the System Level DSM

The assembly level DSM and the system level DSM were compared in terms of dependency intensity, total number of elements in loops and percentage of information flow content. The following observations were made.

The suspended ceiling system interface DSM contains 165 entries (interaction points, or DSM marks), while the assembly DSM contains only 97. The numbers of system elements are similar in both (approximately 40). Therefore, the suspended ceiling system interface is a more complicated problem than the suspended ceiling assembly design.

While the system level DSM contains large iteration loops, the assembly level DSM includes only two very small loops. 60% of the elements of the system level DSM are in one or more loops; this amount is 11% for the assembly level DSM (Table 6.2).

Table 6.2: A Comparison between Assembly- and System-level DSM

	Assembly Level DSM	System Level DSM
Total Number of System Elements	41	43
Total Number of DSM Entries (Marks)	97	165
Total Number of Parameters in Loops	4	26

There are three configurations that characterize a system in DSM theory (Figure 6.18). Parallel and sequential configurations do not include loops, while coupled configurations include iterations. The partitioned DSM of suspended ceiling assembly indicates that parameter decisions at assembly level are made either in a parallel or sequential manner, but at the system level there are couplings. Previous research showed that the time for humans to solve a coupled parameter design problem rises geometrically as coupling size rises linearly (Hirschi and Frey, 2002). This suggests that although suspended ceiling design is simple, it may take more time than planned due to the iterations at the system level.

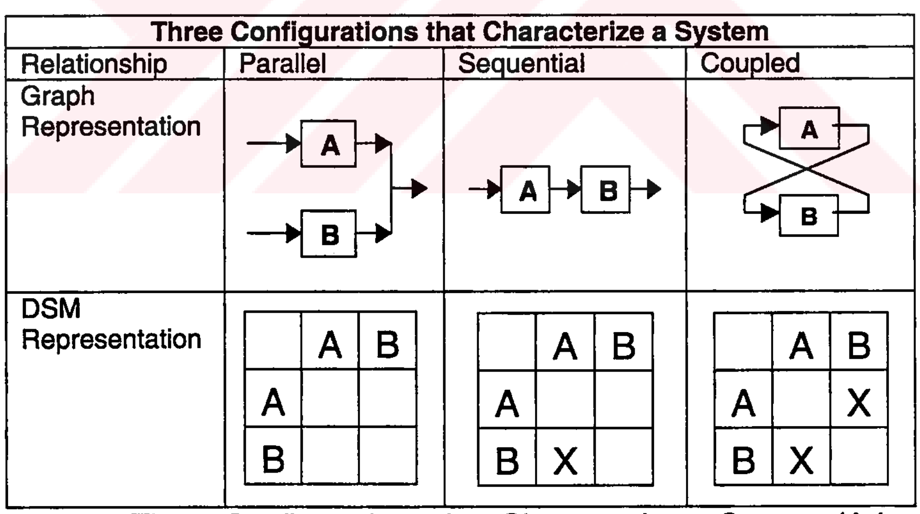


Figure 6.18: Three Configurations that Characterize a System (Adapted from M.I.T DSM Web Site, 2003)

Using the “AutoFilter” option of the Microsoft Excel, the contents of information flows were calculated for both assembly and system level DSMs. Then column charts were produced to document how performance requirements drive design. The results are shown in Figure 6.19.

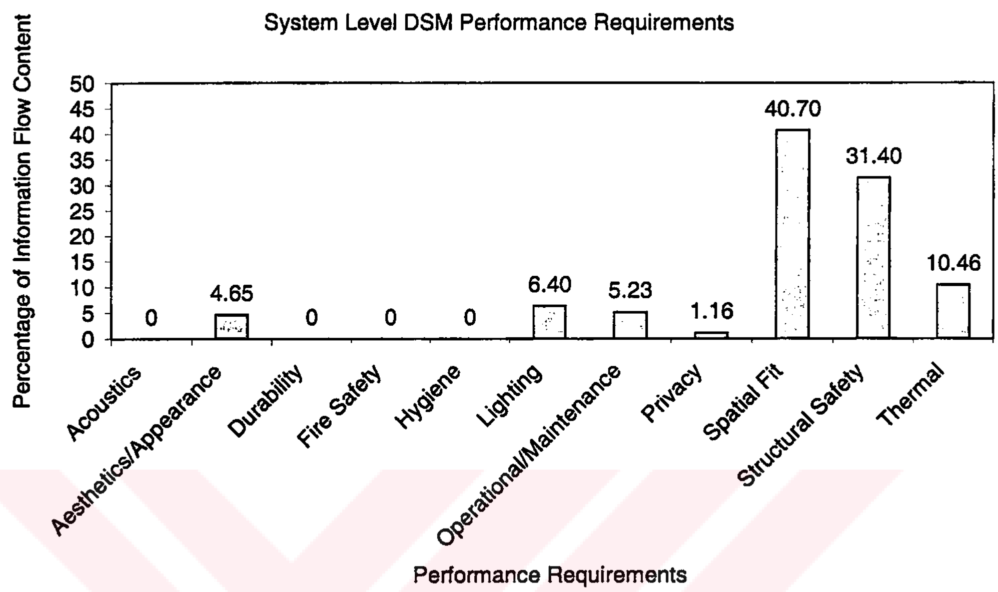


Figure 6.19: Information Flow Percentages in System Level DSM

The analysis indicates that spatial fit is the major driver of suspended ceiling design process at system level (40.70%). This is not surprising, because suspended ceiling design at system interactions level is basically fitting services and lighting equipment as well as structural members in plenum. Structural safety requirements follow spatial fit requirements (31.40%); since carrying the concealed equipment by either suspended ceiling structure or the main structure of the building, and carrying the whole suspended ceiling system via hangers suspended from the superstructure are important concerns. Thermal performance (10.46%), lighting performance (6.40%), operational and maintenance performance (5.23%), aesthetics/appearance (4.65%), and privacy (1.16%) are also effective in suspended ceiling interface design, while acoustics, durability, hygiene, and fire safety do not play a significant role.

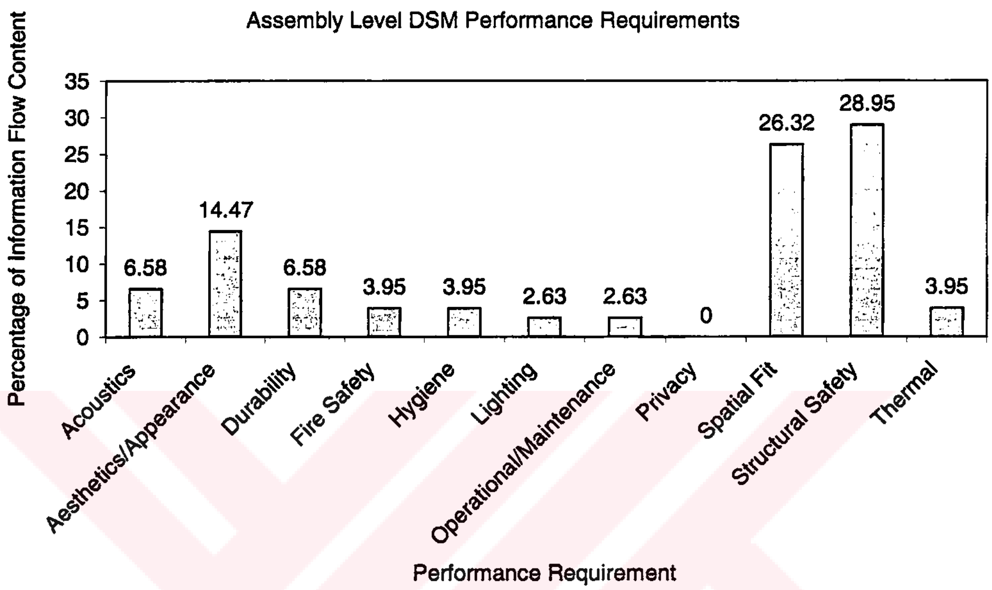


Figure 6.20: Information Flow Percentages in Assembly Level DSM

On the other hand, in suspended ceiling assembly design each specified performance requirement except privacy affects the design process. Spatial fit and structural safety are again the most influential requirements, but in this case the percentage of structural safety slightly exceeds that of spatial fit (structural safety 28.95%, spatial fit 26.32%) (Figure 6.20).

When the banded DSMs of two levels of design are compared, it is observed that while the system level DSM consists of 17 bands (Figure 6.16), the assembly level DSM includes only 11 (Figure 6.17). This finding supports the comments made above, since more bands mean more critical elements and more coupling in the process. On the other hand, fewer bands suggest that the design is more flexible i.e. the order of design decisions in a band can be safely changed, because they are independent of each other.

7. CASE STUDY 2: ELEVATOR DESIGN

7.1 Introduction

In order to explore the research questions posed in Chapter 1 and to expand more on integration of the proposed model with existing methods, another case study was undertaken. The objective of this case study is to apply the proposed method to a building design problem which is complex in itself unlike the previous suspended ceiling design example the complexity of which results only from interactions at system level. Another objective is to demonstrate how parameter-based DSM can be integrated with Industry Foundation Classes (IFC)s as was proposed in Chapter 5.

The case study presented in this chapter analyzes an elevator design process. The system architecture is first explained to familiarize the audience with elevator systems. Then, elevator design process is briefly outlined. Finally, the research process and the results are explained. Since many methodological and practical aspects of this type of research have already been discussed in Chapter 6, these are not repeated in this chapter.

7.2 Elevator System Architecture

There are two general groups of elevators according to their type of drives; namely, electric traction elevators and hydraulic elevators. An electric traction elevator is a powered elevator to which energy is applied by an electric driving machine. This type is used exclusively in tall buildings and in most low buildings. A hydraulic elevator is a powered elevator to which energy is applied by a liquid under pressure in a cylinder equipped with a plunger, or piston. This type is used for low-rise freight service and may be used for low-rise passenger service where low initial cost is desired. For an electric elevator, the car is raised or lowered along its guides by wire ropes controlled by the drawing machine. For a hydraulic elevator, the car is seated on the plunger, which moves up and down under the control of hydraulic pressure.

The main components of an elevator system are hoistway, car, machine room and landing as shown in Figure 7.1.

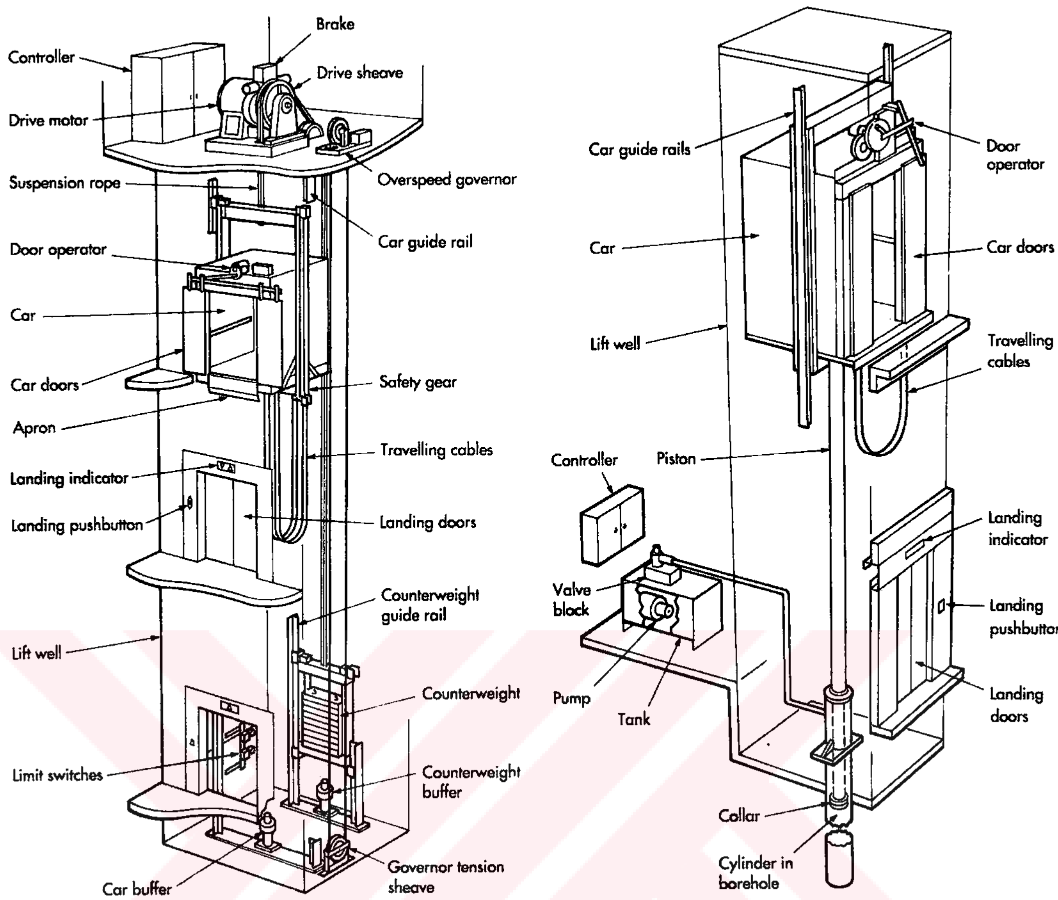


Figure 7.1: System Details of Electric Traction (Left) and Hydraulic (Right) Elevators (Adapted from CIBSE, 1993)

A hoistway in which an elevator travels extends from the bottom of the pit to the underside of the overhead machine room floor; or to the underside of the roof if the hoistway does not penetrate the roof. A hoistway for more than one elevator is called a multiple hoistway. Up to four elevators may operate in a multiple hoistway.

Beams have to be usually provided at vertical intervals in the hoistway enclosure to support steel guide rails along which elevator car run. The rails generally are tee-shape in cross section with smooth guiding surfaces. One rail is installed on each side of the hoistway to guide the car, which has upper and lower guide wheels attached to its supporting frame.

The elevator pit is the portion of a hoistway extending from the threshold level of the lowest landing floor to the floor at the bottom of the hoistway. The pit usually houses buffers and other safety devices. A buffer is a device designed to stop a descending car beyond its normal limit of travel by absorbing and dissipating its kinetic energy.

An elevator car consists of a platform and light metal walls and roof, in which passenger and goods are transported. The platform and enclosure are supported on a structural steel frame. A safety gear which is fixed to the structural frame is often provided if the car is for passenger use.

The car doors may be swinging or sliding, and manually or power operated. They are equipped with safety devices to prevent them from opening while the car is in motion or outside the landing zone. An operating station that includes push buttons, lift position and direction indicators is normally provided within an elevator car. Handrails and mirrors can also be used. Various types of finishes can be applied to the interior of the car according to the style and use of the building. In addition, the interior of the car should be adequately illuminated and an emergency lighting system also should be provided to operate automatically after failure of power for normal lighting.

