PRODUCT ORIENTED COORDINATION BETWEEN DESIGN AND CONSTRUCTION

SONG HONGBIN

NATIONAL UNIVERSITY OF SINGAPORE

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SONG HONGBIN

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SUMMARY

Design and construction are two of the most important stages in the lifecycle of an AEC project. Traditionally, the AEC industry has separated these two stages, resulting in numerous problems since the constraints that each stage puts on the other cannot be fully taken into account. In recent years, design-build has been proposed as an optimal project delivery approach aiming to integrate design and construction. The success for design-build requires careful consideration of the interdependent relationships between design and construction. Problems often occur due to inappropriate management of these relationships. Thus, it is imperative to improve the coordination between design and construction.

This thesis proposes a model to coordinate design and construction activities. The model aims to manage the interdependence between design and construction. The coordination model employs product as the interface since it is the common link between design and construction. The framework of the model is composed of four main parts, namely, parameter, product, design and construction. Parameters play an important role in the coordination, connecting product with design and construction. Any product component can be described by a set of parameters corresponding to different properties of the component. At the same time, parameters are also important to depict design and construction processes since the design activities are concerned with the determination of these parameters while the construction activities realize these parameters based on their values determined in the design stage. For a parameter, it can be in different states during design and construction. Thus a state chain pictures the evolution of the parameter. The state transformations correspond with different process activities in design and construction. A process activity is characterized by its information inputs and outputs which can be described using parameter states.

Furthermore, much related information about parameter states can be grouped to form deliverables (drawing, as-built measurement, etc.).

The whole dependency network is formed by connecting the process activity—parameter state relationships. The network is inherently a network of information dependencies which represents the links between process activities and their information constraints. The fundamental purpose of coordination is to ameliorate the relationship between required information flows and corresponding process sequence. This thesis suggests several practical means to deal with information coordination problems.

This thesis also presents a case study to illustrate the working principles of the coordination model. The coordination model should be effective in dealing with design-construction coordination issues. This model may be of great benefit to project managers who are always frustrated by coordination problems between design and construction. Thus, the application of the model may improve the efficiency of AEC projects.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The architecture, engineering, and construction (AEC) industry has a long history. It contributed and is contributing to the development of world economy. Meanwhile, theories and technologies in AEC have been developing and maturing. A lot of research work has been done in managing AEC projects so as to improve the effectiveness and efficiency.

An AEC project is very complex in that it is composed of many interconnected stages and there are a lot of interdependent participants (Olsson, 1998; Rivard et al., 1995; Sanvido, 1992). These stages include design, procurement, construction, maintenance and so on, each of which contributes to the intended project based on the predefined role. Among the participants involved in a project are client, architect, structural engineer, service engineer, contractor, sub-contractor, supplier, facility operator, to name a few. An essential ingredient of a successful project is good communication and collaboration between the project participants. Due to the fragmentation of these stages and the large number of participants required by the increasingly complex and dynamic nature of today's projects, the need for well-structured collaboration and coordination has become more important than ever.

In the stages to realize a project, design and construction are of great importance and have been the areas of much research (Luiten et al., 1998). Design stage transforms client requirements into drawings and specifications, which are then turned into reality through construction stage. Traditionally, design and construction are treated as two relatively isolated processes (Anumba and Evbuomwan, 1996), each of which is completed by its own team members, namely designers or contractors. This renders many problems (Anumba and Evbuomwan, 1996) since the constraints that each stage puts on the other are not fully considered (Austin et al., 2000a). Thus, the integration of design and construction has been proposed to be the optimal approach to successfully eliminate some of the major problems in the AEC industry. In recent years, the AEC industry has witnessed a growing interest in the area of integration of design and construction (Anumba and Evbuomwan, 1996). Furthermore, AEC clients are looking for companies that can provide complete products to them rather than separate ones (Luiten et al., 1998). All these promote the design/build project delivery approach aiming to integrate these two stages. Because of its obvious advantages compared with traditional approach, design/build has become more and more popular in practice.

However, the success for design/build is not always as easy to reach as expected. Design/build only aligns the interests of designers and constructors. When it comes to production level, many efforts need to be taken to coordinate design and construction. At the production level, a variety of constraints must be fully taken into account in order for design and construction work to be carried out successfully. These constraints include engineering, resources, prerequisite work and so on which come from diverse sources such as clients, designers, contractors, and external regulating authorities. For the coordination of design and construction, the most important constraints are the inter-stage constraints. In other words, design provides information as prerequisite to construction and construction may affect design by as-built measurement information feedback. Since these constraints involve both designers and contractors, the management of them is a formidable task. In addition, it is now common that AEC clients are demanding that projects be delivered in greatly reduced time frames (Bogus et al., 2000). This exacerbates the coordination problem. Thus, it is imperative to deal with coordination between design and construction.

1.2 RESEARCH OBJECTIVES

The main objective of the dissertation is to develop a model to coordinate the design work and construction work in an AEC project. The model aims to deal with the interdependent relationships between design and construction. Since the interactions between design and construction cannot be separated from design process and construction process, relevant design knowledge and construction knowledge should be included in the research to deal with the interactions. For design, the analysis is biased toward the later stages which tend to be relatively structured and concentrates less on the conceptual, creative or otherwise unstructured aspects. For construction, the original network is deemed to be available. Then the main work focuses on the management of relationships between design and construction and within design stage while the construction stage is less discussed. However, this doesn’t mean that construction knowledge will not be addressed. The traditional construction network needs some changes to cater for the need of coordination. The relationships are formed in terms of information requirement/production. However, the information involved in AEC projects is highly complex. This study mainly deals with information produced during design and construction while paying less attention to the various requirements and constraints which come from clients, regulating authorities, codes and so on.

Below are the specific objectives:

1. Propose an appropriate coordination mechanism. A proper mechanism is very important to the success of coordination between design and construction. This mechanism should be able to effectively deal with the relationship between design and construction.

2. Establish information requirement/production for design and construction. The relationship between design and construction is formed based on information dependencies.
3. Derive dependency network. Through information dependencies, a network will be established which includes both design and construction. It is the whole network that is of concern. This network is the basis for coordination.
4. Analyze and manage the dependency network. The dependence network provides information dependences for process. Some typical approaches will be suggested to manage the dependence relationships so as to improve the coordination.

1.3 RESEARCH METHODOLOGY

The research was conducted as follows:

(1) Find out coordination problems existing in AEC projects;

(2) Determine the basic research direction;

(3) Detailed literature review to have an understanding of the research direction;

(4) Determine specific research scope;

(5) Propose models to solve the problems;

(6) Collect data in case study;

(7) Use the case data to testify and optimize the model.

1.4 RESEARCH CONTRIBUTIONS

Through the coordination model, the two relatively independent networks -- design network and construction network, can be connected. This insures that as much relevant information as possible is made available to the involved party that requires it in design and construction. Thus, continuous information flow is achieved so as to improve the coordination.

This model may be of great benefit to project managers who are always frustrated by coordination problems. In AEC projects, coordination-related problems often occur between design and construction. Using this model, these problems may be settled with ease. Thus, the application of the model may improve the effectiveness and efficiency of AEC projects.

1.5 DISSERTATION OUTLINE

This chapter briefly introduces the scope of the research. Chapters 2 to 5 will present the dissertation clearly. To enable readers to fully understand the research concept, chapter 2 gives a detailed review of the relevant work that has been carried out in the research area. As the main part of the dissertation, chapter 3 describes the proposed model. After that, chapter 4 presents a case study to illustrate the working principles of the model. Finally, chapter 5 provides conclusive remarks for the dissertation.

CHAPER 2

LITERATURE REVIEW

Extensive literature review has been conducted to gain a better understanding of the research topic. The materials reviewed cover five key research areas, namely, coordination, product and process integration, product model, design management and construction management, which are all related to the intended research topic.

2.1 COORDINATION

Coordination problems arise naturally in a variety of disciplines such as engineering design, computer science, organization theory, sociology, political science, management science, systems theory, economics, linguistics, and psychology. In recent years, there has been a growing interest in coordination-related problems. Since coordination is a crucial problem in almost all these disciplines, it has been an area of much research and continues to be a focus of considerable attention.

Coordination has a variety of definitions (Malone and Crowston, 1990, 1994). Malone and Crowston (1994) suggested that “Coordination is managing dependencies between activities.” In an AEC project, the different tasks are interdependent in one way or another since they are related to the same project (Olsson, 1998). This suggests that Malone and Crowston’s definition is applicable to the AEC industry. The need for coordination is closely related to the degree of interdependence between different activities (Kadefors, 1995). Different kinds of dependencies need different coordination processes to manage them (Malone and Crowston, 1994). Furthermore, Malone and Crowston (1990) concluded that interdependence between activities can be analyzed in terms of common objects that are involved in some way in these activities. This idea is very important since it suggests a coordination mechanism which is adopted in this research.

In addition, Albino et al. (2002) showed that the coordination of a process mainly consists of the processing of the information necessary for the management of interdependent activities. They proposed a methodology to describe and analyze the information flows involved in the coordination of production processes. In their methodology, a production process is considered as an information processing and communication system where actors (resources) perform tasks, send and receive messages, and process information. Information flows consist of exchanged messages and information processing activities which are necessary for the process coordination and deal with such issues as the agreement among decision-makers. Figure 2.1 shows the framework of their methodology. The key factors affecting the information flow within a production process are identified including the production process, the coordination form, and the context. Based on these factors, the methodology can derive a quantitative index that measures the information flows, i.e. the effort required to properly coordinate the production process. By simulating different coordination mechanisms of the process, the associated quantitative index can be used to select the best options.

While the idea is accepted that the coordination of a production process is closely related to the information flows, and indeed it is used as a fundamental basis for the proposed model in this research, it is questionable that the methodology can be applied to the intended research topic. The main objective of this methodology is to measure information flows on the premise that production process network is available. In other words, only after the task dependencies are identified, can the information flows be derived. However, what the intended research concerns is the coordination of the process based on information flows rather than the measurement of information flows in the coordination process.

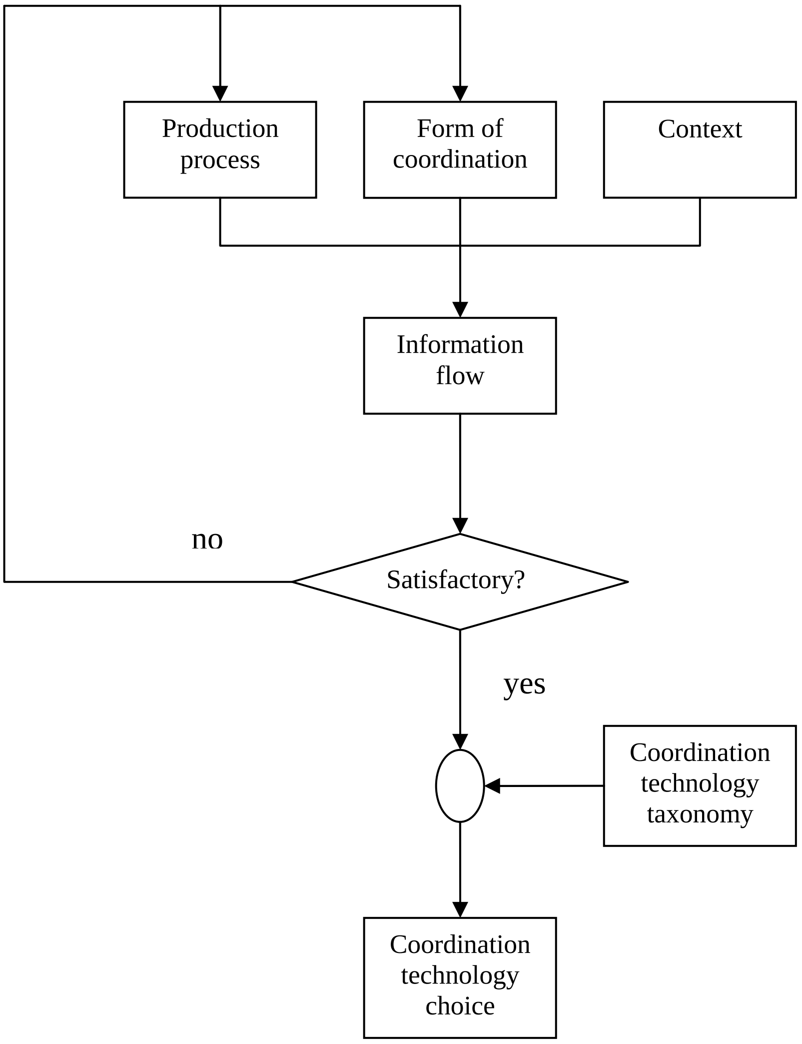


Figure 2.1 Information Flow and Coordination of Production Processes

This research intends to deal with coordination problems between design and construction in AEC projects. The basic ideas in coordination theory can be adopted in this research. Thus, analysis of interdependencies between design and construction is fundamental to coordination. Since AEC area is information-intensive, information flow exists between design and construction. Coordination will focus on information related dependence relationships. A proper mechanism is essential to the success of coordination. In an AEC project, design and construction are all related to the product information. Thus, coordination between design and construction can use the common object -- product as interface.

2.2 PRODUCT AND PROCESS INTEGRATION

The AEC area is information-intensive (Shahid and Froese, 1998). Over these years, the industry has always been bedeviled with great difficulties in managing information flow among its participants (Ndekugri and McCaffer, 1988). With the increasing complexity of AEC projects, effective management of information has become more and more critical throughout the life of AEC projects. The industry has always been looking for approaches and tools to streamline the job of information management (Rezgui, 2001).

To address information management in AEC industry, it is necessary to develop an understanding of the information within an AEC project. Sanvido (1992) presented an Information Architecture (IA) to picture the information contents in an AEC project. Figure 2.2 shows an overview of all the IA elements. The Information Architecture consists of five separate but related classes of information, namely, product, process, process control, feedback, and constraints. Another effort in modeling the information contents is the various project models. Project modeling primarily deals with the overall information in a project (Luiten et al., 1993; Luiten et al., 1998; Stumpf et al., 1996). The most important project models developed include Unified Approach Model (Bjork, 1992a), GenCOM (Froese, 1992), BPM (Luiten and Bakkeren, 1992; cited in a review by Luiten et al., 1993), IRMA (Luiten et al., 1993) and ICIM (Stumpf et al., 1996).

These models provide frameworks for the overall information classes in an AEC project. It can be seen that product and process are two of the most important

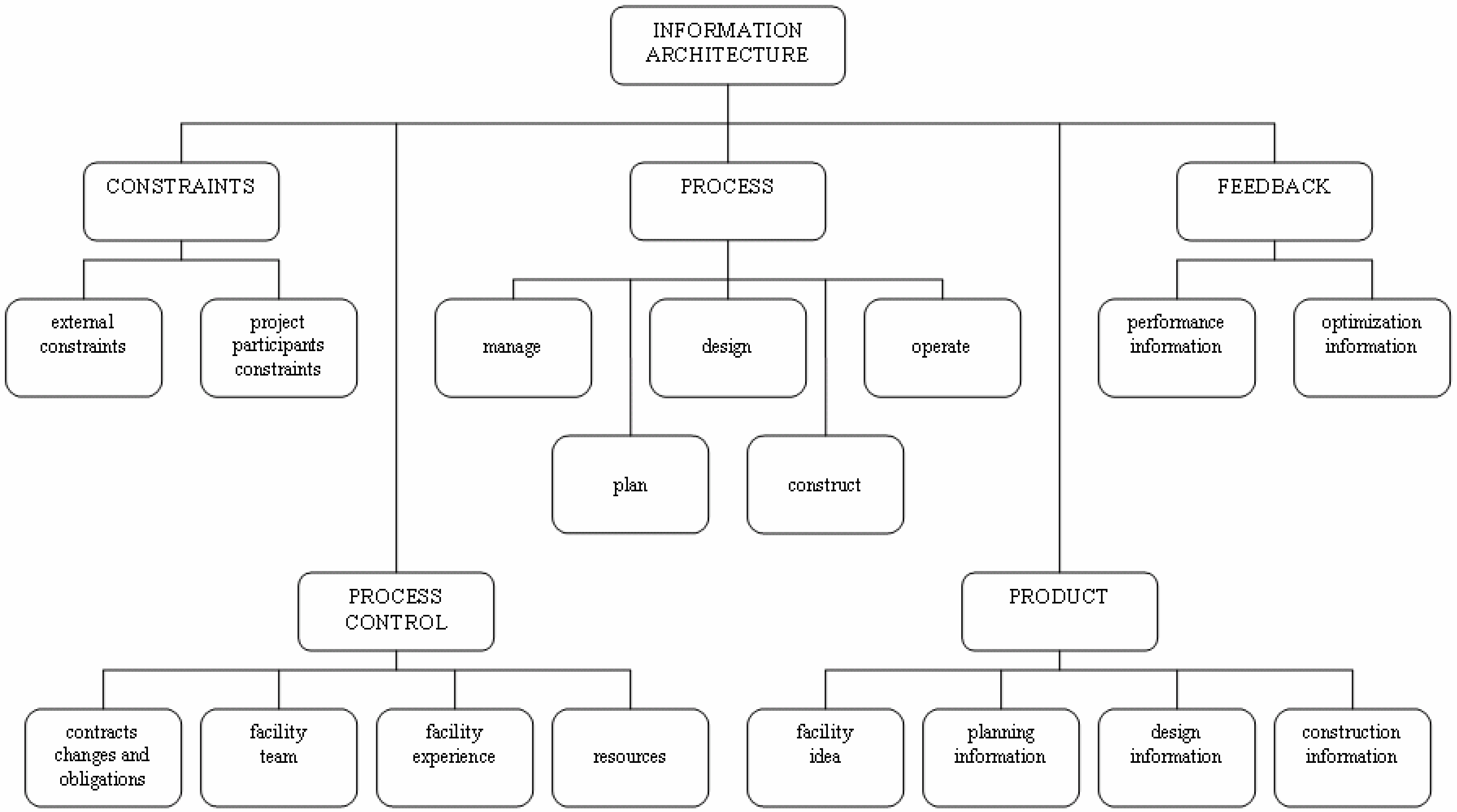


Figure 2.2 Functional Tree of the Conceptual IA Framework

elements, which deal with different kinds of information (Platt, 1996). They are regarded as different views about the project, while each provides a valuable contribution. Product mainly deals with static project information. It contains information regarding what the product looks like. Product status changes with the progress of the process. Although a product undergoes changes as process advances, it provides little information on how these changes can be achieved. Consequently, product information is inadequate for dealing with the dynamics of a project. By contrast, process is rich in information on how a product is transformed from one state to another. It is the dynamics that are of concern. However, process itself provides little insight into the structure and requirements of data within the product.

Traditionally, product and process have been developed independently since the focus on them is quite different (Froese, 1996). This eases the development and makes the model development more flexible (Dubois and Cutting-Decelle, 1996). There is, however, a growing awareness that if these two kinds of models could be successfully integrated with each other, there would be cumulative benefits to be achieved throughout the design and construction process (Platt, 1996). In reality, product and process are interrelated in that process is responsible for product change and product provides information constraints to process, which provides the opportunity for integration.

To make the integration possible, Dias and Blockley (1994) identified a close structural correspondence between product and process models for design through the definition of the role as a generic unit. A process model role has been defined as a collection of responsibilities while a product model role is simply a collection of functions. The organizational relationships of roles have been identified including aggregation/decomposition and generalization/specialization. Such correspondence makes the design process efficient and synergistic. However, this effort only tries to provide structural correspondence between product and process, while interrelationships between product and process have been given less attention. Furthermore, Lee et al. (1996) developed an entity-based integrated design product and process model which used product and process entities to describe design information and design activities, respectively. In this model, the relationships among the entities were identified including organizational, interaction, and sequence relationships. Organizational relationships provide a logical arrangement of product and process entities by organizing entities into hierarchies. Interaction relationships refer to the interdependent nature among product information while sequence relationships identify the sequences in which process entities are initiated during the design process. In this model, the researchers present formal representation for entities and relationships so as to provide a clear understanding of and a theoretical basis for the computer-integrated design system. However, this model focuses on structural design, providing a procedure for building structures design. This model cannot deal with the design of other systems, which are also important for a building. It should be noted that these efforts focus on product and process integration for design stage, while the construction stage is not addressed.

As a major effort to model information classes, the various project models also provide information to product and process integration (Froese, 1996). These models show the relationships between the information elements including product and process. Generally, they treat product as design results and focus on the construction stage when it comes to process analysis. Thus they only provide mechanisms for the integration of design results (product information) with construction process (process information). The design evolution information is rarely discussed in detail in these frameworks.

As another effort, Sanvido (1992) explored an approach to linking the different levels of abstraction of a building design to both a product and a process model. In this approach, design and construction are all included in the process model. Thus, design, construction and product can be connected in this approach. For design and construction, however, this approach only considers one-way information flow -- from design to construction. The as-built information feedback is not taken into account which flows from construction to design.

The integration of product and process establishes the connection between product and process, which is considered as one necessary step for the product-oriented coordination. As described, researchers have done much work in this area and they employ different mechanisms to integrate product and process. While these researches are beneficial, they all have some limitations in terms of coordination between design and construction. Generally, process objects are at the very kernel of these models. The linking between design and construction is performed from a process viewpoint in that process and product are connected through process output, which is defined as group of documents. Thus the linking only provides high-level relationships between product and process. Detailed information links between design and construction cannot be tracked in these models. The proposed model in this dissertation also involves product and process integration. However, it deals with this problem from a different viewpoint—parameter viewpoint. It is a more efficient tool with the capability to deal with the coordination between design and construction based on the evolution of parameters.

2.3 PRODUCT MODEL

In recent years, computers have been used in numerous disciplines. Because of their apparent advantages, computers have also become prevalent in the AEC area. The use of computers considerably improves the capacities of handling the huge amount of information that characterizes an AEC project, which is deemed almost unbelievable for manual, paper-based work. However, most of the applications are isolated, which makes the information sharing and exchange impractical. Thus, computer integrated construction (CIC) emerges with the aim to integrate the different applications. Research and development in the area of CIC has been looking into various aspects of fragments in the construction industry (Turk et al., 2000), exploring the sharing and exchange of project information among all project participants and all project life-cycle stages.

A cornerstone of CIC is the development of data standards, i.e., common information models (Froese, 1996). Among them is the development of standards for the description of buildings in computerized form, so called product models. The introduction of product models represents a revolution to information handling in that the use of product models ease information exchange and information sharing.

2.3.1 Introduction

A product model is a conceptual description of a product which includes the necessary information for that product. Product models contain large amount of information regarding products. Generally, a product model is developed as a common language for a particular type of product rather than as a representation for a single product (Bjork, 1992b).

Several scholars (Bjork, 1989; Bjork and Penttila, 1989; Rivard and Fenves, 2000) addressed the requirements for product models. Two of the most important requirements are multi-view representation and dynamic extension, which are essential characteristics for a practical product model. Multi-view representation is necessary for a product to accommodate different disciplines (Dias, 1996; Howard et al., 1992; Rivard et al., 1999; van Nederveen and Tolman, 1992). It is the foundation of collaborative design (Rosenman and Wang, 1999). Functions are considered as the basis for multi-view representation since different disciplines are interested in different functions of a product (Rosenman and Gero, 1996). Furthermore, a product model should be extensible since it is very difficult to develop an all-inclusive product model (Eastman, 1992; Eastman and Fereshetian, 1994; Ekholm and Fridqvist, 1998; Rivard and Fenves, 2000). Thus, a product model acts as a basis for application so that a user can create new information when necessary.

The basic concepts used in almost all product models are objects, attributes and relationships (Bjork, 1992b; Eastman and Fereshetian, 1994; Shimodaira, 1992). They play fundamental roles in product modeling. An object may correspond to a physical or abstract entity meaningful to the product. Objects use attributes to represent their different aspects of properties. Relationship is used for connecting objects. The two basic types of relationships are decomposition/aggregation and specialization/generalization. Decomposition/aggregation is used for relating different level objects. Generally, the low level objects have “part of” relation with high level object in the decomposition/aggregation relationship. A given global product can have a number of aggregation/decomposition hierarchies where objects can also display cross-hierarchical interactions. Specialization/generalization is used to connect a class of individual objects of similar types with a single named object. The basic idea is to specify all general information on a class level and then to define additional distinguishing parameters on the subclass level. Generally, “type of” relations exist in the specialization/generalization abstraction. In this abstraction hierarchy, data can be managed efficiently by using common attributes which descendent objects inherit from a generic object. These two kinds of relationships form two kinds of orthogonal hierarchies where generalization/specialization hierarchies are defined at each hierarchical level in the aggregation/decomposition hierarchy (Dias and Blockley, 1994). Generally, the generation/specialization hierarchies can be treated as libraries, members of which are instantiated to form members of various aggregation/decomposition hierarchies, which together constitute the model of the global product.

2.3.2 Product Models

In the AEC area, a variety of product models have been developed by both industry and academia. All these efforts aim to provide a foundation for product representation. However, the application scope for these models is different. Some of them are more generic and describe the information structure for a whole branch of industry while others are more specific and describe the information structure for a restricted type or family of products.

RATAS (Developed by the RATAS committee in Finland) is one of the best known product models (Bjork, 1989, 1994; Bjork and Penttila, 1989). RATAS provides an approach to describe building products. Figure 2.3 gives an illustration of RATAS representation. Five abstraction levels, namely, building, system, subsystem, part and detail, are used to describe a building functionally. Objects from the higher levels are especially useful in early design stages for defining functional requirements and for making high-level design choices while objects from the lower levels are more tangible so that they correspond with detail design process. Each of the objects belongs to at least one class. Classes can be arranged in meaningful hierarchies. Two types of relationships are used: part-of and connected-to. Generally, the part-of relationship connects objects from different abstraction levels while connected-to relationships connect objects from the same level (usually lower abstraction levels).

