An Object Model Framework for Interface Management in Building Information Models

by

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ABSTRACT

The construction industry's overall project performance is significantly reduced by numerous interface issues that also hinder its industrialization. Interface Management (IM) is becoming critical to the success of multidisciplinary construction projects. This research deals with three challenging problems associated with IM: 1) how to build a holistic understanding of interface issues for developing all-around IM solutions; 2) how to define and present interface information in a unified, accurate, and efficient way to improve information sharing, coordination, and implementation; and 3) how to resolve interface issues as a whole to optimize IM performance.

Comprehensive cause factors of interface issues are investigated from different yet interrelated perspectives. These cause factors allow for the development of an object data model and a systematic IM strategy. The findings of this multi-perspective approach not only add a holistic view of interface issues to the existing body of knowledge but also provide a theoretical base for researchers and practitioners to seek all-around IM solutions.

As a key innovation, an *object* view of interfaces is defined, resulting in a unified way of presenting interface information. This new technique of modeling interfaces as knowledgeable, intelligent, and active objects is far superior to the traditional use of simple relationships. The proposed Interface Object Model (IOM) framework is the first in the literature to present a comprehensive data structure and its dependencies of interface information for object modeling. This can greatly improve the quality and interoperability of modeled interface information. When integrated into a Building Information Modeling (BIM) approach, this technique can significantly enhance BIM capabilities for interface-related coordination, decision-making, operation, and management.

As a first application, a systematic model-based IM strategy is conceptually developed, which provides a good foundation for creating an implementation environment for the developed interface model. This strategy aims to resolve interface issues as a whole throughout a complete project process.

The multi-perspective approach, the generically structured IOM, and the conceptual, systematic IM strategy all target broad applications. Individually or jointly, they can also be applied to other domains beyond construction.

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CHAPTER 1: INTRODUCTION

Chapter 1 provides the background information for this research including an overview of the United States (U.S.) housing construction industry, definitions of interface and interface management (IM), as well as the scope, importance and urgency of IM in construction. This chapter also presents the problem statement, scope, objectives, methodology, contributions, limitations of this research, and outlines the organization of this dissertation.

1.1 BACKGROUND

U.S. housing construction is selected as the main background for this research. The U.S. housing construction (also called *homebuilding*) industry has been evolving toward industrialization since the Industrial Revolution. However, compared with other industries, e.g., manufacturing, the industrialization in housing construction has lagged far behind. *Modular*, *pre-cut*, *panelization*, *wet-core modules*, *mobile homes*, and *wood components* have been the six most commonly used industrialization techniques for years (U.S. Congress 1986). Nevertheless, so far, *stick-build*, utilizing classical framing lumber and depending on manual labor and labor-intensive processes during on-site construction and assembly, is still the prevailing form of “industrialized” housing. Homebuilding is notorious for its low productivity, waste, poor quality, and out-of-date technologies (O’Brien, Wakefield, and Beliveau 2000).

Reasons adversely affecting the industrialization of housing construction are multifaceted. Moshe Safdie addresses some external reasons: scattered building sites and a fragmented housing market, diverse building codes, conservative and protective trade union practices, etc. (Sullivan 1980). At the same time, the peculiarities of homebuilding, which differentiate the industry from factory manufacturing, are also crucial causes. Those peculiarities include the poorly controlled built environment, the complexity of construction, temporary multi-organization, and the interdisciplinary nature of the project delivery process. Under these circumstances, the industry’s goal—to build a high quality, energy-efficient, comfortable, and healthy house in the most economical way—is virtually unachievable.

Realizing these shortcomings, both industry and academia began to search for technical innovations as well as advanced construction management strategies and tools. Efforts have been made to:

- Increase the use and quality of pre-fabricated building components,
- Explore energy-efficient equipment or appliances,
- Launch supply chain management,
- Employ Information Technology (IT) applications, and
- Improve performance widely in design, planning, scheduling, construction, cost control, and safety management.

Although remarkable progress has been seen in practice, surprisingly, the individual objectives of those efforts have never been completely fulfilled due to frequent incompatibilities and interruptions arising from the dynamic construction environment. Consequently, the building process still faces numerous conflicts and is executed with low efficiency. The final product is also inferior in many aspects and cannot reach original expectations. Interface issues have been considered major causes leading to such conflicts and project failures (Al-Hammad 2000, Pavitt and Gibb 2003, Nooteboom 2004).

The term *interface* carries four meanings. The following are derived from dictionary definitions and properly extended by this research with relevant examples:

- A surface or shared boundary between two functional units, defined by different characteristics such as function, physical interconnection, spatial relationship and signal (*e.g., the boundary between a window and a wall in which the window is embedded*), or in other words, a surface forming a common boundary between adjacent regions, bodies, substances, or phases (*e.g., the boundary between the design and construction phases*);
- A point or place at which independent and often unrelated systems or diverse groups interact (*e.g., interactions and communications between the designer and the owner*);
- Device/equipment making possible interoperation between two systems or the point of interaction or communication between a computer and any other entity, such as a plotter or human operator (*e.g., the user interface by which people operate a computer*);

- A shared logical boundary between two software components (*e.g., the interface between two construction management software components*).

Although all of these interfaces can be found in construction, comparatively, the first two types exist more widely and influence the construction process to a greater extent. Usually, interfaces spread throughout the stages (e.g., design, manufacturing, construction, operation and maintenance) of a housing project. They also lie between pre-fabricated building components, individually designed and erected subsystems, or other active project entities, namely people/participants, processes, resources, etc. The aforementioned efforts dealing with specific technical or management issues ignore such interrelationships or interactions. As a result, diverse interface issues, exemplified as mismatched building parts, systems performance failures, coordination difficulties, assembly conflicts between trades, etc., occur repeatedly and greatly reduce the homebuilder's overall performance in terms of quality, cost, and time. Managing interfaces, therefore, becomes an issue of significant importance.

After reviewing the characteristics of housing construction and the frequent interface issues, this research provides a specific and precise definition for IM as follows:

> **Interface Management is the management of the boundaries among project entities (*people/participants*, *processes/phases*, *resources*, *contracts*, *costs*, *schedules*, *systems/functions*, and *safety/risks*) to enable a dynamic and well-coordinated construction system.**

This definition reflects the complex interactions among project entities in the current housing construction environment, and simultaneously refines the goal of IM.