A machine room contains machines and control equipment, which are necessary to operate an elevator. The dimensions of the machine room depend on the machine sizes. For electric traction drives a suitable lifting beam should also be installed overhead. The machine room is ideally located immediately over the hoistway for this type of drive. Bottom or side drives are sometimes used, but these configurations are less efficient and result in increased installation and maintenance costs. For hydraulic drives, the machine room is ideally located adjacent to the hoistway at the lowest level served. The machine room may be located remote from the hoistway, but if the distance is long, it may be problematic.

Although landing area is outside an elevator system, landing fixtures should be considered as an integral part to it. These include push buttons, lift position and direction indicators and hall lanterns. The design of these systems should complement car finishes.

7.3 Elevator Design Process

Insights into the elevator design process were gained through the interviews conducted as a part of the case study. The process is summarized below in order to provide a background for the detailed models presented in the next section.

Elevator design process begins with studying the feasibility of elevators in building. This involves participation of the client and the architect. If elevators are required, the next step is planning them. The planning of an elevator system is a very involved subject. Although the basic calculations are relatively simple, the results obtained need to be tempered with a great deal of working experience of existing buildings in order to ensure satisfactory design results.

At the beginning of the planning phase, a traffic analysis is undertaken to determine the traffic that the elevator will carry and to establish the quality of elevator service in terms of the speed of elevators and waiting time for service. The architect provides detailed information about the building, including the parameters such as number of stops, interfloor distance, building population, etc. Traffic analysis is often made by the engineer responsible for elevator design. Some elevator providers also offer such a service. The traffic information obtained from the analysis can then be used as input to the downstream processes of deciding access and evacuation strategy and selecting elevator type.

Deciding access and evacuation strategy includes decisions on parameters such as the number of elevator cars, the number of doors for each car and car door width. Fire fighting and disabled access requirements are influential on determining the access strategy.

After deciding the access and evacuation strategy, the elevator type in terms of the method of powering the elevator is selected. The number of floors that an elevator is intended to serve is the main parameter that affects this decision. The amount of space that can be allocated for machine room is another factor to be considered; since electric elevators require machine rooms positioned at the top of the hoistway while for hydraulic elevators, the machine room is placed next to the hoistway at the lowest level.

The car and landing details such as size of elevator cars and car grouping are determined according to the chosen elevator type and the access strategy. Car size directly depends on the traffic analysis and is decided to provide satisfactory service at peak intervals. Car grouping is an important parameter for deciding hoistway details and as a part of the whole circulation system in the building, it is designed by the architect.

Deciding hoistway details involves the architect, the structural engineer, the elevator provider, and the services engineer. Allocating adequate space for a hoistway is an important early design consideration. If the early scheme is not flexible enough, this may create serious conflicts at the later phases. Other hoistway related parameters include type of guide rails, guide rail fixing positions, and machine room and pit details.

Having decided the car, hoistway, and landing details, finishes and fittings are selected. Such decisions are usually in the domain of the architect. Decisions on finishes and fittings are parallel processes which can be conducted concurrently. Another parallel process at the detailed design phase is determining structural item locations and loads. This includes decisions on buffer position and load, pit foundation size, and details of lifting beam and guide rails which are made by the structural engineer.

An elevator design process is briefly outlined above. Detailed information can be found in IDEF0 and DSM models presented in the following section.

7.4 Analyzing Elevator Design Process with Parameter-based DSM

7.4.1 Research Setting

This research was carried out in the architectural design department of TEPE Construction Company and in the offices of their engineering collaborators like the previous case study. It took five months between February 2003 and June 2003. Besides the participants of the previous research, Turkey branch of OTIS Elevator Company also contributed to this research and provided detailed information on elevator provider's processes.

Having been founded by Elisha Graves Otis, who invented the world's first safety elevator in 1853, the OTIS Elevator Company has been one of the pioneers of advanced elevator systems. OTIS is also well-known with its systematic approach to elevator design processes. *Elevator Planning and Selection Guide* of OTIS is a useful design guide (OTIS, 2003). The company has been operating in Turkey under the title Buga OTIS since 1991 and it has provided elevators to some well-known buildings in Turkey such as İş Bankası Towers, Akmerkez, Galeria in İstanbul and many others.

7.4.2 The Scope and Limitations of the Model

The elevator design process model developed in this dissertation is subject to following limitations.

1. The analysis includes only standard passenger elevators with both electric traction and hydraulic drives. Observation elevators, special elevators for the aged and people with special needs, goods elevators, service elevators, motor vehicle elevators, rack and pinion elevators, scissor elevators, and elevators that are powered by other means are left out of the scope.
2. The analysis includes only the design phase of an elevator life cycle. Agreement with an elevator provider, production of working drawings, construction and maintenance of elevators are left out of the scope.
3. It is assumed that the traffic analysis is based on Up-peak interval only.

4. It is assumed that there is no need to change to a different elevator during the travel i.e. no express zone.

7.4.3 Objectives of the Analysis

The objectives of the analysis are to:

1. Identify and document important relations specific to elevator design process.
2. Study information flow and coupling in elevator design.
3. Identify critical parameters that cause large iteration cycles.
4. Identify assumptions to be made in the process.
5. Show knowledge ownership.

7.4.4 The Procedure

The procedure that was followed in this part of dissertation research is as follows:

1. Choose a particular design problem; define the system and its scope.
2. Do a literature research on elevator design to get more familiar with the subject and the terminology.
3. Interview designers to define the elements involved in the system and the interactions between them.
4. Produce IDEF0 diagrams to outline the processes graphically.
5. Build an information database to record the interactions.
6. Show the information database to the designers and make revisions if necessary.

7. Construct and analyze the matrix and comment on the design process.
8. Evaluate the results with the participants.

7.4.4.1 Data Collection

The data was collected through inspection of design documents and interviews with designers. Since all of the participants except the elevator design engineer from OTIS were familiar with the DSM method, the early steps of the data collection process (explanation of the aim and the procedure of the study and of how DSMs work) were relatively short. The early interviews were open-ended type and recorded. Besides these interviews, some design documents such as manufacturers' information, drawings, and design guides have been examined. A draft version of elevator design process model was produced according to the collected data. In the later phases of the data collection process, the matrix was revised according to the comments from the participants. In addition to the observations on the data collection process discussed in the previous case study, the following points were identified in this study:

1. The design participants might have different perspectives on the issues due to their different disciplinary backgrounds. In this case, the interviewer had to act as a mediator. Thus, this study revealed that in data collection for DSM analyses the interviewer should posses the knowledge of the system to some degree and be able to discuss different aspects of the process.

2. Occasionally, different design participants had different views on how one element related to the other. This was sometimes due to an indirect interaction. For example, "Uppeak Interval" affects "Contract Capacity" and "Car Width" depends on "Contract Capacity" (Uppeak Interval $\Rightarrow$ Contract Capacity $\Rightarrow$ Car Width). Thus, a designer might say that "Uppeak Interval" affects "Car Width" due to their intuition from work experience. In this situation, the interviewer explained to the designers why a mark should be put in row "Contract Capacity" and column "Uppeak Interval", instead of row "Car Width" and column "Uppeak Interval." Although there is no mark between the "Uppeak Interval" and "Car Width", the two would reach each other indirectly.

7.4.4.2 The IDEF0 Models

Before building DSMs, the author produced IDEF0 models of the elevator design process. Interviews revealed that the IDEF0 elevator design model produced by the UK Chapter of International Alliance for Interoperability (IAI UK, 99) would need very little change to be adapted to the Turkish practice. While producing the diagrams, the framework proposed in the U.S. NIST (National Institute of Standards) IDEF0 Standard (U.S. NIST, 1993) was used. Microsoft Visio Professional Edition was used as the graphical modeling tool. First, A0 context diagrams were drawn for elevator life cycle (Figures 7.2 and 7.3), and then the model was detailed to reflect the design process (Figures 7.4, 7.5 and 7.6). These documents guided the DSM building process in the later phases.