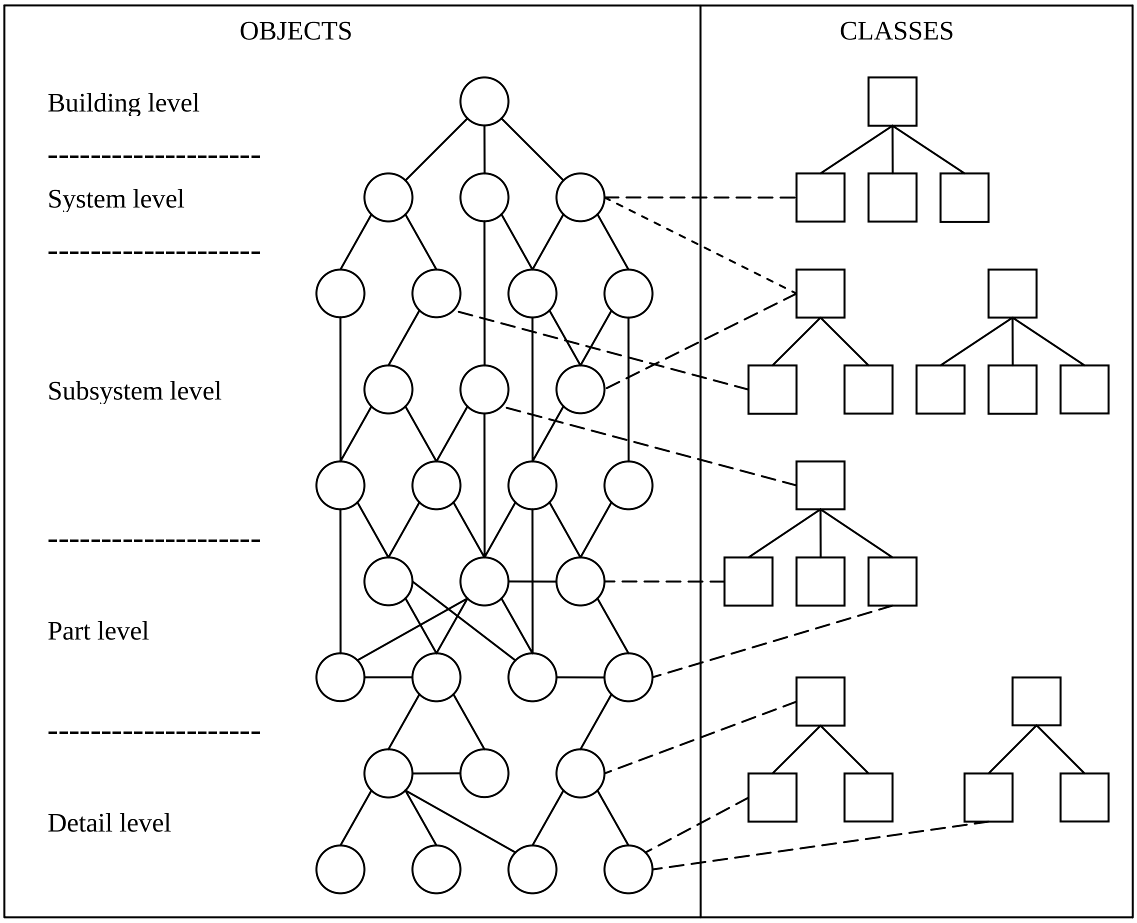


Figure 2.3 Overall Structure of the RATAS Model

Another important product model has been developed in SEED-Config, which is one of the modules of SEED (Software Environment to support the Early phases in building Design) (Fenves et al., 2000; Rivard and Fenves, 2000; Rivard et al., 1996). This building representation consists of two levels of abstraction models defined on top of the object-oriented data model. The first level is an information model, called the BENT (Building ENtity and Technology) model, which defines a set of basic constructs that can represent any building design domain. Figure 2.4 shows the class

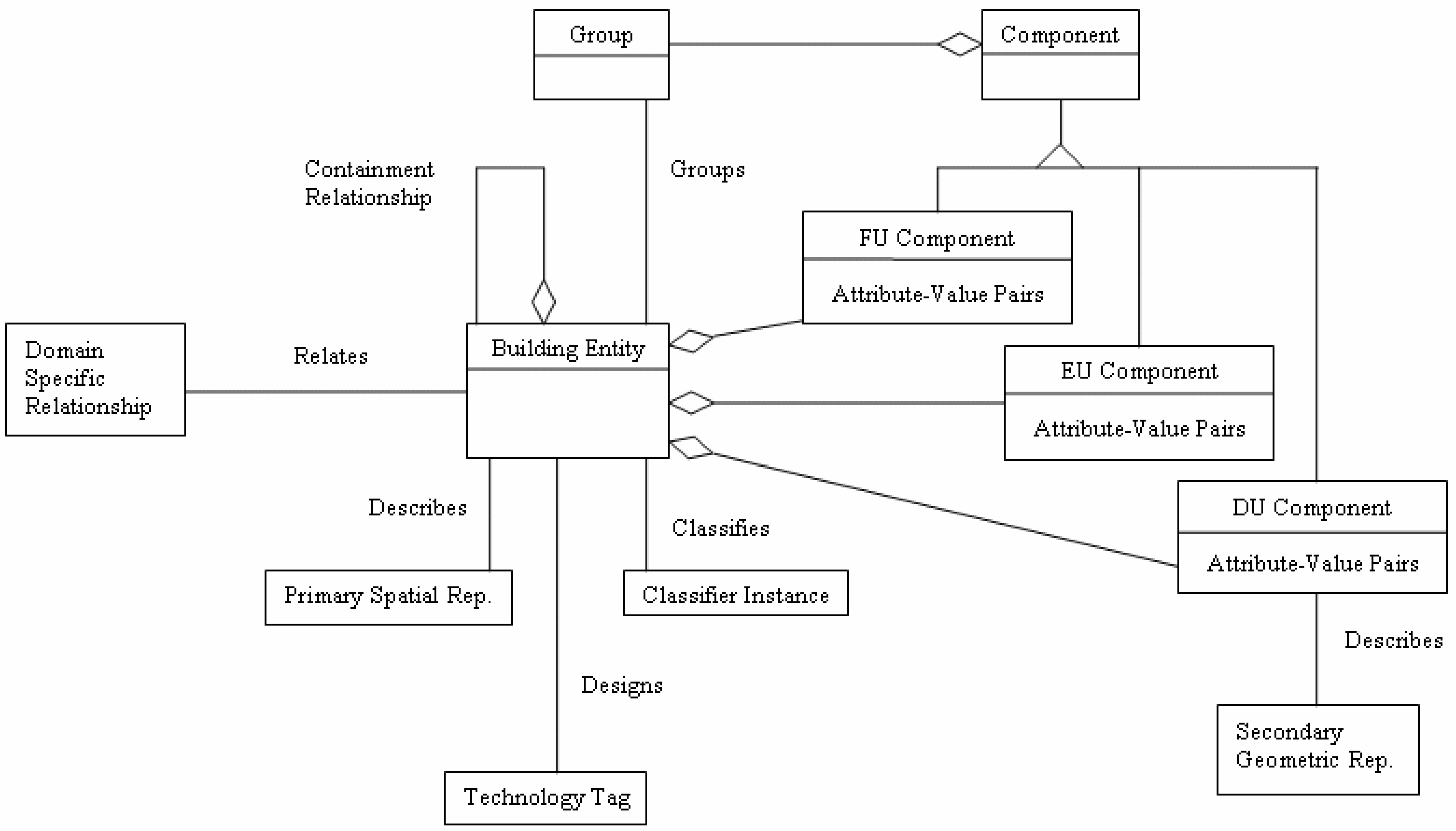


Figure 2.4 Class Diagram of Building Entity

diagram of the building entity and the other constructs. The second level is a conceptual model that defines the types of objects, relationships, and data needed to represent the information in a particular design domain. It refines the first level representation by specifying the categories of information used in a particular domain. SEED models provide representation for conceptual design of buildings. They store design data as they are generated during conceptual design. The aim of these models is to support early design exploration -- the fast generation of alternative design concepts and their rapid evaluation against a broad spectrum of relevant and possibly conflicting criteria. However, they are not applicable to later stages of design.

Other product models include EDM (Eastman, 1992), ICON (Ford et al., 1994), GOOD_B (Biedermann and Grierson, 1995), CIMSTEEL (Crowley and Watson, 1997), and so on.

Most of these models are design-centric (Harfman and Chen, 1993) in that they are closely related to the design process. They have been developed to support design evolution and exploration (Rivard and Fenves, 2000). Since the end user’s concern is space, spatial properties have been addressed by some authors to support the design process (Bjork, 1992b; Eastman and Siabiris, 1995; Ekholm and Fridqvist, 1996, 2000; Maher et al., 1997).

Although there are common objects for these different product models, each of them has its own characteristics and application scope. The logical extension of these models is standardization. Standard models are developed to guarantee some degree of uniformity within different applications by using the same standards (Fischer and Froese, 1996).

There are two most important international standardization efforts that address the product models, namely, ISO-STEP (Burkett and Yang, 1995) and more recently

IAI-IFC (Kiviniemi, 1999). Standard models also include LexiCon, which has been developed by STABU (the Dutch national building specification organization) (Woestenenk, 2002). LexiCon can be seen as an extension to STEP and IFC. All these provide standards libraries from which a user can select necessary entities to model a product. Although standardization has been accepted in the industry, there are still some limitations for standard models (Rezgui, 2001; Tolman, 1999).

This research intends to deal with product-oriented coordination which uses product information as the interface for coordination between design and construction. Thus, product model is closely related to this research. However, this research focuses on the application rather than the development of product models. The various efforts in product modeling contribute much to this research by providing an understanding of the basic ideas and concepts for product models. In the proposed coordination model, a product is composed of different level components with relationships among them. The components are described by parameters which correspond to different characteristics of components.

2.4 DESIGN MANAGEMENT

Design is a problem solving stage. In this stage, the client's requirements are conceptualized into solutions which are generally represented using procedures, drawings and technical specifications. Design is extremely important for the success of a project since the quality of design has an extensive impact on all subsequent stages of a project's life cycle. IDPM (Integrated Design Process Model) provides a comprehensive view of the entire design stage (Sanvido and Norton, 1994). It represents the major functions and activities necessary for a successful design. Figure 2.5 shows the general break-down of the IDPM through its first three levels of detail.

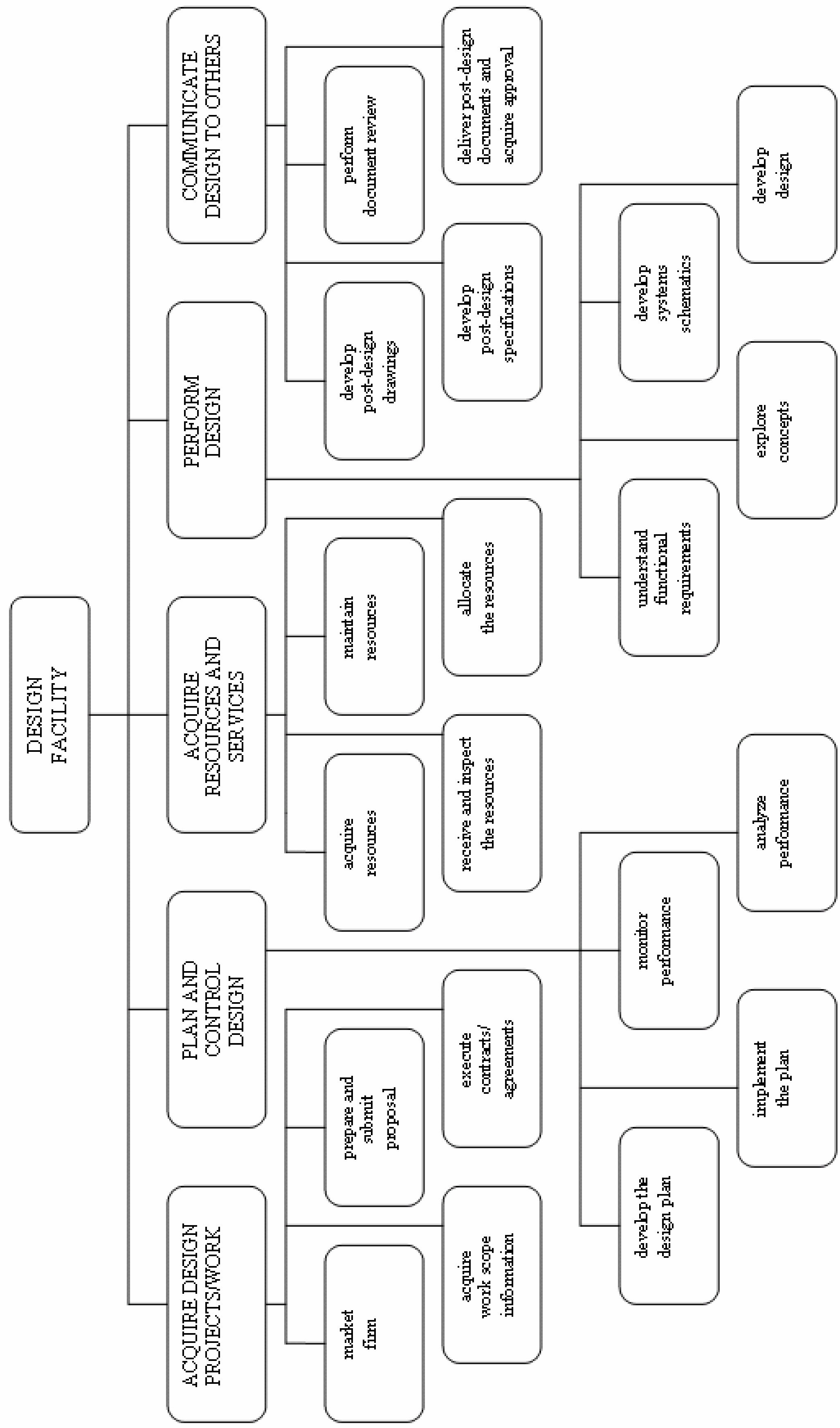


Figure 2.5 IDPM Node Tree

2.4.1 Characteristics of Design

1. Evolution

Design is generally composed of several evolutionary phases including feasibility study, conceptual design, preliminary design and final design. In each phase, the design problem is partially solved at a level of abstraction (Wilson and Shi, 1996). Along the stages of design, abstract concepts are incrementally refined so that design solutions are determined in more and more details. Throughout the evolution of the design process, information continues to flow and accumulate. The work to capture, store, and retrieve design information is one of the major challenges in design management.

Shooter et al. (2000) proposed a design information flow model which concentrates on the information that flows among individual design activities regardless of the activities' particular sequence. It aims to support a semantics-based approach for developing information exchange standards. The model organizes design information into levels of abstraction, each of which is a view of a design problem that includes only the issue designers are considering relevant at a given time in the design process. Then it identifies the various transformations within a level of abstraction and between levels of abstraction. Figure 2.6 shows the design information flow model within a level of abstraction.

As another effort, de la Garza and Alcantara Jr. (1997) suggested the representation of design evolution information using parameter dependency network (PDN). PDN shows how other object-parameter pairs affect a certain object-parameter pair. Designers solve decision problems by determining required functions and transforming these requirements into specific performance parameters. These performance parameters then form the basis for the generation and evaluation of

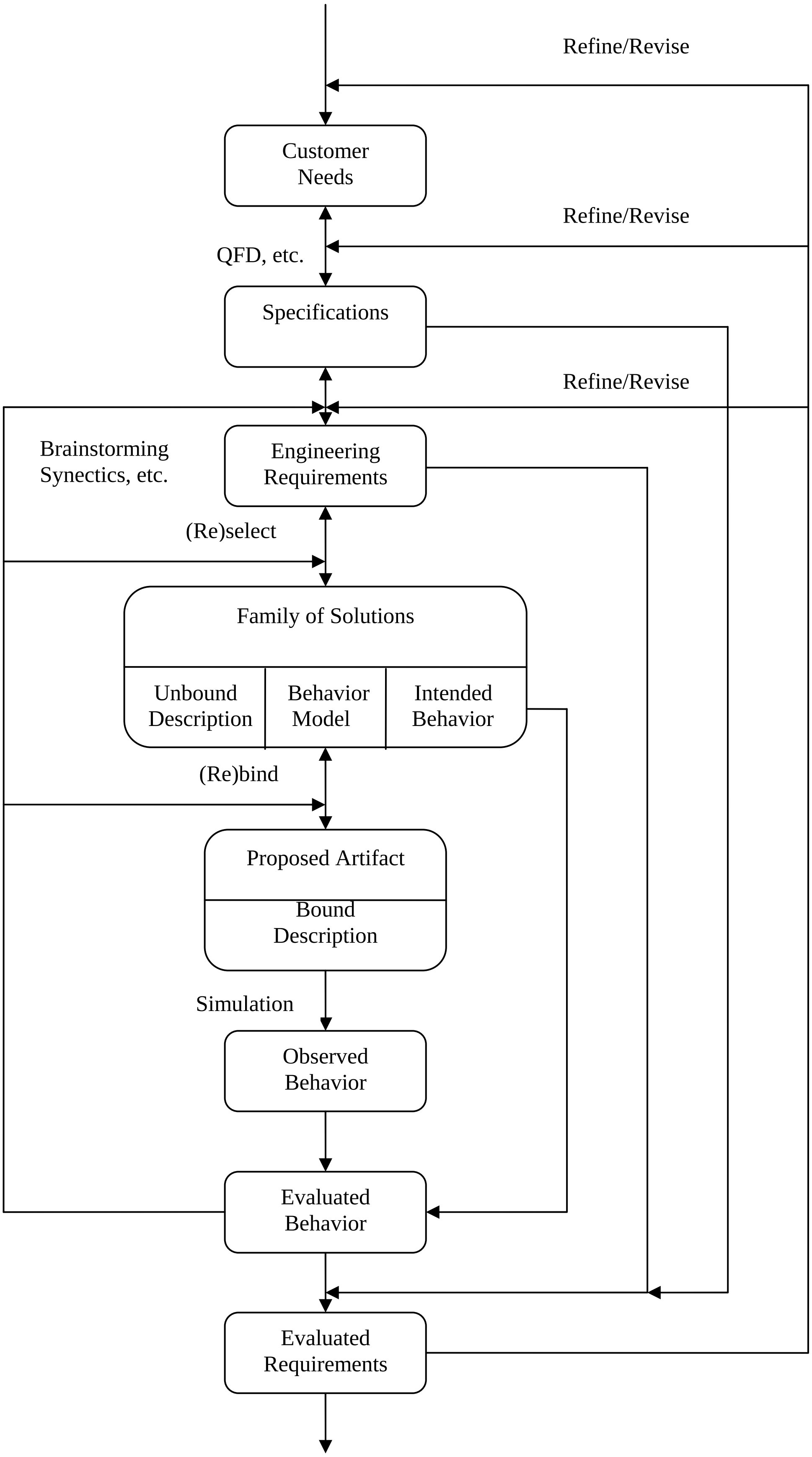


Figure 2.6 Design Information Flow Model within a Level of Abstraction

design alternatives. This approach is based on a representation of object design rationale as performance criteria. Figure 2.7 shows an example of the PDN. In Figure 2.7, the object-parameter pair Mechanical Room--Function affects the object-parameter pair Mechanical Room--Fire Resistance Rating, which, in turn, affects the object-parameter pairs Door--Fire Resistance Rating, Wall--Fire Resistance Rating, and HVAC Equipment--Fire Resistance Rating. Then these performance parameters are used to select door, wall and HVAC equipment materials.

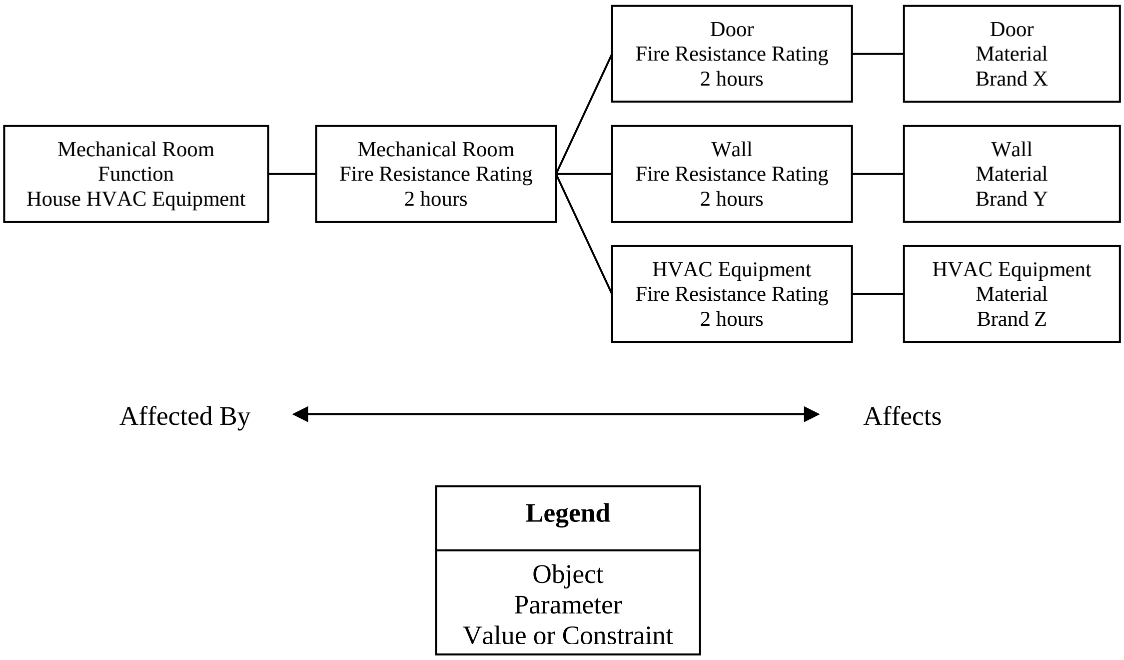


Figure 2.7 Parameter Dependency Network

All these efforts focus on the knowledge representation. They provide understanding for the design process evolution.

2. Multidiscipline

Design is multidisciplinary in nature in that it involves clients, architects, designers, contractors and so on, each of which has its own area of concern. Experts from these disciplines, loosely organized as a design team, work together to finish the design of a project. Communications among these participants are frequently impeded (Rivard et al., 1999). A quality design is highly dependent upon effective collaboration and coordination among the diverse disciplines to produce a coherent set of final design documents. Generally, these participants are geographically distributed so that much research work has been done related to distributed design coordination and collaboration (Anumba et al., 2002; Brazier et al., 2001; Rosenman and Wang, 2001; Tiwari and Gupta, 1995; Wang et al., 2002; Whitfield et al., 2002). During these years, a variety of coordination approaches and systems have been developed in the field of engineering design (Coates et al., 2000; Whitfield et al., 2000). More recently, lean thinking principles have been adopted to coordinate different design disciplines (Andery et al., 2000). Furthermore, as a step towards effective design coordination, Hegazy et al. (1998) conducted a questionnaire survey related to design coordination at the inter-team level and the interdisciplinary level as well. This questionnaire reveals the coordination problems encountered and solutions to resolve them. In addition, Law and Krishnamurthy (1996) developed a three layered data management model for multidisciplinary collaboration design. All these efforts suggest the importance of design coordination and collaboration.

3. Iteration

Design is distinct from other processes in that iteration and rework are commonplace. Usually, the design work is performed in a process of iterative step-wise refinement. Iterations represent conflicts in the flow of information within the design process (Yassine et al., 1999). The presence of iterations leads to difficulty in finding appropriate sequence of the design process activities (Smith and Morrow, 1999). As one of the principal causes for inefficient design, iterations drive up both development time and cost. Some mathematical models have been suggested to minimize the number of iterations between design activities (Ahmadi et al., 2001).

These inherent characteristics contribute much to the complexity of design projects. Due to the complexity of design, research has been conducted in diverse areas related to design improvement (Hegazy et al., 1998).

2.4.2 Design Process Management

Generally, design is based on decomposition principles in that the design process is decomposed into many tasks (Boujut and Laureillard, 2002). Each task involves certain problem analysis which is necessary for achieving the goal of the design. Information is treated as connector between tasks in that each task is driven by certain input information and produces output information. The output information of one task may affect the input information of another task (Lee et al., 1996). Thus, relationships exist between these tasks. However, the information relationships between tasks are highly complex in design projects. Figure 2.8 shows three possible relationships for two design tasks based on input/output (Eppinger et al., 1994).

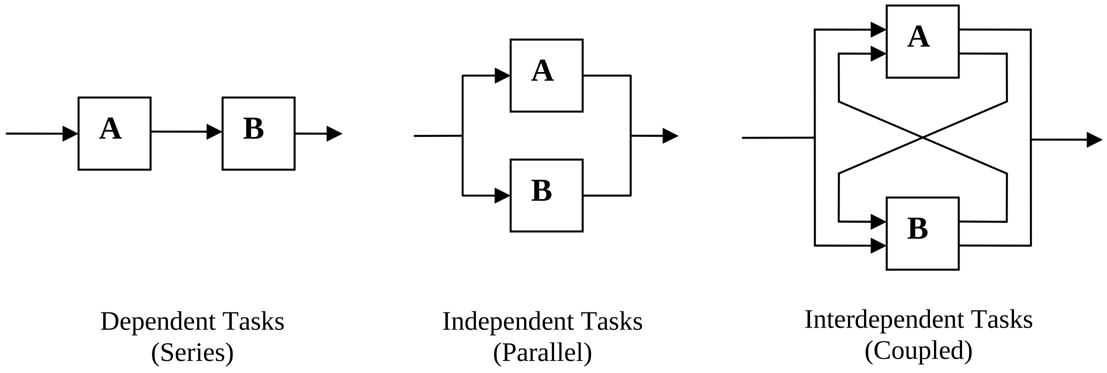


Figure 2.8 Three Typical Relationships for Two Design Tasks

It is common that tasks are mutually dependent on each other’s information output (Ahmadi et al., 2001). The interdependent tasks comprise a loop, which may include many tasks (Figure 2.9).

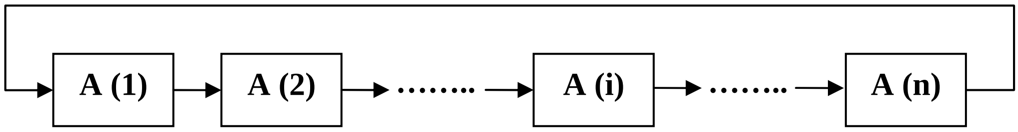


Figure 2.9 Design Loop

Generally, it is easy to manage series and parallel relationships. However, the management of coupled relationship is a formidable task. The success of a design project requires the coordination of design tasks with complex information dependencies between them (Ahmadi et al., 2001).

1. Tools

Streamlining design processes has always been regarded as an important step to the success of design products. Many tools have been employed to structure processes (Park and Cutkosky, 1999; Rogers, 1999). Traditional tools such as CPM and PERT can be used in processes with sequential relationships. However, they are not applicable to design process analysis since they cannot handle iterations and feedback loops (Kusiak et al., 1995; Park and Cutkosky, 1999; Rogers, 1999; Smith and Morrow, 1999; Yassine et al., 1999). Thus, new tools have been developed to address design process such as Incidence Matrix (Kusiak and Wang, 1993; Kusiak et al., 1995) and DR (Design Roadmap) (Park and Cutkosky, 1999). However, IDEF0 and DSM may be two of the most widely used tools.

As an influential tool, IDEF0 is frequently used in process modeling (Malmstrom et al., 1999). In IDEF0 representation, the information modeling is performed in four aspects, namely, input, output, control and mechanism. Furthermore, IDEF0 can use top-down decomposition to break up a complex process into small sub-processes. IDEF0 representation provides a good overview for a process, however, it suffers from practical size limitations in that IDEF0 models tend to grow fast in complexity for a large number of tasks. Although IDEF0 can represent a process, it does not offer any capability to optimize it. In addition, the IDEF0 methodology gives weak support for the modeling of iterations and feedback loops, because of its strong feed-forward focus. Since one of the challenges in design management is to deal with iterations, a modeling technique for design should be able to handle them. The IDEF0 technique is weak in this area, which makes it less efficient for dealing with design problems.

Another powerful tool is DSM, which provides a simple, compact, and visual representation of a complex system by using a matrix. DSM is a very robust technique that can be used in many different problems (Browning, 2001). A DSM helps identify problem areas within a process and can support restructuring of it in order to make it more efficient. DSM representation overcomes the size and visual complexity of all graph-based techniques. It provides a better overview than IDEF0, since the complexity of DSMs does not grow as fast as that of IDEF0 diagrams (Malmstrom et al., 1999). Thus it can be applied to large problems, while maintaining a relatively good overview of the problems. The primary advantage of the DSM format is the capability to deal with iterations commonly found in a design project. The DSM handles iterations well and is relatively easy to understand. Due to these advantages, it can be used in the current research proposed model to deal with network analysis.

2. Models

Many models have been developed to manage design processes. However, they address the problem from different viewpoints and apply to different conditions.

ADePT (Analytical Design Planning Technique) is a model with the capability to schedule the building design process (Austin et al., 1999a, 1999b, 2000a, 2000b, 2000c). The ADePT methodology is composed of three stages, namely, design process modeling, DSM-based analyzing and design schedule generation. The first stage is the creating of design process model (DPM). The model is represented using a modified version of the IDEF0 methodology, which shows design activities and their information flows. The data in the DPM are then linked to a DSM (Dependency Structure Matrix) analysis tool in the second stage. DSM is used in this stage to identify iteration within the design process and optimize the sequence of the activities based on their information flows. This is the central part of ADePT methodology. In order for DSM to be used as a means of controlling the design process, the analysis result needs to be represented against a timescale. Thus the third stage produces a design programme – a schedule for the design activities based on the optimised process sequence determined in the second stage. DePlan is another model which combines ADePT and Last Planner (Hammond et al., 2000). In this model, ADePT is used to provide an improved design sequence while the Last Planner methodology will then be used to schedule and control the design process. In addition, Clarkson and Hamilton (2000) proposed “signposting”--a parameter-based model of design. The distinct feature for this model is to use design parameters as a basis for identifying the next task so as to form design process network.