In the literature of building construction, interface related studies are very limited. However, scattered research efforts are still able to disclose the most common interface issues and to identify their potential causes. Insufficient and inaccurate interface information, as well as inefficiencies in information sharing, are among the most often mentioned causes leading to many critical interface issues (Al-Hammad and Al-Hammad 1996, Al-Hammad 2000, Khanzode et al. 2000, Miles and Ballard 2002). Without sufficient information, IM, which involves intensive decision-making, cannot be properly performed.

In practice, interfaces have been largely neglected by construction management personnel because interface information has neither been adequately defined nor represented in the best way for their use. Simultaneously, the large number of interfaces and their complexity prevent the most capable people from visualizing potential interface issues and then managing these issues. Computer assistance in the IM process will be essential. Thus a standard and efficient way of presenting, recording, tracking, checking, and managing the large amount of interface information is needed. The interface information should be easily applied to advanced IT tools. **Responding to such a need, this research aims at finding an accurate and standardized way to present interface information as well as facilitating the use of the information in IT-oriented interface management**.

1.2 PROBLEM STATEMENT

In the construction industry, IM is an emerging area and also a very challenging task of project management. Due to poor IM performance, numerous interface issues have significantly reduced overall project performance in the construction project delivery process and implicitly hindered industrialization of construction. This research identifies three critical problems associated with IM as follows:

- How to build a holistic understanding of interface issues in the current built environment for developing all-around IM solutions;
- How to define and present interface information in a unified, accurate, and efficient way to improve information sharing, coordination, and to allow for implementation in IT applications;
- How to resolve interrelated interface issues as a whole to optimize IM performance in a construction project.

Previous studies investigated and dealt with interface issues mainly in one specific area (Al-Hammad and Assaf 1992; Hinze and Andres 1994; Alarcón and Mardones 1998; Miles and Ballard 2002; Pavitt et al. 2001; Pavitt and Gibb 2003). Interface issues have seldom been considered as a whole, and comprehensive causes for such issues are still missing. As a result, overall IM performance in a construction project is difficult to optimize since other untreated interface issues largely influence the ones being treated. This research conducts an innovative multi-perspective approach, systematically exploring the comprehensive cause factors of interface issues. The purpose is to build an unprecedented, holistic view of interface issues and lay the theoretical foundation for practitioners and researchers' seeking all-around IM solutions.

In the literature, interfaces are simply treated as dependencies or relationships between two or more entities such as building components, systems, or people/organizations. Also, interface information (of many kinds) is presented in different ways, e.g., specifications, drawings, written reports, models, videos, contracts, and meetings. Presenting and dealing with interface information in the above ways reduces the accuracy, completeness, and interoperability of interface information, which in turn causes deterioration in information sharing, coordination, implementation, and related decision-making. Particularly, interfaces are usually modeled as relationships in currently existing modeling methods. Such relationships contain very limited information for a model to operate, and also depend on external controls to achieve functionality. Consequently, those models hardly take any responsibility for interface coordination or management. This research proposes a new way of presenting comprehensive interface information by defining interfaces as distinct objects in an object-oriented model. An Interface Object Model (IOM) framework is created to present the data structure and dependencies of interface information.

IM performed casually and not coordinated with other aspects of project management is difficult to optimize. As mentioned above, computer assistance in the IM process is also essential due to the large number and the complexity of interfaces in construction projects. This research develops a conceptual, systematic model-based strategy that aims to implement the interface object modeling technique to allow for more efficient and effective IM. It is envisioned that this strategy will greatly enhance overall project performance in construction.

1.3 Scope of Research

This research conducts an interface-related analysis to explore the comprehensive cause factors for various interface issues in the current built environment. Then, this research creates an Interface Object Model (IOM) framework that presents a data structure and dependencies of interface information for modeling. This research also develops a conceptual, systematic model-based interface management (IM) strategy that can implement the IOM. Figure 1-1 illustrates the overall research scope in detail.