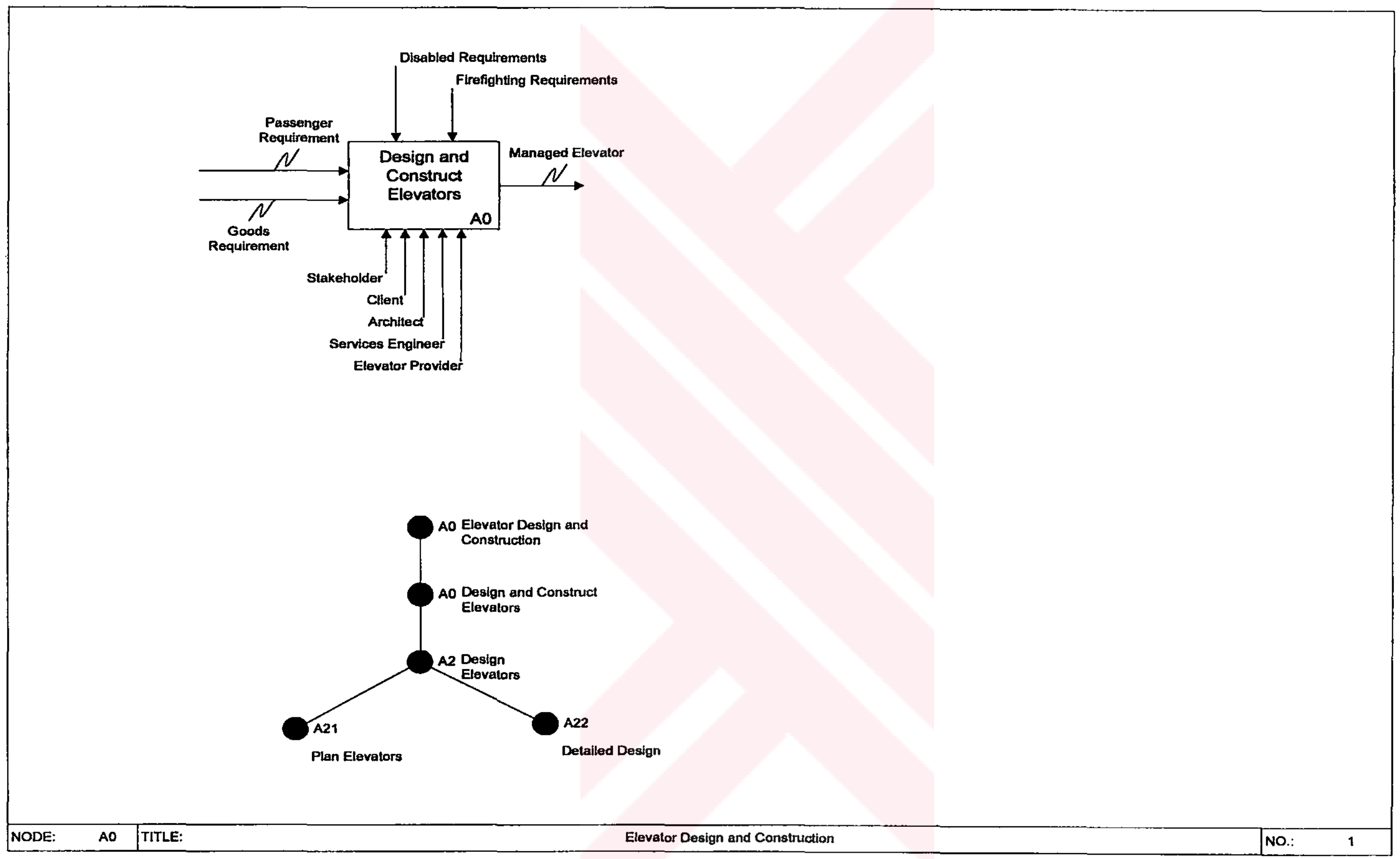


Figure 7.2: The Context Diagram of Elevator Design Process

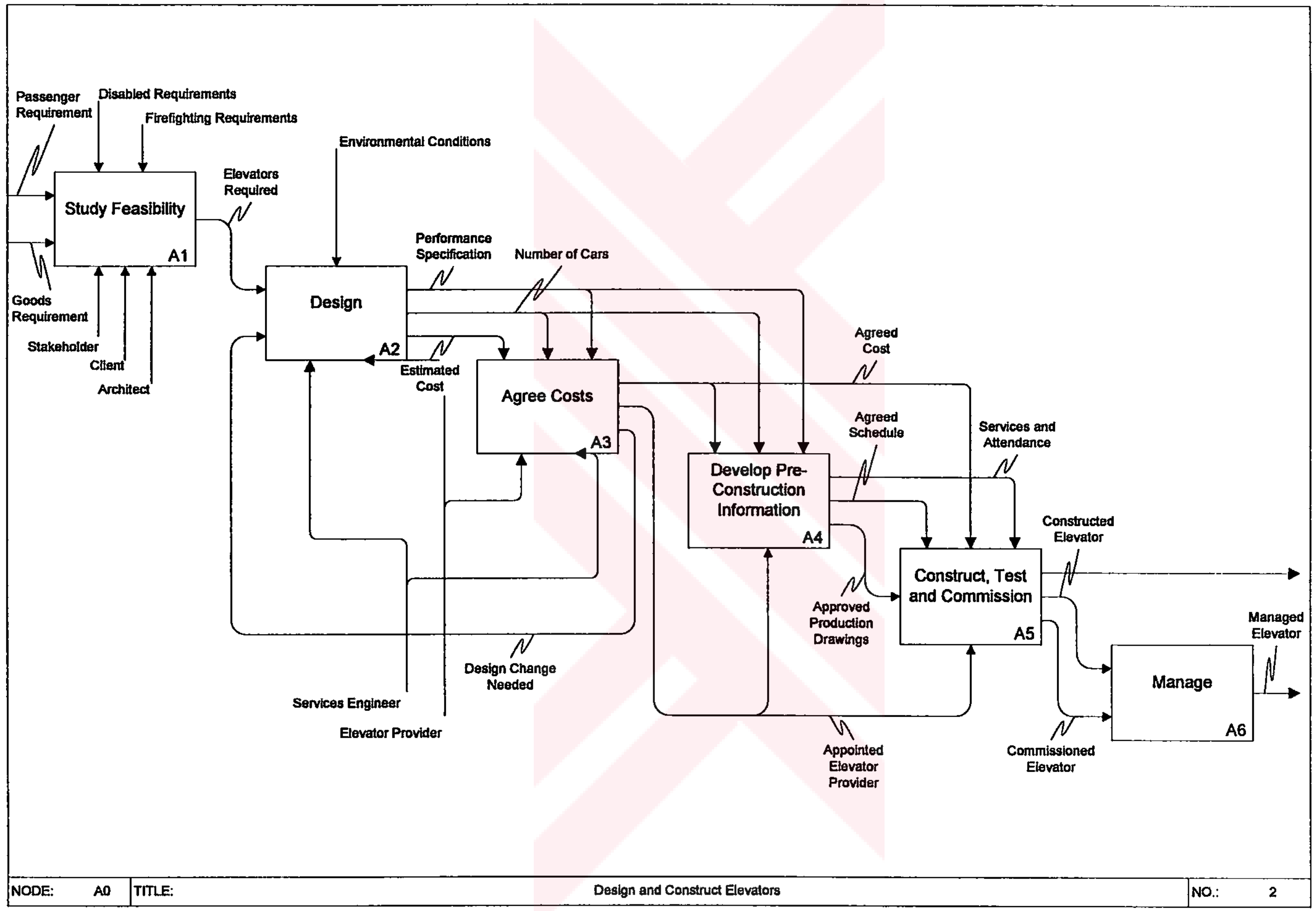


Figure 7.3: An IDEF0 Model of Elevator Life Cycle

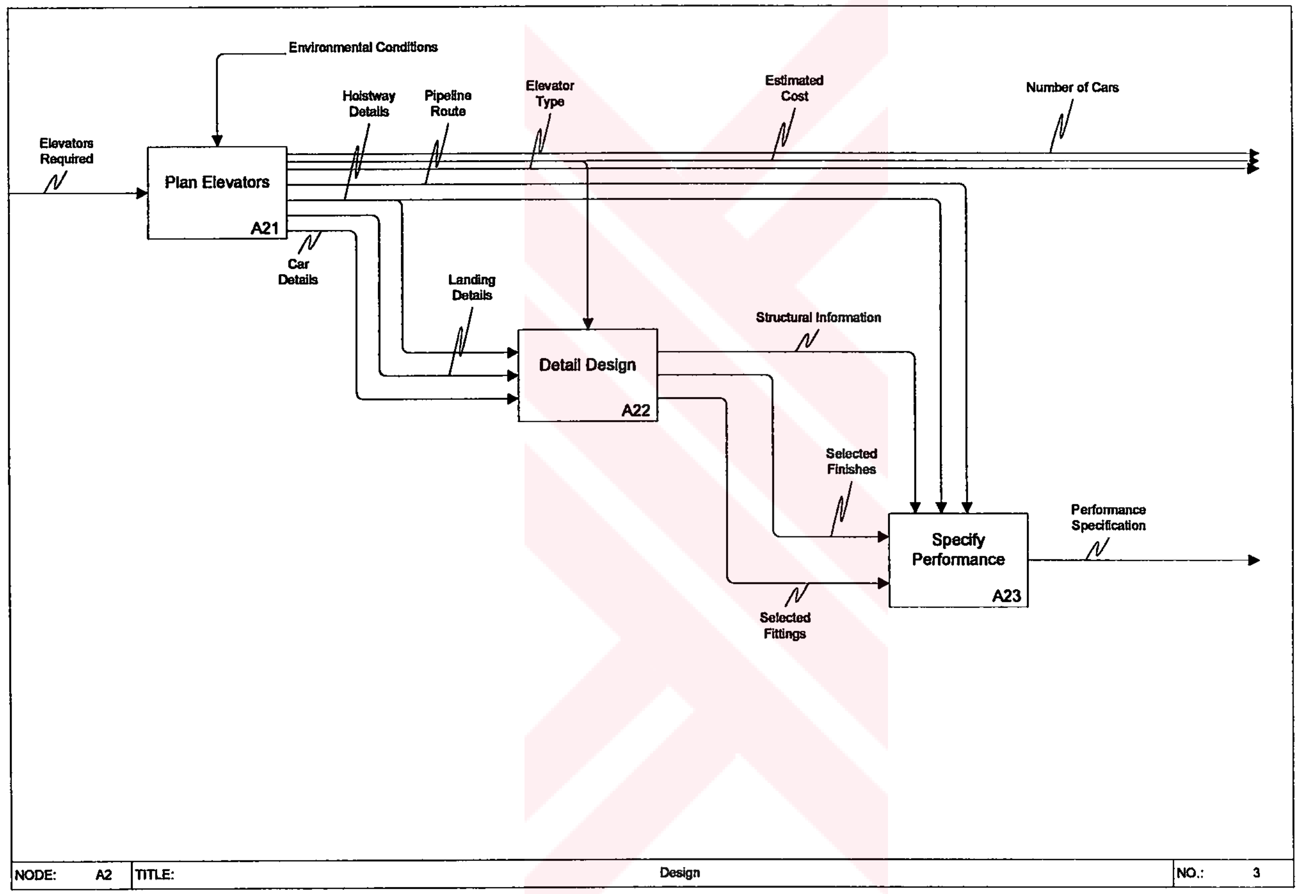


Figure 7.4: An IDEF0 Model of Elevator Design

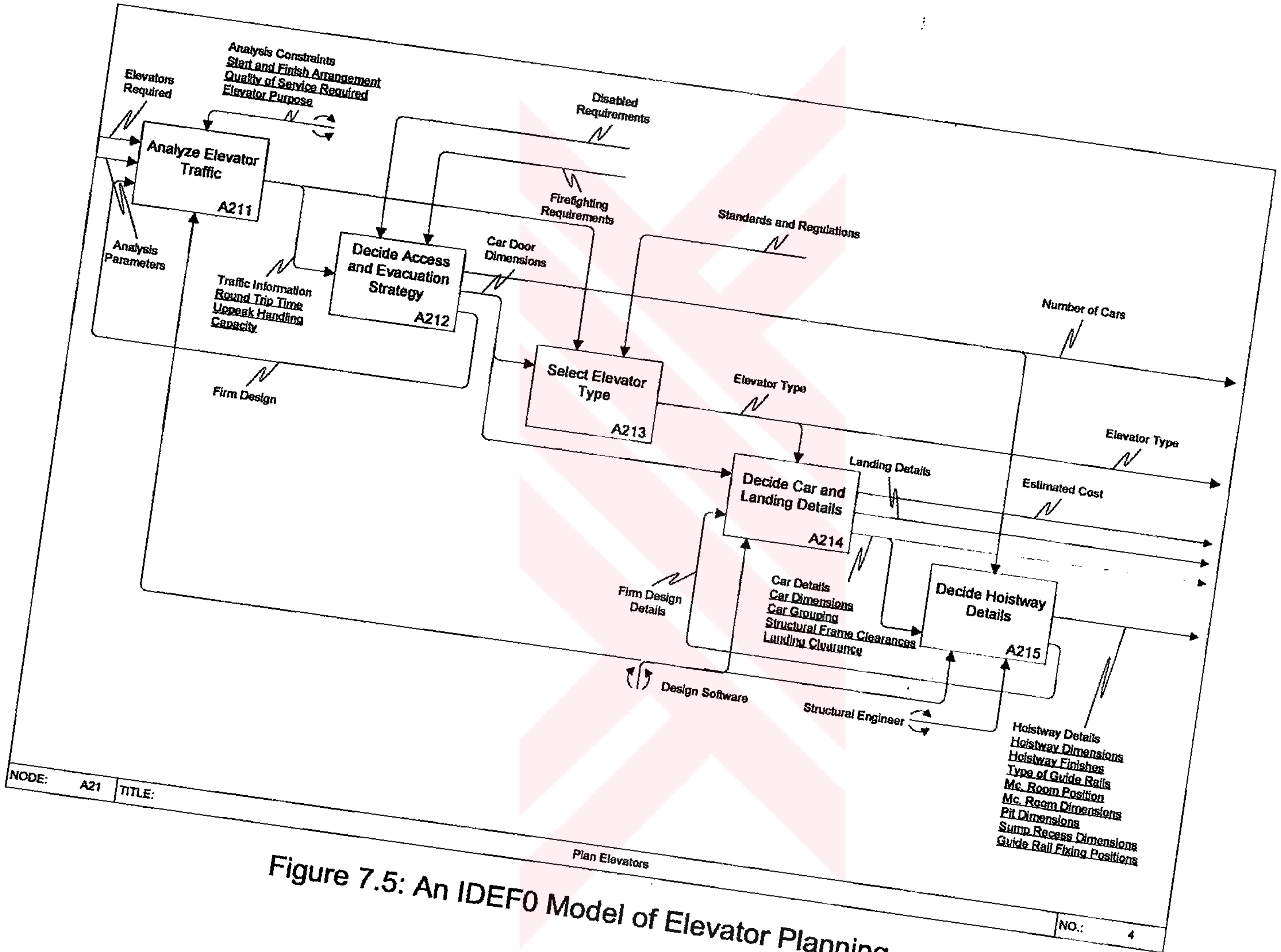


Figure 7.5: An IDEF0 Model of Elevator Planning

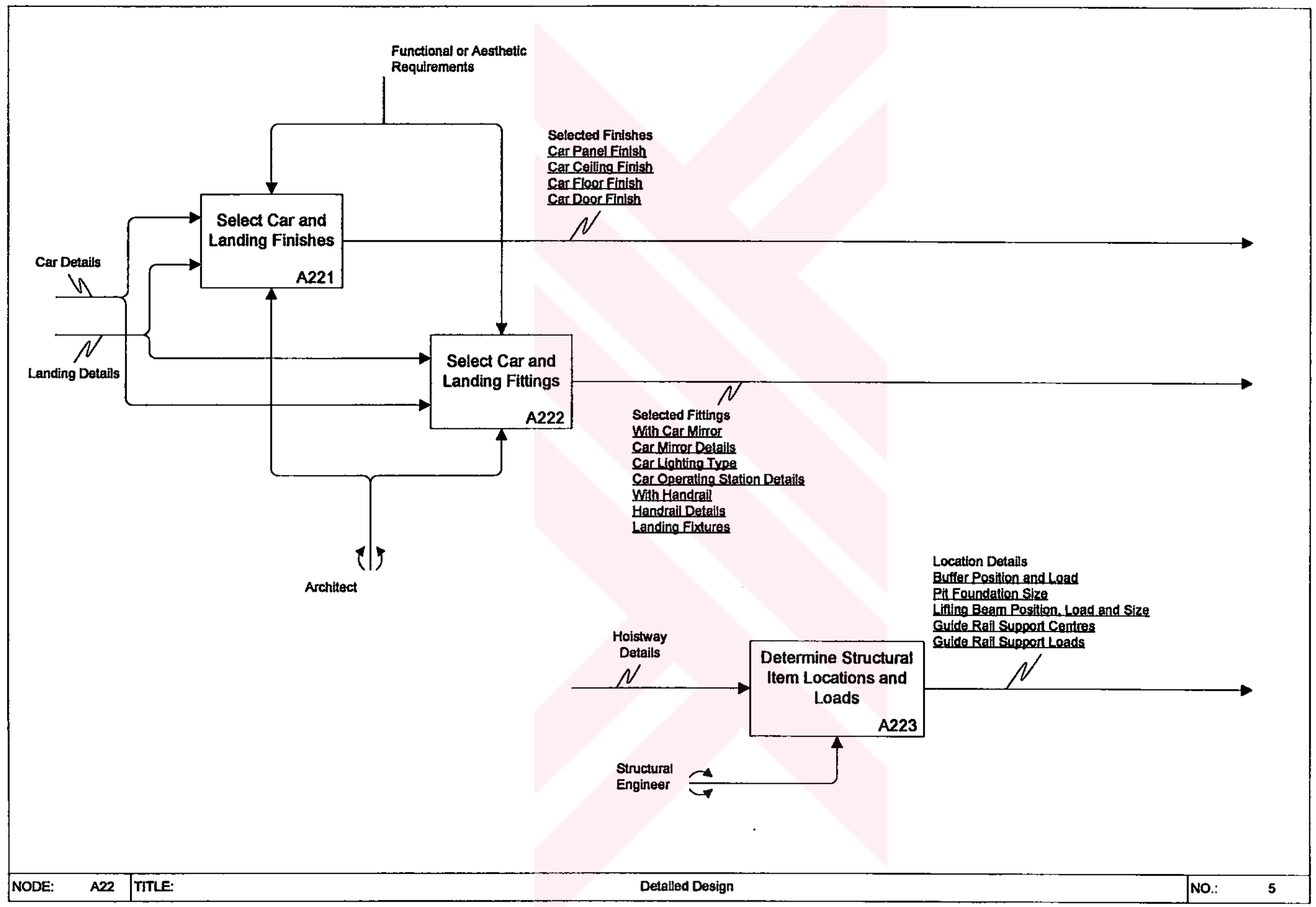


Figure 7.6: An IDEF0 Model of Detailed Design of Elevators

7.4.4.3 The Information Database

The collected information has been stored in a Microsoft EXCEL database which was developed in the previous case study. The information database contains 78 parameters and 268 information flows. Since the details of the information database were discussed in the previous chapter, these will not be repeated here. Detailed descriptions of the parameters can be examined in Appendix B.2.

7.4.4.4 Production of the Matrix and Analyses

A DSM was produced automatically according to the recorded data in a process similar to the one described in the previous chapter. The parameters were categorized according to the activities that produce them. In this way, the initial matrix can be used as a process map which shows the detailed flows between the activities (Figure 7.7). This method of classifying parameters has also been presented elsewhere (Taşlı Pektaş, 2003a). Partitioning (Figure 7.8) and banding (Figure 7.9) were made to identify couplings and parallel parameter decisions in the process. The results of the analyses are presented below.

7.5 Results and Discussion

The following observations were made about the elevator design process.

Although the DSM represents the whole process, it is possible to divide the process into two phases: planning elevators (A21 in the IDEF0 model, and the parameters between the 6th and the 52nd in the initial DSM) and detail design (A22 in the IDEF0 model, and the parameters between the 53rd and the 78th in the initial DSM). The former phase includes 47 parameters except 5 system level parameters presented in beginning of the parameter list of the initial DSM. The latter stage contains 26 parameters (Figure 7.7)

The DSM analysis revealed considerable differences in these two general stages. In the partitioned DSM, it was observed that the most problematic phase of elevator design process is planning elevators (Figure 7.8). This phase contains three overlapping loops. 28 parameters are in these loops. This means that approximately 60% of the parameters in the planning phase are included in one or more information cycles. However, there is no cycle in the detailed design phase.