These models aim to structure the design process from a process viewpoint in that the design process is represented as a number of tasks which, when ordered appropriately, enable successful design development. They employ different mechanisms to order the process activities.

More recently, Chua et al. (2003) presented PPI (Process-Parameter-Interface) model. This model is different from those activity-based models in that it is parameter-centered. It focuses on the parameter relationships. This model can deal with the iterations and improve design knowledge sharing. Furthermore, it supports the regrouping of parameters to form new tasks and networks. This model provides a flexible representation of design process and can improve design process management.

It can be seen that two viewpoints are available for design management -- process viewpoint and parameter viewpoint. They are complementary to each other. Process viewpoint focuses on the inter-task information transfers, however, they ignore many important technical interactions among the engineering parameters, which can be explicitly described from parameter viewpoint. The proposed model in this research provides a better management of design by combining these two viewpoints. Furthermore, parameter evolution will be taken into account. By employing these approaches, the design process can be improved.

2.4.3 Design Change Management

Throughout the design process, changes are frequently introduced for many reasons. The changes inevitably and continuously affect the quality of design documents. Thus, the effective management of design changes becomes crucial to the success of a project.

Design changes are in fact modifications to some design data. As the design data are interdependent, the modifications normally impact other data. Until all the related data are adjusted accordingly, the designs remain incompatible (Mokhtar et al., 1998). In some cases, the designer who initiated the change may forget to inform other affected designers. Therefore, the difficulty in design change management is how to make designers of any discipline aware of all changes which affect their own design (Mokhtar et al., 1998). This requires full understanding of the rationale behind the original design.

In recent years, a novel parametric approach was suggested to address the issue of design changes (Soh and Wang, 2000; Wang and Soh, 2001). This approach can facilitate the coordination of design information through managing design changes. A parametric coordinator was proposed which provides each building component with the linking knowledge. Then the design consistency between building components can be achieved through the proposed linking knowledge as well as a group pattern module. Furthermore, this study extended the technique of knowledge-based approach from single-view 2D model to manage the relationships of entities between different views by incorporating the projection knowledge and graphic inference. A corresponding multiview constraint solver was developed. This knowledge-based constraint solver can be combined with the linking knowledge between building components to facilitate the coordination of design information for multiview models. This approach essentially limits design changes to geometry-related information. Thus it aims at resolving dimension-change problems.

In addition, some researchers presented information models to provide improved design coordination through managing design changes (Hegazy et al., 2001; Mokhtar et al., 1998; Zaneldin et al., 2001). The core idea of the model proposed by Mokhtar et al. (1998) is to assign the task of design change propagation to the building components themselves. Each component is equipped with the necessary linking knowledge to identify the disciplines that are affected by a specific design change and how they are affected. The model uses a central database to carry the building components data and capture the linking knowledge in the form of rules. When design change occurs to a building component attribute, the component checks all the rules that are stored in the database. If any of these rules applies to the change, messages are automatically sent to the relevant designers. In addition to its ability to propagate design changes, the model is capable of tracking past changes and helping in the planning and scheduling of future ones. The model uses textual data rather than drawings as the main media for storing and communicating design information and it does not address the issue of automation of the design change process. Furthermore, it does not capture design rationale, which is an essential requirement for properly managing design changes. The design rationale information is incorporated into the information model proposed by Hegazy et al. (2001) and Zaneldin et al. (2001). This model is built around a central library of generalized building components that can be used to describe a complete building project hierarchy. Each component allows the designer to store desired performance criteria and related design rationale. Each component is also sensitive to its own changes and automatically communicates such changes to affected parties through preset communication paths. The rationale, however, only identifies the components related to a component attribute. The relationships between attributes of these components cannot be tracked directly.

All these models, as such, provide improved design coordination and control over changes, thus helping to increase the consistency and productivity of the overall design process. A common characteristic for them is the attaching of linking knowledge to components, which serves as the basis of change propagation. Although design change management will not be addressed in this research, the model in this research provides potential to deal with design changes by employing product as the interface for coordination. Design change is product-oriented in that it is generally the modification of product component properties. Once product information is changed, the related process information will be affected accordingly based on the product-process connection. Thus, the proposed coordination model can also be used to manage design changes if necessary.

2.5 CONSTRUCTION MANAGEMENT

Managing construction is a highly practical profession. Demands for efficient management and control in construction are growing due to the increasingly complexity of construction projects. Areas in this scope include planning and scheduling, estimating, cost control, accounting and so on. Planning and scheduling are among the most important functions and much work has been conducted related to these areas. The process of Planning and scheduling is typically done in a top-down fashion. Generally, master, lookahead and commitment plan/schedule are three levels of abstraction used by construction project managers. They are used in different conditions and serve different functions.

Many tools have been developed to plan and schedule the construction work. CPM and PERT are two of the most widely used tools. Other early planning systems include OARPLAN (Darwiche et al., 1988) and MDA Planner (Jagbeck, 1994). More recently, Fischer and Aalami (1996) suggested computer-interpretable construction method models which support the automated generation of realistic construction schedules. To take advantage of the increasingly accepted lean ideas, Choo et al. (1999) suggested WorkPlan to systematically develop weekly work plans according to the Last Planner method. Work packages are used as scheduling unit in WorkPlan. Furthermore, Choo and Tommelein (2000) developed WorkMovePlan to address distributed planning and coordination. WorkMovePlan can be employed to develop lookahead plans and weekly work plans. In addition, as an effort to overcome the limitations of traditional scheduling methods, Chua et al. (2003) proposed IPS (Integrated Production Scheduler) as a new scheduling tool to help produce quality-assured lookahead schedules. IPS enhances the reliability of planning by modeling two additional types of hidden constraints on activities. In recent years, lean production has been applied in the area of construction management. By adopting lean ideas, Chen et al. (2003) presented Information Flow Integrated Process Modeling (IFIPM) technique to incorporate information flows into CPM planning. The technique can improve construction productivity through balancing conversion processes and information flows. All these planning and scheduling tools are process-oriented in that they all schedule the construction work from process viewpoint. Starting from a different viewpoint, Chua and Song (2003) and Song and Chua (2002) suggested POST (Product Oriented Scheduling Technique) as an alternative intelligent scheduling tool for programming construction work from the product point of view. The POST model can reduce errors and improve constructability analysis.

Since construction management is not the focus of this research, these efforts can be treated as the basis of construction network in the proposed model. However, traditional construction network is weak in dealing with as-built measurement information, which is very important to the coordination between design and construction. The as-built measurement information is generally considered as side-product of construction activities in the traditional construction network. In the proposed model, a new kind of activities is added which produces as-built measurement information. Thus, the proposed model can improve the coordination by explicitly representing the as-built measurement information.

2.6 CONCLUSION

The work related to the proposed research topic spans across various areas including coordination, product and process integration, product model, design management and construction management. From the forgoing discussion of the literature, researchers have mainly focused on process viewpoint, with limited consideration on parameter viewpoint when it comes to design and construction analysis. Also, most of the research efforts related to parameter viewpoint dealt mainly with design stage and treated a parameter as a whole. Although these features are beneficial, they are not sufficient alone to meet the expectations of a coordination model. The evolution of parameters should be taken into account from design to construction. Another problem is the as-built measurement information feedback. Most of the research efforts related to design-construction coordination only considered the information flow from design to construction, while the as-built measurement information feedback from construction to design was rarely discussed. The shortcomings of these efforts lead to inefficient coordination. There is a clear need, therefore, for an effective approach to address this crucial problem. The next chapter will describe the proposed coordination model.

CHAPTER 3

MODEL DEVELOPMENT

3.1 WHY USE PRODUCT AS INTERFACE?

This research intends to coordinate design and construction. A proper mechanism is very important to the success of coordination. Based on the coordination theory which deals with the interdisciplinary study of coordination, the interdependence between activities can be analyzed in terms of common objects (Malone and Crowston, 1990). In reality, product is the common link between design and construction.

Product contains static project information. The basic objects in a product are components, which can be in different abstraction levels such as system level, subsystem level or individual entity level. In practice, design work and construction work are all related to these components. Designers typically break down complex design work into many parts, each of which is concerned with a set of specific and meaningful product components. Detailed design tasks are based on these product components. On the other hand, the construction work is also closely related to the product components since the completion of a component or system of components can be considered as the result of many relevant construction activities. It can be seen that product is the common object for design and construction. The product, thus, serves as the interface for coordinating design and construction. Figure 3.1 shows the relationship between design/construction and the related product information. Since product is used to describe static project information, design and construction results can be recorded in product as product-design and product-construction information, respectively. Design tasks treat product-design information as input/output, which is the basis to form design network. Similarly, construction network can be formed by using product-construction information as input/output of construction tasks. In addition, relationships also exist between design and construction in that construction tasks need design result information as prerequisite and design tasks may require construction result information as feedback.

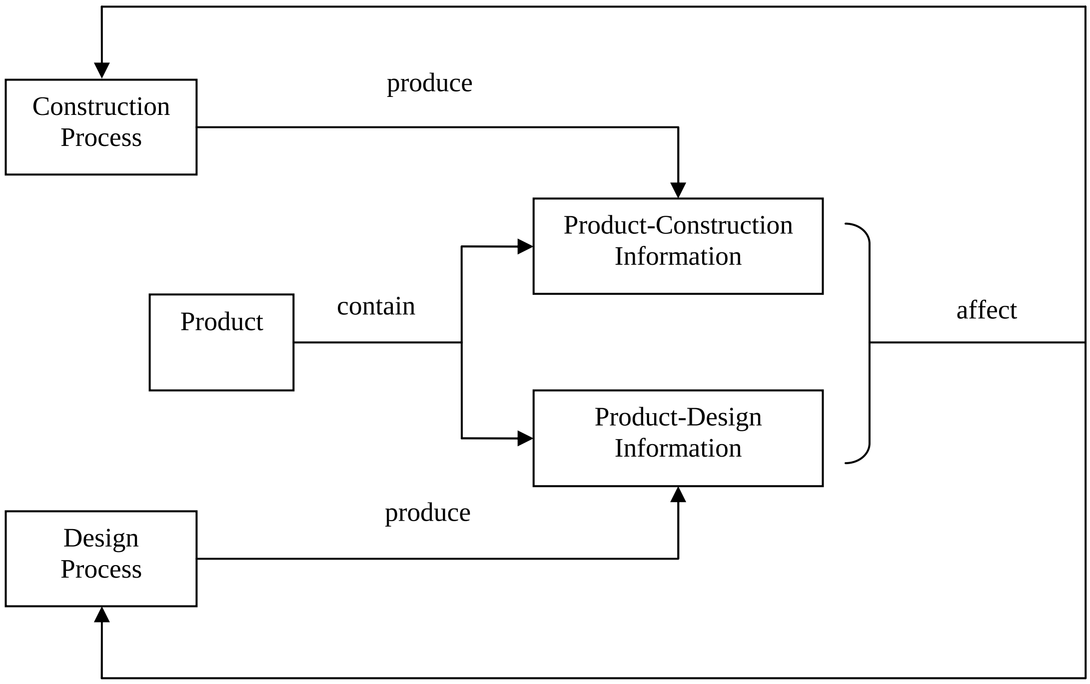


Figure 3.1 Relationship between Design/Construction and Product

3.2 HOW TO REALIZE THE PRODUCT-ORIENTED COORDINATION?

As described, product can serve as the interface for the coordination between design and construction. The realization of product-oriented coordination is through parameters in that any product component can be described by a set of parameters corresponding to different properties of the component. During the project, the design activities are concerned with the identification, estimation and iterative refinement of these parameters, until a sufficient level of confidence in these parameters is achieved while construction activities realize these parameters based on their values determined in the design stage.

Parameters play an important role in the coordination. They are not only closely related to product, but also important to depict design and construction. To representing design and construction, activity-based description and parameter-based description are introduced in this study. Both types of descriptions are very useful and insightful in different ways.

Activity-based representation provides an overview of a process. It makes people have a clear understanding of what should be done to achieve the goal. However, activity-based description has some limitations such as the lack of flexibility. In activity-based representation, all the activities are predefined. It is well known that a design process is flexible in that a variety of design activities can be defined to achieve the design goal. Furthermore, activity-based representation aims to form design activities network, while the relationships among the parameters cannot be represented clearly. In activity-based representation, a design activity is characterized by a group of parameters as input and another group of parameters as output. For one activity, it seems as if the group of output parameters depends on the group of input parameters. In reality, the relationships between the individual parameters are missed. In addition, activity-based representation may provide a “false” sense for inter-activity information transfer. In activity-based representation, if the output parameters of some former activities are connected to a latter activity, it means that the latter activity depends on those output parameters of the former activities. Sometimes this may not be true. The real parameter that the latter activity depends on may be the derived parameter of those dependent parameters. Generally, the derivation relationship is embedded in the latter activity.

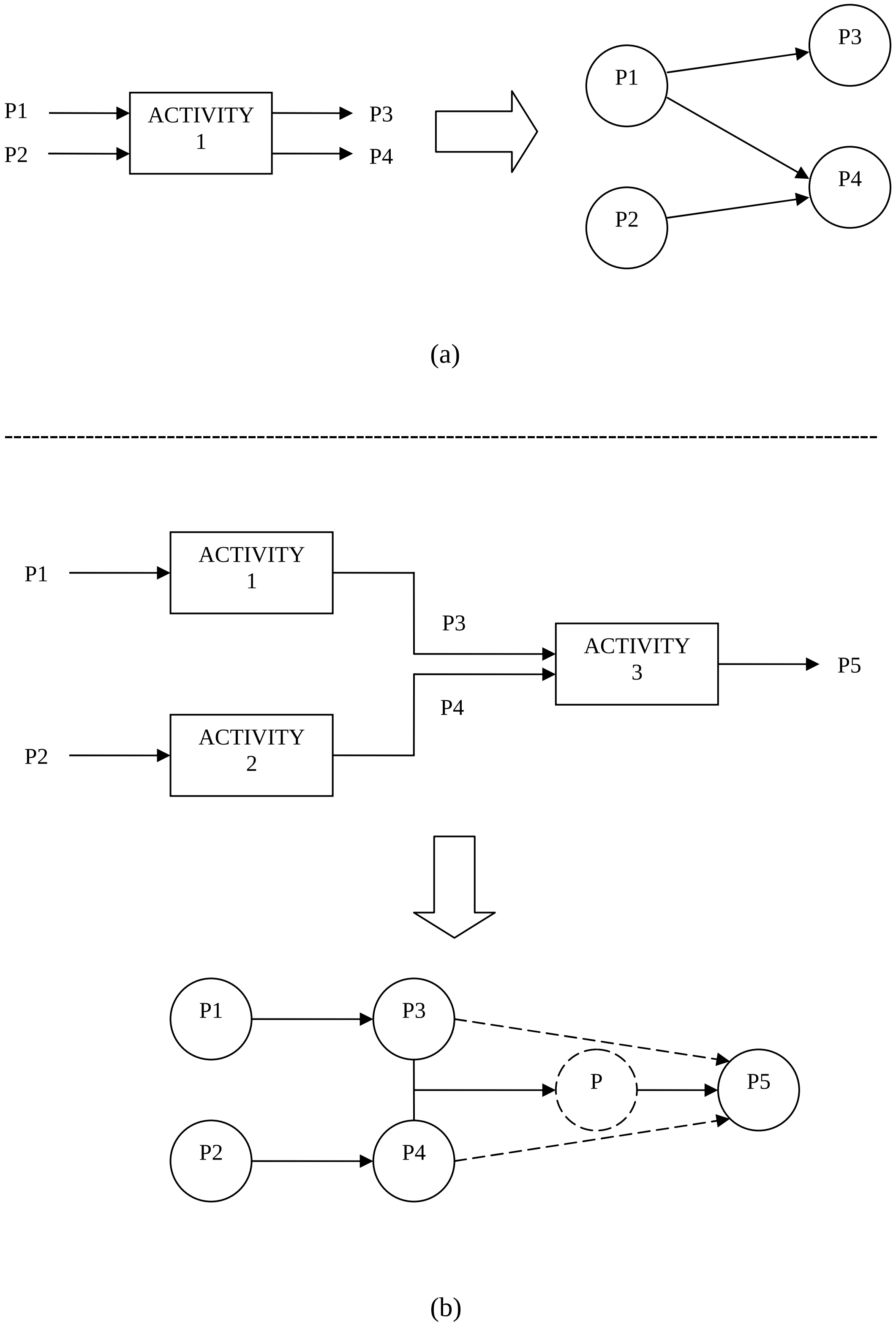


Figure 3.2 Activity and Parameter

Figure 3.2 shows activity-based representation and the real parameter relationships. In this figure, (a) is the representation of individual activity and intra-activity parameter relationships. From activity-based representation, it can only be known that (P3, P4) depends on (P1, P2), while the real dependency is missed. (b) is the representation of several related activities and inter-activity parameter relationships. In the activity-based representation, “P5” depends on “P3” and “P4”. In reality, “P5” depends on “P” which is derived from “P3” and “P4”. In this case, “P” is an implicit parameter embedded in “ACTIVITY 3”.

With regard to a construction process, the general activity-based representation is also inadequate for design/construction coordination. In the traditional construction network, the as-built measurement information cannot be described clearly. In reality, the as-built measurement information can also be represented from parameter viewpoint.

Thus, to improve coordination, parameter relationships need to be explicitly represented in sufficient level of detail. This would depend on the interface between the different disciplines or teams. Parameter-based description documents the relationships between individual parameters. Parameter-based description is very important for coordination analysis since the information transfers between design and construction (design information or as-built measurement information) are generally parameter-based interactions. Furthermore, parameter-based representation supports reorganizing of parameters based on the dependencies to form new activities, which makes it more flexible.

It can be seen that activity-based description and parameter-based description are complementary to each other. The former is strong in providing overall view but inflexible and ignores too many important technical details, while the latter documents the detail relationships for parameters and supports flexible formation of process elements but lacks the overall context. The combination of these two viewpoints can enhance the coordination efficiency.

3.3 MODEL FRAMEWORK

Based on the previous analysis, the model is established which is composed of four main parts, namely, parameter, product, design and construction. Product is described by parameters while design determines the values of these parameters, which will then be realized by construction. Figure 3.3 shows the basic structure of the model.

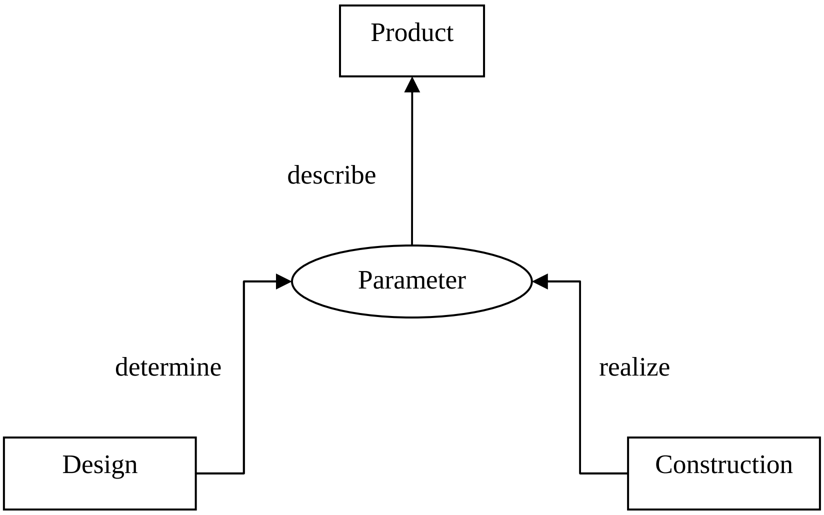


Figure 3.3 Basic Structure of the Model

A building product is composed of many inter-related components. A product component can be a system, a subsystem, a structural frame, an individual entity such as a column, a beam. Figure 3.4 shows the hierarchical structure of a building product. It should be pointed out that this structure is only one option for building product decomposition. It is possible for a building product to have other kinds of hierarchical structures.

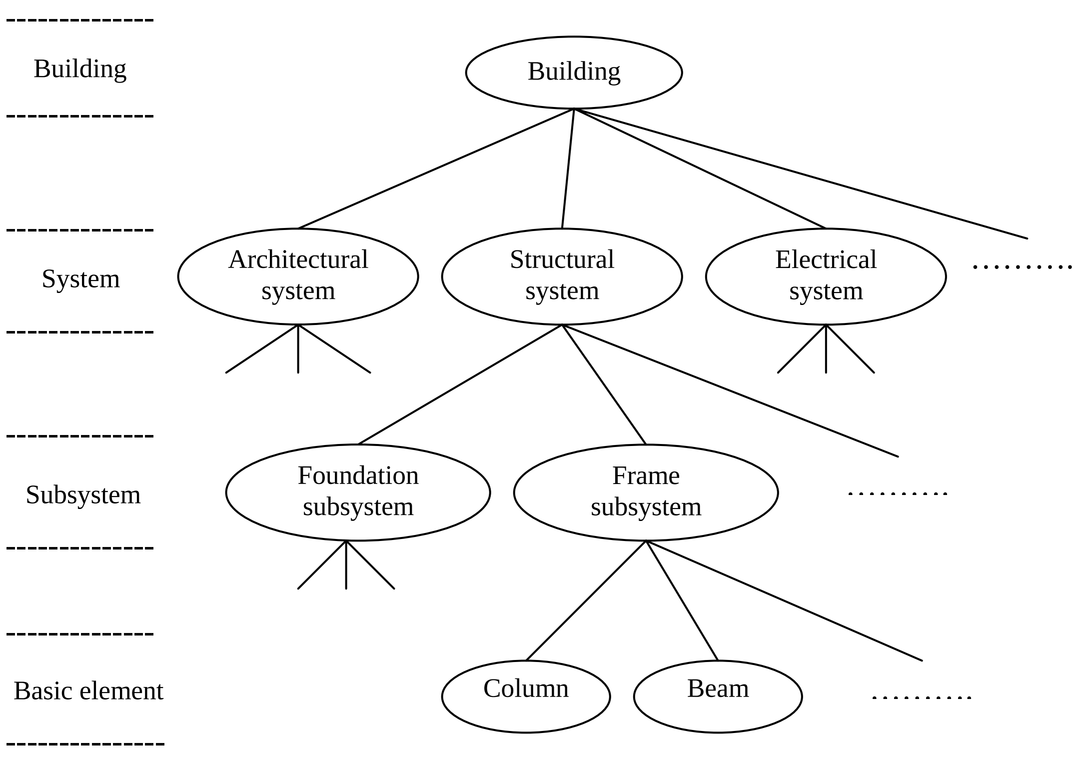


Figure 3.4 Hierarchical Decomposition of Building Product

A component can be described by a set of parameters corresponding to its different properties. For a parameter, it goes through evolution during design and construction. That means it can be in different conditions with the progress of a project. The concept of ‘state’ is used to represent various status of a parameter. The state transformations correspond with different process activities in design and construction. The state description is useful for process analysis since a process activity is characterized by its information inputs and outputs which can be represented using parameter states. Furthermore, parameter states can group to form deliverables such as drawings, as-built measurement information units and so on.

3.3.1 Product and Parameter

Parameters are used to describe product components. “Parameter” is a broad term given to the key variables that define the product components, which provide a better insight to the product. They cover various aspects of the product components including physical properties (dimension, material), evaluation-related attributes (cost, stress distributions), and so on. These key parameters are critical for the coordination between design and construction.

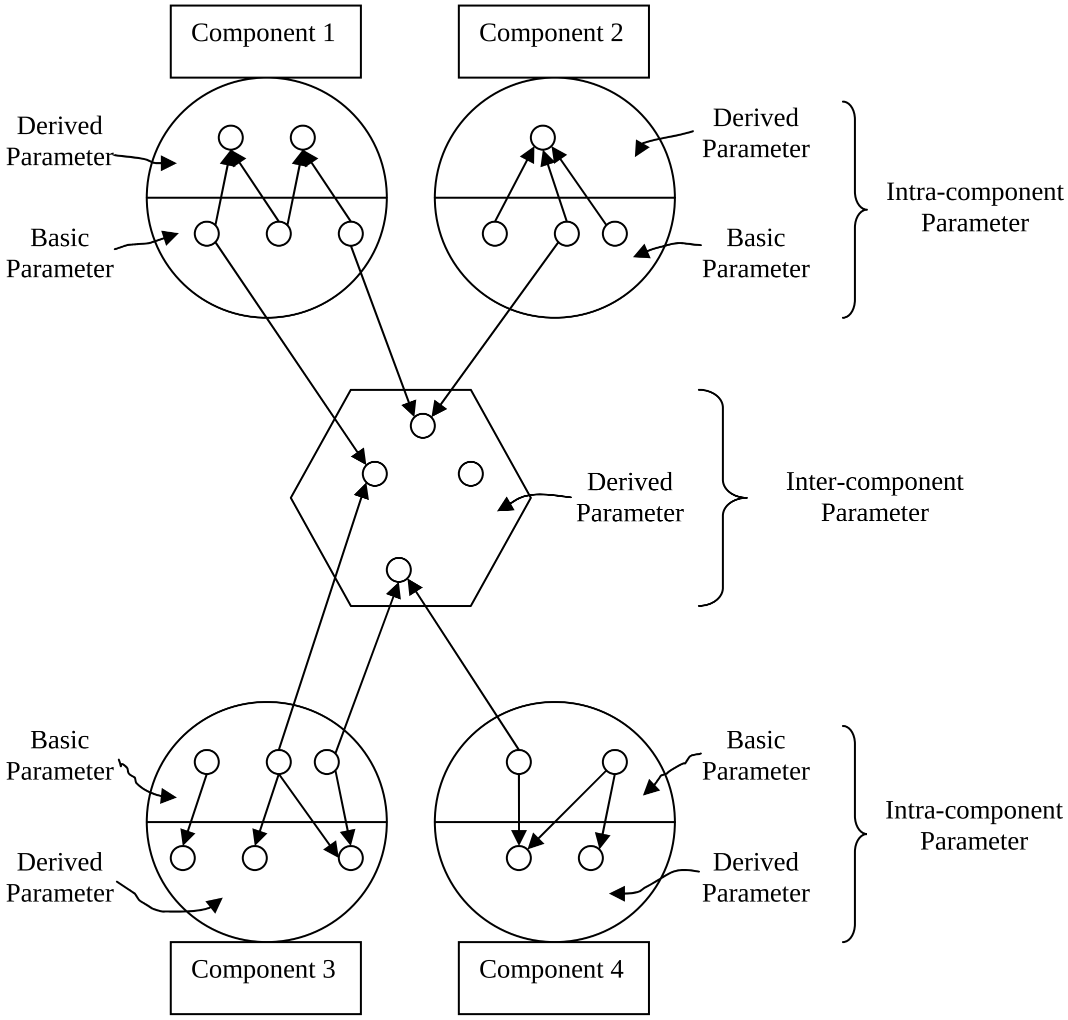


Figure 3.5 Parameter Classification

Figure 3.5 shows the relationship between product components and parameters. The parameters belonging to a component are called intra-component parameters since they describe the properties of this component. The intra-component parameters are classified into two types, namely, basic parameters and derived parameters. Basic parameters are those defining the component's basic characteristics, such as its dimension, material properties. Derived parameters are derived from the basic parameters. Generally, a derived parameter is the combination result of several basic parameters. For example, weight of a component is a derived parameter. It can be derived from dimension and material properties of the component which are basic parameters. However, a parameter may involve several components. In that case, it is termed inter-component parameter. Inter-component parameters are generally derived parameters which are related to the basic parameters of different components (such as the gap between a mechanical duct and an electrical duct). In this figure, four groups of intra-component parameters are presented, which belong to four different components. At the same time, interactions exist between these components in that some inter-component parameters are produced by the parameters of these components. A "derivation" relation is used to represent the relationship between basic parameters and the derived parameter (Figure 3.6).