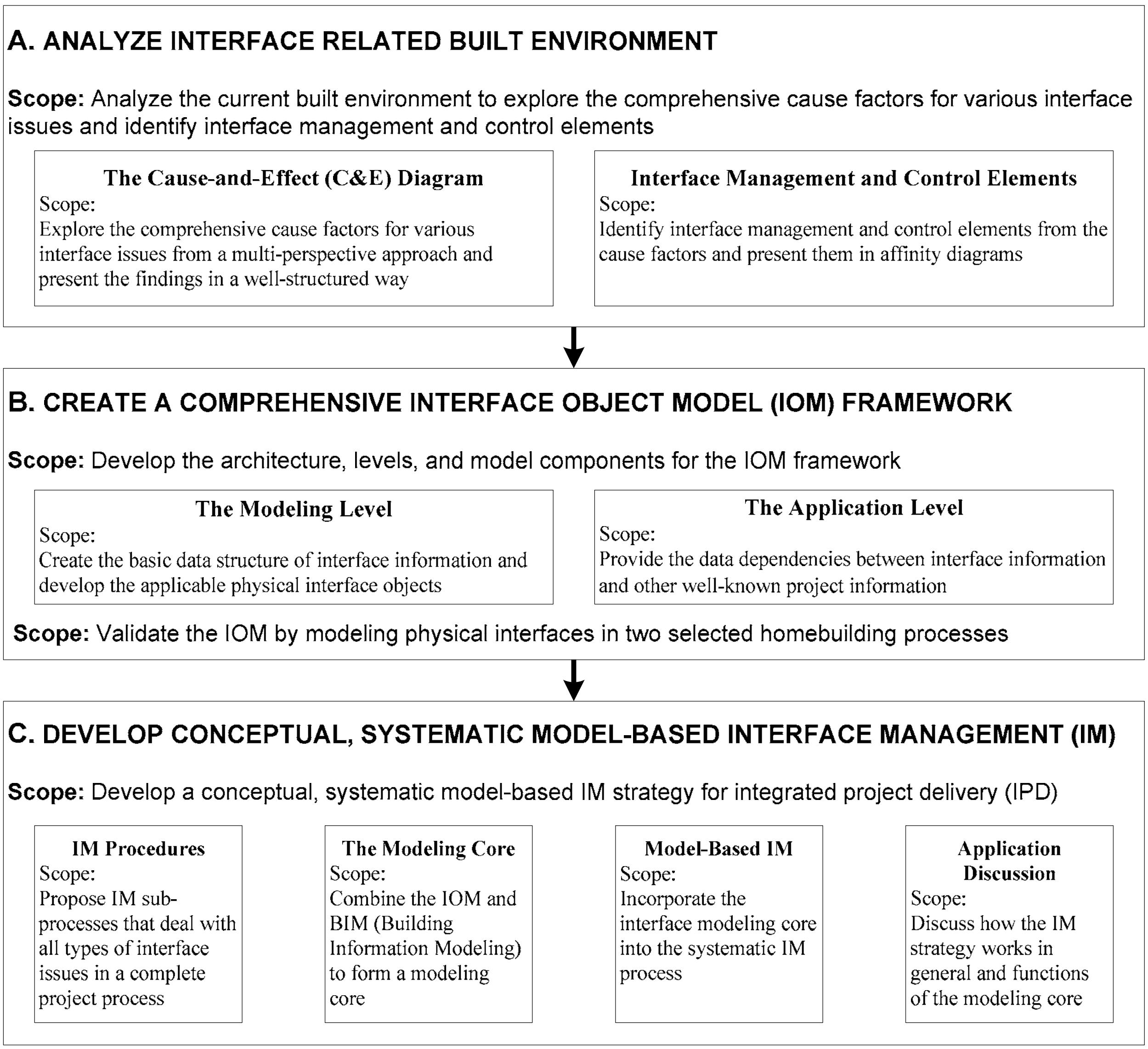


Figure 1-1: Overall Research Scope

This scope consists of three distinguishable parts as described below:

In the first part of Figure 1-1 (A), the current built environment is analyzed to explore comprehensive cause factors of various interface issues. In order to avoid the unilateralism, a multi-perspective approach using the *Cause-and-Effect* (C & E) diagram method is employed.

This approach first identifies interrelated perspectives as main cause areas and then explores major causes, minor causes, and sub-factors for interface issues within them. All the defined cause factors are presented in the C & E diagram in a hierarchical way. Subsequently, a series of interface management and control elements are summarized and displayed in affinity diagrams to represent the same information in a more applicable format for future research use.

The second part of Figure 1-1 (B) focuses on creating a comprehensive IOM framework. It starts with the creation of a framework architecture. This architecture specifies the two levels (the *Modeling* level and the *Application* level) and the associated model components of the proposed IOM as well as their functions. Based on the information, the model component development processes are designed and some development examples are given. These processes and examples will act as guidelines for the IOM's future development. The second part also includes an IOM validation that demonstrates how to model physical interfaces in two selected construction processes.

The third part of Figure 1-1 (C) develops a conceptual, systematic model-based IM strategy. The development implements three consecutive steps. Firstly, IM sub-processes that can deal with various types of interface issues are proposed and integrated into a complete project delivery process. Secondly, an interface modeling core is built to combine the IOM with current BIM (Building Information Modeling) approaches. This core outlines an integrated BIM environment. Finally, the modeling core is incorporated into the IM enhanced project delivery process to perform model-based IM. Based on the established concept, this research discusses how the strategy works in general and what specific functions the modeling core performs. This will provide further clues for IM strategies for future development and implementation.

1.4 Research Objectives

The primary objective of this research is to enhance the construction industry's overall project performance by improving interface modeling through systematic model-based IM. Several detailed objectives are generated below:

- Perform an interface-related built environment analysis to explore the comprehensive cause factors for various interface issues. A series of interface management and control elements can then be identified to help develop the IOM framework and seek all-around IM solutions.

- Create an IOM framework to present the basic data structure and dependencies of interface information. In this comprehensive framework, the development processes and examples for the proposed model components are presented to assist their full development in future research.
- Validate the IOM by modeling physical interfaces in two selected construction processes. This validation is based on a fully developed physical interface object category and related data dependencies presented in the framework. It is in preparation for one future research task that will incorporate physical interface modeling into a currently existing BIM approach.
- Develop the concept of a systematic model-based IM strategy for integrated project delivery (IPD). This strategy aims to incorporate the IOM and BIM into an IM enhanced project delivery process.

1.5 RESEARCH METHODOLOGY

In order to accomplish the research objectives, the following five main tasks with their subtasks need to be performed:

1) Conduct a thorough literature review for interface issues and IM

- Review the evolution of IM and establish its importance and urgency in building and housing construction
- Introduce IM practices in manufacturing and offshore construction
- Examine previous research work related to interface definition, interface categorization, interface issues and causes, and IM methods and tools in building and housing construction
- Investigate existing information modeling methods concerning interfaces and IM
- Review and evaluate the Industry Foundation Class (IFC) object model and the Unified Modeling Language (UML) that are referred to or extensively used in this research

2) Perform an interface-related analysis of the current built environment based on a multi-perspective approach

- Select the C&E diagram method
- Determine main perspectives/categories for the C&E diagram

- Determine major causes, minor causes, and sub-factors contributing to various interface issues and present them in a well-structured, hierarchical way
- Explain those cause factors by categories
- Summarize interface management and control elements in affinity diagrams

3) Create a comprehensive framework of the IOM
   - Determine the method of object-oriented modeling and the purpose of the IOM
   - Determine the architecture, levels, and model components of the IOM
   - Create development guidelines for model components
   - Develop model components into different depths based on the research needs

4) Validate the proposed IOM
   - Develop a decision-making model for the selection of appropriate physical interface objects for modeling physical conditions
   - Perform a field study to investigate and record two complete construction processes including *foundation wall installation* and *componentized superstructure framing*
   - Model physical interfaces in the selected construction processes by using UML and the applicable physical interface objects with relevant date dependencies

5) Develop the concept of a systematic model-based IM strategy for IPD
   - Propose IM sub-processes that deal with all types of interface issues in a complete project process and present them in a process flow chart
   - Build an interface modeling core that combines the IOM and BIM
   - Create a systematic model-based IM strategy by incorporating the modeling core into the IM enhanced process flow chart
   - Explain how this strategy works in general and what specific functions the modeling core performs in the systematic model-based IM strategy

1.6 RESEARCH CONTRIBUTIONS

This research makes several significant contributions to the existing body of knowledge in the proposed area of study.

<u>The most significant contribution of this research lies in the introduction of an *object* view of interfaces and its inherent interface object modeling technique.</u> Consequently, various types of

interfaces in construction projects can be accurately defined and modeled as objects in an object-oriented modeling environment. Those objects are able to capture all data, operations, and methods associated with real-world interfaces. They become active entities and can automatically take actions (e.g., in decision-making and analysis processes). They can also react to outside requests or events. In the modeling environment, interface objects outperform interface relationships, which are neither knowledgeable nor active and depend on external controls to achieve functionality.