The "Analyze Elevator Traffic" activity creates the largest cycle, which contains 16 parameters, in the process. The critical parameters in this cycle are uppeak interval, contract speed, time consumed when stopping, with gearing, floor cycle time, average passenger transfer time, round trip time, and number of elevators. This cycle represents the activity of deciding on the number of elevators required in the building.

The second cycle in the process consists of the components between the 22nd and the 29th parameters and it corresponds to the activity of determining car width and depth. The critical parameters in this cycle are average passenger transfer time, round trip time, number of elevators, car door width, car width, and car depth.

The last cycle in the process involves 13 parameters and represents the activity of deciding hoistway width and hoistway depth. The critical parameters in this cycle are number of elevators, car door width, car width, car depth, hoistway width, and hoistway depth.

One should pay attention to a larger possible cycle which contains all of the three cycles mentioned above. This is shown with a darker rectangle on the partitioned DSM and represents the relationship of the elevator system with two building system level parameters, namely, floor area and building structure layout. The width and depth of the hoistway is an important consideration in architectural design at an early stage especially in tall buildings. Proper assumptions should be made about these parameters while the architect prepares the spatial layout. Further changes are rather costly and difficult. Similarly, the structural engineer should consider the hoistway dimensions while preparing the initial structural layout. Structural costs are often reduced by using elevator hoistways for structural purposes. The hoistways can serve as load-bearing supports for floors and roofs and as shear walls for resisting lateral forces from wind and earthquakes. Thus, correct assumptions about the hoistway dimensions are also critical from the structural design point of view. This large cycle in the process creates an "iteration-in-iteration" situation which has also been addressed by the other researchers (Mascoli, 1999; Dong, 1999).

The banded DSM of elevator design process shows that while there are 18 bands in the planning stage, detailed design stage consists of only 4 bands (Figure 7.9). This suggests that early parameter decisions of elevator design process tend to be either sequential or coupled; however, decisions at the detailed design phase are mostly parallel. Therefore, detailed design does not require a strict order of decisions.

Some parameters such as structural frame and landing clearances are already available at the start of the process, since they are determined by strict standards. Thus, they can be placed at the beginning of the parameter decision sequence. In the partitioned matrix, they are placed next to the related parameters in order to show where they fit in the process (Figure 7.8).

When the initial and partitioned matrices of elevator design process are compared, it is observed that except a few changes in the sequence of parameters, the order of parameter decisions almost the same, while there are large cycles. This suggests that those cycles are inevitable in the process. Like the suspended ceiling system level DSM, the elevator design DSM also shows inevitable cycles in the process.

8. DISCUSSION AND CONCLUSIONS

This chapter presents the conclusions of the study following a discussion of the implications on the design process drawn from the case studies. The contributions of this dissertation to the subject field and the challenges of the proposed method are discussed and suggestions are made for further research.

8.1 Implications on the Design Process drawn from the Case Studies

The well-defined geometric and functional bounds of elevator and suspended ceiling systems enabled the author to establish a readily understood and accepted scope for the case studies. Besides the insights gained into the individual design processes, some common implications can also be drawn as below:

The first observation about the design processes concerns the types of information flows. There are at least four types of knowledge used in determining the parameter values:

1. There exist a number of formulas such that existing design values are used to compute a new parameter value. These formulas are often based on physical laws. For example, in elevator design the following formula is used:
   Floor Cycle Time = Single Floor Transit Time + Door Opening/Closing Time. Elevator design process involves more

such formulas than suspended ceiling design does. This is probably due to the mechanical nature of elevator design.

2. Some parameters create constraints for other parameters. In other words, they bring limitations on the choices for other parameters. For example, in suspended ceiling design, hanger spacing puts limitations on maximum weight of lighting fixtures and air diffusers that can be carried by the suspended ceiling structure.
3. The design professionals use preferences to decide on a parameter value when no other parameter dictates a choice. These preferences can be measured with an ordinal scale. Preferences with a higher value are considered more important (e.g. lowest cost). This is often the case when decisions are made on finishes. Parameters related to finishes are mostly not dependent on other parameters (although they depend on each other to ensure compatibility in design), but based on client's and/or designer's preferences.
4. When a design problem occurs, for example, if a violation of a constraint indicates that a rework is needed, the designers use fixes to modify the design. Each fix affects specific parameters that are depended on the changed parameter. Parameter-based DSM is very useful to track the parameters affected by such changes.

In the case studies, it was also observed that certain aspects of design are more prone to iterations. The identification of these aspects may be useful for predicting problem areas in other designs. First of all, the case studies showed that early design stage includes more iterative cycles. The problematic situation of early design (also called conceptual design) is well addressed in the literature. In building design, most of the important decisions (orientation, circulation, functional layout, etc.) are made in the early stages of design. However, most design software can not support this stage of design development (Taşlı, 2001b).

Early design stage is characterized also by the following:

Use of incomplete and imprecise descriptions of the building.

Focus on qualitative aspects rather than quantitative details (Fruchter et al., 1996).

Thus, decisions made in the early steps of design often have far-reaching and unanticipated impacts at later stages. However, it is often too costly to modify early design decisions as the design advances since they affect many parameters and are likely to create "iterations in iterations." In order to resolve this dilemma, the assumptions related to early design parameters should be accurate and/or parameter values should be determined with tolerances to compensate for future changes.

Furthermore, it was observed in the case studies that the most critical parameters, from design management perspective, are those that affect many parameters. These include;

1. System parameters: which affect either all or most the parameters (e.g. floor area, floor height, etc.)
2. Interface parameters: which specify a relation between two system components engineered by different design professionals (fitting dimensions, forces to be transmitted, etc.).

The DSM analyses revealed that the technical aspects of designing a building part are usually well understood and relatively easy to manage. Suspended ceiling design at assembly level and detailed design phase of elevator design process are examples of this type of design which is also called "standard design" or "kit-of-the-parts" design. In fact, the interviews revealed that most of the elevator design is actually "standard design," meaning that the design is based on relatively simple variations on a standard elevator design. Therefore, software systems that are able to automatically propose an elevator system can be effectively used for many cases. However, problems often occur when parts are integrated into a system, and have to interact with other elements in the system. Suspended ceiling design at system level and the planning phase of elevator design are the examples for this phenomenon. This latter type of design is difficult to manage and often not suitable for automation. In most of the cases, human intervention is essential to deal with the conflicts in system level design.

8.2 Conclusions

The AEC industry, like many others, is increasingly aware of the need to improve efficiency of processes in a competitive marketplace. However, the industry has experienced difficulties in identifying ways of capturing, understanding, and replicating design processes. Having guided by the observations above, this dissertation proposed parameter-based design structure matrix as a system analysis and process modeling tool for building design. The remaining sections conclude the findings of the study and makes suggestions for further research.

8.2.1 Contributions of the Study to the Subject Field

In this dissertation, several proposals were made for the use of parameter-based DSM in building design. The expected benefits of the method were envisaged to be in three groups: process improvement, process integration, and the use of the method in combination with the other information processing applications. A knowledge management framework was also proposed for parameter-based DSM applications in building design. The framework addressed the following issues:

1. The need for explicit definitions of parameters was identified and integrating DSMs with the IFC definitions was proposed as a solution.
2. The four views that characterize parameter-based design were defined and classification schemes for parameters were devised according to these views.

3. In order to deal with large DSMs, a two level scheme for DSM analysis was developed. DSMs were produced at assembly level and at system interface level.
4. The complementary use of IDEF0 and parameter-based DSM was suggested.
5. Proposals were made in order to explain how the method can be utilized as software.

Two case studies were undertaken in order to apply the proposed framework in real life design problems. It was observed that the expected benefits of the method were realized in a great extent in the case studies. Furthermore, the case studies enabled to extract some general implications on building design process.

Parameter-based DSMs provided a structural map of the design processes analyzed in the case studies. They identified iterative cycles, critical parameters, and assumptions made. They also suggested proper sequence of design decisions and provided insights into the concurrency in the processes. Although the method has a prescriptive value, unlike many other process modeling methods used in the industry, in the case studies it was found that DSM analysis does not dictate a single "right" process. Instead, it pictures the structure of the dependency relations in the process so that designers may produce several "what-if" scenarios to determine the effects of change.

An advantage of the DSM method experienced in the case studies was its compactness. The DSM method enabled to represent a huge amount of information in a single sheet. If the processes studied in the case studies were modeled with a graphical technique, the models would probably occupy a bunch of sheets. Thus, their management and integration would be a considerable problem.

The case studies also revealed that, in most cases, design knowledge needed to resolve design issues resides in more than one design professional. The databases developed in the case studies showed what information needs to be exchanged as well as dependencies between the decisions. A database as such can serve to accumulate the learning in design firms, providing a complement to the existing inefficient documentation practice. It can serve as a browser for designers to find out what decision they need to be made and whom they need to communicate.

8.2.2 Challenges of the Proposed Method

Although parameter-based DSM is a powerful tool to model the design processes and information flows involved, as a method, it also faces a few challenges. Some of these challenges have already been identified in the preceding chapters and some solutions were provided. However, an in-depth discussion of the difficulties experienced in this research may facilitate for further researches. The challenges of the method observed in the case studies include data collection, data representation, and enabling the widespread use of the tool.

8.2.2.1 Data Collection

The difficulties encountered during data collection were discussed in Chapters 6 and 7. The amount of information involved and sometimes the poor understanding of the process of the participants may make the data collection process very time consuming. In fact, in knowledge-intensive applications like DSM, the problem of knowledge elicitation is often addressed (Taşlı and Özgüç, 2001). Sources of knowledge include human experts, textbooks, work files and previous cases, but there is no single elicitation technique that may be uniformly applied. This problem is known as the “knowledge elicitation bottleneck” (Schreiber, 1993). Elicitation from human experts is especially difficult. Individual experience may be incomplete, irrelevant, or even incorrect. Moreover, as the expert’s proficiency increases, the knowledge becomes more instinctive and thus harder to elicit.

In order to ease the data collection process for DSM development Sabbaghian and Eppinger (1998) developed a web-based tool for collecting data over the Internet. Danilovic and Börjesson (2001) point out that in almost all of the DSM studies data has been gathered by a single researcher. They discuss that in these studies, individual cognitive limitations prevent the system being captured, since individuals are able to grasp only limited parts of the system analyzed.

In order to avoid this handicap, they propose a participatory approach to DSM building in which data providing professionals actively participates the DSM building process.

The author's experience in DSM building suggests that definition of the content and scope of DSM analysis is an important step in the beginning of the data collection process, since different definitions of the problem may result in different DSMs. Explicit definition of parameters is also essential to avoid confusion over the parameter contents. Among building design professionals, such confusions are likely to occur, since each group use their own terminology. In the previous DSM studies, explicit definitions of parameters have been lacking which probably put limitations on the re-use of the models.

Standardization of parameter definitions is also desirable in order to provide compatibility of different DSM applications. The case study on elevator design in this dissertation demonstrated how IFCs can be used for defining parameters in parameter-based DSMs in building design.

8.2.2.2 Data Representation

Another challenge of the parameter-based approach mentioned in this dissertation is the large number of parameters involved in building design. The number of parameters needed to fully determine the properties of a product depends on its complexity. Rouibah and Caskey (2003) estimate that an automobile can be described from 10^5 to 10^6, while an aircraft or ship may have more than 10^6 parameters. There is no available estimation of approximately how many parameters a building may involve, but a really huge number is to be expected. Consequently, to capture and manage all describing parameters in building design may be unrealistic. Therefore, a selection should be made depending on the purpose of the parameter deployment.

In Chapter 7, it was explained that the most important parameters in building design are the ones that affect many other system components. These critical elements were grouped into two: system parameters and interface parameters. If the number of considered parameters is based on these two groups, the number of parameters to be captured considerably reduces.

8.2.2.3 Enabling the Widespread Use of the Method

The most common complaint the author of this dissertation got from talking to the building design professionals about information management in design was that they are so busy dealing with design problems that they do not have the time to monitor the processes that they undertake. In order to encourage the designers to spend time to design management, this dissertation recommends that the proposed method should be utilized as software.

8.3 Suggestions for Further Research

Since the use of parameter-based DSM in building design is innovative, it may trigger further researches in many aspects. Some further research topics are listed below.

This dissertation utilized only binary parameter-based DSMs. Further research may be done to enhance the existing models via assigning numerical values to the dependencies. A multitude of attributes that provide more detailed information on the relationships can be provided such as importance and strength of the dependency. Probability of repetition, variability of information exchanged, and the impact of an iteration can also be included in the analysis in order to simulate the modeled processes.

Using the parameter-based DSM, comparison of different design configurations is possible. A DSM can be produced for each design option and different designs may be compared in terms of their complexity and how a change in design affects the overall process structure. In this case, the amount of system elements and information flows would be a good indicator of design complexity. When design configurations are compared, their problematic aspects can be identified and new designs can be modified in the light of the gained insights.

Incompatibility of building design software was addressed in Chapter 2 as an important information related problem in the industry. Software developers can use the method to integrate separated applications. The flow of information between design software can be effectively modeled using the tool and integrative applications can be developed.

This dissertation proposed the integrative use of the parameter-based DSM in combination with the existing methods. This type of use of the method was demonstrated via a simple example in Chapter 5. Further research may exploit this capability of the tool.

Last but not least, in this dissertation it was suggested that the method should be utilized as software. Within the scope of this dissertation, only a basic framework was presented for the implementation of such a tool. Further research is needed to develop the tool and to make it available for building design professionals.

REFERENCES

Akın, Ö. (1986). *Psychology of Architectural Design.* London:Pion.

Amor, R., Augenbroe, G., Hosking, J., Rombouts, W., & Grundy, J. (1995). Directions in Modeling Environments. *Automation in Construction, 4,* 173-187.

Anumba, C. J. & Duke, A. K. (2000). Telepresence in Concurrent Lifecycle Design and Construction. *Journal of Artificial Intelligence in Engineering - Special Issue on Collaborative and Concurrent Engineering, 14* (3), 221-232.

Arditi, D. and Günaydın, H. M. (1998). Factors that Affect Process Quality in the Life Cycle of Building Projects. *Journal of Construction Engineering and Management, 124* (3), 194-203.

Atkin, R. H. (1974). *Mathematical Structure in Human Affairs.* New York: Crane, Russak and Company.

Atsuko, K., Nakahama, K., Hamada, S., Yamaguchi, S., & Sasada, T. (2001). Collaborative Design System with Hypermedium and Networking. *Automation in Construction, 10,* 309-318.

Austin, S., Baldwin, A., Li, B., & Waskett, P. (1999). Analytical Design Planning Technique: A Model of the Detailed Design Process. *Design Studies, 20* (3), 279-296.