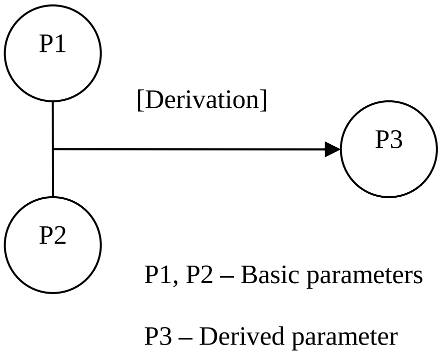


Figure 3.6 Basic Parameter and Derived Parameter

All parameters undergo evolution during product design and construction, which can be pictured by state chains. Generally, typical state chain for a basic parameter can be described as (Initial → As-proposed → As-confirmed → As-designed → As-built → As-built measured) (Figure 3.7).

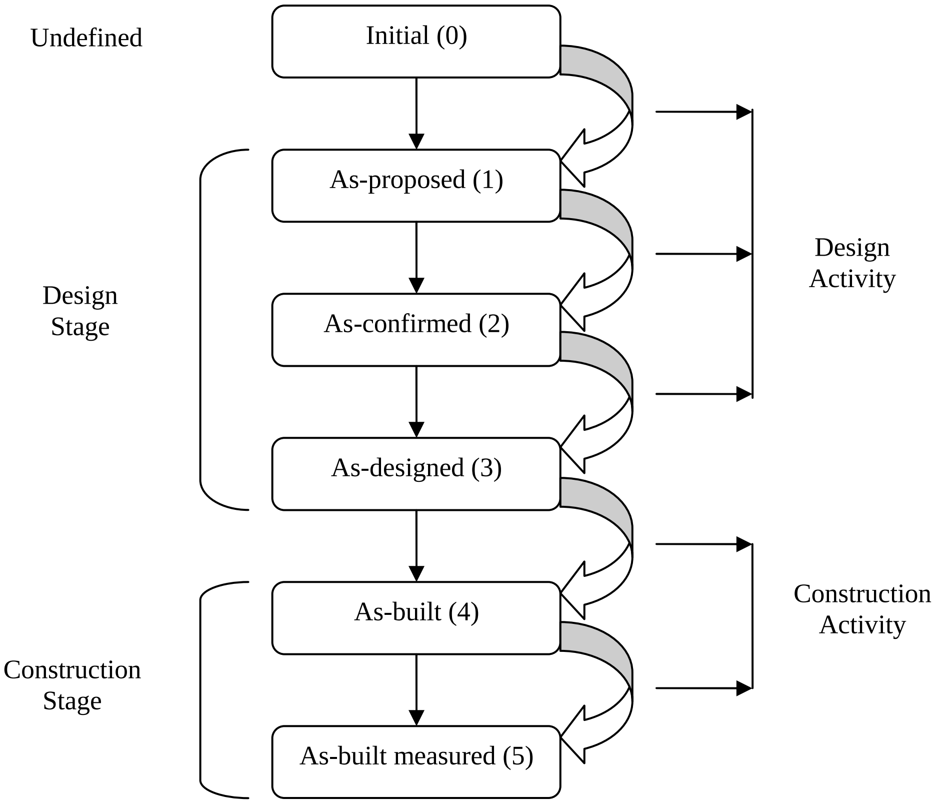


Figure 3.7 State Chain of a Basic Parameter

Initial represents the undefined state of the parameter, which is the starting point of design analysis. (As-proposed; As-confirmed; As-designed) are the states in design stage while (as-built; as-built measured) are the states in construction stage. The state transformations correspond with different process activities in design and construction.

Table 3.1 State Description

State No.	Name	Description	
0	Initial	Starting point of design analysis	Undefined
1	As-proposed	Preliminary determination of parameter value	Design stage
2	As-confirmed	Parameter value is checked and confirmed by involved designers	
3	As-designed	Parameter value is ready for construction use	
4	As-built	The related component is constructed	Construction stage
5	As-built measured	Measurement value of parameter	

Table 3.1 provides description for these states. For a derived parameter, its states are defined to match those of the basic parameters that derive it. As shown in Figure 3.8, P3 is derived from basic parameters P1 and P2. If P1 and P2 are in state n, then P3 is also in state n. This is generally the case since it ensures a coincidence between these two kinds of parameters.

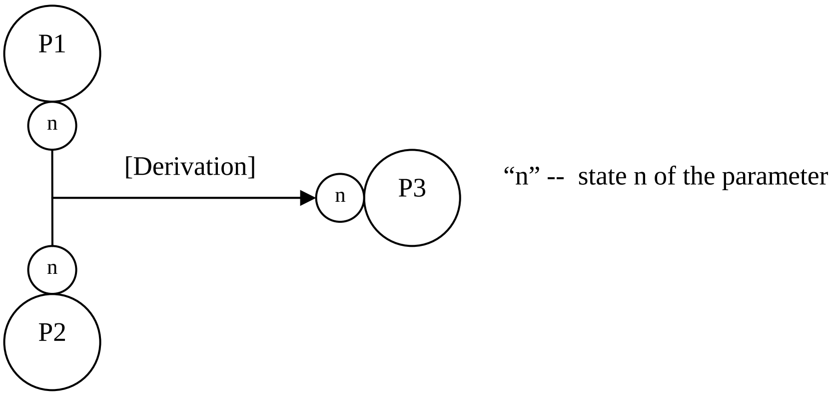


Figure 3.8 State of a Derived Parameter

Parameter state chain provides clear evolution information for a parameter. At the same time, it is also important for process analysis. In the traditional process analysis, activity input and output are parameters rather than the states of parameters. In reality, although several different activities need the same parameter, it is possible for them to require a different status of the parameter.

Note that only the states in design and construction are shown since this research aims to manage the interdependence between design and construction. A parameter may have states in other stages of the project. Furthermore, the proposed state chain for design and construction is only one option. It does not mean that all parameters must undergo these states in any condition. For example, as-built measured state only exists in such parameters whose as-built measurement information is useful in coordination analysis. The intent of this research is to develop the basic concepts rather than all the possible states. The state chain proposed can be changed based on real conditions.

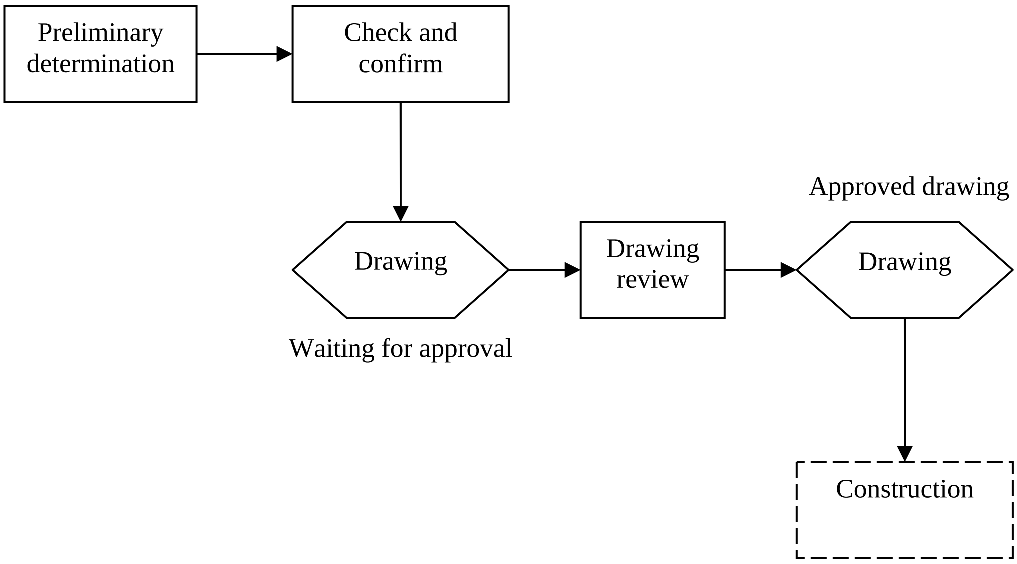
3.3.2 Design Process and Parameter

Design is flexible in that design processes vary widely from one organization to another reflecting the cultures of design teams. Individual design teams can follow a multitude of design process models for a same design project. As a result, it is almost impossible to use one process representation to support a wide range of design projects. Thus, the design process description in this research is only one choice. It allows customization to any firm. Since process evolution is closed related to state transformations, different process representation may require different state chain.

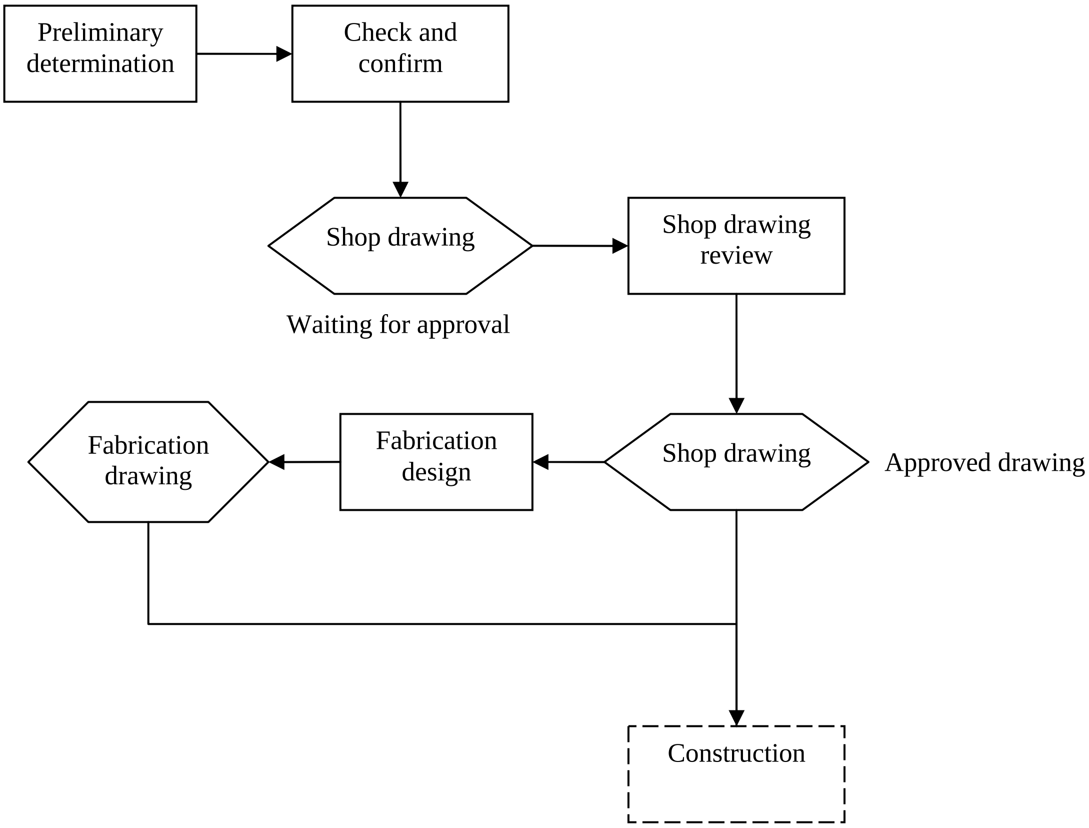
Designers solve a design problem through a continuous refinement where the designers expand the problem’s description by incorporating additional detail. Figure 3.9 shows the typical design process.

Generally, the design process is composed of three stages, namely, preliminary determination, check and confirm, and drawing review. After check and confirm, drawings will be produced. The drawings will then undergo review activity which intends to generate approved drawing. The review task is generally conducted by external parties including the main contractor, architects, engineers and design consultants. This process is represented in case 1.

However, for those components requiring shop fabrication, the design process is slightly different. In that case, the shop drawing review will be followed by an extra stage -- fabrication design, which produces fabrication drawings. The fabrication drawing design is controlled by the shop drawing design. Generally, the fabrication drawings do not need to be reviewed. The design process including fabrication design is shown in case 2.



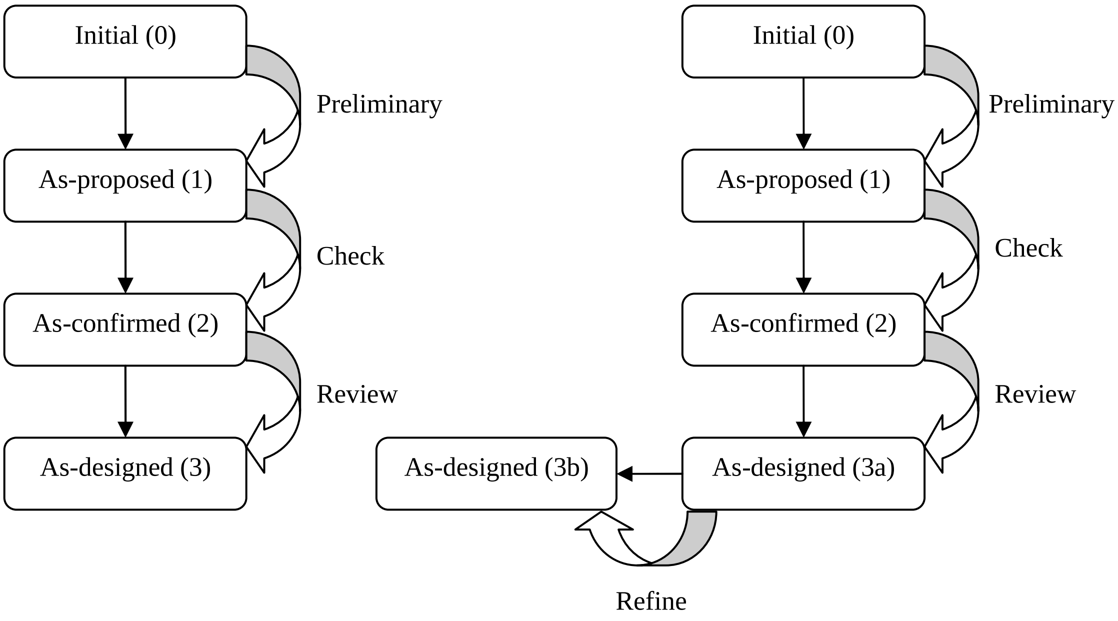
(a) Case 1



(b) Case 2

Figure 3.9 Typical Design Process

Based on this process, a design activity itself may take the form of a "Preliminary", a "Check", a "Review" or a "Refine", which correspond to preliminary determination, check and confirm, drawing review and fabrication design, respectively. These activities are responsible for the state transformations of a basic parameter in design stage (Figure 3.10).



(a) Case 1

(b) Case 2

Figure 3.10 State Transformations of a Basic Parameter in Design Stage

A "Preliminary" transforms a parameter from initial state (state 0) to as-proposed state (state 1), which will be turned into as-confirmed state (state 2) by a "Check". For the transformation from state 2 to state 3, two conditions exist which correspond with the two design processes described previously. In case 1, the as-confirmed state (state 2) information of parameters can be grouped into drawings. These drawings will undergo "Review" activities, which can be performed by designers or external parties. "Review" updates the information in drawings so as to produce approved drawings which contain the as-designed state (state 3) information of parameters. In case 2, the as-designed state (state 3) is divided into two parts, namely states 3a and 3b. State 3a is directly related to the reviewed shop drawings while state 3b is closely related to fabrication drawings. From state 2 to state 3a, the procedure is similar to that of case 1. However, there is a transformation from state 3a to state 3b in case 2, which is completed by "Refine" activities. Thus, there are two typical state chains for design stage, namely, (0→1→2→3) (case 1) and (0→1→2→(3a→3b)) (case 2).

As described, design activities are responsible for the state transformations in design stage. However, a design activity may require external information to fulfill the transformation function. The external information constraints may be produced by other design activities, construction activities (as-built information feedback), or external influences (loads). A design activity is characterized by its information inputs and outputs. Different types of design activities have different types of information inputs/outputs. Figure 3.11 and Figure 3.12 show the four kinds of design activities.

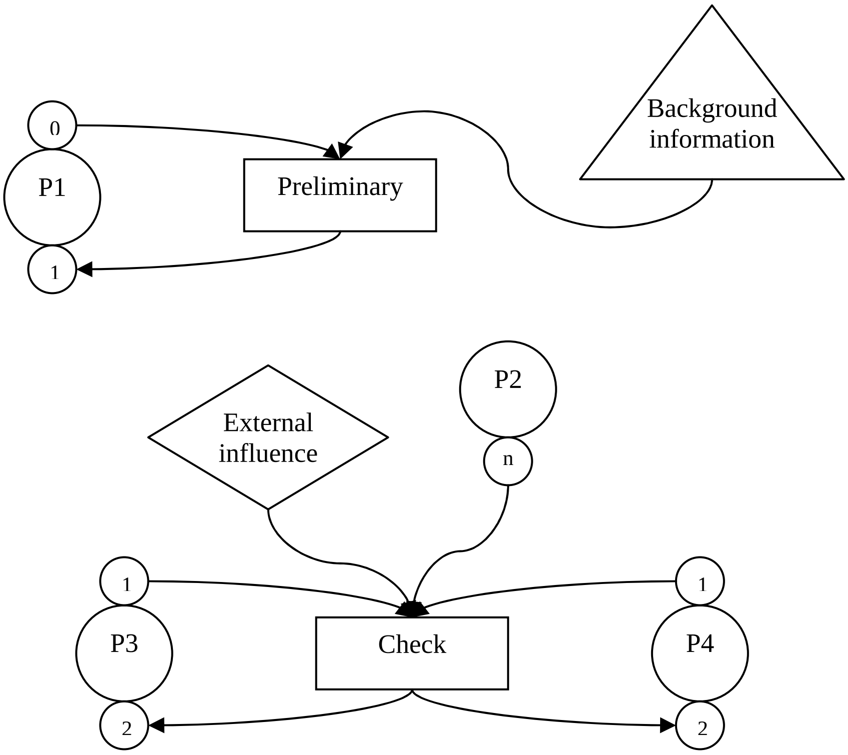
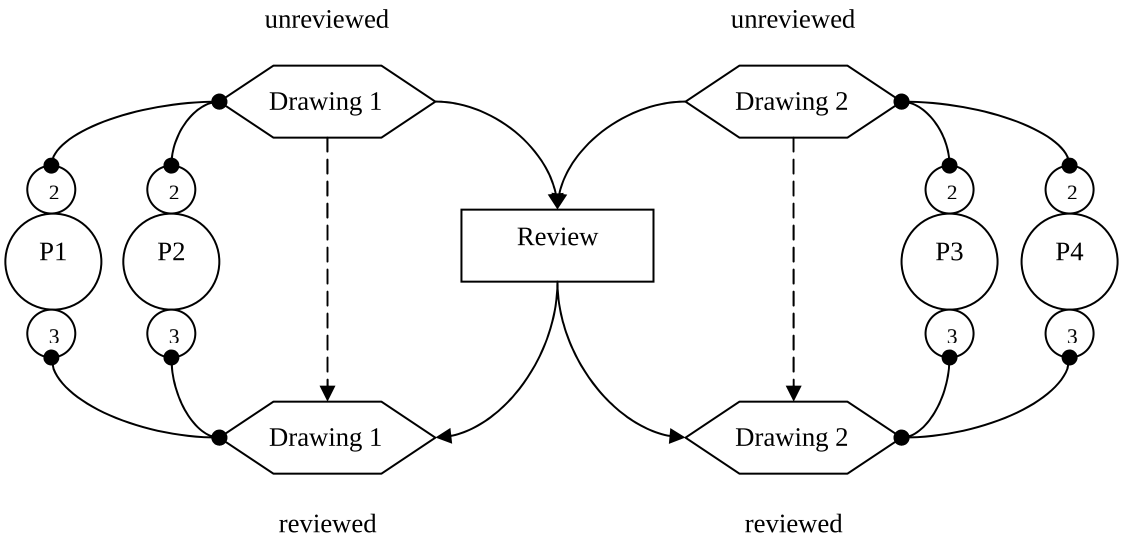
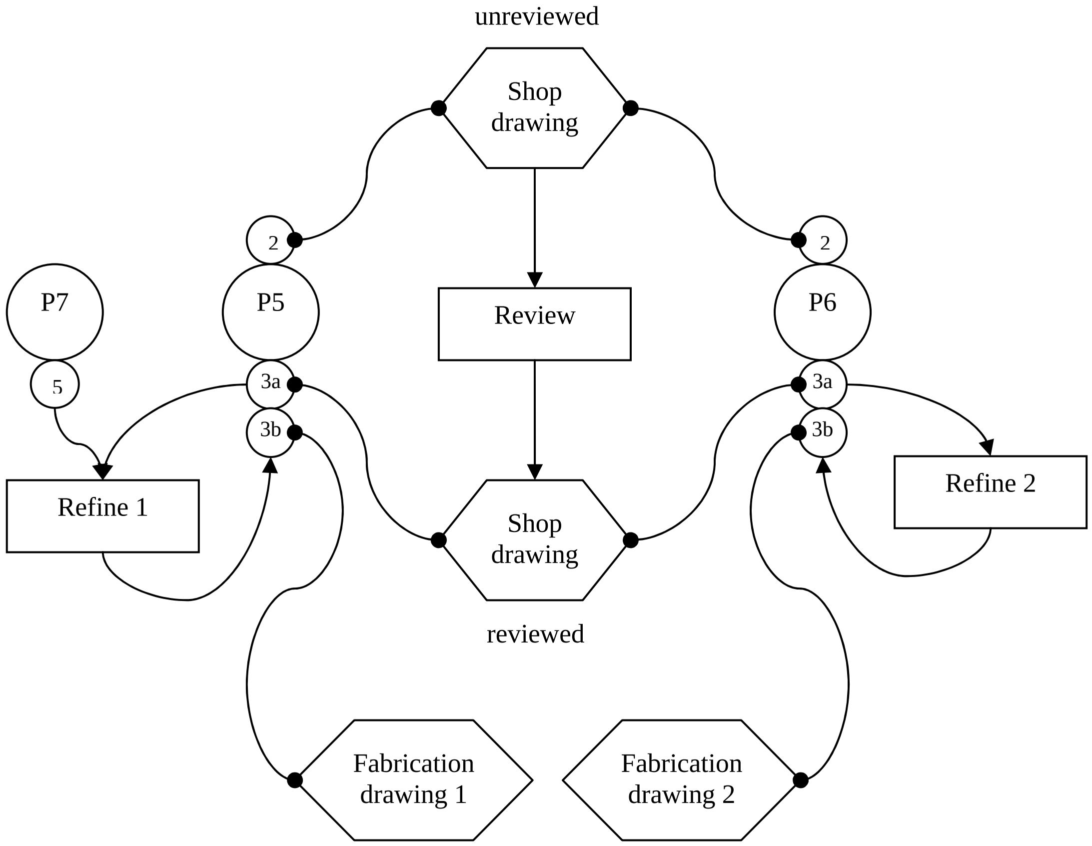


Figure 3.11 Preliminary and Check



(a) Case 1



(b) Case 2

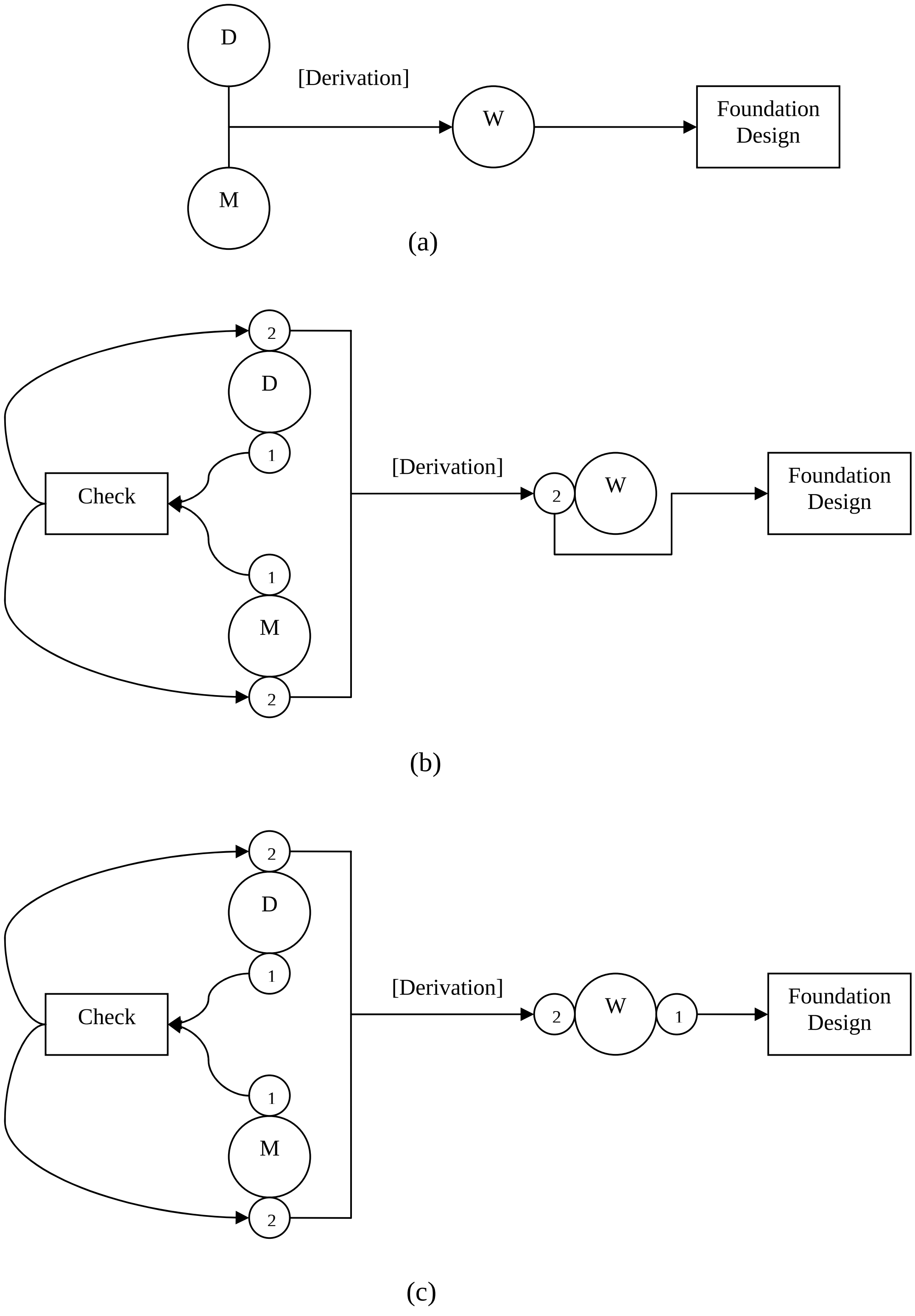
Figure 3.12 Review and Refine

For “Preliminary”, it transforms a parameter (such as P1) from the initial state (state 0) to the as-proposed state (state 1). Generally, it needs “Background information” such as general project information. In this respect, there seems to be a reliance on the experience of designers. A “Check” is concerned with the evaluation of the as-proposed state (state 1) based on component performance such as stress, deflection, crack and so on. Other parameter states (such as P2 at state n) and “External influence” (such as loads) may be involved in the “Check” activity. After “Check”, the as-proposed state (state 1) is turned into as-confirmed state (state 2). For review, its input and output are drawings — different states of drawings, namely “unreviewed” state and “reviewed” state. Since drawings are connected with the states of parameters, “Review” is related to parameter states (state 2 and 3 (3a)) indirectly. For the design process involving fabrication design, “Refine” is responsible for parameter transformation from state 3a to state 3b. As-built measurement information may be a constraint for “Refine”. For example, “Refine 1” transforms P5 from state 3a to state 3b, which requires as-built measurement information, namely state 5 of P7.