This interface modeling technique can greatly enhance BIM capabilities. For example, it can not only provide accurate and comprehensive interface information but also coordinate and manage potential interface conflicts in broad project areas. Possible applications include but are not limited to design, construction, team and resource organization, or cost and time management.

Modeling interfaces as objects allows for complex actions that can be of great value when integrated into a BIM approach. The benefits include:

- A building information model (BIM) enhanced with interface objects is capable of representing information on a building project with a completeness that has not been achieved before. This extended level of information content will improve and open new ways for operation, process and decision-making modeling.
- When it comes to change management, interface objects can act as parameters to extend component relationships that are defined in a parametric building model. This significantly increases the depth and breadth of automatic coordination between building or project components when compared with mainly geometric-based coordination.
- Interface objects can take actions to simulate, analyze, visualize, and finally guide field interface operations.
- Interface objects can be repeatedly used in BIMs. They incorporate past solutions and generalize them for future use. Interface operations therefore become stable and standardized. This leads to the best practice and optimization of interface management and operations.

The Interface Object Model (IOM) framework developed within this dissertation is the first in the literature to present a data structure for interface information and its data dependencies with other well-known project information entities. The data structure consists of several object categories, which cover all thematic interface types (e.g., physical, functional, organizational, etc.) that can be found in real-world construction projects. Within these categories, applicable interface objects can be further broken down in a hierarchical way for interface modeling.

The IOM becomes the backbone of interface modeling as well as the foundation of interface databases. It can also supplement the IFC object model's limited relationship types to provide a complete data structure for BIMs. Most importantly, the IOM framework provides a structure that is open for future development, be it corrections or extensions. Related interface databases can also be populated with an ever-growing collection of reusable interface object classes. The information is presented in a widely used object-oriented modeling language (UML) that can be easily adopted by various software models and IT solutions to assist future interface related project operations and management.

This research makes a second significant contribution in the area of identifying comprehensive cause factors for various interface issues. It takes a multi-perspective approach to analyzing the interface related built environment. This approach surpasses other research methods that analyze interface issues in a loose and unilateral way. Therefore, it provides an unprecedented understanding of what (in the current built environment) causes interface issues and simultaneously builds a solid basis to search for all-around IM solutions. It benefits both practitioners and researchers.

The comprehensive cause factors for various interface issues are explored from different yet interrelated perspectives (e.g., People/Participants, Methods/Processes, etc.). Accordingly, 155 cause factors are identified and presented in a hierarchical way. Based on these factors, a series of interface management and control elements are summarized to help develop the IOM framework and seek all-around IM solutions in future research.

This research also conceptually develops a systematic model-based IM strategy that provides a good foundation for creating an implementation environment for interface object modeling. This strategy proposes to connect the IOM with current BIM approaches and merge both models into a single application that facilitates interface-related project operations and management. In detail, the systematic model-based IM strategy targets a complete project delivery process. It applies *systems engineering* thinking in solving interface issues for integrated project delivery. Sub-processes are considered interacting process components in a system for project management. Various interfaces are modeled, coordinated, and controlled systematically to avoid inherent issues in advance or to resolve irregular issues timely.

This research develops the strategy's core that incorporates the IOM with a BIM to form an integrated BIM environment, and connects sub-processes with the core for information modeling, processing and exchange. Once fully developed, this core can be a powerful engine to monitor thousands of interfaces, automatically check conflicts, instantly give notice of IM needs to certain activities, but also provide a platform for interface risk analysis or the automated generation of comprehensive IM documents and guidelines. Interface modeling is now recognized for its strategic importance in the IM process. Ultimately, the fully developed strategy will provide an IM tool for industry users to deal with their interface issues.

In addition, this research provides further potential for broad applications. Although this research chooses the U.S. housing construction industry as its main background, the application to a broader construction setting is not affected. The IOM framework can guide the development of a widely applicable IOM in the AEC/FM (Architecture, Engineering and Construction/Facility Management) domain. The proposed model is developed generically so that it could even be applied anywhere outside the construction domain where interface issues are present. This systematic IM strategy could be adapted in other project delivery environments *when project participants are willing to contribute and share project information*.

1.7 RESEARCH LIMITATIONS

This research has several limitations:

First of all, most model components in the IOM framework are not developed into the application level. The IOM's overall efficacy might not be evident at the current stage. However, the efficacy can be demonstrated in future research. For some highly developed components, restrictions apply. For example, in the *Interface Object Hierarchy Diagram*, names for interface subcategories and applicable objects can only be properly understood after the user has learned the specific situations they represent. In the *UML Physical Interface Object Diagram*, attributes listed for each object might not be all-inclusive and should be supplemented later on.

Second, this research only performs physical interface modeling to validate the IOM, and does not demonstrate how to model other types of interfaces. The two selected construction processes are described and modeled based on the author's observation and understanding. Future research should find more industry applications and further validate this model to its full potential.

Third, the systematic model-based IM strategy is only conceptually developed. It lacks detail for immediate implementation. Future research is needed to help this model-based IM strategy achieve extensive usage and success in construction project management.

1.8 DISSERTATION ORGANIZATION

This dissertation is organized in the following seven chapters:

Chapter 1 Introduction: Gives background information leading to the study; describes the statement of the problem; defines the research's scope, objectives, and methodology; and explains contributions and limitations of this research. Chapter 1 also presents the organization of this dissertation.

Chapter 2 Literature Review: Reviews the evolution of IM in construction and establishes its importance and urgency. IM practices in manufacturing and offshore construction are introduced. This chapter also reviews research efforts that define and categorize interfaces, identify interface issues and causes, and seek IM strategies and tools. Finally, information modeling methods in the studied area are discussed and an examination of the IFC and UML is presented.

Chapter 3 Interface-Related Built Environment Analysis: Presents a multi-perspective approach that analyzes the current built environment in search of comprehensive cause factors for various interface issues. The C&E diagram with six interrelated categories (perspectives) is illustrated and explained. According to those cause factors, a series of interface management and control elements are identified and presented in affinity diagrams.

Chapter 4 Interface Object Model Framework: Presents a comprehensive IOM framework. The framework consists of two levels where five model components exist. Level one, *the Modeling Level*, presents the data structure of interface information in class models. Level two, *the Application Level*, presents data dependencies of interface information. How far each model component is developed is determined based on the needs of this research.