Austin, S., Baldwin, A., Li, B., & Waskett, P. (2000). Analytical Design Planning Technique (ADePT): A Dependency Structure Matrix Tool to Schedule the Building Design Process. *Construction Management and Economics, 18,* 173-182.

Austin, S., Baldwin, A., & Newton, A. (1994). Manipulating the Flow of Design Information to Improve the Programming of Building Design. *Construction Management and Economics, 12,* 445-455.

Austin, S., Newton, A., Steele, J., & Waskett, P. (2002). Modeling and Managing Project Complexity. *International Journal of Project Management, 20,* 191-198.

Austin, S., Steele, J., Macmillan, S., Kirby, P., & Spence, R. (2001). Mapping the Conceptual Design Activity of Interdisciplinary Teams. *Design Studies, 22* (3), 211-232.

Axiomatic Design Inc. (2003). Axiomatic Design Company Web Page. Retrieved June 2, 2003, from http://www.axiomaticdesign.com

Baldwin, A. N., Austin, S., Hassan, T. M., & Thorpe, A. (1999). Modelling Information Flow during the Conceptual and Schematic Stages of Building Design. *Construction Management and Economics, 17,* 155-167.

Baldwin, A. N., Austin, S., Hassan, T. M., & Thorpe, A. (1998). Planning Building Design by Simulating Information Flow. *Automation in Construction, 8,* 149-163.

Ballard, G. (2000). Positive Vs. Negative Iteration in Design. *International Group for Lean Construction*, Eighth Annual Conference. Retrieved June 2, 2002, from http://www.sussex.ac.uk/spru/imichair/iglc8/05.pdf

Baykan, C., & Pultar, M. (1995). The Structure of Space-Activity Relations in Houses. Unpublished Research Report, Bilkent University, Turkey.

Björk, B. C. (1994). A Conceptual Model of Spaces, Space Boundaries, and Enclosing Structures. *Automation in Construction, 3,* 193-214.

Black, T. A., Fine, C. F., & Sachs, E. M. (1990). A Method for Systems Design Using Precedence Relationships: An Application to Automotive Break Systems. Working Paper, MIT School of Management, Cambridge, MA, 3208.

Booch, G., Rumbaugh, J., & Jacobson, I. (1998). *The Unified Modeling Language User Guide.* Reading, MA: Addison-Wesley.

Bovill, C. (1991). *Architectural Design: Integration of Structural and Environmental Systems.* New York: Van Nostrand Reinhold.

Broadbent, G. H. (1988). *Design in Architecture*. New York: Wiley.

Browning, T. R. (1998). *Modeling and Analyzing Cost, Schedule, and Performance in Complex System Product Development.* Ph.D. Dissertation, Technology, Management, and Policy Program. Massachusetts Institute of Technology. Retrieved May 14, 2002, from http://theses.mit.edu

Browning, T. R. (2001). Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions. *IEEE Transactions on Engineering Management, 48* (3), 292-306.

Browning, T. R. (2002). Process Integration Using the Design Structure Matrix. *Systems Engineering, 5* (3), 180-193.

Caneparo, L. (2001). Shared Virtual Reality for Design and Management: The Porta Susa Project. *Automation in Construction, 10,* 217-228.

Cesiel, D. S. (1993). A Structured Approach to Calibration Development for Automotive Diagnostic Systems. M.Sc. Dissertation, Department of Electrical Engineering. Massachusetts Institute of Technology. Retrieved April 17, 2003, from http://theses.mit.edu

Charette, R. P., & Marshall, H. E. (1999). *UNIFORMAT II Elemental Classification for Building Specifications, Cost Estimating, and Cost Analysis*. Gaithersburg, MD: U.S. National Institute of Standards and Technology.

Chen, C., Ling, S. F., & Chen, W. (2003). Project Scheduling for Collaborative Product Development Using DSM. *International Journal of Project Management, 4,* 291-299.

Chinowsky, P. S., & Robinson, J. (1995). Facilitating Interdisciplinary Design Education through Case Histories. Retrieved June 2, 2002, from http://fie.engrng.pitt.edu/fie95/4a3/4a32/4a32.htm

Clarkson, P. J., & Hamilton, J. R. (2000). "Signposting", A Parameter-driven Task-based Model of the Design Process. *Research in Engineering Design, 12,* 18-38.

Cronemyr, P., Ronnback, A. O., & Eppinger, S. D. (2001). A Decision Support Tool for Predicting the Impact of Development Process Improvements. *Journal of Engineering Design, 12* (3), 177-199.

Cross, N. A. (1989). *Engineering Design Methods*. Chichester, West Sussex: John Wiley and Sons.

Cross, N. A. (1993). History of Design Methodology. In De Vries, M. J., Cross, N., & Grant, D. P. (Eds.) *Design Methodology and Relationships with Science*. London: Kluwer.

Danilovic, M., & Börjesson, H. (2001). Participatory Dependence Structure Matrix Approach. *Proceedings of the Third Dependence Structure Matrix (DSM) International Workshop*, October 29-30, Massachusetts Institute of Technology (MIT), Massachusetts, Boston, Cambridge, USA. Retrieved October 7, 2002, from http://extra.ivf.se/multiplan/dokument/Participatory_DSM_approach_FINAL.pdf

De Marco, T. (1979). *Structured Analysis and System Specification*. Englewood Cliffs, NJ.: Prentice Hall.

Decision Sciences Inc. (2002). Decisions Sciences Company Web Page. Retrieved November 29, 2002, from http://www.dsifl.com/webdsm.asp

Demirkan, H. (1998). Integration of Reasoning Systems in Architectural Modeling Activities. *Automation in Construction, 7,* 229-236.

Denker, S., Steward, D. and Browning, T. (1999). Planning Concurrency and Managing Iteration in Projects. *Center for Quality of Management Journal, 8* (2), 55-62.

Dias, W. P. S. (1996). Multidisciplinary Product Modeling of Buildings. *Journal of Computing in Civil Engineering,* 10 (1), 78-86.

Dong, Q. (1999). *Representing Information Flow and Knowledge Management in Design Using the Design Structure Matrix.* M.Sc. Dissertation, Department of Mechanical Engineering. Massachusetts Institute of Technology. Retrieved September 7, 2002, from http://theses.mit.edu

Eastman, C. (1999). *Building Product Models: Computer Environments Supporting Design and Construction.* Boca Raton: CRC Press.

Elmasri, R., & Navathe, S. B. (1994). *Fundamentals of Database Systems.* Redwood City, California: Benjamin/Cummings.

English, K., Bloebaum, C. L., & Miller, E. (2001). Development of Multiple Cycle Coupling Suspension in the Optimization of Complex Systems. *Structural and Multidisciplinary Optimization, 22* (4), 268-283.

Eppinger, S. D., Whitney, D. E., Smith, R. P., & Gebala, D. A. (1994). A Model-based Method for Organizing Tasks in Product Development. *Research in Engineering Design, 6,* 1-13.

Eppinger, S. D. (2001). Innovation at the Speed of Information. *Harvard Business Review, 79,* 149-158.

Formoso, C. T., Tzotzopoulos, P., Jobim, M. S. S., & Liedtke, R. (1998). Developing a Protocol for Managing the Design Process in the Building Industry. *International Group for Lean Construction, Sixth Annual Conference.* Retrieved April 24, 2002, from: http://www.ce.berkeley.edu/~tommelein/IGLC-6/FormosoTzotzopoulosJobimLeidtke.pdf

Fruchter, R., Clayton, M. J., Krawinkler, H., Kunz, J., & Teicholz, P. (1996). Interdisciplinary Communication Medium for Collaborative Conceptual Building Design. *Advances in Engineering Software, 25,* 89-101.

Galle, P. (1995). Towards Integrated, "Intelligent", and Compliant Computer Modeling of Buildings. *Automation in Construction, 4,* 189-211.

Hamer, A. P., Nihtila, J., & Rehn, J. (1999). Document Viewpoint on One-of-a-kind Delivery Process. *International Journal of Product Research, 37,* 1319-1336.

Hew, K. P., Fisher, N., & Awbi, H. B. (2001). Towards an Integrated Set of Design Tools based on a Common Data Format for Building and Services Design. *Automation in Construction, 10,* 459-476.

Hirschi, N. W., & Frey, D. D. (2002). Cognition and Complexity: An Experiment on the Effect of Coupling in Parameter Design. *Research in Engineering Design, 13,* 123-131.

Hong, N. K., & Hong, S. (2001). Application of Entity-based Approach for Unified Representation of Design Alternatives for Structural Design. *Advances in Engineering Software, 32,* 599-610.

Howell, G. A. (1999). What is Lean Construction? *Proceedings of the Seventh Annual Conference of the International Group for Lean Construction,* 26-28 July 1999, University of California, Berkeley, CA, USA. 1-10. Retrieved January 9, 2001, from http://www.ce.berkeley.edu/~tommelein/IGLC-7/PDF/Howell.pdf

Hubka, V. (1982). *Principles of Engineering Design.* Guildford, Surrey: Butterworth Scientific Press.

Huovila, P., & Seren, K. J. (1998). Customer-oriented Design Methods for Construction Projects. *Journal of Engineering Design, 9* (3), 225-238.

International Alliance for Interoperability (IAI), the North America Chapter. (2003). Projects Web Page. Retrieved June 9, 2003, from http://www.iai-na.org/technical/projects.php

International Alliance for Interoperability (IAI), the UK Chapter. (1999). *Elevator Design Model.* Retrieved February 18, 2003, from http://www.iai.org.uk/design_integration/technical_documentation/R3_bs_elevators.pdf

Jackson, B. (1997). The Development of TOTAL Studio: A Comprehensive Computer-Mediated Studio Environment for Architecture and Engineering. Retrieved December 16, 1999, from http://www-ec.njit.edu/ec_info/image1/text_files/jax/papers/total_97.html

Jones, J. C. (1970). *Design Methods: Seeds of Human Futures.* New York: John Wiley and Sons.

Kalay, Y. E., Khemlani, L., & Choi, J. W. (1998). An Integrated Model to Support Distributed Collaborative Design of Buildings. *Automation in Construction, 7,* 177-188.

Karhu, V. (2000). Proposed New Method for Construction Process Modelling. *International Journal of Computer Integrated Design and Construction, 2* (3), 166-182.

Karhu, V. (2001). A Model based Approach for Construction Process Modelling. Retrieved May 6, 2003, from www.lib.kth.se/Sammanfattningar/karhu011109.pdf

Karstila, K. (2000). About Process Modelling: Methods and Tools for Construction Process Support. Retrieved June 9, 2002, from http://www.arcada.fi/personal/heffe/04%20hut%20it%20tfif%20merit/itecon_course/TKK_Rak-63_200_Lecture2_ProcessModelling_KKa_200-02-04.pdf [sic]

Krishnan, W. (1993). *Design Process Improvement: Sequencing and Overlapping Activities in Product Development.* Ph.D. Dissertation, Department of Mechanical Engineering. Massachusetts Institute of Technology. Retrieved February 6, 2002, from http://theses.mit.edu

Kvan, T. (2000). "Collaborative Design: What is it?" *Automation in Construction, 9,* 409-415.

Larson, N., & Kusiak, A. (1996). Managing Design Processes: A Risk Assessment Approach. *IEEE Transactions on Systems, Man, and Cybernetics, 26* (1), 749-759.

Lean Aerospace Initiative (LAI). (2002). Lean Aerospace Initiative Web Site. Retrieved January 10, 2002, from http://lean.mit.edu

Lean Construction Institute (LCI). (2002). Lean Construction Institute Web Site. Retrieved January 10, 2002, from http://www.leanconstruction.org

Lee, E., Woo, S., & Sasada, T. (2001). The Evaluation System for Design Alternatives in Collaborative Design. *Automation in Construction, 10,* 295-301.

Liebich, T., & Wix, J. (2003). Highlights of the Development Process of Industry Foundation Classes. Retrieved January 14, 2003, from http://www.iai-na.org/technical/highlights_ifc.pdf

Lockledge, J. C., & Salustri, F. A. (2001). Design Communication Using a Variation of the Design Structure Matrix. *International Conference on Engineering Design*, ICED 01 Glasgow, August 21-23. Retrieved March 16, 2003, from http://www.dig.bris.ac.uk/iced/iced01/webpages/HTML/204-Lockledge.html

Lottaz, C. (2000). Increasing Understanding during Collaboration through Advanced Representations. *Electronic Journal of Information Technology in Construction (ITcon).* Retrieved March 1, 2000, from http://www.itcon.org/2000/1/paper.htm

Low, B. K., & Sloan, B. (2001). A Perspective on the Digital Interactive Service Industry for Building Professionals. *Automation in Construction, 10,* 229-237.

Macmillan, S., Steele, J., Austin, S., Kirby, P., & Spence, R. (2001). Development and Verification of a Generic Framework for Conceptual Design. *Design Studies, 22,* 169-191.

Malmström, J., Pikosz, P., & Malmqvist, J. (1999). Complementary Roles of IDEF0 and DSM for the Modeling of Information Management Processes. *Concurrent Engineering – Research and Applications, 7* (2), 95-103.

Mascoli, G. J. (1999). A Systems Engineering Approach to Aero Engine Development in a Highly Distributed Engineering and Manufacturing Environment. MIT SDM Thesis, Massachusetts Institute of Technology. Retrieved January 7, 2003, from http://theses.mit.edu

Merritt, F. S., & Ambrose, J. (1990). *Building Engineering and Systems Design.* New York: Van Nostrand Reinhold.

MIT DSM Research Group. (2003). MIT DSM Web Site. Retrieved June 3, 2003, from http://www.dsmweb.org/

Mitchell, W. J. (1994). Three Paradigms for Computer-Aided Design. In G. Carrara and Y. E. Kalay (Eds.), *Knowledge-Based Computer-Aided Architectural Design* (pp. 379-89). Amsterdam: Elsevier.

Moller, C. (1997). The Virtual Organisation. *Automation in Construction, 6,* 39-43.

Nelson, M., Lee, A., Cooper, R., Kagioglou, M., & Fleming, A. (1999). Process Re-engineering in the Construction Industry – Buzzword or Reality? Retrieved December 28, 2002, from http://pp2.dct.salford.ac.uk/pdf/cobrapaper1999.pdf

OTIS Elevator Company. (2003). Elevator Planning and Selection Guide. Retrieved February 11, 2003, from http://www.otis.com

Pahl, G., & Beitz, W. (1984). *Engineering Design.* London: The Design Council.

Pena-Mora, F., Hussein, K., Vadhavkar, S., & Benjamin, K. (2000). CAIRO: A Concurrent Engineering Meeting Environment for Virtual Design Teams. *Automation in Construction, 14,* 203-219.