It can be seen that other parameters may be involved in the state transformations of a parameter. These external parameters may come from other project participants. The source activities and participants of these parameters should be found so that information responsibility can be clearly determined. These interactions mostly happen in “Check” and “Refine” activities. For “Check”, the involved state of other parameters may be the as-proposed state, the as-confirmed state, the as-designed state or the as-built measured state depending on the project conditions. Generally, later states give greater confidence for the parameter value. However, it may take a longer time to obtain the parameter value of later states so that the related activity is delayed. For “Refine”, it may involve as-built measured state (state 5) of other parameters since refine represents the fabrication design which generally requires exact pre-design information.

Generally, as-proposed state (state 1) is not allowed to be used to produce other parameters, since it is only the estimated value of a parameter. However, sometimes it is necessary to use the as-proposed state of a parameter to save time. Although it sacrifices the exactness of the parameter and is in danger of rework, it saves much time which is considered more important in some projects. In this situation, the designed component based on estimation will have extra capacity to buffer downstream design parameters, although this may not be economical. An obvious case in view is foundation design. For foundation design, the weight of aboveground structure is a parameter. Theoretically, only after the design of the aboveground structure is completed can its weight be obtained. However, since the construction of the foundation precedes that of the aboveground structure, the design of foundation should be completed as early as possible to save time. Then the weight of the aboveground structure can be estimated so that it can be used in foundation design.

Figure 3.13 shows an example for the application of as-proposed state. This example is about the design of a column and its foundation. D, M and W represent the dimension, material and weight of the column, respectively. Foundation design needs the weight of the column, which is derived from its dimension and material. In the figure, (a) shows the relationship between column parameters and foundation design. This is the general representation for information dependence. (b) shows the relationship based on column parameter states. In this case, foundation design needs the as-confirmed state (state 2) of W, which is derived from the as-confirmed state (state 2) of D and M. In contrast, (c) shows the use of state 1 in foundation design. Under this situation, foundation design can start with an estimation of the column



D – Dimension
M – Material
W – Weight

1 – As-proposed state
2 – As-confirmed state

Figure 3.13 Application of As-proposed State weight (state 1 of W). The use of state 1 makes design flexible, which is important to the information coordination.

The preceding section has identified the different kinds of design activities and explained the relationships between design activities and parameter states. To better understand design, Figure 3.14 provides an overview for design. This figure includes four kinds of design activities and two kinds of drawings described previously. It also shows the formation of the different kinds of design drawings. “Preliminary” is responsible for P1 and P2’s transformation from state 0 to state 1, which requires “Background information” to fulfill the transformation function. The state 1 of P1 and P2 is then turned into state 2 by “Check”. “External influence” and state 2 of P3 are external constraints for “Check”. After “Check”, state 2 of P1 and P2 will form shop drawing which is in “unreviewed” state. The “unreviewed” shop drawing undergoes “Review” intending to produce “reviewed” shop drawing, which is related to state 3a of P1 and P2. Two “Refine” activities exist in this figure. “Refine 1” transforms P1 from state 3a to state 3b. As-built measurement information is involved in “Refine 1”, which is represented by state 5 of P4. State 3b of P1 forms fabrication drawing 1. Similarly, “Refine 2” is responsible for P2’s transformation from state 3a to state 3b, which is related to fabrication drawing 2.

3.3.3 Construction Process and Parameter

Construction management is not the focus of this research. The construction activity network is deemed to be available. However, the traditional network is not enough to be used in the coordination analysis. To cater for coordination use, the design information and as-built measurement information need to be attached to the construction network. Design information can be treated as input to construction

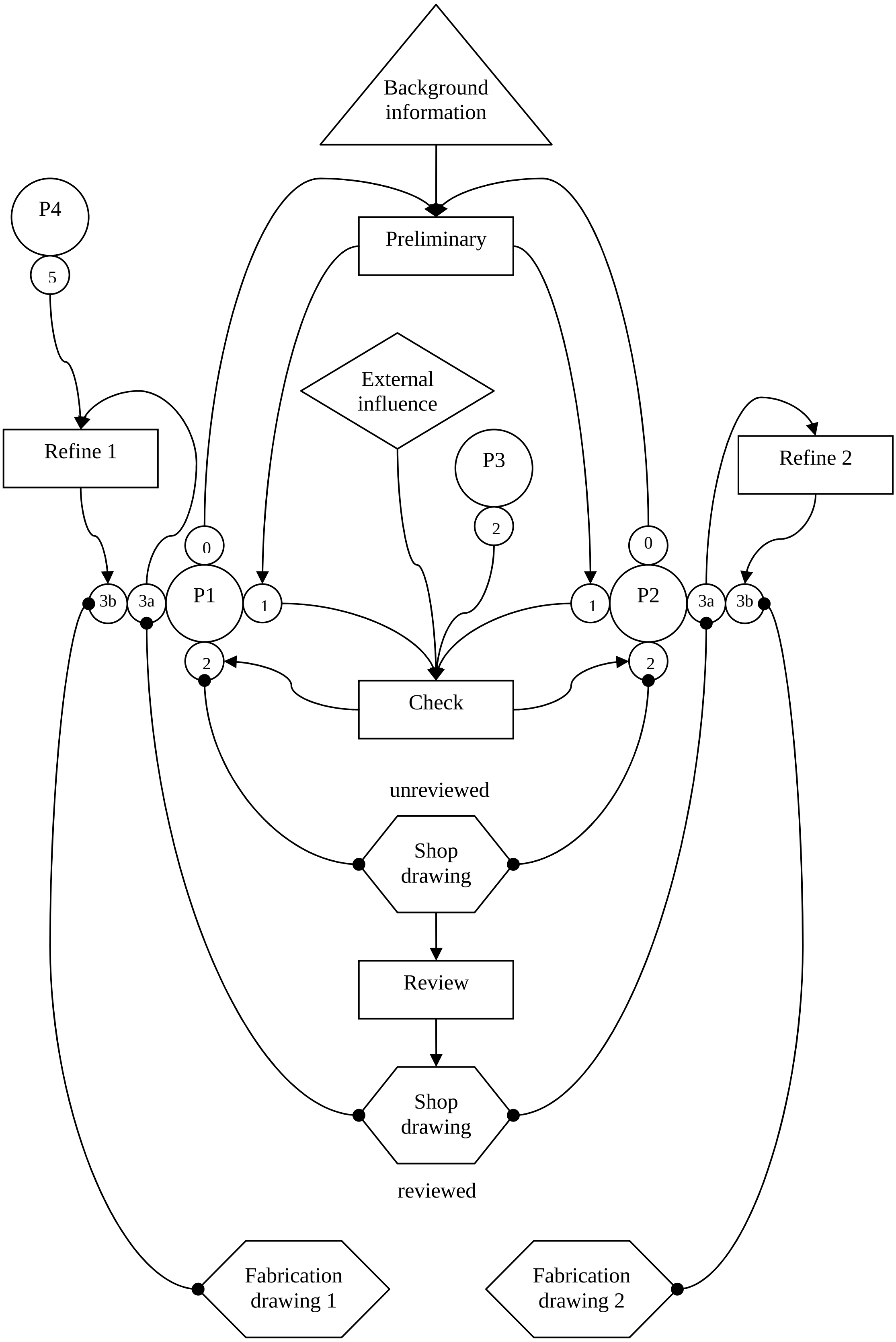


Figure 3.14 Design Process

network while as-built measurement information is the output of the construction network serving as the input for design shop and fabrication drawings.

The as-built measurement information feedback plays an important role in the coordination. Construction is the stage of parameter realization. The realized parameter value may be different from what has been designed. Generally, a little deviation is acceptable since all component parameters have allowable tolerance for their values. However, it may be very serious for work requiring exact pre-design information such as glass fabrication design in glass wall projects. This kind of design work needs actual as-built information of the related components. In this case, the related components must be constructed and the parameters are measured before the detailed design can begin. This kind of dependency increases the complexity of the network since it means that the design of a component depends on the construction finish of other components. As-built measurement feedback is very important for components with long procurement and fabrication times. For these components, they need to be designed as early as possible. However, the required as-built information may not be available when design is to start.

To manage the as-built measurement information feedback, a new kind of activities is added to the traditional network. Since traditional construction activities transform the product into reality, they are called “Conversion” activities in this model. The new activities are called “Measurement”. Thus, design information can be attached to conversion activities which are followed by measurement activities to produce as-built measurement information. In this case, “Conversion” turns as-designed state into as-built state while “Measurement” is responsible for the transformation from as-built state of a parameter to as-built measured state (Figure 3.15).

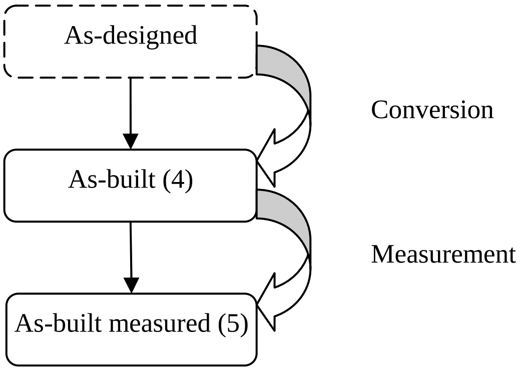


Figure 3.15 State Transformations of a Basic Parameter in Construction Stage

Certainly, the as-designed state can be state 3 or the combination of states 3a and 3b.

A construction activity is characterized by its information inputs and outputs (see Figure 3.16).

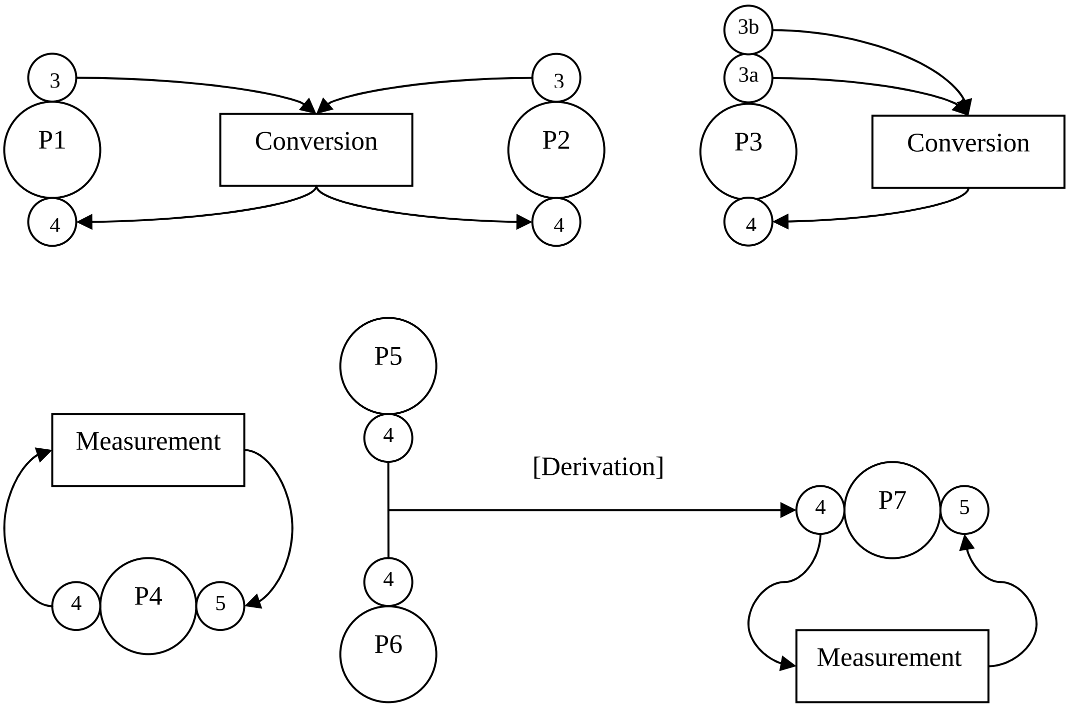


Figure 3.16 Construction Activity and Input/Output

For a “Conversion” activity, its information constraints may include design information, precedence constraints, resources and so on. Only design information is modeled while other inputs are deemed to be available. The design information refers to the as-designed state of parameters, which can be state 3 or the combination of state 3a and 3b. The output of a “Conversion” activity is the as-built state of parameters. In this figure, state 3 of P1 and P2 is transformed into state 4 by “Conversion”. This applies to projects which do not involve fabrication design. If fabrication design exists, the as-designed state of the parameter (such as P3) is represented by states 3a and 3b. Under this situation, “Conversion” transforms P3 from states 3a and 3b to state 4. For a “Measurement” activity, its input is the as-built state of the parameter and output is the as-built measured state of the parameter. Generally, as-built measurement is geometry-related problems which may involve one component or several components. In other words, the measured parameter may be an intra-component parameter or inter-component parameter. For inter-component parameter, a “Derivation” relation exists. In this figure, P4 and P7 are involved in measurement. P4 is an intra-component parameter while P7 is an inter-component parameter which is derived from P5 and P6 (in state 4).

The as-built measured states of parameters are grouped into many units to be released for design use. Figure 3.17 shows the formation of one as-built measurement information unit. This figure includes two kinds of construction activities (“Conversion” and “Measurement”) and a “Derivation” relation. “Conversion 1” transforms P1 and P2 from state 3 to state 4 while “Conversion 2” is responsible for P3’s transformation from states 3a and 3b to state 4. The state 4 of P1 is turned into state 5 by “Measurement 1”. In addition, the state 4 of P4 is derived from the state 4 of P2 and P3. P4 is an inter-component parameter. “Measurement 2” is responsible for P4’s transformation from state 4 to state 5. The state 5 of P1 and P4 forms one “As-built measurement information unit” which is used by design.

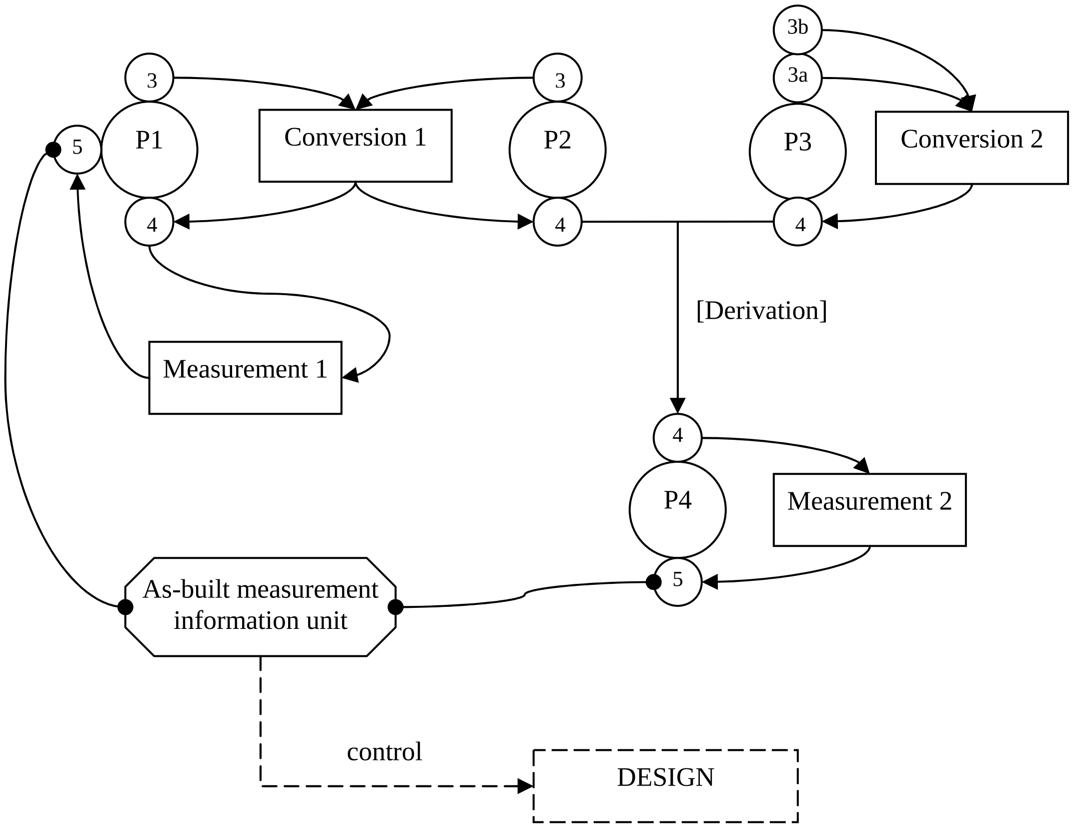
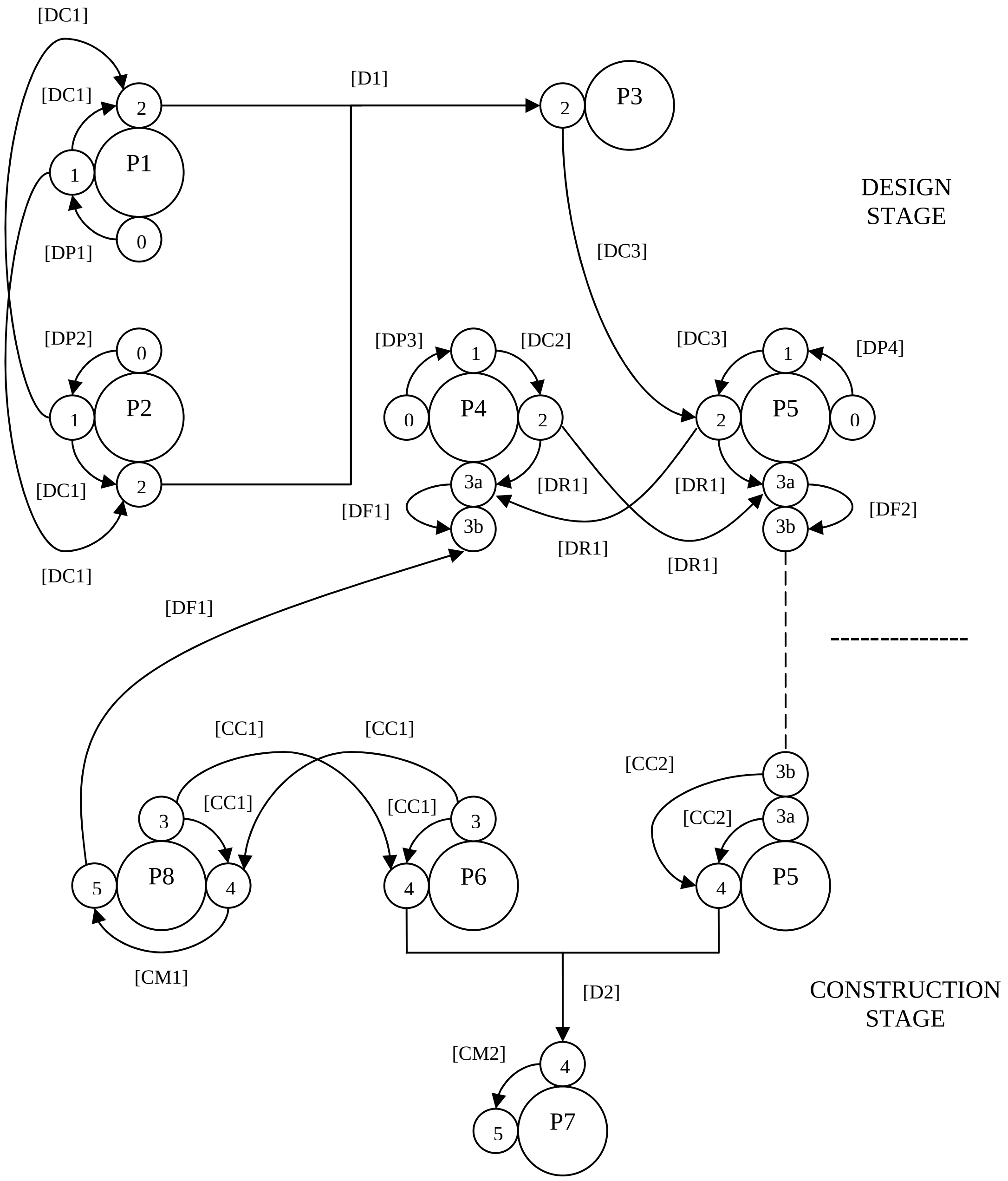


Figure 3.17 Construction Process

3.4 COORDINATION ANALYSIS

3.4.1 Form Original Network

The original network is formed by connecting the basic process activity--parameter state relationships, which involves both design and construction. Figure 3.18 gives an example of the network. The network is parameter state centered while activities are embedded in the state-state relationships. Since this network intends to show activity—parameter state relationships, other items such as drawings and external influences are excluded. Eight parameters are included in this figure. To simplify the representation, only some states are displayed for these parameters. P1, P2, P3 and P4 are involved in the design state analysis while the construction states of P6, P7 and P8 are shown. P5 is included in both design and construction analysis. These



[DP1], [DP2], [DP3], [DP4] – Preliminary activities in design

[DC1], [DC2], [DC3] – Check activities in design

[DR1] – Review activity in design

[DF1], [DF2] – Refine activities in design

[CC1], [CC2] – Conversion activities in construction

[CM1], [CM2] – Measurement activities in construction

[D1], [D2] – Derivation relations

Figure 3.18 Original Network

parameters undergo state transformations with the action of relevant activities. At the same time, interactions occur between the states of different parameters such as P4 and P5, which are reviewed together. Relationships are also shown between design and construction. For example, design information (states 3a and 3b) of P5 controls its construction. As-built measurement information feedback is also displayed between P4 and P8. The state 5 of P8 is used to produce state 3b of P4.

3.4.2 Analyze and Manage the Network

The original network is inherently a network of information dependencies, which presents the links between process activities and their information constraints. It enables modeling of the information flow between process activities. In this way, the information flow can be better coordinated and managed.

The coordination should insure that the required information for process activities can be obtained on time. Because of the complexity of the dependence relationships, it is not so easy to solve the information constraints for these activities. The most frequently occurred coordination problems are information delays and loops (iterations). Thus it is necessary to adjust the activities such that the availability of information required is maximized and the number and size of iterative loops is minimized. Generally, several approaches can be used to solve these coordination problems:

1. Adjust time attributes of activities (start/finish time, duration)

This approach is effective in dealing with information delays. For example, the start and finish time of the activities in the non-critical paths can be adjusted so that these activities can release production information earlier.

2. Re-order activities

Some information coordination problems are caused because of inappropriate work sequence. By re-ordering the activities, these problems can be solved.

Figure 3.19 shows the original plan and the dependency relationships for six activities, namely A1, A2, A3, A4, A5 and A6. It can be seen that a big loop exists in the original plan (A1 → A2 → A3 → A4 → A5 → A6). This loop is due to the interdependence between A2 and A5. In reality, the loop can be reduced by re-ordering these activities.

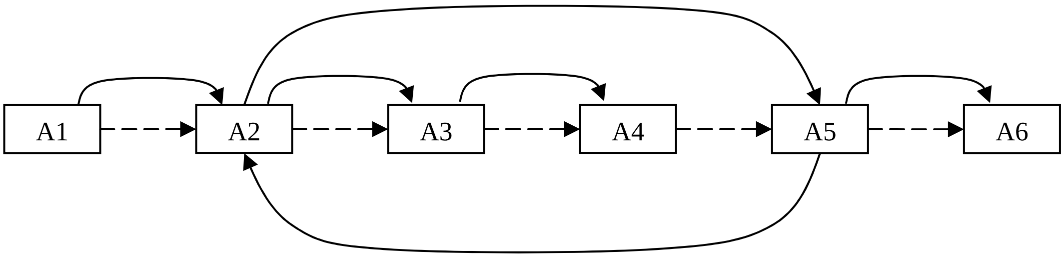


Figure 3.19 Original Plan

Figure 3.20 shows the result after re-ordering. The loop is reduced through the re-ordering of these activities.

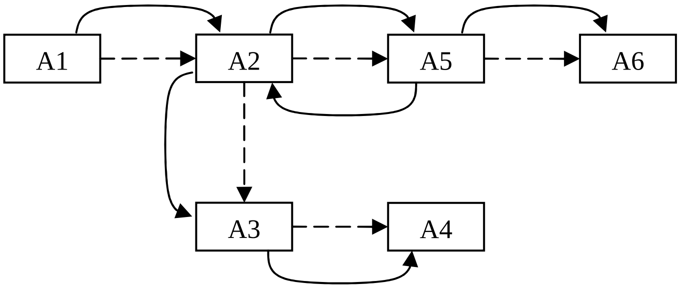


Figure 3.20 Result after Re-ordering

In a project, there are many activities with complex relationships. The re-ordering can be achieved with the help of the method of Design Structure Matrix (DSM) (Yassine et al., 1999).

3. Divide an activity into several sub-activities

In practice, one activity may involve several components, each of which has its own parameters. Thus the output of this activity includes a group of parameters. Generally, the output parameters are released together at the end of the activity. Before its completion, some parameters are generated which may be required by another design activity. This provides the opportunity to divide an activity into several sub-activities, which produce the output parameters separately to cater for different needs. This approach is generally used to solve information delays. But before this can be exploited, a mapping of the parameter dependencies is required to adequately design the sub-activities.

As shown in Figure 3.21, there are two activities, namely “Activity 1” and “Activity 2”. P1, P2 and P3 are inputs of “Activity 1” while P4 and P5 are its outputs. “Activity 2” depends on “Activity 1” in that “Activity 2” requires P4, which is one of the output parameters of “Activity 1”.

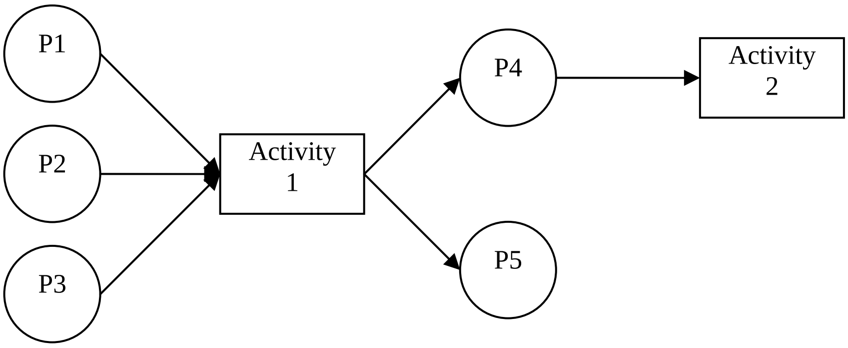
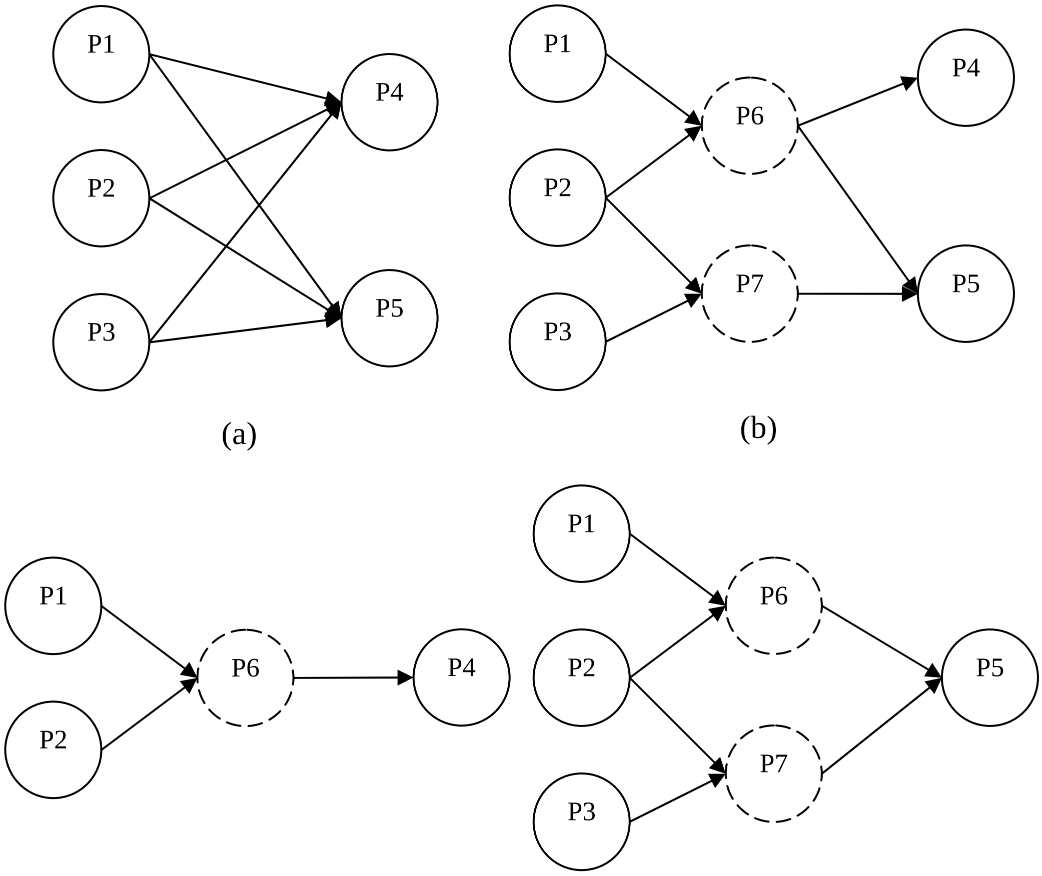


Figure 3.21 Original Activities

From the activity perspective, the implied parameter dependencies for “Activity 1” are as shown in Figure 3.22 (a). This means that delay in any of the parameters P1, P2 and P3 will affect both P4 and P5 so that “Activity 2” is also delayed. However, the real parameter dependencies may not be the same as those in Figure 3.22 (a). For example, the real dependencies may be as shown in Figure 3.22 (b). In this case, P6 and P7 are embedded in “Activity 1”. Actually, the real dependency network can be divided into two sub-networks (see Figure 3.22(c)).