Chapter 5 Interface Object Model Validation: Presents the validation process for the proposed IOM. This chapter first presents a decision-making model that shows how to select appropriate physical interface object subcategories and applicable objects for modeling different types of physical conditions. Then two housing construction processes, foundation wall installation and componentized superstructure framing, are described. Following each of them, physical interface modeling is presented in UML.

Chapter 6 Systematic Model-Based Interface Management: Presents a conceptually developed systematic model-based IM strategy in an integrated process flow chart. This strategy is based on an IPD process and incorporates the IOM, the BIM approaches, and the IM procedures. How this strategy works in general and the functions of the modeling core in the process are discussed.

Chapter 7 Conclusions and Recommendations: Summarizes the research findings including the comprehensive cause factors of interface issues, the IOM framework, and the conceptually developed systematic model-based IM strategy. This chapter also recommends directions and specific tasks for future research.

CHAPTER 2: LITERATURE REVIEW

This chapter first presents the evolution of IM (Interface Management) in construction and simultaneously establishes its importance and urgency. Then, IM practices in manufacturing and offshore construction are briefly introduced. Following this is an examination of relevant research work in defining interfaces and interface categories, identifying interface issues and causes, and seeking IM strategies and tools, which helps build the foundation of this research. Finally, modeling methods for presenting interface information and managing interfaces are investigated; the IFC and UML are reviewed and evaluated. Based on the literature review, the best approach for defining and modeling interface information is developed.

2.1 THE EVOLUTION OF IM

IM is a very new topic in many industries. IM is not uniquely defined and usually varies based on an industry's characteristics and management needs. In the following, several construction-related IM definitions are introduced.

The first definition is from the offshore construction industry involving construction of structures and pipelines in a marine environment for the production and transmission of oil and gas. Construction in a marine environment is dangerous, therefore offshore construction mainly depends on modular construction—assembling individual modules onshore and lifting them into place. There, IM is defined as "the management of common boundaries between people, systems, equipment, or concepts" (Nooteboom 2004). In the civil engineering construction field, Wideman (2002) provides two definitions for IM: 1) "the management of communication, coordination and responsibility across a common boundary between two organizations, phases, or physical entities which are interdependent;" and 2) "managing the problems that often occur among people, departments, and disciplines rather than within the project team itself." These three definitions jointly define what IM means in construction and what scope is covered by IM. IM has been a hidden aspect of project management for a long time (Nooteboom 2004). Only recent years have seen an increased awareness of this missing link in the construction industry. In some specific construction domains, e.g., offshore-construction, IM has become a critical area of project management. However, in building and housing construction, interface issues and IM have still not received wide acceptance and relevant research contributions are scarce. In the following, starting from offshore construction, continuing to building construction, and finally reaching housing construction, some real world interface issues with their adverse effects are reviewed. Although this is not an all-inclusive list of interface issues, through these instances the importance and urgency of IM can be visualized.

In offshore construction, serious cost overruns and delays often result from poorly defined interfaces between different scopes of work or equipment supply, and failure to properly manage resulting conflicts (Nooteboom 2004). Usually, contractors can easily coordinate interface issues within their teams by focusing on work scopes and schedules of their own. Nonetheless, when such issues cut across different contractual teams, they are difficult to handle or never get adequate attention before leading to severe consequences. Furthermore, the multiplicity of teams involved makes it even harder to determine who has the ownership of a particular interface. Therefore, detailed project assessment needs to be conducted to clearly define the scope of work (INTEC Engineering 2004). In addition, IM is needed in expansive project stages and areas. More effective IM—meaning proactive avoidance or mitigation of any project issues (e.g., design conflicts, installation clashes, new technology application and regulatory challenges)—is the key of the successful delivery of mega-projects on time and on budget (Nooteboom 2004).

In building construction, physical interfaces, joints, and connections between different elements or sections cause many critical problems for building design, manufacture, construction, and operation throughout the life of the buildings. Conflicts on physical interfaces usually reduce the constructability. Additionally, poor management and control over organizational and contractual interfaces also lead to project failures. As noticed, contractual interfaces are one of the leading causes resulting in physical interface problems. According to O'Brien and Willmott (2001), if the façade is split into several work packages, the interfaces might not be properly designed, followed by serious physical interface issues at the construction stage. Fritschi (2002/2003) indicates that interface issues arising from the coincidence of different processes or competence areas form weak points of quality.

The workforce now in building construction is mainly subcontractor-based. The general contractor (GC) has to be the construction coordinator who plans and manages the interfaces between works and subcontractors. GCs' needs for effective IM have been forcefully emphasized (Gibb 1995). Moreover, Pavitt and Gibb (2003) state that IM is crucial in many project areas including design, procurement, logistics, programming, contracting, management, external influences, and human relationships.

In most traditional project delivery systems (non Design-Build), architects usually take coordination responsibilities for interface design issues while project managers or superintendents concentrate on field interface conflicts. In that case, design and construction parties work separately with limited cooperation and coordination. The design stage is performed with little or no constructability input from contractors, and the designers are seldom involved in the construction stage. Indeed, interface design information is very useful for construction planning and scheduling. According to Nakajima (1998), the assembly order for building members and consequent activity schedule can be generated by a computer using a knowledge-based system (KBS) that is based on such characteristics of components as the mating surfaces, connection types, and jointing methods. This information should be provided in interface design.

The broken design-construction interface forces both the design and construction parties to perform tasks based on their own knowledge and experience. This limitation produces numerous interface-related design errors as well as field conflicts. Without holistically and accurately defining interfaces of a building project in the design phase, or reasonably separating work scopes and determining a compatible subcontracting strategy before a project starts, design and construction parties confront some inherent drawbacks in their processes and can hardly overcome them.

Examples of interface issues have been widely seen in building construction. The lack of accurate interface parameter information has led to inferior interface design, design inconsistency and errors, and component malfunction. Inappropriate work packaging or subcontracting resulted in an excessive amount of interdependencies among work packages, increased the number and complexity of interfaces in a project, and increased the likelihood of delays (O'Connor et al. 1987). Lack of attention to the construction interfaces (e.g., activity characteristics and relationships, workplace interfaces) between different scopes of work during the planning stage led to installation interruptions later. The more complex the project, the more often interface conflicts occurred. The same is true in housing construction.