Peng, C. (1999). Flexible Generic Frameworks and Multidisciplinary Synthesis of Built Form. *Design Studies, 20,* 537-551.

Phillips, R. (2001). *The Architect's Plan of Work.* London: RIBA Publications.

Problematics. (2003). Problematics Company Web Site. Retrieved December 21, 2002, from http://www.problematics.com

Pugh, S. (1986). Design Activity Models: Worldwide Emergence and Convergence. *Design Studies, 7* (3), 167-173.

Pultar, M. (1990). Progress Based Construction Scheduling. *Journal of Construction Engineering and Management, 116* (4), 670-688.

Pultar, M. (1999). Building Education: From Fragmentation to Integration. In G. Sağlamer, A. Melezinek & S. İncecik (Eds.), *Engineering Education in the Third Millennium: Referate des 28. Internationalen Symposiums "Ingenieur Pedagogik'99* (pp. 373-379). Alsbach: Leuchtturm Verlag.

Qian, D., & Gross, M. (1999). Collaborative Design with Netdraw. *Proceedings of the Eighth International Conference on Computer Aided Architectural Design Futures,* Atlanta, USA, June, 213-26. Retrieved March 15, 2000, from http://depts.washington.edu/dmgftp/publications/pdfs/caadfutures99-netdraw.pdf

Radford, A. D., & Gero, J. S. (1988). *Design by Optimization in Architecture, Building and Construction.* New York: Van Nostrand Reinhold.

Rezgui, Y., Brown, A., Cooper, G., Yip, J., Brandon, P., & Kirkham, J. (1996). An Information Management Model for Concurrent Construction Engineering. *Automation in Construction, 5,* 343-355.

Rezgui, Y., & Zarli, A. (2001). Information and Communication Technology Advances in the European Construction Industry. *Electronic Journal of Information Technology in Construction (ITcon).* Retrieved February 19, 2003, from http://www.itcon.org/2001/7/

Rezgui, Y., Zarli, A., Bourdeau, M., & Cooper, G. (2002). Inter-enterprise Information Management in Dynamic Virtual Environments: the OSMOS Approach. *Proceedings of the International Council for Research and Innovation in Building and Construction CIB w78 Conference.* Retrieved February 15, 2003, from http://cic.cstb.fr/ilc/publicat/rezgui_cibw78.pdf

Rogers, J. L., & Salas, A. O. (1999). Toward a more Flexible Web-based Framework for Multidisciplinary Design. *Advances in Engineering Software, 30,* 439-444.

Rotheroe, K. (2002). A Vision for Parametric Design. *Architecture Week.* Retrieved December 23, 2002, from http://www.architectureweek.com/2002/0710/tools_1-1.html

Rouibah, K., & Caskey, K. R. (2003). Change Management in Concurrent Engineering from a Parameter Perspective. *Computers in Industry, 50,* 15-34.

Rowe, P. G. (1991). *Design Thinking.* Cambridge, Mass: MIT Press.

Rundell, R. L. (2002). Parametrics in Building Design. *CAD Server: Online Resource for the CAD Community.* Retrieved December 23, 2002, from http://www.cadserver.co.uk/common/viewer/archive/2002/Apr/9/feature.htm

Rush, R. D. (1986). *The Building Systems Integration Handbook.* Boston: Butterworth-Heinemann.

Sabbaghian, N., & Eppinger, S. (1998). Product Development Process Capture and Display Using Web-based Technologies. *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics*, San Diego, CA, Oct. 11-14, 2664-2669. Retrieved June 10, 2003, from http://web.mit.edu/dsm/pdf/nader_paper.pdf

Sanders, K. (1996). *The Digital Architect.* New York: John Wiley and Sons.

Sanvido, V. E., & Norton, K. J. (1994). Integrated Design Process Model. *Journal of Management in Engineering, 5,* 55-62.

Schreiber, G. (1993). *KADS: A Principled Approach to Knowledge-based System Development.* New York: Academic Press.

Schulz, R. C. (2000). Decision Tracking in AEC Projects. Retrieved June 2, 2002, from http://www.integrated_aec.com/Comm_in_AEC/Com_AEC.PDF

Shi, J. J., & Deng, Z. (2000). Object-oriented Resource-based Planning Method (ORPM) for Construction. *International Journal of Project Management, 18,* 179-188.

Smith, R. P., & Eppinger, S. D. (1993). Characteristics and Models of Iteration in Engineering Design. Retrieved November 12, 2002, from http://www.citeseer.nj.nec.com/ 476788.html

Smith, R. P., & Morrow, J. A. (1999). Product Development Process Modelling. *Design Studies, 20,* 237-261.

Steward, D. V. (1981). The Design Structure System: A Method for Managing the Design of Complex Systems. *IEEE Transactions on Engineering Management, 28,* 71-74.

Stuurstraat, N., & Tolman, F. (1999). A Product Modeling Approach to Building Knowledge Integration. *Automation in Construction, 8,* 269-275.

Suh, N. P. (1998). Axiomatic Design Theory for Systems. *Research in Engineering Design, 10,* 189-209.

Svensson, D., Malmstrom, J., Pikosz, P., & Malmqvist, J. (1999). A Framework for Modeling and Analysis of Engineering Information Management Systems. *Proceedings of the 1999 ASME Design Engineering Technical Conferences*, September 12-15, 1999, Las Vegas, Nevada, USA. Retrieved February 17, 2003, from http://www.ppd.chalmers.se/~joma/publications/eim99-paper.pdf

Tang, D., Zheng, L., Li, Z., Li, D., & Zhang, S. (2000). Re-engineering of the Design Process for Concurrent Engineering. *Computers and Industrial Engineering, 38,* 479-491.

Taşlı Pektaş, Ş. (2003a). Process Integration in Building Design Using the Parameter-based Design Structure Matrix. *9th EuropIA International Conference: E-Activities and Intelligent Support in Design and the Built Environment*, October 8-10, 2003, Istanbul Technical University, Turkey (Forthcoming).

Taşlı Pektaş, Ş. (2003b). A Framework for Building Design Process Modeling with Parameter-based Design Structure Matrices. In C. J. Anumba (Ed.), *Innovative Developments in Architecture, Engineering, and Construction.* (pp. 25-31). Rotterdam: MillPress.

Taşlı, Ş. & Özgüç, B. (2001). Dynamic Simulation in Virtual Environments as an Evaluation Tool for Architectural Design. *Architectural Science Review, 44* (2), 139-144.

Taşlı, Ş. & Sagun, A. (2002). Proposals for Creative Uses of Computer Graphics in Architectural Design. *Digital Creativity, 13* (3), 189-192.

Taşlı, Ş. (2001a). Bridging the Gap between Theory and Practice in Architectural Education: The Case of CAAD Teaching. In N. Çağlar (Ed.) *Proceedings of the 19th EAAE International Conference, Re-integrating Theory and Design in Architectural Education,* May 23-26, 2001, Ankara, Turkey. (pp. 203-209). Ankara: Gazi University.

Taşlı, Ş. (2001b). What does Computer Aided Design Offer for Producing Livable Buildings in the 21st Century? *Proceedings of the Livable Environments and Architecture International Congress (LIVENARCH 2001).* July 4-7, 2001, Trabzon, Turkey. 278-282.

The Chartered Institution of Building Services Engineers (CIBSE). (1993). *Transportation Systems in Buildings.* London: CIBSE.

The National Research Council of Finland (VTT). (2003). The Fractured Information System. Retrieved May 16, 2003, from http://cic.vtt.fi/technical/IFC_2.0/iai/page2.htm

Tolman, F. P. (1999). Product Modeling Standards for the Building and Construction Industry: Past, Present and Future. *Automation in Construction, 8,* 227-235.

Ulrich, K. T., & Eppinger, S. D. (1999a). Fiat Auto-Digital Layout Process. Retrieved December 10, 2002, from http://web.mit.edu/dsm/Scrap_book/Fiat.htm

Ulrich, K. T., & Eppinger, S. D. (1999b). Cheetah Project-Cartridge Development Process Example. Retrieved June 11, 2003, from http://web.mit.edu/dsm/Scrap_book/Cartridge.htm

University of Salford. (2002). The Generic Design and Construction Protocol Process Maps Web Site. Retrieved December 5, 2002, from http://pp2.dct.salford.ac.uk/processmap.htm

U.S. National Institute of Standards and Technology. (1993). *Draft Federal Information Processing Standards Publication 183. The Standard for Integration Definition for Function Modeling (IDEF0).* Gaithersburg, MD: U.S. National Institute of Standards and Technology.

Valkenburg, R. C. (1998). Shared Understanding as a Condition for Team Design. *Automation in Construction, 7*, 111-121.

Veeramani, D., Tserng, H. P., & Russell, J. S. (1998). Computer-integrated Collaborative Design and Operation in the Construction Industry. *Automation in Construction, 7,* 485-492.

Wakefield, R. R., & Damrianant, J. (1999). Petri Net Modelling - A Simulation Tool for Use in Construction Process Re-engineering. *International Journal of IT in Architecture, Engineering, and Construction, 1* (2), 20-34.

Wheeler, C. H. (1998). Architects and Engineers Need to be Educated together so They can Learn How to Work better together. *Architectural Record, 186* (8), 183-184.

Wittenoom, R. (1999). Automating Realization of Integrated Project Models. *Automation in Construction, 8,* 249-267.

Wix, J., & Katranuschkov, P. (2002). Defining the Matrix of Communication Processes in the AEC/FM Industry: Current Developments and Gap Analysis. *Proceedings of the International Council for Research and Innovation in Building and Construction CIB w78 Conference.* Retrieved

January 20, 2003, from http://www.cib-w78-2002.dk/papers/papers/cib02-63.pdf

Woo, S., Lee, E., & Sasada, T. (2001). The Multiuser Workspace as the Medium for Communication in Collaborative Design. *Automation in Construction, 10,* 303-308.

Wu, S., Fleming, A., Aouad, G., & Cooper, R. (1998). The Development of the Process Protocol Mapping Methodology and the Tool. *European Product Data Technology Conference, Building Research Establishment, March 1998, Watford, UK.* Retrieved April 5, 2002, from http://pp2.dct.salford.ac.uk/pdf/pdt98.pdf

Yassine, A., Falkenburg, D., & Chelst, K. (1999). Engineering Design Management: An Information Structure Approach. *International Journal of Product Research, 37,* 2957-2975.

Zakarian, A., & Kusiak, A. (2000). Analysis of Process Models. *IEEE Transactions on Electronics Packaging Manufacturing, 23* (2), 137-147.

Zamanian, M. K., & Pittman, J. H. (1999). A Software Industry Perspective on AEC Information Models for Distributed Collaboration. *Automation in Construction, 8,* 237-248.

APPENDIX A

A.1 Classification of Building Parts in UNIFORMAT II

ASTM Uniformat II Classification for Building Elements (E1557-97)

Level 1 Major Group Elements	Level 2 Group Elements	Level 3 Individual Elements
A SUBSTRUCTURE	A10 Foundations	A1010 Standard Foundations A1020 Special Foundations A1030 Slab on Grade
	A20 Basement Construction	A2010 Basement Excavation A2020 Basement Walls
B SHELL	B10 Superstructure	B1010 Floor Construction B1020 Roof Construction
	B20 Exterior Enclosure	B2010 Exterior Walls B2020 Exterior Windows B2030 Exterior Doors
	B30 Roofing	B3010 Roof Coverings B3020 Roof Openings
C INTERIORS	C10 Interior Construction	C1010 Partitions C1020 Interior Doors C1030 Fittings
	C20 Stairs	C2010 Stair Construction C2020 Stair Finishes
	C30 Interior Finishes	C3010 Wall Finishes C3020 Floor Finishes C3030 Ceiling Finishes
D SERVICES	D10 Conveying	D1010 Elevators & Lifts D1020 Escalators & Moving Walks D1090 Other Conveying Systems
	D20 Plumbing	D2010 Plumbing Fixtures D2020 Domestic Water Distribution D2030 Sanitary Waste D2040 Rain Water Drainage D2090 Other Plumbing Systems
	D30 HVAC	D3010 Energy Supply D3020 Heat Generating Systems D3030 Cooling Generating Systems D3040 Distribution Systems D3050 Terminal & Package Units D3060 Controls & Instrumentation D3070 Systems Testing & Balancing D3090 Other HVAC Systems & Equipment
	D40 Fire Protection	D4010 Sprinklers D4020 Standpipes D4030 Fire Protection Specialties D4090 Other Fire Protection Systems
	D50 Electrical	D5010 Electrical Service & Distribution D5020 Lighting and Branch Wiring D5030 Communications & Security D5090 Other Electrical Systems
E EQUIPMENT & FURNISHINGS	E10 Equipment	E1010 Commercial Equipment E1020 Institutional Equipment E1030 Vehicular Equipment E1090 Other Equipment
	E20 Furnishings	E2010 Fixed Furnishings E2020 Movable Furnishings
F SPECIAL CONSTRUCTION & DEMOLITION	F10 Special Construction	F1010 Special Structures F1020 Integrated Construction F1030 Special Construction Systems F1040 Special Facilities F1050 Special Controls and Instrumentation
	F20 Selective Building Demolition	F2010 Building Elements Demolition F2020 Hazardous Components Abatement

A.2 A Classification of Building Design Performance Factors

1. Amenity, comfort
    - Heat/cold resistance
    - Wind, drafts
    - Water intrusion, leakage
    - Humidity, condensation
    - Light/glare; sight/privacy
    - Sound, noise
    - Accessibility
    - Convenience
    - Apparent cleanliness
    - Odor
    - Appearance
    - Texture, feel

2. Health, safety
    - Emergency (egress/alarm)
    - Falling, tripping, slipping
    - Cutting, breakable materials
    - Fire source
    - Ignitibility, combustibility
    - Fire spread
    - Smoke
    - Accidental explosion
    - Electric shock, static
    - Radiation
    - Chemicals
    - Disease, infection
    - Vermin, animals
    - Intrusion, security, terror
    - Pollution, environmental. Impact
    - Flood
    - Hurricane, tornado
    - Vehicular collision

3. Structural
    - Static, dead loads
    - Live, vertical loads
    - Horizontal, wind loads
    - Seismic loads
    - Impact, concentrated loads
    - Load resistance
    - Deformations

4. Durability
    - Time (service life)

- Time (aesthetic service life)
- Exposure to touch
- Moisture, condensation
- Corrosion, chemical action
- Rot, fungus, insects
- Dirt, grease, stains
- Cleaning, scrubbing
- Abrasion, scratching
- Temperature changes
- Atmosphere, pollution
- Light, ultraviolet
- Vandalism
- Animals
- Hurricane, tornado
- Flood
- Vehicular collision

5. Operational, maintenance
    - Power, water, fuel use
    - Use, misuse
    - Waste, by-products
    - Cleaning, servicing
    - Repairing
    - Replacing
    - Relocating, adapting

Performance factors are adapted from McClendon, S. (2002)

Performance Specifying. http://www.csinet.org/xp/p-cs/i-1998050101/a-910015481/article.view

APPENDIX B

B.1 Suspended Ceiling Design Parameter Definitions[1]

Air Diffuser Layout: The layout of the air diffusers on the suspended ceiling.