(a) (b)

(c)

Figure 3.22 Parameter Dependencies in Activity 1

Based on the two sub-networks, the original “Activity 1” can be divided into two sub-activities, namely, “Activity 11” and “Activity 12” (see Figure 3.23). For “Activity 11”, its dependent parameters are P1 and P2 while its production is P4. For “Activity 12”, its dependent parameters are P1, P2 and P3 while its production is P5. Now “Activity 2” depends on “Activity 11”. After the division, the delays for “Activity 2” can be resolved. For example, the receipt of P3 is delayed for some reason. In the original plan, this will retard the production of P4 so that “Activity 2” is also delayed. However, with the new configuration based on the underlying parameter dependencies, P4 will not be affected by P3. Thus, “Activity 11” can be performed earlier so that “Activity 2” will not be delayed.

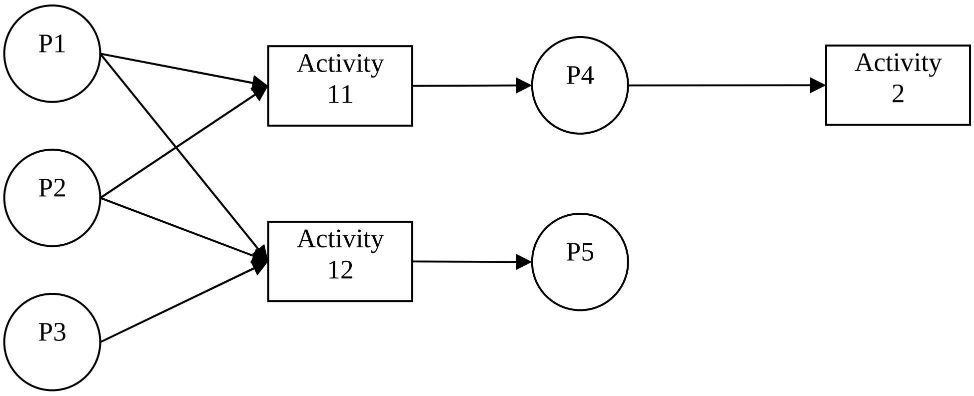


Figure 3.23 Divide an Activity into Two Sub-activities

4. Use an earlier state

For a parameter, different states represent different values of the parameter during design and construction. Although later states provide more exact information for the parameter value, it may take a longer time to obtain them. Thus, using later states may cause information delays. To solve these problems, earlier states can be used. The earlier the state is, the sooner the related value can be obtained. Although it sacrifices the exactness of the parameter, using an earlier state can produce the required information sooner so as to solve information delays which is considered more serious in some projects.

As shown in Figure 3.24, the as-design state (state 3) of parameter P1 provides more exact information than the as-confirmed state (state 2) of parameter P1 since state 3 represents the parameter value after drawing review. However, review may take a long time in some projects. Then the activity (“Check 2”) requiring the information (state 3 of parameter P1) needs to put on hold to wait for the information. In reality, the as-confirmed state (state 2) of parameter P1 can be used in “Check 2”, which is produced in an earlier time. Under this situation, there should be a verification process after the state 3 of P1 is obtained. If the difference between state 3 and state 2 of P1 is not acceptable, then there will be rework for “Check 2”.

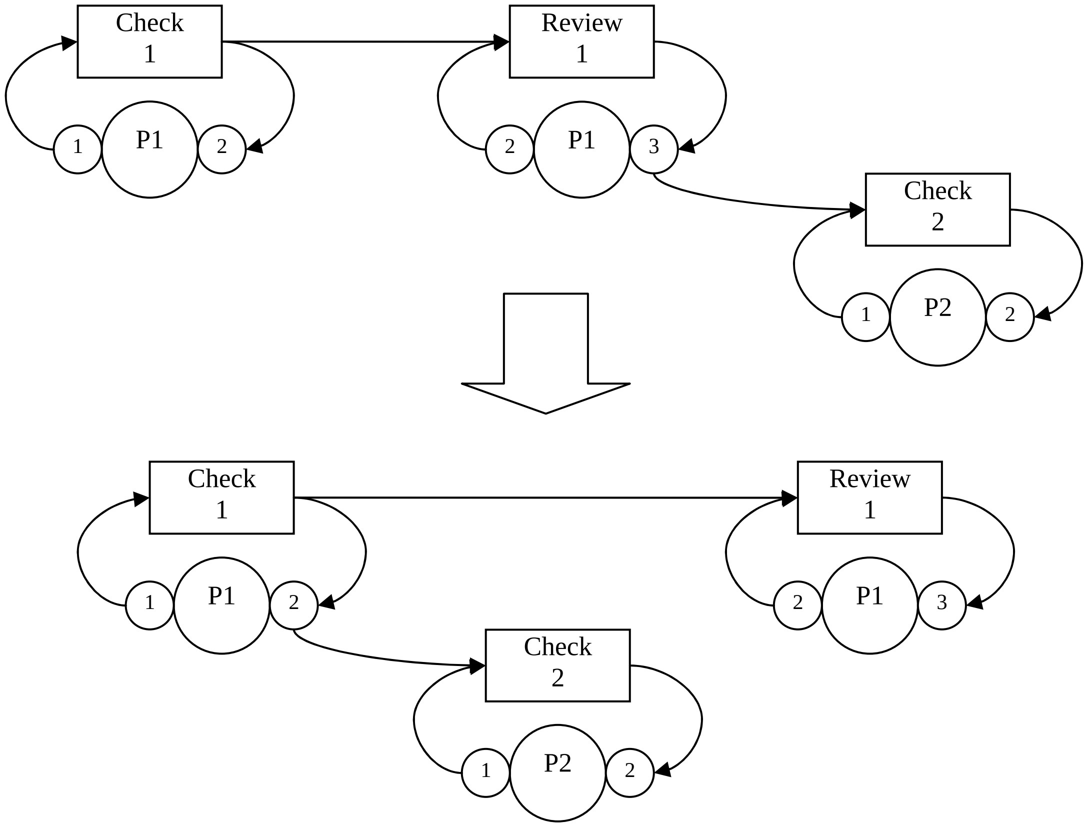


Figure 3.24 Use an Earlier State

3.5 CONCLUSION

This chapter introduces the proposed coordination model. This is the main part of the dissertation. The model aims to improve the coordination between design and construction. It has been developed using product information as the interface. Parameters play an important role in the product-oriented coordination in that they are employed to describe the properties of the product components. Furthermore, activity-based representation and parameter-based representation are combined together to depict design and construction processes. In addition, a new kind of activities is added to the construction network to deal with as-built measurement information.

One of the most important characteristics of the model is that states are used to represent the different status of parameters. Through the parameter states, relationships can be established between design and construction activities. The whole dependence network is formed by connecting these dependence relationships. By forming the network, the model is capable of making information flows more explicit. Based on the network, action can be taken to deal with information coordination problems. It should be noted that the proposed approaches are not isolated. Effective coordination will be achieved by fully considering all these approaches.

To illustrate the working principles of this model, the next chapter will present one case study.

CHAPTER 4

CASE STUDY

A case is presented in this chapter to illustrate the working principles of the proposed coordination model. This case is about the design and construction of a glass wall, which is one part of a building. The original data for this case was taken from Chen (2002).

The glass wall was completed by a glass wall specialist subcontractor. As a small-sized specialist subcontractor, its information coordination problems are comparatively simpler than those of the other bigger companies. However, it still encountered many difficulties with regard to the coordination between design and construction. The glass wall is selected for the case study because it is compact enough to show the relationships between design and construction, thus providing a good context for the application of the model.

4.1 INTRODUCTION

The glass wall is composed of two main parts — primary steel frame and surface glass panel. Normally, the glass panels are supported by frames. Some auxiliary components are necessary to fix glass panels such as bolts, spider clamps and so on. Figure 4.1 exhibits the perspective views of the glass wall from both outside and inside.

A typical glass wall project includes three main stages, namely, design, fabrication and installation, which are related to each other (Figure 4.2). Since glass wall system is a high-tech, complex, and high quality item, the design-build delivery system was adopted by the specialist subcontractor to better maintain quality and constructability. However, the fabrication work was subcontracted to a fabrication company so that the glass wall specialist subcontractor can concentrate on the design and installation work.

Figure 4.1 Perspective Views of a Glass Wall

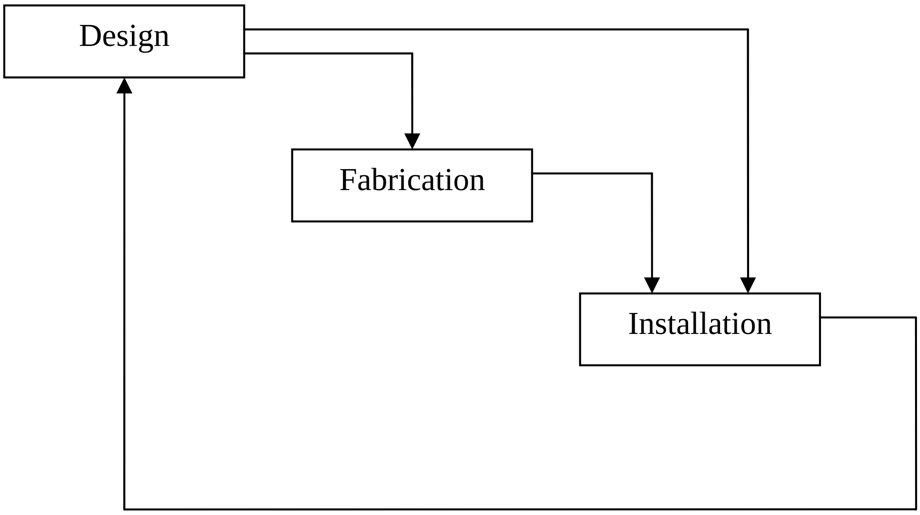


Figure 4.2 Glass Wall Project

The design stage is information-intensive, which needs a variety of technical information as well as financial and controlling information coming from many kinds of internal and external sources. The designer is responsible to provide qualified drawings for fabrication and installation use. Generally, the glass wall design is composed of shop drawing design and fabrication drawing design, which generate the shop and fabrication drawings, respectively (see Figure 4.3).

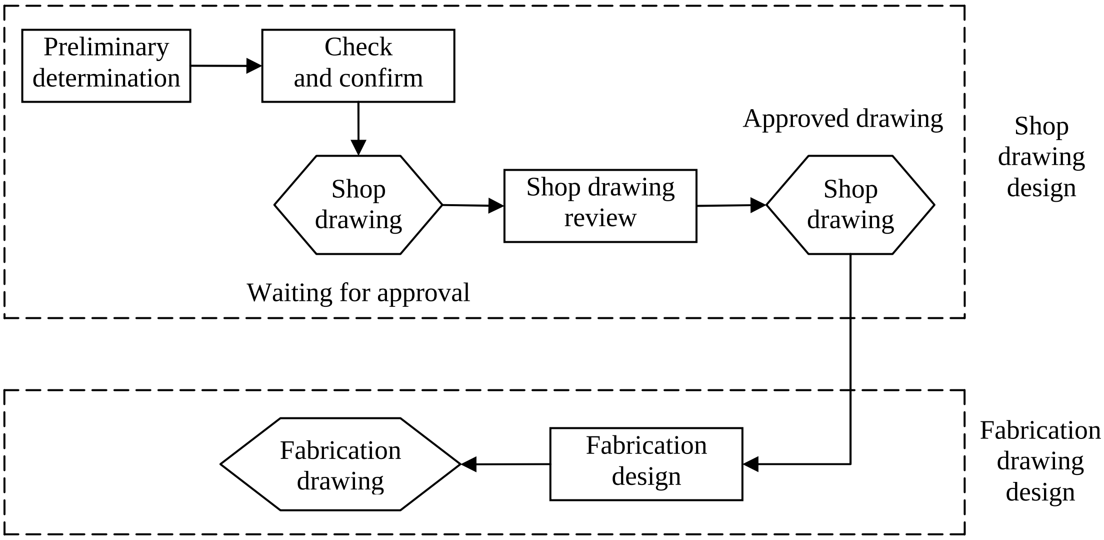


Figure 4.3 Glass Wall Design

The fabrication drawing design is controlled by the shop drawing design. The shop drawing design includes three processes, namely, “preliminary determination”, “check and confirm”, and “shop drawing review”. After “check and confirm”, shop drawing will be produced. Shop drawing will then undergo a review before it is approved. The review task is generally conducted by external parties including the main contractor, architects, engineers and design consultants.

The main fabrication tasks include glass and steel fabrication. Generally, the fabrication work is conducted in the factory. Since fabrication is not the focus of the case analysis, detailed information for fabrication will not be discussed.

Installation follows fabrication. Glass wall installation comprises two main tasks -- steel installation and glass installation. Installation process can be executed successfully only with a combination of needed resources and information, such as design information, fabrication products, technical workers, and appropriate tools and equipment under well-prepared site conditions. It should be noted that the installation may affect the design by providing as-built measurement information.

4.2 INFORMATION FLOW ANALYSIS

In the glass wall project, design and installation are two crucial stages which experienced a lot of information flow problems. Figure 4.4 presents the information flows involved in this project. This figure provides an overview of the information flows among project processes. Two kinds of information flows can be identified, namely, internal information flow and external information flow.

4.2.1 Internal Information Flow

Internal information flow is related to the information relationships between different processes within the glass wall project.

For the two sub-stages of glass wall design, shop drawing design provides "approved drawing" to control fabrication drawing design including glass fabrication design and steel fabrication design. At the same time, "approved drawing" is also used to direct construction activities -- glass installation and steel installation. The fabrication design is followed by fabrication and shipment before installation work. Thus, both "approved drawing" and "steel fabrication drawing" influence the steel installation. Similarly, the glass installation is affected by "approved drawing" and "glass fabrication drawing". The conventional viewpoint suggests that construction

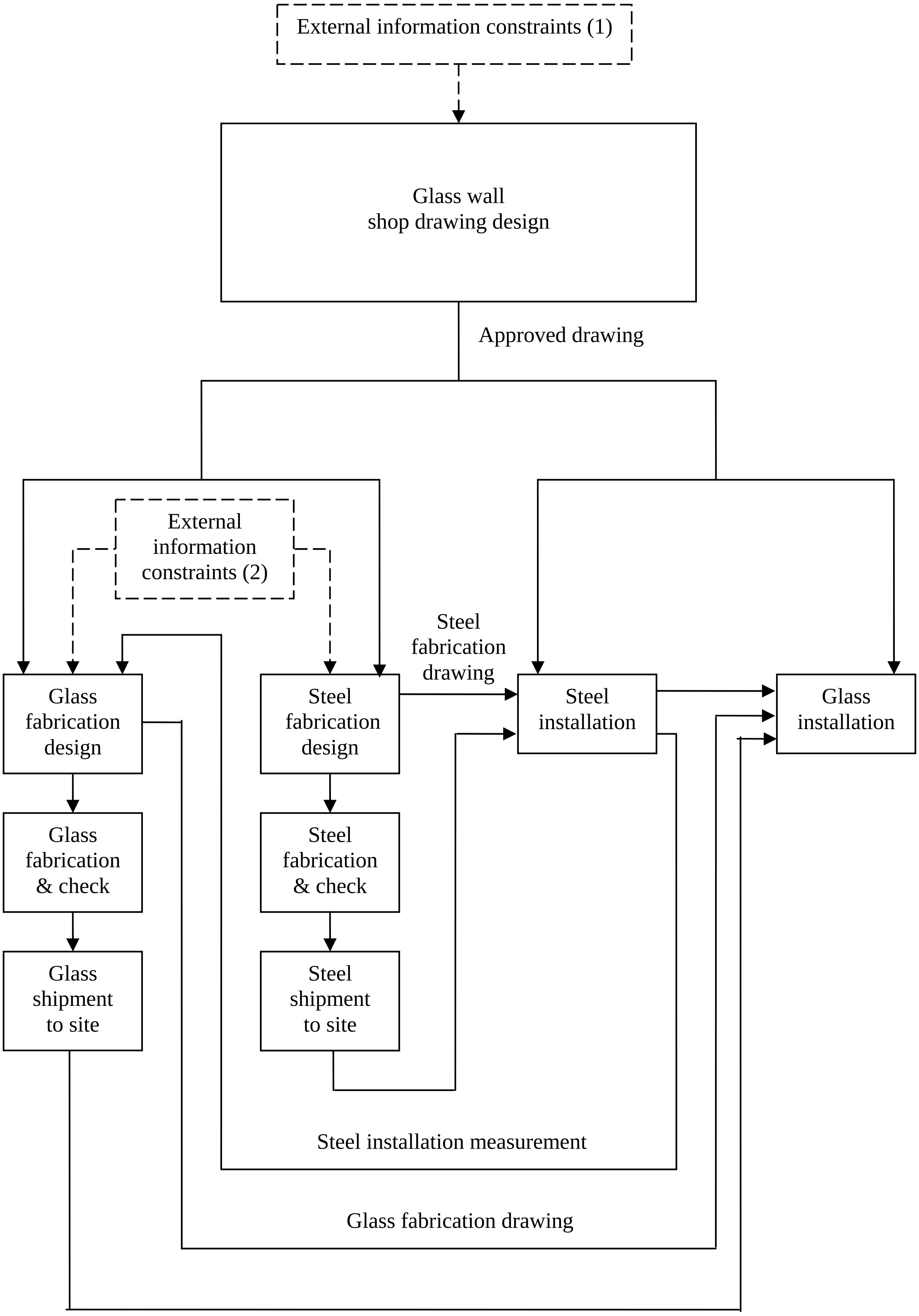


Figure 4.4 Information Flows in the Glass Wall Project

should not start until the relevant drawings are ready. In this way, the design process becomes the key constraint to the installation process.

However, the installation process also affects the design process by providing as-built measurement information. In this project, the as-built measurement information of steel frame is of great importance for the glass fabrication design. In glass fabrication, any error in the fabrication drawings leads to failure and re-fabrication. Thus, accurate fabrication drawing information is very essential to the glass fabrication. Since the glass panels are to be installed in steel frame, the information of steel frame is definitely necessary to determine accurate dimension details for glass panels. Since steel frame installation is difficult to control due to site complexity, the steel frame information can only be verified after the installation of steel frame. The availability of "steel installation measurement" information is crucial to produce accurate glass fabrication design that will not pose problems on site later. One of the difficulties for this project lies in the glass fabrication design since it has two critical internal constraints including "approved drawing" and "steel installation measurement".

4.2.2 External Information Flow

External information flow refers to the information constraints coming from other project participants. Generally, a single project involves many participants working together to complete the project successfully. Inter-participant information interference is inevitable. It is impossible for a participant to finish his part of the work without relying on information of other participants.

Since the glass wall is only one part of a building, it has close relationship with the work of some other participants. The external information constraints of Figure 4.4 are shown in Figure 4.5.

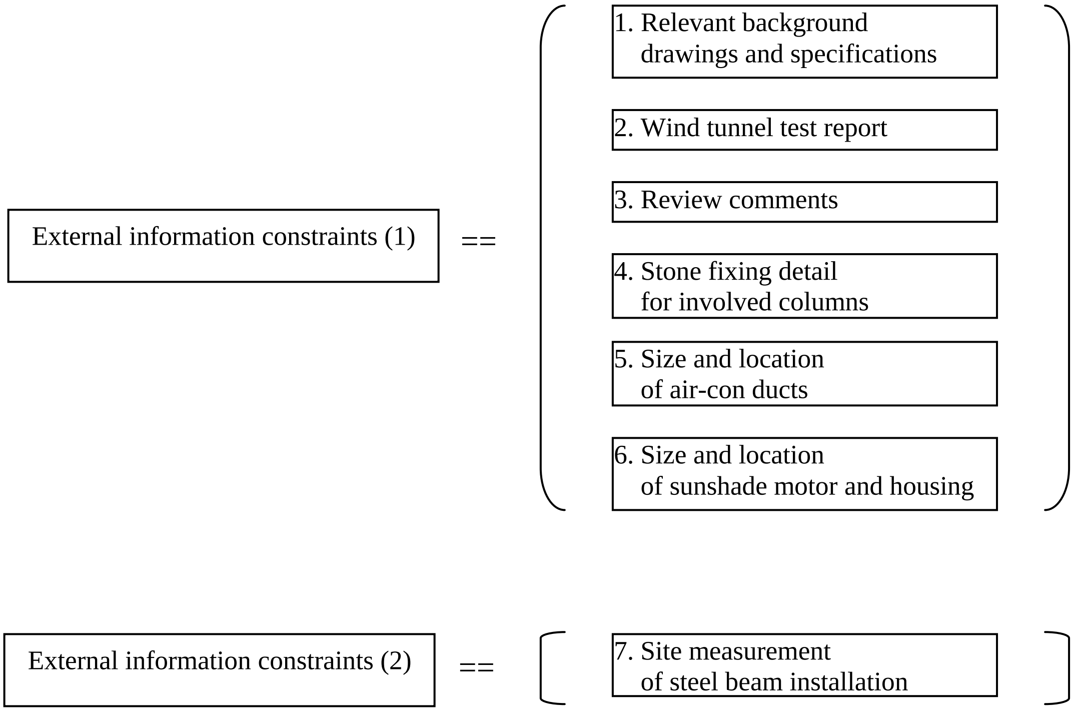


Figure 4.5 External Information Constraints

There are seven external information items. These information items are classified into two groups, which control glass wall shop drawing design and glass wall fabrication design, respectively. The glass wall shop drawing design is very complex in that it is dependent on six external information items, namely, “relevant background drawings and specifications”, “wind tunnel test report”, “review comments”, “stone fixing detail for involved columns”, “size and location of air-con ducts”, and “size and location of sunshade motor and housing”. The fabrication design also requires one external information constraint -- “site measurement of steel beam installation”.

These information items come from many other participants. If the relationships among the different participants are not well linked, effective information coordination is difficult to achieve. Table 4.1 provides the source activities and responsible participants for these external information items.

Table 4.1 External Information Constraints

No.	Description	Source activity	Responsible participant
1	Relevant background drawings and specifications	Subcontract award	Main contractor
2	Wind tunnel test report	Wind tunnel test	RWDI consultant
3	Review comments	Shop drawing review	Architect, engineer and consultant
4	Stone fixing detail for involved columns	Shop drawing design	Stone work contractor
5	Size and location of air-con ducts	Shop drawing design	HVAC contractor
6	Size and location of sunshade motor and housing	Shop drawing deign	Facility supplier
7	Site measurement of steel beam installation	Steel beam installation	Steel work contractor

It can be seen that these items are produced by seven different external activities including “subcontract award” (main contractor), “wind tunnel test”(RWDI consultant), “shop drawing review”(architect, engineer and consultant), “shop drawing design”(stone work contractor), “shop drawing design”(HVAC contractor), “shop drawing design”(facility supplier), and “steel beam installation”(steel work contractor).

Through these information links, the activities in the glass wall can be connected with the relevant external activities. Figure 4.6 presents the task links for inter-participant information dependencies. Since these external constraints affect the design stage of the glass wall, only design activities are shown for the glass wall. Since glass wall shop drawing design includes three processes, its six external information constraints are linked to the corresponding processes. The “relevant background drawings and specifications” provides background information to “preliminary determination” while “review comments” is incorporated into “drawing review”. The remaining four items are connected with “check and confirm” including “wind tunnel test report”, “stone fixing detail for involved columns”, “size and location of air-con

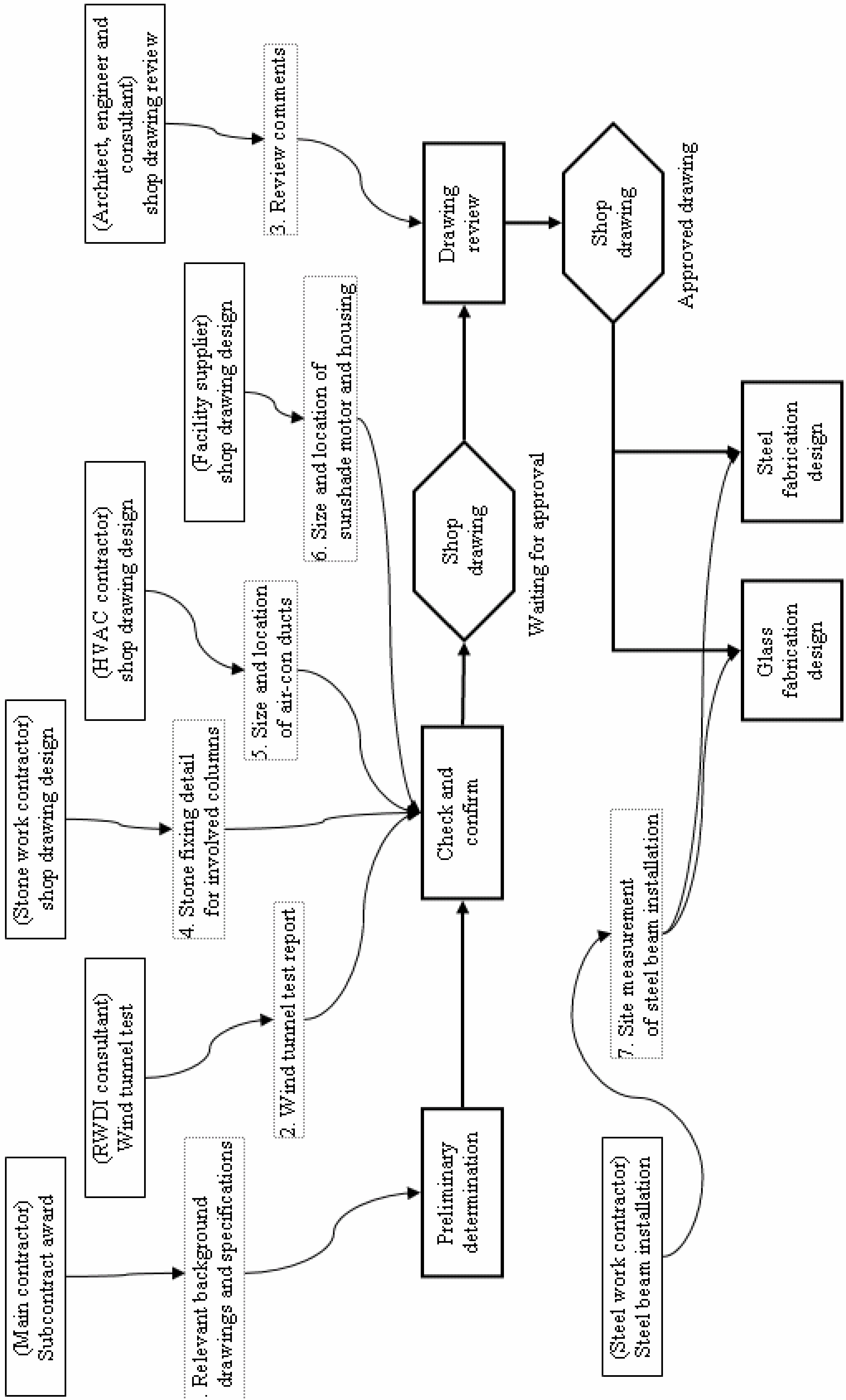


Figure 4.6 Inter-participant Information Dependency

ducts", and "size and location of sunshade motor and housing". In fabrication design stage, the information item "site measurement of steel beam installation" affects both "glass fabrication design" and "steel fabrication design". Among the glass wall processes, "check and confirm" has the most external constraints with 4 external information items, three of which are related to the shop drawing designs of other participants. It should be noted that the procedure of these external shop drawing designs is similar to that of the glass wall shop drawing design stage (see Figure 4.7).