The rapid rise in customizations and the highly fragmented and distributed nature of the industry have increased the complexity of homebuilding to an unprecedented level. Although small-sized homebuilders beyond number lack the knowledge and resources for IM, their IM need is actually less pressing, due to fewer subcontractors involved and more full-time supervision. However, it would be difficult for larger-sized homebuilders not to adequately consider IM in their management systems. They face more critical interface issues. Compared with other industries or other types of construction, the least coordination efforts have been made in housing construction by subcontractors.

Stemming from the constant development of building knowledge and the increasing standard of living, there are higher expectations for an optimized house in terms of comfort and health. In addition, the cyclical energy crisis and economic decline require houses that are more affordable to buy, as well as to operate and maintain. Systems integration, an important approach to improving the quality of house design, construction, operation and maintenance, triggers complex systems interface issues. Based on O'Brien and Wakefield (2004), the performance implications of system conflicts are still obscure at present and improvised resolutions are not optimized. Better interface design and construction methods regarding the house as a coordinated whole system are urgently needed.

The operation & maintenance stage has now been accounted in evaluating the quality of housing design and construction. Consequently, the scope of IM should be extended into this after-project-stage. Complete interface maintenance documents should be available for maintenance teams. When replacement or renovation is needed years after the house was built, new materials and components can still easily fit into the house due to compatible physical interfaces.

Until now, IT applications employed in the design and construction processes have been less useful in solving interface issues. Progress made in improving design, construction, and project management does help avoid and resolve some interface issues, but is of little help to inherent interface conflicts (e.g., conflicts caused by improper workpackaging). Additionally, IM has never been considered systematically like other established project management approaches such as Total Quality Control. Dealing with interface issues is still done in a casual manner and its efficacy hinges on the executives' personal experience and behavior. Therefore, this research aims to develop a systematic model-based IM strategy that targets all kinds of interface issues in a project delivery process and enhances the overall IM performance.

2.2 IM IN MANUFACTURING

In the industrialization process, a close link between manufacturing and construction has been established. Regarded as one type of site production, construction is similar to manufacturing in many respects. Consequently, management strategies successfully employed in manufacturing may achieve the same success in construction. In the following, manufacturing IM strategies are first reviewed; and strategies that can be adopted by construction are explicated. Then lean production, the widely applied manufacturing management philosophy in construction, is introduced and its close relationship with IM is discussed. Lastly, agile manufacturing, which is able to respond to unexpected changes/iterations and frequent interactions in an unpredictable environment, is examined.

2.2.1 Manufacturing IM Strategies

IM is effectively implemented in manufacturing. Several reasons are given below. First, in manufacturing, material and information flows have been well established between crews or workstations. This is not difficult since manufacturing activities repeatedly occur at fixed locations under well-controlled factory environments. Second, the design-manufacturing interfaces receive careful attention in the areas of manufacturability-oriented design and efficient communication between designers and manufacturers, due to processes such as DFM (Design for Manufacture) and DFMA (Design for Manufacture and Assembly) by Boothroyd Dewhurst. Third, the operational interfaces between users and machines, also called *man-machine* interfaces, are more effective and user-friendly than ever before. This is due to a high level of industrialization and IT implementations in manufacturing. Fourth, supply chain management successfully controls interfaces between suppliers and manufacturers to stabilize the supply and to keep a moderate inventory (acting as a buffer) for smooth production.

Beside the well-controlled interfaces mentioned above, physical interfaces between product parts are always the biggest concern in product development. Incompatible or poorly-designed physical interfaces between separately manufactured components could lead to conflicts or inefficiency along the assembly line. The loss of time and profit can be extremely critical.

Product architecture is a very important parameter for properly determining product components and related physical interfaces. Varying from modular to integral, product architecture decides the decomposition of a product from the functional elements to basic physical components. It also specifies interfaces among interacting physical components, modules, and subsystems (Ulrich 1995; Ulrich and Eppinger 1995; Mikkola 2001). For a proposed manufacture, IM plays a very important role in optimizing its product architecture.

In integral product architectures, interfaces shared between the components are coupled (Ulrich 1995). IM concentrates on standardizing interfaces of customized components. This greatly reduces production costs since changes to one component do not necessarily incur changes to other components. In modular product architectures, IM is closely related to the enhancement of modularity, which permits components to be separately produced, loosely coupled, and interchangeably used while still maintaining system integrity. Mikkola (2001) proposes three ways to help realize a higher level of modularity: 1) physical reduction of the number of interfaces through component integration, 2) standardization of interfaces, and 3) multi-functionality of the sub-modules (substitutability). Here, IM also deals with the issues of component integration or multiplexing.

Sanchez (1999) tries to categorize manufacturing interfaces in developing products. Seven different types are defined as *attachment*, *spatial*, *transfer, control and communication*, *environmental*, *ambient*, and *user*. This categorization is based on the product itself. Sanchez (2004) further indicates that manufacturing interfaces should be characterized by interface specifications, which define the protocol for the fundamental interactions across all product components.

Due to increasing global competition in product manufacturing, a challenging shift from a single product development to a product family development appears to meet various customer needs (Sundgren 1999; Sanchez 2004). The shift requires a very strong IM process, which can be defined as “the distinct process of developing and finalizing the physical interfaces between the platform and the end-product unique subsystems” (Sundgren 1999). According to Sanchez (2004), a person acting as the “product architect” is necessary to take responsibility for identifying the desired range of component variations and establishing interface specifications. Recently, such a shift has also been seen in production homebuilders’ practice.

Regardless of the aforementioned housing construction peculiarities, which prevent the industry from applying manufacturing IM strategies, IM in housing construction still lags far behind what could be achieved. Currently, overall housing construction is inferior to advanced manufacturing (e.g., the automobile or computer industry) in many ways, for example, how to develop and construct a product. Although the industry has employed some manufacturing techniques to produce homes such as HUD (U.S. Department of Housing and Urban Development) code/mobile homes or modular homes, the quality and efficiency of housing manufacturing are comparatively lower; this trend is also not dominant.

Most houses are still designed and built in a conventional manner. That is, a house shell is first erected on site by manually joining a wide variety of building materials and components, and then acts as a weatherproof platform for receiving subsystems. In such a built environment, IM is largely neglected. Physical interfaces are seldom carefully planned and coordinated in advance. Construction processes are performance-based. Builders rarely consider the influence of variation or standardization on those processes. Therefore, the homebuilding industry can actually learn a great deal from advanced manufacturing product architectures as well as manufacturing IM strategies.