Air Diffuser Quantity: The amount of the air diffusers required in the space to which the suspended ceiling is applied.

Air Diffuser Size: The sizes of the air diffusers to be placed within the plenum.

Air Diffuser Weight: The weight of the lighting fixture to be used within the suspended ceiling system.

Air Duct Width and Length: The width and length of the air ducts that are placed in the plenum.

Beam Depth: The clear depth of the beam measured from the lowest point of the slab to the lowest point of the beam.

Building Structure Layout: The layout of the structural members (i.e. beams and columns) of the building.

Floor Area: The area of the space for which a suspended ceiling is designed.

Floor Structure: The type of the structural system of the floor (e.g. reinforced concrete)

Floor to Ceiling Height: The clear height measured from the finished floor level to the finished suspended ceiling.

Hanger Crosssections: The crosssection of the wire employed to suspend the acoustical ceiling from the existing structure.

Hanger Spacings: The distance between the hangers of the suspended ceiling system.

HVAC Distribution Layout: The layout of the HVAC distribution system. There are several system choices available; for example, systems that use only air, systems that use both air and water, and systems that use only water.

HVAC Equipment and Superstructure Integration Scheme: The way the HVAC equipment and the structural members are placed. In general, there are two basic schemes, namely, layered and integrated.

Lighting Fixture Layout: The layout of the lighting fixtures on the suspended ceiling.

---

[1] The parameter definitions are alphabetically listed.

Lighting Fixture Quantity: The amount of the lighting fixtures required in the space to which the suspended ceiling is applied.

Lighting Fixture Size: The sizes of the lighting fixtures to be placed within the plenum.

Lighting Fixture Weight: The weight of the lighting fixture to be used within the suspended ceiling system.

Load Test Data: The load carrying capacity of the main beams and the cross tees of the suspended ceiling.

Main Runner and Cross Tee Color: The color of the main runners and the cross tees.

Main Runner and Cross Tee End Detail: The detail of the uppermost part of the profiles which is used to connect the profiles to the hangers (e.g. peaked or straight).

Main Runner and Cross Tee Face Dimension: The width of the lowest part of the main runner and the cross tee.

Main Runner and Cross Tee Interface: The connection detail of the main runners and the cross tees (e.g. override, or flushfit).

Main Runner and Cross Tee Profile Length: The profile length of the main runners and the cross tees.

Main Runner and Cross Tee Structural Classification: The classification of the system according to the load carrying capability of grid components in kilograms per meter. There are three types in general: heavy duty, intermediate duty, and light duty.

Main Runner and Cross Tee Surface Finish: The type of surface finish applied to the main runners and cross tees.

Main Runner and Cross Tee Web Height: The height of the main runner and the cross tee measured from the face to the top of the top bulb.

Main Runner and Cross Tee Weight: The weight of the main runner and the cross tee.

Maximum Air Diffuser Weight: The maximum allowed air diffuser weight in the suspended ceiling structure.

Maximum Lighting Fixture Weight: The maximum allowed lighting fixture weight in the suspended ceiling structure.

Panel Acoustics CAC: Ceiling Attenuation Class (CAC) rates a ceiling's efficiency as a barrier to airborne sound transmission between adjacent closed spaces.

Panel Acoustics NRC: Noise Reduction Coefficient (NRC) of the suspended ceiling panel rates of ability of a ceiling panel to absorb sound. This value may typically range from 0.4 to 1.00.

Panel Antimicrobial Treatment: A treatment applied to inhibit or retard growth of mold or mildew on products' painted surfaces.

Panel Color: The color of the suspended ceiling panel.

Panel Edge and Joint Detail: The type of joint applied at the panel edges (e.g. reveal, flush reveal, square edge, etc.)

Panel Fire Resistance: The suspended ceiling's property of acting as a barrier to fire. Acoustical ceiling systems form a membrane to contain fire within a room. Fire-rated assemblies are given ratings of one, two, three, or four hours.

Panel Humidity Resistance: The resistance of the suspended ceiling panel to the relative humidity. Standard acoustical panels are designed for installation within the normal occupancy condition range of maximum 70% relative humidity. When the in-service use relative humidity is expected to exceed this range, the use of acoustical units specifically designed for these applications should be considered.

Panel Material: The material of the suspended ceiling panel.

Panel Sag Resistance: The resistance of the suspended ceiling panel to sag.

Panel Surface Pattern: Suspended ceiling panels may be one of or a combination of two or more of the following patterns: perforated, fissured, textured, smooth, printed, embossed, surface scored, and random swirl.

Panel Surface Reflectance: The suspended ceiling's property of reflecting light. The measure of light reflectance is that fraction of the specified incident light, which is reflected by the surface.

Panel Thermal Insulation Value: (R factor) A number measuring a material's resistance to heat flow. R stands for resistance, the inverse of conductivity.

Panel Thickness: The thickness of the suspended ceiling panel.

Panel Weight: The weight of a single panel.

Panel Width and Length: The width and length of the suspended ceiling panels.

Plenum Depth: The space above the suspended ceiling in which beams, HVAC and lighting equipment are concealed.

Required Depth for HVAC Equipment: The required depth for the HVAC equipment that is placed in the plenum.

Required Depth for Lighting Equipment: The required depth for the lighting equipment that is placed in the plenum.

Space Function: The function of the space for which a suspended ceiling is designed (e.g. office, store, restaurant, etc.).

Structural Element Connection Details: The connection details of the structural elements.

Suspended Ceiling Structural Grid Layout: The layout of the structural grid system of the suspended ceiling (e.g. modular grid in one direction, modular grid in both directions, etc.).

Suspended Ceiling Structure-Air Diffuser Connection Detail: The connection detail of the suspended ceiling structure and the air diffuser.

Suspended Ceiling Structure-Lighting Fixture Connection Detail: The connection detail of the suspended ceiling structure and the lighting fixture (recessed, flush finish, etc.).

Suspended Ceiling Type: The type of the suspended ceiling in terms of its structural system (linear/grid, exposed/concealed) and panel type (demountable/fixed).

Wall Angle Crosssections: The crosssection of the profile connecting the suspended ceiling system to the surrounding walls.

B.2 Elevator Design Parameter Definitions

Average Highest Call Reversal Floor: The highest floor the lift visits during before returning to the main floor.

Average Interfloor Distance: Total travel distance of the elevator divided by the number of possible stopping floors above the main terminal level.

Average Number of Passengers per Trip: The average number of passengers carried by the elevator for a single trip.

Average Number of Stops: The average number of stops of the elevator during the Round Trip Time.

Average Passenger Transfer Time: The average time taken to transfer a passenger from one place to another.

Buffer Load: The load that may be transmitted through the buffer to the foundation in which the elevator pit is formed.

Buffer Position: The position of the buffer or bumper in the elevator pit.

Building Population: The anticipated maximum number of people within the facility that the elevator(s) will serve.

Building Structure Layout: The layout of the structural members (i.e. beams and columns) of the building.

Building Style: The style of building e.g. standard or prestige.

Building Type: The type of building in terms of its use e.g. office, housing, education, etc.

Car Ceiling Finish: The finish applied to the ceiling of the elevator.

Car Depth: The horizontal dimensions between the inner surfaces of the car walls measured at right angles to the car width and at 1m above the car floor.

Car Door Finish: The finish applied to the elevator car door(s).

Car Door Opening Configuration: The configuration employed for opening the doors.

Car Door Width: The width of an opening in a hoistway at a landing that enables access into the car.

Car Floor Finish: The finish applied to the floor of the elevator.

Car Grouping: Grouping arrangement of two or more elevators.

Car Handrail Surface Finish: The finish applied to the handrail in the elevator car.

Car Handrail Type: The type of handrail used in the elevator car.

Car Height: The inside vertical distance between the entrance threshold and the constructional roof of the car. Light fittings and false ceilings are accommodated within this dimension.

Car Lighting Type: The type of lighting applied in the elevator car.

Car Mirror Height: The height of the mirror.

Car Mirror Position: The position of the mirror within the elevator car.

Car Mirror Type: The type of mirror placed within the elevator car.

Car Mirror Width: The width of the mirror.

Car Operating Station Display Type: The type of display used in the car operating station.

Car Operating Station Panel Finish: The finish applied to the panel in the car operating station.

Car Operating Station Panel Type: The type of panel used in the car operating station.

Car Panel Finish: The finish applied to the vertical panels of the elevator car.

Car Width: The horizontal dimensions between the inner surfaces of the car walls measured parallel to the front entrance and at 1m above the car floor.

Clear Overhead: The distance between the maximum vertical point of travel of the elevator and the upper bounding surface of the hoistway.

Contract Capacity: The maximum rated load carrying capacity of a passenger elevator in terms of the number of passengers.

Contract Speed: The maximum speed at which an elevator is contracted to travel.

Counterweight: A weight which counterbalances the weight of an elevator car plus approximately 40% of the capacity load.

Door Opening/Closing Time: The time required for opening and closing elevator doors.

Elevator Type: The type of elevator in terms of its main usage and the means for powering the elevator.

Floor Area: The areas of the floors served by the elevator.

Floor Cycle Time: The time taken by an elevator to travel between two adjacent floors including door opening and closing times.

Guide Rail Fixing Positions: Fixing positions of the guide rails to the structure below.

Guide Rail Support Centres: The centres of the guides.

Guide Rail Support Loads: The load imposed by the movement of cables within the guides that must be resisted by the structure.

Hoistway Depth: The horizontal distance between the inner surfaces of the hoistway walls measured parallel to the car depth.

Hoistway Finishes: The finish applied to the hoistway walls.

Hoistway Height: The vertical distance from the lower bounding surface of the hoistway to the upper bounding surface.

Hoistway Width: The horizontal distance between the inner surfaces of the hoistway walls measured parallel to the car width. Width may be single, double, triple etc.

Landing Clearance: The horizontal distance between the elevator car and the landing sill.

Landing Fixtures: Fixtures typically placed on an elevator landing such as push buttons, position and direction indicators, and hall lanterns.

Lifting Beam Load: The load that must be borne by the lifting beam.

Lifting Beam Position: The position of the lifting beam.

Lifting Beam Size: The size of the lifting beam.

Machine Room Depth: The horizontal dimension of the machine room measured parallel to the car depth.

Machine Room Headroom: The vertical distance between the lower bounding surface of the machine room and the underside of the lifting beam.

Machine Room Height: The vertical distance between the finished machine room floor above the well and the machine room ceiling including any lifting beam height.

Machine Room Position: The location of the machine room.

Machine Room Width: The horizontal dimension of the machine room measured parallel to the car width.

Number of Elevators: The number of elevators estimated to be required within the facility as a result of analysis.

Number of Floors Served above Main Terminal: The total number of floors served by the elevator above its datum level.

Passenger Arrival Rate: The rate at which passengers arrive per unit time.

Pit Foundation Size: The Size of the foundation from which the pit is formed.

Pit Headroom: The vertical distance allowed for headroom within the pit.

Pit Sump Recess Depth: The depth of the sump recess below the base of the pit.

Pit Sump Recess Length: The length of the sump recess at the base of the pit.

Pit Sump Recess Width: The width of the sump recess at the base of the pit.

Round Trip Time: The time taken for a complete travel cycle from the main terminal to the highest reversal floor and back.

Single Floor Transit Time: The time taken by an elevator to travel between two adjacent floors when travelling at the contract speed i.e. making no stops at the floors.

Structural Frame Front Clearance: The distance required between the hoistway wall and the outer surface of the elevator car to enable travel.

Structural Frame LH Side Clearance: The distance required between the hoistway wall and the outer surface of the elevator car to enable travel.

Structural Frame Rear Clearance: The distance required between the hoistway wall and the outer surface of the elevator car to enable travel.

Structural Frame RH Side Clearance: The distance required between the hoistway wall and the outer surface of the elevator car to enable travel.

Tenancy Type: The type of tenancy i.e. multiple or single tenancy.

Time Consumed when Stopping: The amount of time that an elevator spends at a landing when making a stop.

Type of Guide Rails: The type of guide rails used in the elevator system.

Uppeak Handling Capacity: The handling capacity of the elevator at peak demand when travelling upwards.

UpPeak Interval: The interval between arrival of elevators at a given point at peak time for upward travel.

With Car Mirror: Whether or not a mirror is used in the elevator car.

With Gearing: Whether or not gearing is used in the elevator.

With Handrail: Whether or not a handrail is used in the elevator car.

APPENDIX C

C.1 A Computer Program For Building the Design Structure Matrix

This program was developed by Qi Dong (1999) using Microsoft EXCEL Visual Basic and modified by Sait Emre Pektaş to include parameter classification schemes proposed in this dissertation. This appendix provides information on user instructions, user interface, as well as the actual program codes.

User Instructions

1. In the sheet “system description,” in Cell 1B, type in the total number of system parameters. Starting from Cell 4A, type in the list of system parameters.
2. Using the “Fill Color” tool of Microsoft Excel, assign colors to different parameters or group of parameters according to the classification scheme you want to apply (Figure 1).

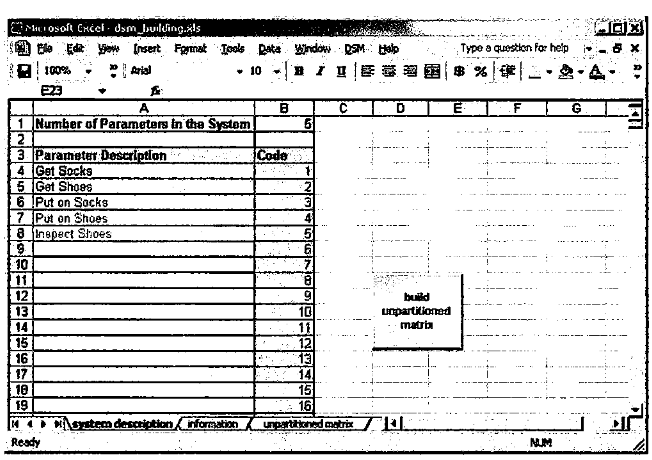


Figure 1. System Description Sheet

3. Open the sheet “information” and enter all the existing relations. The elements that provide information must be entered into the “From” column, and the elements that receive information must be entered into the “To” column. At the end of the “From” column, type in “end” (Figure 2).