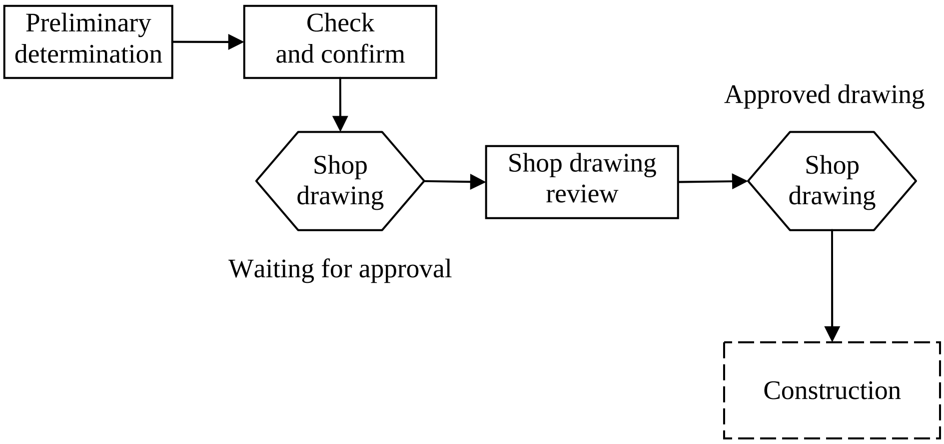


Figure 4.7 Procedure for External Shop Drawing Design

Although all the seven information items are important for the project, the analysis will focus on "stone fixing detail for involved columns", "size and location of air-con ducts", "size and location of sunshade motor and housing" and "site measurement of steel beam installation" since problems that often occur are related to these items.

Efficient information flows are difficult to achieve due to the complexity of the information dependencies. Problems occurred in this project because of inappropriate management of internal and external information flows. Thus, information coordination is very important and necessary for the glass wall subcontractor to resolve these problems.

4.3 MODEL FRAMEWORK

4.3.1 Identification of Key Parameters

Many components are involved in this project. Parameters are identified based on these components. For the glass wall, there are two main components, namely, steel frame and glass panel, each having one parameter. The relevant external components and parameters are also very important since they are related to the external information flow. All the main components and parameters involved in the project are provided below in Table 4.2.

Table 4.2 Parameter Identification

	Description		Component	Parameter
1	Glass wall	Steel frame	S	D(S) (dimension detail of steel frame)
2		Glass panel	G	D(G) (dimension detail of glass panels)
3	Relevant external work	Stone work	C	D(C) (Stone fixing detail for involved columns)
4		Air-con duct	H	D(H) (Size and location of air-con ducts)
5		Facility work	F	D(F) (Size and location of sunshade motor and housing)
6		Steel beam	B	D(B) (dimension detail of steel beam)

Six parameters are identified based on the corresponding components. The two parameters D(S) and D(G) are used to describe the dimension properties of the glass wall steel frame and glass panel, respectively. The other four parameters, namely D(C), D(H), D(F) and D(B), are related to the external work. These parameters are not all the parameters of the relevant components. Generally, other parameters such as material properties, have been determined in previous stages. All the identified parameters are intra-component parameters in that each of them only involves one component. Furthermore, they are basic parameters since they describe the basic properties of the relevant components.

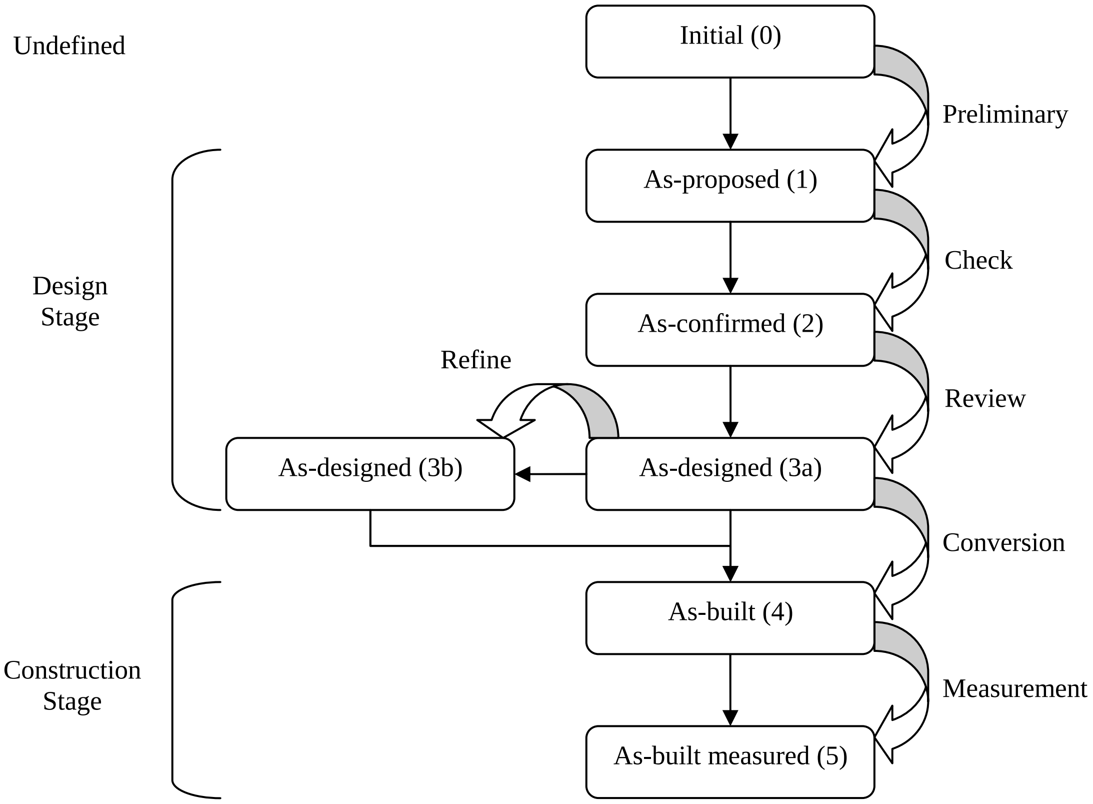


Figure 4.8 State Chain of D(S)

These parameters undergo state transformations during design and construction. As shown in Figure 4.8, state chain for parameter D(S) can be described as

Initial (0) → As-proposed (1) → As-confirmed (2) → As-designed (3a-3b) →

As-built (4) → As-built measured (5)

As shown in Figure 4.9, state chain for parameter D(G) can be described as

Initial (0) → As-proposed (1) → As-confirmed (2) → As-designed (3a-3b) →

As-built (4)

D(S) has as-built measured state (state 5) while as-built measured state is not involved in D(G).

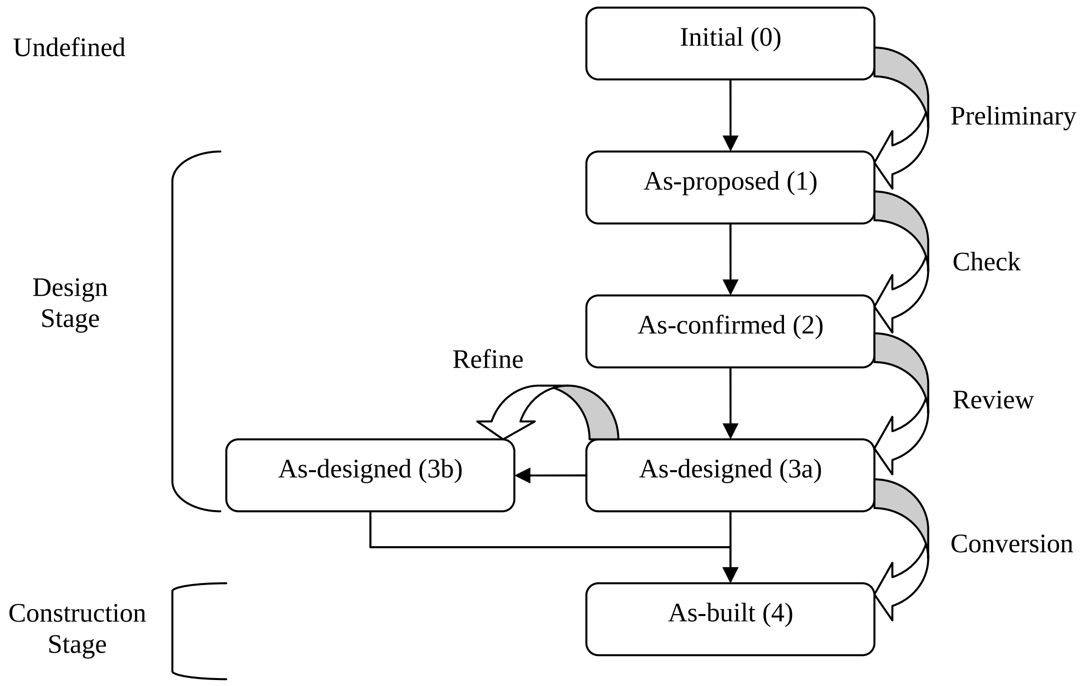


Figure 4.9 State Chain of D(G)

The external parameters, namely, D(C), D(H), D(F) and D(B), provide external information constraints for the glass wall design. They also have state chains. Since the evolution of these parameters is not the focus of this case analysis, their state chains will not be shown. The involved states for D(C), D(H), D(F) are as-confirmed state (state 2) and as-designed state (state 3), which represent design information of these parameters. However, the as-built measured state (state 5) of D(B) is included in the case analysis, which provides as-built measurement information.

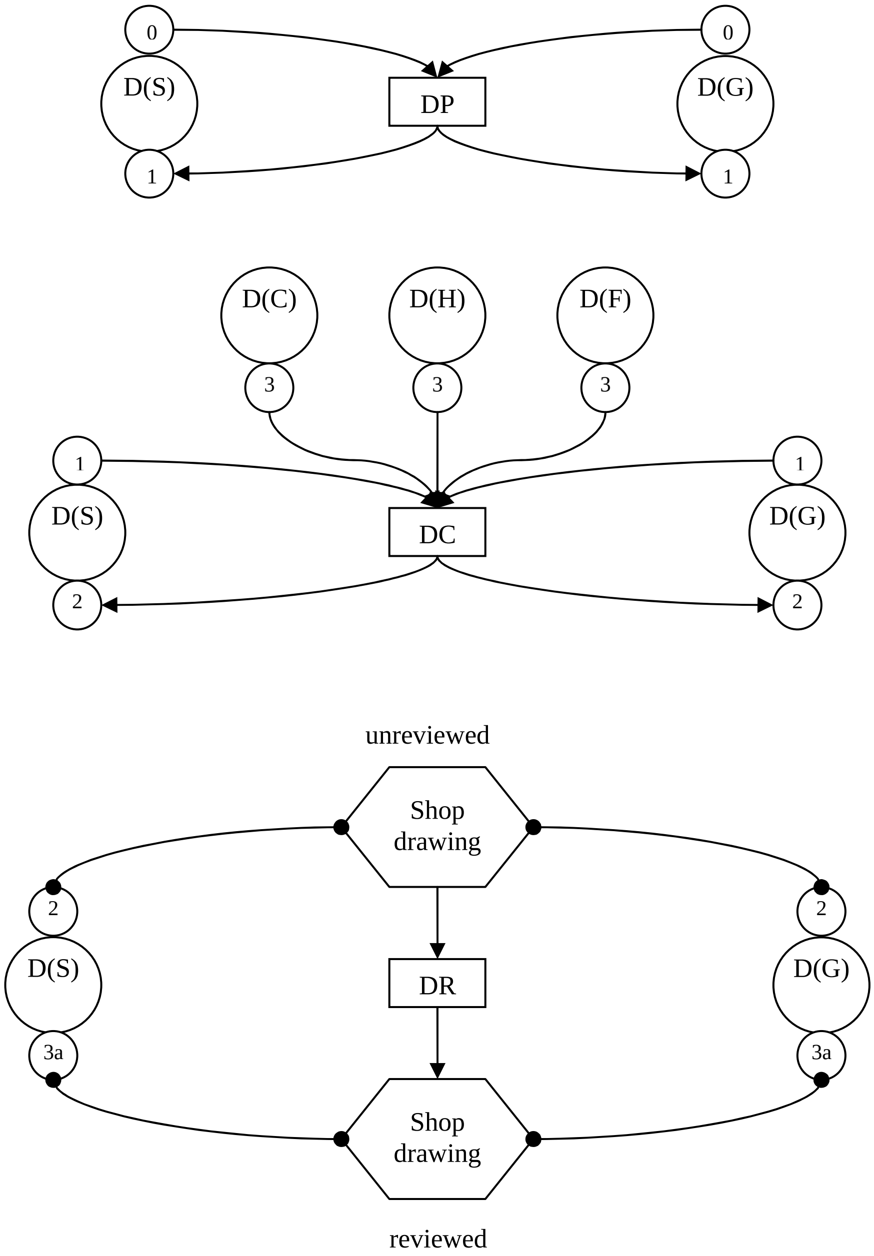
4.3.2 Analysis of Design Process

The glass wall design is composed of two stages – shop drawing design and fabrication drawing design. Furthermore, the shop drawing design includes three processes, namely, “preliminary determination”, “check and confirm”, and “shop drawing review”. Thus, all the four kinds of design activities, namely “Preliminary”, “Check”, “Review” and “Refine”, are involved in the glass wall design. Table 4.3 shows all the design activities for glass wall. Since the design of steel frame and the design of glass panels are tightly coupled in the shop drawing design stage, they are combined together for “Preliminary”, “Check” and “Review”.

Table 4.3 Design Activities

No.	Name	Type	Description	
1	DP	Preliminary	Preliminary determination of steel frame and glass panel dimension	Glass wall
2	DC	Check	Check and confirm for steel frame and glass panel dimension	
3	DR	Review	Shop drawing review	
4	DF1	Refine	Steel frame fabrication design	
5	DF2	Refine	Glass panel fabrication design	

These activities are characterized by their information inputs/outputs which can be described using parameter states. Figure 4.10 shows the activities and their relationships with parameter states in the glass wall shop drawing design. The preliminary activity “DP” is responsible for D(S) and D(G)’s transformation from initial state (state 0) to as-proposed state (state 1), which is then turned into as-confirmed state (state 2) by the check activity “DC”. “DC” needs external information which is represented by as-designed state (state 3) of D(C), D(H) and D(F). The state 2 information of D(S) and D(G) can be grouped into shop drawings. These drawings will undergo review activity “DR”, which is performed by external parties. “DR” updates the information in drawings so as to produce approved drawings which contain the as-designed state (state 3a) information of D(S) and D(G). For review, its input and output are different states of drawings, namely unreviewed state and reviewed state. Since drawings are connected with the states of parameters, “DR” is related to state 2 and 3a of D(S) and D(G) indirectly.



State:

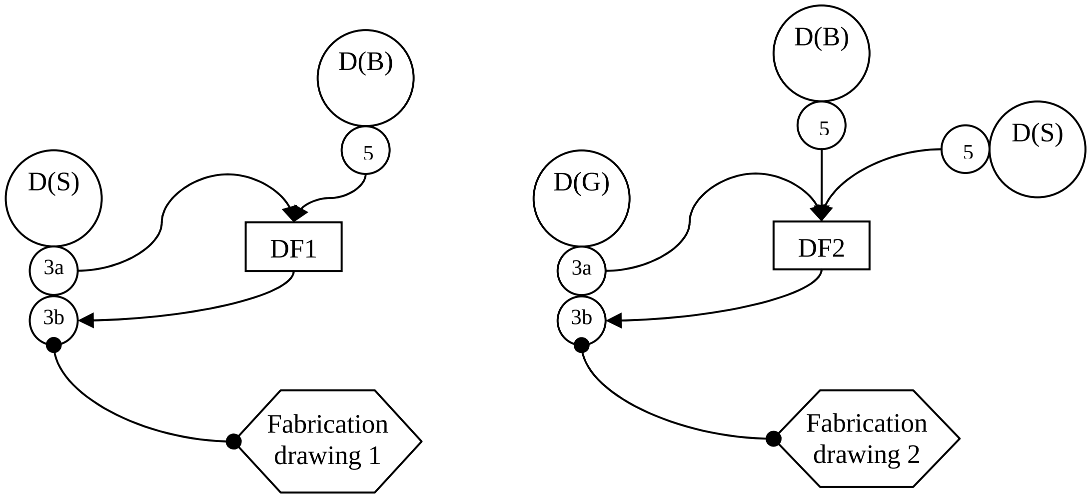
State 0: Initial
State 1: As-proposed state
State 2: As-confirmed state
State 3a: As-designed state
(for shop drawing)

Activity:

DP: (Preliminary) Preliminary determination
of steel frame and glass panel dimension
DC: (Check) Check and confirm for steel frame
and glass panel dimension
DR: (Review) Shop drawing review

Figure 4.10 Glass Wall Shop Drawing Design

Figure 4.11 shows the activities and their relationships with parameter states in the glass wall fabrication drawing design. Two refine activities exist in the glass wall fabrication drawing design. Refine may involve as-built measured state (state 5) of other parameters since it represents fabrication design which generally requires exact pre-design information. The steel frame fabrication design “DF1” is responsible for D(S)’s transformation from as-designed state (state 3a) to as-designed state (state 3b). It needs as-built measurement information which is represented by as-built measured state (state 5) of D(B). The steel fabrication drawing is related to the state 3b of D(S). Similarly, glass panel fabrication design “DF2” transforms D(G) from state 3a to state 3b. The involved as-built measurement information for “DF2” is described using state 5 of D(B) and D(S). State 3b information of D(G) will form glass fabrication drawing.



State:

State 3a: As-designed state
(for shop drawing)
State 3b: As-designed state
(for fabrication drawing)
State 5: As-built measured state

Activity:

DF1: (Refine) Steel frame fabrication design
DF2: (Refine) Glass panel fabrication design

Figure 4.11 Glass Wall Fabrication Drawing Design

4.3.3 Analysis of Construction Process

As described in Chapter 3, a construction activity may be a “Conversion” or “Measurement” activity. These two kinds of activities exist in steel work since the site measurement of the steel frame is necessary for the glass fabrication design. However, only conversion activity is involved in glass work because the as-built measurement information of glass panels is not very important for the case analysis. In addition, the steel beam construction is also relevant to this case study. Since the steel beam supports the steel frame for the glass panels, the measurement information after steel beam installation is crucial to steel frame and glass fabrication design. Thus, the construction activities for the steel beam include “Conversion” and “Measurement”. Table 4.4 shows the construction activities for these components.

Table 4.4 Construction Activities

No.	Name	Type	Description	Component
1	CC1	Conversion	Steel frame installation	Glass wall
2	CC2	Conversion	Glass panels installation	
3	CM1	Measurement	Site measurement of steel frame installation	
4	CC	Conversion	Steel beam installation	Steel beam
5	CM	Measurement	Site measurement of steel beam installation	

A “Conversion” activity transforms parameters from as-designed state (state 3 or the combination of 3a and 3b) to as-built state (state 4), which will be turned into as-built measured state (state 5) by “Measurement” activity. Figure 4.12 shows the glass wall construction activities and their relationships with state transformations. The steel installation activity “CC1” is responsible for D(S)’s transformation from states 3a and 3b to state 4, which is changed to state 5 by the site measurement of steel installation “CM1”. The glass installation activity “CC2” transforms D(G) from states 3a and 3b to state 4. “CC1” precedes “CC2” based on the construction precedence relationship.

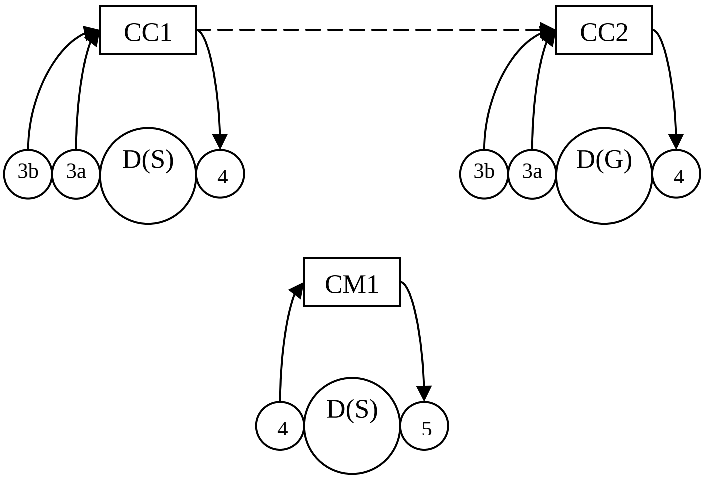


Figure 4.12 Glass Wall Construction Activities

The parameter state transformations for the construction activities of the steel beam are provided in Figure 4.13. The steel beam installation "CC" is responsible for D(B)'s transformation from as-designed state (state 3) to as-built state (state 4) while the as-built measurement "CM" turns state 4 into as-built measured state (state 5) for D(B).

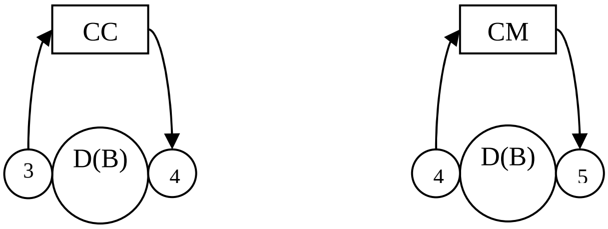
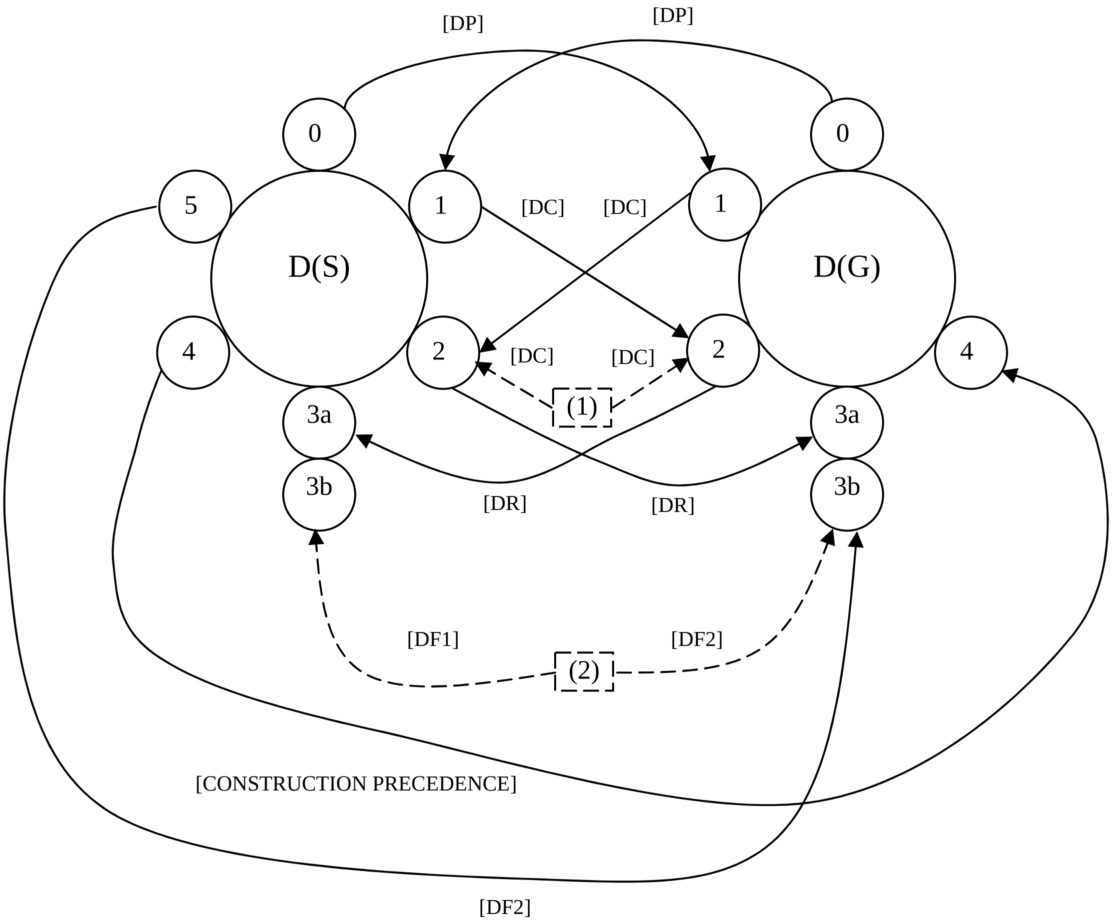


Figure 4.13 Steel Beam Construction Activities

4.4 COORDINATION ANALYSIS

4.4.1 Form Original Network

Many activities are involved in this project. These activities are connected through parameter states. A network is formed by connecting the relationships (Figure 4.14).



(1) == External information constraints for glass wall shop drawing design

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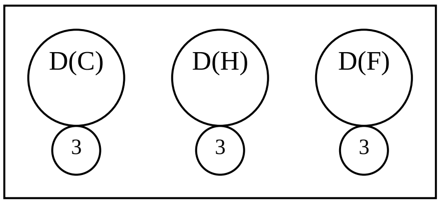

(2) == External information constraints for glass wall fabrication drawing design

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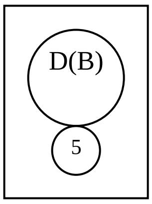


Figure 4.14 Original Network

The network is parameter state centered while activities are embedded in the state-state relationships. D(S) and D(G) undergo state transformations with the action of relevant activities. The state transformations within D(S) and D(G) are not shown since they are easy to understand. At the same time, interactions occur between the states of these two parameters showing the dependencies of their design and construction. D(S) and D(G) are tightly coupled in the shop drawing design stage. In addition, relationships are presented between the states of D(S) and D(G) and those of the external parameters. It can be seen that the as-confirmed state (state 2) of D(S) and D(G) depends on the as-designed state (state 3) of D(C), D(H) and D(F) while the as-built measured state (state 5) of D(B) affects the as-designed state (state 3b) of D(S) and D(G). The state transformations for these external parameters are not shown since they are not the focus of the case analysis. It should be noted that a construction precedence relationship exists between the as-built state (state 4) of D(S) and the as-built state (state 4) of D(G).