2.2.2 Lean Production

Lean production philosophy, also called world class manufacturing, just-in-time (JIT), total quality control (TQC), and time based competition, originated in Japan in the 1950s and then spread to other countries and industries. Instead of the conventional view of production as only conversion activities, this philosophy views production as a continuous flow of materials and/or information, starting from raw materials to the final product (Koskela 1992). Its basic idea is to keep the production system and organization simple and to avoid waste (Melles 1994).

Since the 1980s, the construction industry has gradually accepted and adopted lean production philosophy. Due to construction peculiarities, which differ from manufacturing, the industry needs to be very flexible to accommodate lean production implementations. In order to guide such attempts for improvement, Koskela (1992) summarizes eleven heuristic principles:

1. *Reduce the share of non value-adding activities.*
2. *Increase output value through systematic consideration of customer requirements.*
3. *Reduce variability.*
4. *Reduce the cycle time.*
5. *Simplify by minimizing the number of steps, parts and linkages.*
6. *Increase output flexibility.*
7. *Increase process transparency.*
8. *Focus control on the complete process.*
9. *Build continuous improvement into the process.*
10. *Balance flow improvement with conversions improvement.*
11. *Benchmark.*

These principles of lean are universally applicable to contractors' practice (Davis and Standard 1999). They are helping the industry build a systematic quality management system. Based on these principles, many lean techniques have been developed and employed, such as TQC, Last Planner Technique (LPT), Construction Process Analysis (CAP), Concurrent Engineering (CE), and Re-Engineering. However, for various reasons the application of lean production in construction has not made much progress. Researchers still keep looking for better applications.

Applying lean production in the homebuilding industry is a potential breakthrough since the mass production of similar single-family houses or townhouses is quite similar to manufacturing. In the literature, the similarities and differences between industrialized housing and automobile production at Toyota had been explicated (Gann 1996). Gann also answers the following two questions:

- How can the housing industry adopt lean production strategies to manage design and sales systems, house components manufacturing, and construction site assembly for accommodating customization?
- How can a wider range of choices be delivered through managing the whole production system and balancing the use of standard components with flexibility in assembly?

In practice, it has been proven that the lean philosophy can be employed to enhance the industrialization of residential construction. The outstanding demonstration is in Japan where manufacturing principles derived from the automobile industry have been successfully utilized to produce homes. While measures compatible with the characteristics of housing construction are discovered, lean production philosophy can have broader applications in housing construction.

CE, a lean technique dealing primarily with the product design phase, has been implemented in the study of industrialized housing (Elshennawy et al. 1991). Armacost et al. (1992) employ this approach to investigate the production of an essential building component—the exterior structural wall panel—and concentrate on the methodology for identifying and integrating customer requirements. An on-going research and development project aimed at the industrialized development of a timber frame house system has used CE to integrate customer-oriented design and production (Stehn & Bergström 2002).

In order to achieve a lean design process or a lean project delivery system, a comprehensive project definition is needed, which is usually generated in the project conception phase. Ballard and Zabelle (2000) regard the project definition as the first phase in project delivery, which consists of three modules: 1) determining purposes (stakeholder needs and value), 2) translating those purposes into criteria for both product and process design, and 3) generating design concepts against which requirements and criteria can be tested and developed. The movement through purposes, criteria, and concepts is necessarily iterative, which explains why the design process in construction is complex, information-intensive, and time-consuming. Here, purpose is the logical starting point in the three-point cycle. Upgrading of purposes, criteria, or concepts within budget and schedule can add value to the project.

Value-adding processes are the basis for process re-engineering (Hammer and Champy 1993). Roy et al. (2003) introduce a program conducted by a major house builder in the UK, which focuses on re-engineering of the build process through a combination of new technology, product engineering, and changes in working practices. Roy et al. (2003) also indicate that system integration for industrialized housing and mass customization contains three components: design for modularity and efficiency of assembly, process engineering, and efficient supply chain management. Bashford et al. (2003) propose the implementation of the even flow production technique in the U.S. housing industry to bring more reliable planning to the building process involving many trade subcontractors.

Since 1999, the Center for Housing Research at Virginia Polytechnic Institute and State University has been conducting a HUD funded research project for industrializing the residential construction site. In the published project stage reports, lean production philosophy has been reviewed and existing applications in the residential construction industry are evaluated (O'Brien, Wakefield, and Beliveau 2000; Wakefield, O'Brien, and Beliveau 2001; O'Brien, Wakefield, and Beliveau 2002). Potential lean applications in this domain are discussed further in a paper based on case studies conducted by the above research project (Chen et al. 2004).

IM studied in this research has a close two-fold relationship with lean production. On the one hand, IM is very important in applying lean principles or techniques to construction. There are four reasons.

Firstly, non value-adding activities (e.g., inspecting, moving and waiting, communicating and coordinating, correcting, etc.) significantly increase when a task is divided into subtasks executed by different specialists (Koskela 1992). Effective IM on contractual boundaries can smooth information and material flows between sub-processes or disciplines and thus minimize conflicts and waste. As a result, flow improvement is successfully balanced with conversion improvement. It is worth mentioning that although communicating and coordinating are non value-adding activities, they should be conducted more efficiently rather than suppressed.

Secondly, a good interface between clients and designers helps incorporate customer requirements into design and increase the output value and flexibility. Efficient IM simultaneously ameliorates other organizational interfaces between designers, contractors, suppliers, fabricators, or installers. The whole project process becomes more transparent and control of the complete process can be augmented.

Thirdly, IM emphasizes reducing the number of physical interfaces through component integration and standardizing interfaces. Integration decreases the number of parts, steps, and linkages, and therefore simplifies the construction process as well as the quality management system. Standardizing interfaces lessens the variation in a project and makes the whole system simpler and more controllable. Ultimately, the construction cycle time is shortened.

Lastly, IM solves issues coupled with the implementation of several lean techniques and therefore ensures their success. For example, CE, shortening the total time of a project, makes the design-construction interface more complicated and challenging. Especially in fast-track projects, the management of such an interface becomes critical to project success. For another example, Re-Engineering, focusing on value-adding construction processes, cannot be conducted without understanding and satisfying construction interface requirements between building subsystems, components, or processes. Under these circumstances, IM acts as a facilitator to help lean production achieve its goal.