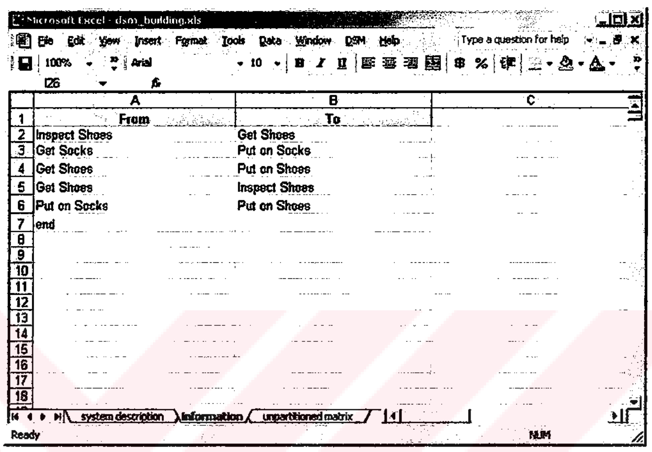


Figure 2. Information Sheet

4. Open the sheet “unpartitioned matrix” and clear contents.
5. Open the sheet “system description” and click the button “build unpartitioned matrix”
6. Open sheet “unpartitioned matrix” to view the resulting matrix (Figure 3).

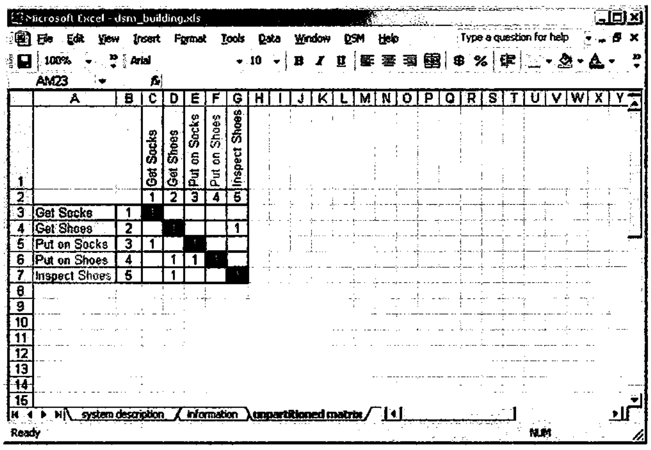


Figure 3. Unpartitioned Matrix

The Program Code in Microsoft Visual Basic

```
'
' build_unpartitioned_matrix Macro
'
'

Public i As Integer 'i records the total number of system elements in the
matrix
Public parameter(150) As String 'parameter array records all the system
elements in the matrix
'assume the system parameter won't be more than 150
Public R(150, 150) As Integer

Sub build_unpartitioned_matrix()
  Dim judge, k, m, judge1 As Integer
  Dim m1, m2 As Integer
  Dim counter, counter1 As Integer

   'find the number of parameters and assign the value to i
   Sheets("system description").Select
   Cells(1, 2).Select
   i = ActiveCell.Value
   Cells(4, 1).Select

   'assigning the system element titles to the parameter array
   For counter = 1 To i
      parameter(counter) = ActiveCell.Value
      Cells(4 + counter, 1).Select
   Next counter

   'set initial values of R(m,n)
```

```
    For counter = 1 To i
        For counter1 = 1 To i
            If counter = counter1 Then
                R(counter, counter1) = 1
            Else
                R(counter, counter1) = 0
            End If
        Next counter1
    Next counter

    'assigning the value of parameter relation to R(m,n)
    Sheets("information").Select
    judge = 1
    k = 2
    Do Until judge = 0
        judge1 = 1
        m = 1
        Cells(k, 1).Select
        Do Until judge1 = 0
            If Cells(k, 1).Value = parameter(m) Then
                judge1 = 0
            ElseIf m > i Then
                judge1 = 0
            Else
                m = m + 1
            End If
        Loop
        m1 = m
        Cells(k, 2).Select
        judge1 = 1
        m = 1
        Do Until judge1 = 0
            If Cells(k, 2).Value = parameter(m) Then
                judge1 = 0
            ElseIf m > i Then
                judge1 = 0
            Else
                m = m + 1
            End If
        Loop
        m2 = m
        R(m2, m1) = 1
        k = k + 1
        If Cells(k, 1).Value = "end" Then
            judge = 0
        End If
    Loop

'output un-partitioned matrix
Sheets("unpartitioned matrix").Select
```

```
'fill in matrix titles
For counter = 3 To i + 2
   Cells(counter, 1).Value = parameter(counter - 2)
   Cells(1, counter).Value = parameter(counter - 2)
Next counter

'fill in R(m,n) values in the matrix
   For counter = 1 To i
      For counter1 = 1 To i
         If R(counter, counter1) = 1 Then
            Cells(counter + 2, counter1 + 2).Value = R(counter, counter1)
         End If
      Next counter1
   Next counter

End Sub
```

C.2 A Computer Program For Partitioning and Banding the Design Structure Matrix

This program was developed by MIT DSM team (2001) using Microsoft EXCEL Visual Basic and modified by Sait Emre Pektaş to include parameter classification schemes proposed in this dissertation. This appendix provides information on user instructions, user interface, as well as the actual program codes.

User Instructions

1. Open the file that you have produced the initial matrix with the program explained in the previous appendix; open the sheet "unpartitioned matrix" and copy the contents.
2. Open a new file including the macro presented in this appendix and paste the initial matrix in the sheet "DSM" (Figure 1).

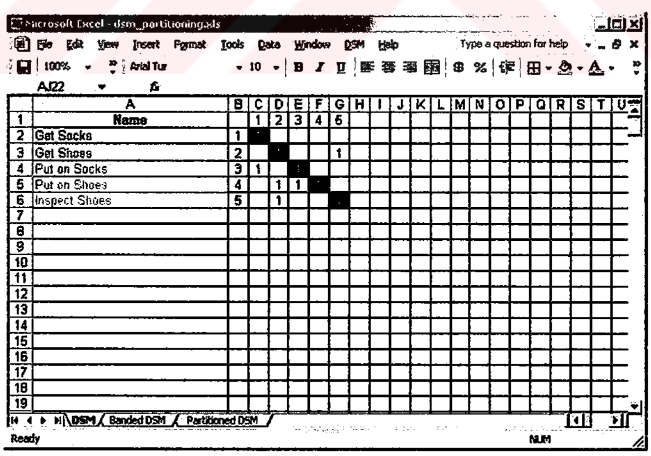


Figure 1. Initial DSM in the Partitioning Program

3. Open the "DSM" menu in the menu bar of EXCEL and choose the "partition DSM" option.

4. Open the sheet "partitioned DSM" to view the partitioned matrix.

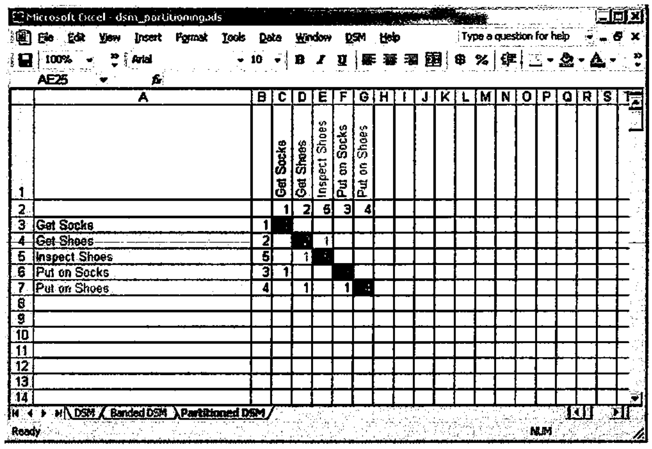


Figure 2. Partitioned DSM

5. Open the "DSM" menu in the menu bar of EXCEL and choose the "band partitioned DSM" option.
6. Open the sheet "banded DSM" to view the banded matrix.

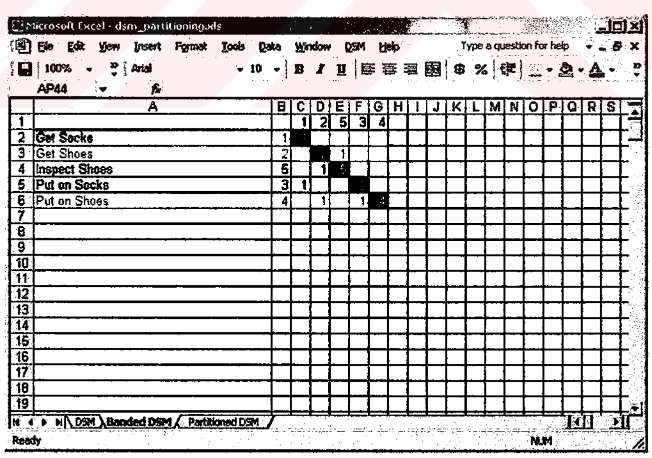


Figure 3. Banded DSM

The Program Code in Microsoft Visual Basic

```
' Reachability Macro
' This macro partitions the matrix based on the reachability matrix result
'
Option Explicit
Option Base 1
Public reach As Variant    'reach contains the elements in the
reachability matrix
Dim temp1, temp2 As Variant
Public color(150)

Sub reachability_matrix()

    Dim i, j, k, m As Integer
    ReDim reach(n, n), temp1(n, n), temp2(n, n)
    Dim counter As Integer

''''''''''''''''''''''''''''''''''''''''''
' Clear contents

Application.ScreenUpdating = False

Partitioned = 1                    ' flag to indicate that the problem is
partitioned now

    'Worksheets("DSM").Select

    'Cells(2, 1).Select

    'counter = 1
    'Do While (Len(ActiveCell.Value) > 0)
    '   color(counter) = ActiveCell.Interior.ColorIndex
    '   counter = counter + 1
    '   Cells(1 + counter, 1).Select
    'Loop



    Worksheets("New Sequence").Select
    Range(Cells(1, 2), Cells(250, 250)).Select
    Selection.ClearContents
    Cells(1, 1).Select

    Worksheets("Partitioned DSM").Select
    Range(Cells(1, 1), Cells(250, 250)).Select
    Selection.ClearContents
    With Selection.Interior
        .ColorIndex = 2
        .Pattern = xlPatternNone
```

```
    End With

    For i = 1 To n
    Cells(i + 2, i + 2).Select
    With Selection.Interior
       .ColorIndex = 1
       .Pattern = xlSolid
    End With
    Next i
''''''''''''''''''''''''''''''''''''''''''''''''

    For i = 1 To n                          'loading DSM(n,n,1) values
       For j = 1 To n
          DSM(i, j, 1) = Worksheets("DSM").Cells(i + 1, j + 2)
       Next j
    Next i

For i = 1 To n
    DSM(i, i, 1) = 1
Next i

For i = 1 To n
    For j = 1 To n
       temp2(i, j) = DSM(i, j, 1)
    Next j
Next i

Sheets("DSM").Select                        'loading parameters
Cells(2, 1).Select
For i = 1 To n
    Parameter(i) = Cells(i + 1, 1)
    color(i) = ActiveCell.Interior.ColorIndex
    Cells(2 + i, 1).Select
Next i

'start calculating the reachability matrix
    For i = 1 To n - 1
       For j = 1 To n
          For k = 1 To n
             temp1(j, k) = temp2(j, k)
          Next k
       Next j
       For j = 1 To n
          m = 1
          Do Until m > n
             For k = 1 To n
                temp2(j, m) = temp1(j, k) * DSM(k, m, 1) + temp2(j, m)
                If temp2(j, m) > 1 Then temp2(j, m) = 1
             Next k
             m = m + 1
```

```
        Loop
      Next j
    Next i

'now, the final temp2 array contains the answer for the reachability
matrix
'so give the values in temp2 to the reachability matrix
    For i = 1 To n
      For j = 1 To n
        reach(i, j) = temp2(i, j)
      Next j
    Next i

Partition
Find_Levels

End Sub

' partition Macro
' This macro partitions the matrix based on the reachability matrix result
'
Option Explicit
Option Base 1
Public row As Variant
'row(x,y) contains the reachability set of each element in DSM
'x indicates the element in the matrix this variable is associated with
'y indicates the order of the variable in the reachability set of element
Public column As Variant
'column(x,y) contains the antecedent set of each element in DSM
'x indicates the element in the matrix this variable is associated with
'y indicates the order of the variable in the antecedent set of element
Public total_row As Variant 'total number of elements in the reachability
set
Public total_column As Variant  'total number of elements in the
antecedent set

Sub Partition()
Dim i, j, k As Integer
ReDim row(n, n), column(n, n)
ReDim total_row(n), total_column(n)

Application.ScreenUpdating = False

For i = 1 To n
   'assign values to the reachability set of element i
    k = 0
    For j = 1 To n
      If reach(i, j) <> 0 Then
        k = k + 1
        row(i, k) = j
```

```
         End If
      Next j
      total_row(i) = k
      'assign values to the antecedent set of element i
      k = 0
      For j = 1 To n
         If reach(j, i) <> 0 Then
            k = k + 1
            column(i, k) = j
         End If
      Next j
      total_column(i) = k
   Next i

   End Sub


   ' banding Macro
   ' This macro creates bands in the matrix
   '

   Sub Banding()                    'finds the most upstream set of activities
   that can be worked concurrently in the time step

      Dim in_band As Boolean


      For i = 1 To n
         WN(i) = False              'initialize all activities to do NO work during
   this time step
      Next i
      j = n + 1                     'keeps from looking for full band when no
   activities left

      For i = 1 To n                'find first activity that can do work during the
   current time step
         If W(i) > 0 Then
            WN(i) = True
            j = i + 1               'sets j to the following activity
            Exit For                'leave loop once the first activity is found
         End If
      Next i

     ' band_complete = False        'all activities for band have not been
   found

      Do While j <= n               'begin to identify remaining activities in
   the band
         If W(j) > 0 Then           'if next activity needs work
            in_band = True
```

```
        For k = i To j - 1
           If (Partitioned_DSM(j, k, 2) > 0) And (W(k) > 0) Then  'if
dependent on an upstream activity needing work
              in_band = False          'then the complete band has been
found
              Exit For
           End If
        Next k                          'keep checking vs. activities in band
        If in_band = True Then
        WN(j) = True                    'if complete band not yet found...
        End If
     End If
     j = j + 1
  Loop                                  'see if next activity can be added to the
band

End Sub
```