The dependency network is very complex. To make it easier to understand, Figure 4.15 provides an alternative representation of the network. The relationships are classified into two groups, namely design related relationship and construction related relationship, which are represented by solid lines and dashed lines, respectively. Design related relationship includes design interdependence and design dependence while construction related relationship includes construction precedence and as-built measurement feedback. In this case, the design interdependence refers to the coupled relationships between D(S) and D(G) in the shop drawing design stage. For external constraints, they can be design related constraints or construction related constraints. In this case, the as-designed state (state 3) of D(C), D(H) and D(F) is design related constraint while the as-built measured state (state 5) of D(B) is construction related constraint.

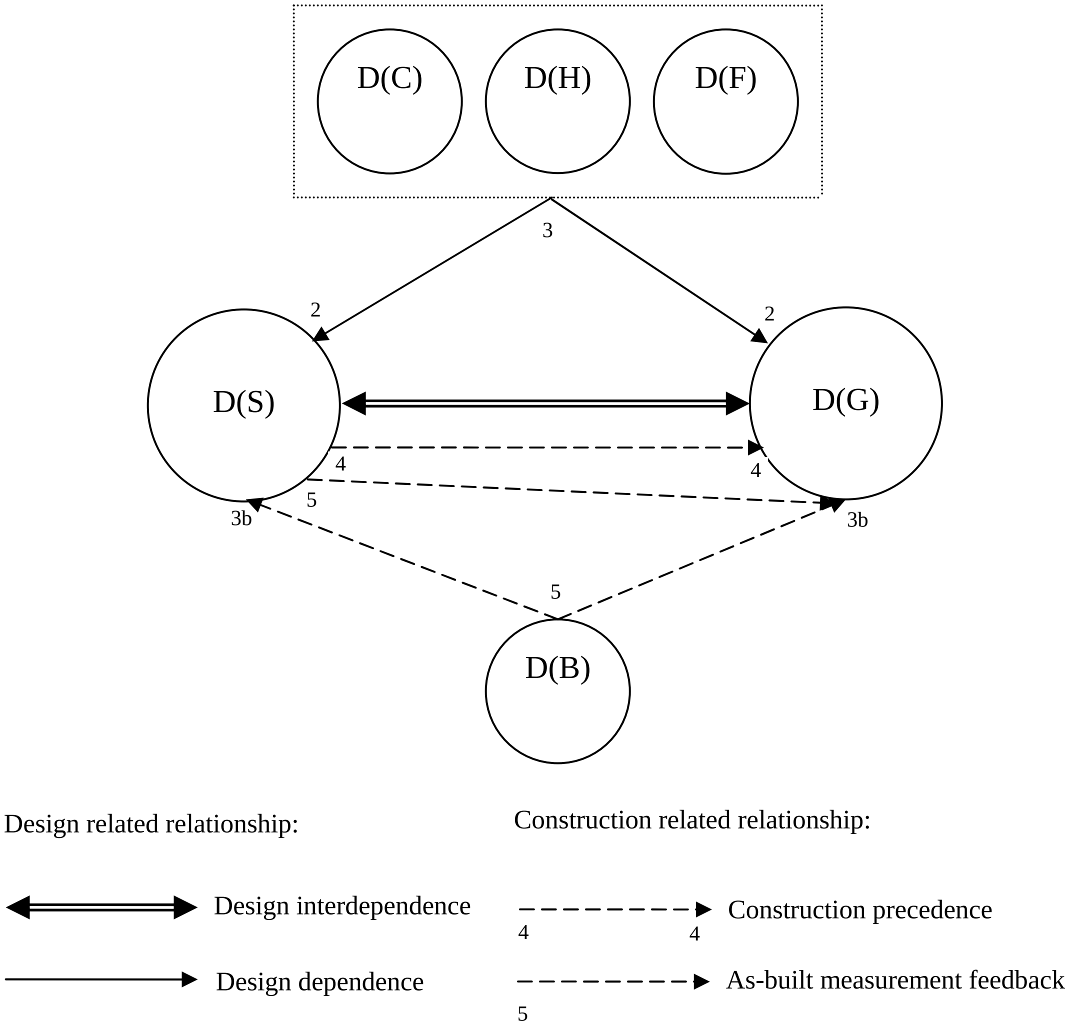
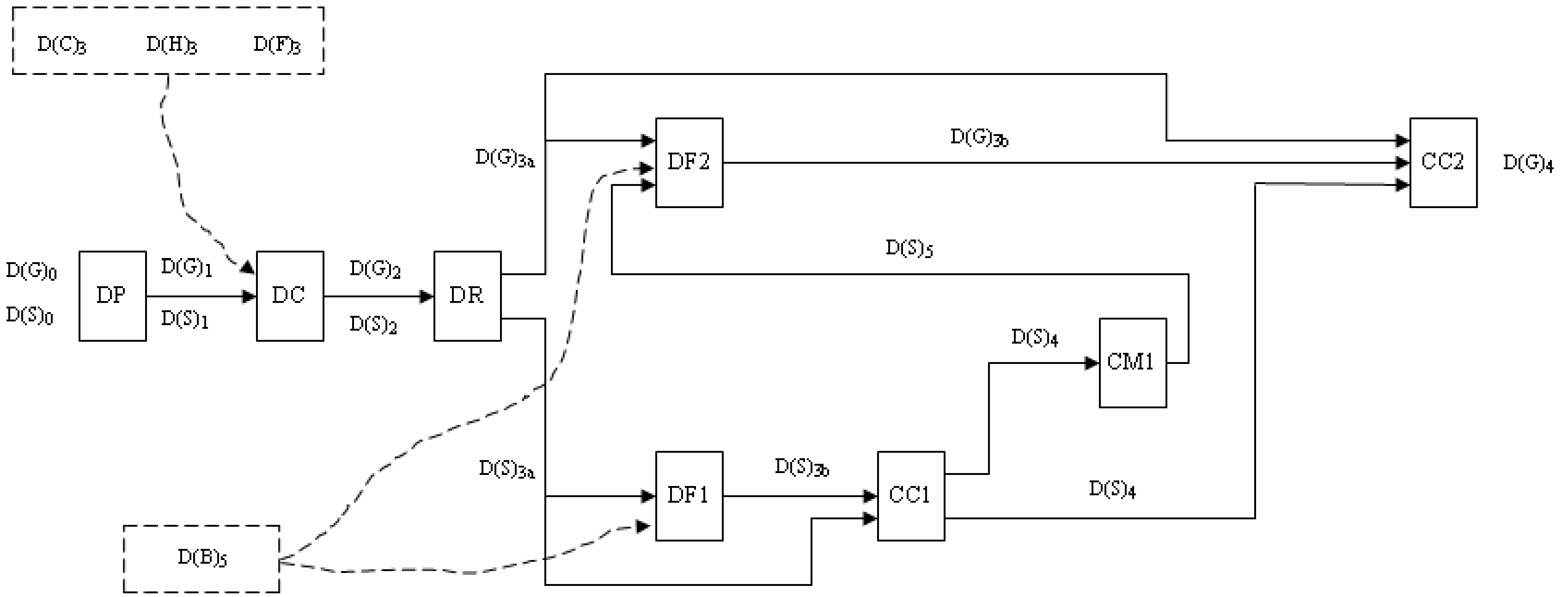


Figure 4.15 General Representation of the Network

4.4.2 Analyze and Manage the Network

1. Coordination problems

In the beginning of project plan, information dependencies among the different tasks cannot be fully taken into consideration because of the large number of tasks and the complexity of the information relationships. Therefore, information problems may occur due to unreasonable project plan. Figure 4.16 shows the traditional plan and information dependencies between these activities.



Design activities:
DP—(Preliminary) Preliminary determination of steel frame and glass panel dimension
DC—(Check) Check and confirm for steel frame and glass panel dimension
DR—(Review) Shop drawing review
DF1—(Refine) Steel frame fabrication design
DF2—(Refine) Glass panel fabrication design

Construction activities:
CC1—(Conversion) Steel frame installation
CC2—(Conversion) Glass panels installation
CM1—(Measurement) Site measurement of steel frame installation

Figure 4.16 Traditional Plan and Information Dependencies

It should be noted that the information dependencies in this figure match those in Figure 4.14. In this figure, only the design and installation activities are shown while the fabrication activities are excluded since this figure aims to describe the information flows between design and construction. From the activity perspective, the fabrication will follow the fabrication design and precede installation.

(1) Problems related to internal information flow

A problem occurred in this case because of the as-built measurement information feedback. In glass fabrication, any error in the fabrication drawings leads to failure and re-fabrication. Thus, accurate fabrication drawing information is very essential to the glass fabrication. Since the glass panels are to be installed in steel frame, the information of steel frame is definitely necessary to determine accurate dimension details for glass panels. Because steel frame installation is difficult to control due to site complexity, its information can only be verified after the installation of steel frame. The availability of steel installation measurement information is crucial to produce accurate glass fabrication design.

Generally, glass fabrication design is followed by glass fabrication, which can proceed only after the detailed fabrication drawing information is confirmed. Normally, the fabrication of glass panels has a long lead time. Therefore, it is necessary to start the fabrication design and fabrication of glass panels much earlier to avoid delay. In addition, glass panels are fragile so that damages may occur in transportation, handling, or installation. If the fabrication is performed earlier, the contractor will have time to replace them in case of damage or mistake.

As shown in this figure, based on the information dependency, “CC1” and “CM1” should be completed before “DF2” starts. This means that “DF2” has to be put on hold to wait for the as-built measurement information. Under this situation, the project schedule will be affected because of the long lead time for glass fabrication. Thus, the dilemma is that the glass fabrication design “DF2” should start early to avoid delay, but it cannot start until the as-built measurement information of steel frame (D(S) at state 5) is obtained. This requirement for as-built information has often led to schedule overruns in specialist work such as the glass wall specialist subcontractor. A proper method is then needed to resolve this problem.

(2) Problems related to external information constraints

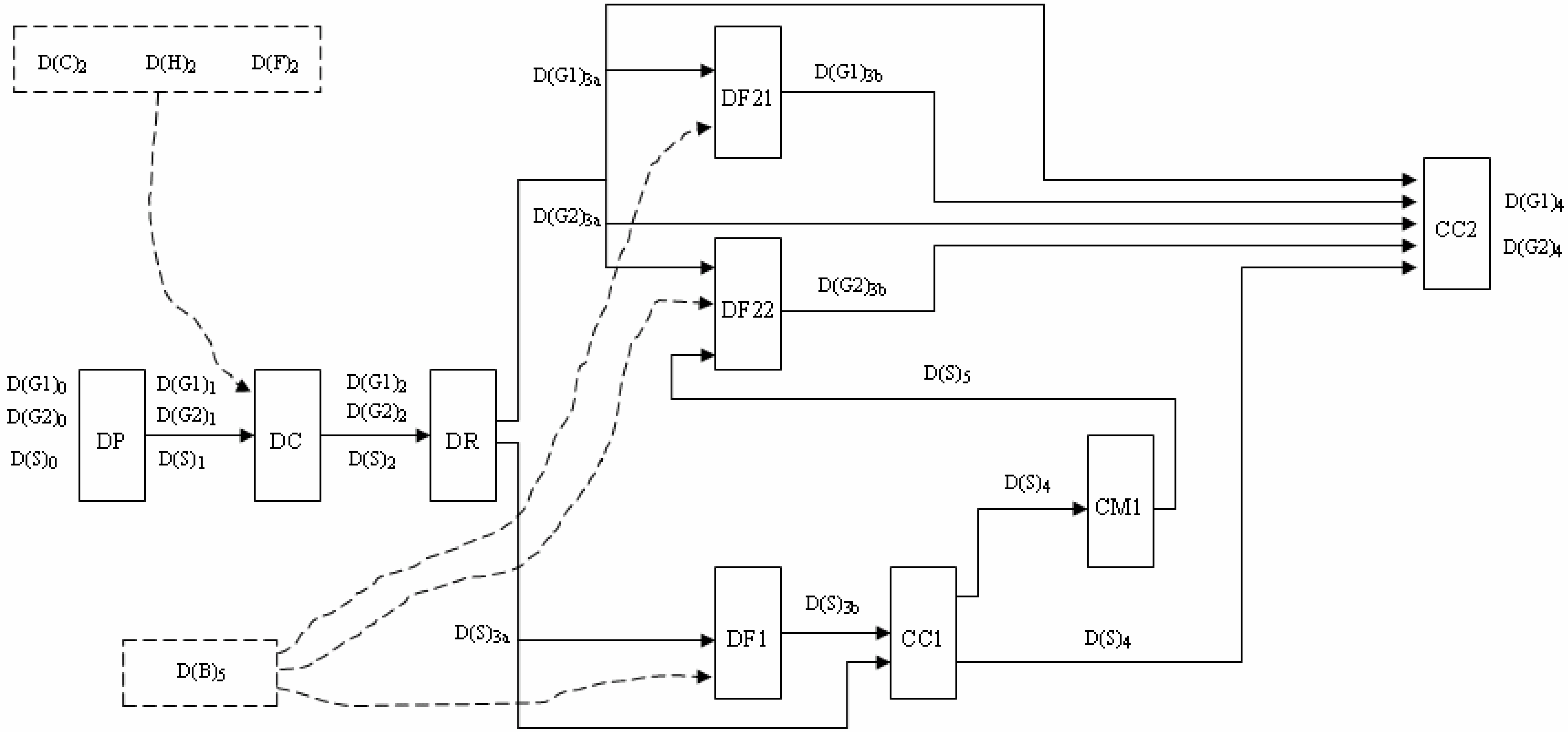
Based on the traditional plan presented above, two groups of information delays can be identified from external information constraints.

---- Information delays for glass wall shop drawing design

Check activity “DC” in the glass wall shop drawing design depends on the availability of three external information items relating to the shop drawing design of stone work contractor, HVAC contractor and facility supplier. In this project, information delays are identified for “DC” due to the late receipt of these external information items. These information items are generally generated and released at the end of the relevant shop drawing designs. Generally, shop drawing design includes drawing review and revision. This means that “DC” is delayed because it cannot get the information related to as-designed state (state 3) of D(C), D(H) and D(F) as early as it should.

---- Information delay for glass wall fabrication design

Regarding the glass wall fabrication design, the site measurement of steel beam installation, namely the as-built measured state (state 5) of beam dimension (D(B)), affects both steel fabrication design “DF1” and glass fabrication design “DF2” since the steel beam supports the steel frame for the glass panels. In this case, both ‘DF1” and “DF2” were often delayed because of the late receipt of state 5 of D(B).



Design activities:
- DP — (Preliminary) Preliminary determination of steel frame and glass panel dimension
- DC — (Check) Check and confirm for steel frame and glass panel dimension
- DR — (Review) Shop drawing review
- DF1 — (Refine) Steel frame fabrication design
- DF21 — (Refine) Typical glass panel fabrication design
- DF22 — (Refine) Special glass panel fabrication design

Construction activities:
- CC1 — (Conversion) Steel frame installation
- CC2 — (Conversion) Glass panels installation
- CM1 — (Measurement) Site measurement of steel frame installation

Figure 4.17 Solutions for the Coordination Problems

2. Solutions for these coordination problems

The preceding section has identified and explained the existing information coordination problems in the glass wall project. Proper measures should be taken to improve the flows of required information. Since information flows and project processes are closely interrelated, appropriate adjustments of processes can be an effective approach to alleviate the information coordination problems. Figure 4.17 shows the solutions for these coordination problems.

The approaches 2 and 3 described in the last chapter, namely “Re-order activities” and “Divide an activity into several activities”, can be combined together to deal with the as-built information feedback in the internal information flow. In reality, the glass wall includes many different types of glass panels. Not all the glass panels require the as-built measurement information of the steel frame. Based on their different conditions, the glass panels can be classified into two groups—typical glass panels and special glass panels. This means that the glass component “G” is divided into two components, “G1” and “G2”, which are described by “D(G1)” and “D(G2)”, respectively. Accordingly, glass fabrication design “DF2” is divided into two tasks “DF21” and “DF22”. For the typical glass panels “G1”, the related fabrication design “DF21” can be performed earlier because the glass panels in “G1” are comparatively regular and do not need the as-built measurement information. However, since the special glass panels in “G2” are very irregular or their related steel work is difficult to control due to site complexity, their fabrication design “DF22” should be postponed until steel frame installation “CC1” is finished and as-built measurement “CM1” is taken. Resulting from this adjustment, the number of glass panels requiring as-built measurement information is decreased so that less time is needed for their fabrication design and subsequent fabrication. Thus, the project schedule could be better accommodated.

To deal with the information delays for the check activity “DC” in the glass wall shop drawing design, approach 4 suggested in the chapter 3, namely “Use an earlier state” can be used. The delays are caused because of the late release of the as-designed state (state 3) information of D(C), D(H) and D(F). Actually, the external shop drawing designs were retarded because drawing reviews took a long time and were beyond the control of the glass wall specialist. Since the glass wall shop drawing design is not so sensitive to the external parameters as the glass fabrication design, the as-confirmed state (state 2) of D(C), D(H) and D(F) can be used which is produced before drawing reviews. Although it sacrifices the exactness of these parameters and is in danger of rework, it saves much time which is considered more important in this project.

For the information delay related to steel fabrication design “DF1” and glass fabrication design “DF2”, approach 1, namely “Adjust time attributes of activities”, can be employed. This delay occurred because the as-built measured state (state 5) of D(B) cannot provide timely information to “DF1” and “DF2”. Since the steel beam installation and subsequent site measurement are not on the critical path, it is then possible and practical to do some adjustments on them. Then the steel work subcontractor can shift the steel beam installation and subsequent site measurement to an earlier time so that they can be accomplished prior to the time as required. Thus the information delay problem can be resolved.

Figure 4.18 shows the parameter dependency network after these adjustments. This network focuses on the interactions among these parameters. Compared with the original network representation in Figure 4.15, D(G) is divided into D(G1) and D(G2).

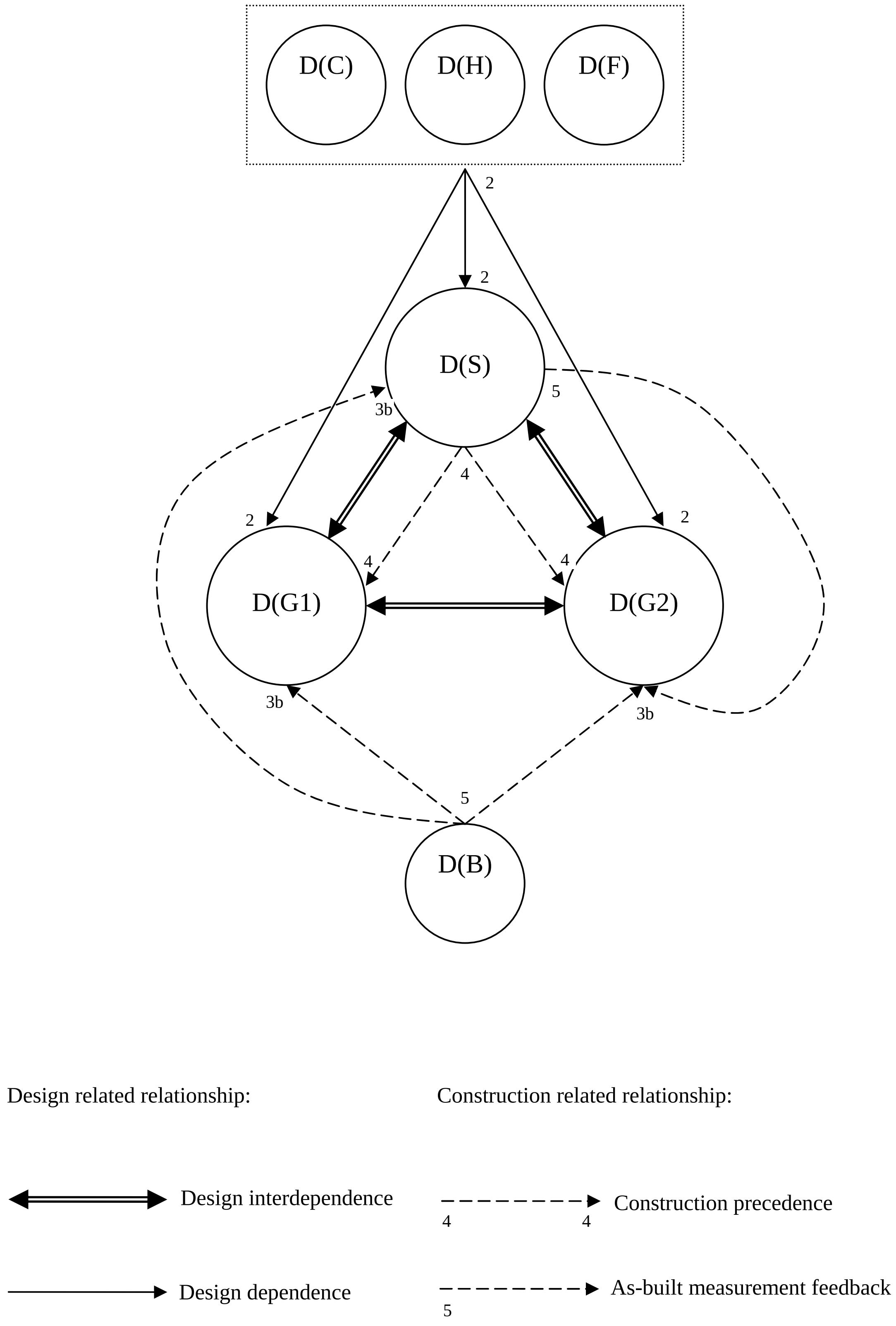


Figure 4.18 Parameter Dependency Network after Adjustments

Since the steel frame and the glass panels are tightly coupled in the shop drawing design stage, design interdependence exists between D(S), D(G1) and D(G2). Because the steel frame should be constructed before the installation of all the glass panels, the as-built state (state 4) of D(S) provides constraints to the as-built state (state 4) of D(G1) and D(G2). For the two groups of glass panels, only the fabrication design of the special panels (G2) requires the as-built measurement information of the steel frame. Thus, the as-designed state (state 3b) of D(G2) depends on the as-built measured state (state 5) of D(S). For external information items, the as-confirmed state (state 2) instead of the as-designed state (state 3) of D(C), D(H) and D(F) provides constraints to the as-confirmed state (state 2) of D(S), D(G1) and D(G2) while the as-built measured state (state 5) of D(B) affects the as-designed state (state 3b) of D(S), D(G1) and D(G2).

By applying the proposed approaches, all the existing information coordination problems have been successfully eliminated. Although these amendments look simple, they are very useful in reality. Successful application will improve the information coordination to a great extent. The proposed model for representing parameter dependencies in design and construction enables the information related flows between design and construction activities to be better understood and represented so that the proposed approaches can be exploited. It is also evident that these approaches did change the involved participants' original plans and schedules to some degree. Although this kind of changes may lead to some delays or extra costs, it is necessary if the damage caused by the information-related issues is more serious.

4.5 CONCLUSION

A case is presented in this chapter to show the coordination between design and construction of a glass wall. The case study provides a clear understanding of how the coordination model works. The suggested model makes the relationships between glass wall design and construction explicit by using parameter states. Through parameter dependency network, the information flows are clearly displayed for the glass wall. Thus, the information coordination problems can be identified easily. The suggested coordination approaches are employed to solve these problems successfully. The case indicates that the coordination model is effective in dealing with design-construction coordination issues so as to enhance the project efficiency.

However, this case is only about a small project. Not all the concepts are shown for the coordination model. In reality, AEC projects may be much more complex than the glass wall. There will be more parameters involved in the projects. Accordingly, the parameter dependency network will become more and more complicated with the increase in the number of parameters and states. Although the coordination model applies to them, more attention should be paid in the application.

Up to now, the main work for the proposed model has been described. The next chapter will conclude the dissertation with an overview of the model.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Design and construction are two of the most important stages in the lifecycle of an AEC project. Traditionally, the AEC industry has separated these two stages. In recent years, design-build has been proposed as an optimal project delivery approach, which tries to integrate design and construction. The success for design-build requires careful consideration of the constraints that each stage puts on the other. Problems often occur due to inappropriate management of these constraints. Thus, it is imperative to improve the coordination between design and construction.

This research attempted to develop a model to coordinate design and construction work. The model aims to manage the interdependence between design and construction. The coordination model has been developed employing product as the interface since product is the common link between design and construction. Parameters play an important role in the product-oriented coordination in that any product component can be described by a set of parameters corresponding to different properties of the component. At the same time, parameters are also important to depict design process and construction process. Four types of design activities are identified for design process, which are concerned with the determination of the parameters of product components. In construction, these parameters are realized into reality by construction activities. To deal with the as-built measurement information, a new kind of activities is added to the traditional construction network.

One of the most important characteristics of the model is that states are used to represent the different status of parameters. The state transformations correspond with different process activities in design and construction. The state representation is useful for process analysis since a process activity is characterized by its information inputs and outputs which can be described using parameter states. Through the parameter states, dependency relationships can be established between design and construction activities. Furthermore, parameter states can group to form deliverables (drawing, as-built measurement, etc.).

The whole dependency network is formed by connecting the basic process activity--parameter state relationships. The network is inherently a network of information dependencies which represents the links between process activities and their information constraints. By forming the network, the model is capable of making information flows more explicit. The fundamental purpose of coordination is to ameliorate the relationship between required information flows and corresponding process sequence. Several practical means have been suggested to deal with information coordination problems. It should be noted that these approaches are not isolated. Effective coordination will be achieved by fully considering all these approaches. Although these approaches may lead to some changes to the original project plan, it is worth doing if the coordination problems are more serious.

After the model was established, it was tested with one case. The case study provided a clear understanding of how the coordination model works. Results indicated that the coordination model is effective in dealing with design-construction coordination issues so as to enhance the project efficiency.

The proposed model eases coordination analysis between design and construction through the application of “state” to parameters for both design stage and construction stage. Design is very complex in that it is composed of many interrelated sub-stages. By recording different design states of a parameter, the changes of the parameter in design stage can be traced so that a better understanding of design evolution is achieved. This is beneficial to design improvement. Furthermore, two more states in construction stage are added to complete the evolution chain of a parameter and support the construction and the as-built feedback. The as-built information feedback is critical for the coordination analysis. Thus, by using parameter states, the evolution of design and construction and the information flows between design and construction are represented clearly so that the coordination between these two stages can be achieved easily.

5.2 RECOMMENDATIONS FOR FUTURE WORK

This model may be of great benefit to project managers who are always frustrated by coordination problems. In AEC projects, coordination-related problems often occur. Using this model, these problems may be settled with ease. Thus, the application of the model may improve the effectiveness and efficiency of AEC projects. However, it is very difficult to develop an all-inclusive model because of the wide-ranging aspects of the AEC industry. Since the research and case study have been done in Singapore, this model is most applicable to the AEC projects in Singapore. Although the basic theories are common, the model may need some modifications to cater for different conditions when applied in other countries because of the difference in work flow.

Parameters play an important role in the proposed model. This model focused on the parameter dependency relationship. However, the attributes of parameters have not been addressed, which include the range of the parameter value, the degree of ease for estimation, and so on. These attributes provide a better understanding for parameters and direct the parameter state utilization. Actually, the attributes of parameters were discussed in the Process-Parameter-Interface (PPI) model (Chua et al., 2003). The proposed model in this study can be further developed to incorporate parameter attributes so as to improve the coordination efficiency.

It is also noted that the proposed parameter dependency network can be quite cumbersome with the increasing number of parameters and states. Although the conventional terms in network models can be used to define the problem, it is very difficult to represent a dependency network clearly with so many parameters and states using conventional network model. Consequently, an alternative more compact representation was employed in the case study without losing information on the parameter state dependencies from design and construction perspectives. Further work should be done in this alternative representation so that the interdependencies of design can be better encapsulated in the proposed model.

This research proposed the model aiming at improving the coordination between design and construction by managing the information flows. The research work focused on developing the ideas. However, this research did not develop applicable software to facilitate the process of coordination. In order to realize an extensive implementation of the proposed model, an intelligent software prototype should be developed in further research so that the information transformations can be achieved automatically. If the proposed framework can be further integrated with a feature-based CAD design platform, the changes in the parameters can be automatically captured and shared.

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