On the other hand, if IM is considered an individual operation system within a construction project, lean principles can in turn improve the performance of IM. Examples are given below. The lean principles—*minimizing the number of steps, parts and linkages, reducing variability, and increasing output flexibility*—help solve physical interface issues. *Focusing control on the complete process* and *building continuous improvement into the process* suggest a systematic IM approach. *Increasing process transparency* helps clarify interface information. Therefore, with the increasing implementation of lean production, IM in construction can be enhanced gradually. Lean principles, as hidden essentials, also quietly spread into the whole process of this research.

2.2.3 Agile Manufacturing

Agile thinking, production, and project management has evolved since 1990 in response to the gains made in Japanese manufacturing. Besides the implementation in the information systems industry, its application to construction has also been considered (Owen and Koskela 2006).

Agile manufacturing stemmed primarily from the management science of Deming, which has made great success in Japanese industries (Liker 2004). Differentiated from lean production, agile manufacturing focuses on how to respond to constant changes or adapt proficiently (thrive) in an unpredictable environment (Dove 1995, Sanchez and Nagi 2001). In order to realize the agility, flexible manufacturing systems should achieve the following (SM Thacker & Associates 2006):

- To determine customer needs quickly and continuously reposition the company against its competitors
- To design things quickly based on those individual needs
- To put them into full-scale, quality production quickly
- To respond to changing volumes and mix quickly
- To respond to a crisis quickly

These can only be accomplished through well established and maintained relationships between the customer, manufacturer, and suppliers as well as a win-win system of cooperation within the manufacturing organization as emphasized in Deming's 14 principles (Deming 2000). In particular, in an agile manufacturing system, the interface between the designer and manufacturer should be well coordinated through efficient communication. Simultaneously, priority should also be given to the creation and sustainment of small interactive multi-disciplinary teams (Owen and Koskela 2006). The construction project system should follow the same rules for achieving its agility.

Although the scope of agile project management is not clearly stated here, it has some obvious overlap with the scope of IM. They mutually improve each other's performance and efficiency.

2.3 IM IN OFFSHORE CONSTRUCTION

As mentioned before, interface issues have received proper recognition in offshore construction and IM has already become a critical area for a company's project management. The following review shows how IM can be put into practice in the offshore construction practitioners' project management and control systems.

According to Sorrel et al. (1996), interface coordinators are designated in their project to handle interfaces between teams while each team only focuses on its specific area of responsibility. Hesketh-Prichard et al. (1998) describe how the GC can maintain a register of all interfaces between adjoining systems and facilities and track the status of each one during project execution. Cameron (1996) introduces an enhanced management structure where a "manager of systems engineering” is appointed to handle the dynamic changes to system definitions, architecture, technical performance standards, and interface definitions. This person, supported by a working group, is responsible for coordinating all control system interfaces internally and externally. These practical measures have proven to be very successful in dealing with general interface issues.

INTEC Engineering, a leading company in the offshore construction field, once experienced budget and schedule failures due to bad policies or poor management of the inter-company interfaces. Recently, they have developed an IM program that can be adapted to any size or type of multifaceted project for controlling the technical, scheduling, and commercial aspects of the interfaces from design through commissioning (INTEC Engineering 2002). The IM program is incorporated into four offshore project phases:

Phase 1 Conceptual Design: The contracting strategy is formed, boundaries for contracts are defined, and certain high-level interface responsibilities are determined. The prepared documentation includes 3D field layout drawings identifying the main interfaces, responsibility matrix, IM procedures, and interfacing philosophy.

Phase 2 Front-End Engineering Design (FEED): The GC is required to effectively incorporate dedicated IM personnel (i.e., regular meetings with contractors and maintaining a register of interfaces); therefore relevant IM procedures can be executed earlier and conflicts can be identified and resolved during the phase. The documentation includes an interface clarification register, interface data forms, outline interface schedule, project interface website, etc.

Phase 3 Execution: During this phase, a well-formed IM system makes various parties aware of any interface problems and assists in rescheduling the project.

Phase 4 Installation and Commissioning: IM includes identifying the equipment and tooling requirements for the interfaces and specifying packaging details, tagging confirmation, maintenance of interfaces, etc.

A good IM process relies heavily on planning, interface identification, assessment, monitoring, control, closeout, as well as interactions with other company and contractor processes (INTEC Engineering 2003). Such a complicated management process needs the assistant of effective and efficient tools. So far, INTEC Engineering has developed a Web IM System, an Interface Clarification Register, an Experience Catalogue, and an Interactive Database and Reporting Mechanism. They jointly provide an interface database that identifies the responsible interface contacts, technical attributes, responsibility requirements, etc. They also facilitate rapid exchange of information to identify external interface issues between contractors, suppliers, and vendors associated with a project (INTEC Engineering 2003).

Despite the achievements, several important issues exist in their IM practice. Firstly, from the detailed descriptions of the four project phases, it appears that this IM process does not include the offshore project design phase but starts at the planning and subcontracting stage. The broken design-construction interface prevents the IM process from reaching its full potential. Secondly, the tools developed by this private company are of many types and not learned by the public. How interface information is presented there remains unknown. However, available information implies that various interface information is identified and recorded by different tools (drawing, matrix, register, etc.) employed at individual project stages. In other words, information is not presented in a unified way. Thirdly, no evidence shows how efficiently these tools could be implemented in offshore construction. At the same time, how broadly these tools could be applied to construction is also questionable since the nature, technical characteristics, and interface issues of offshore construction are very different from other types of construction. Due to these limitations and unknowns, it is believed that the insights and methodology for approaching the interface issues, rather than the tools noted above, are important to this research.

2.4 INTERFACE RELATED RESEARCH

Although interface related research is scarce in construction, the nature of interfaces, common or specific interface issues, and IM strategies and tools have been discussed to some degree. In the following, relevant research work is reviewed and evaluated for the area this research focuses on.

2.4.1 Defining and Categorizing Interfaces

Whether interfaces are adequately defined in a construction project is a concern frequently raised by researchers. Interface definition is essential in design and construction. Alarcón and Mardones (1998) indicate that the technical response to potentially preventing design defects is the work specification, which includes the interface specification. Krueger (2002) points out that the design of an interface between two systems depends upon how the systems are understood and characterized by the designer. In practice, interfaces in a construction project are not adequately defined. Although the well-developed classification/taxonomy that accurately models construction operations (Al-Masalha 2004) can be used to define interface related construction processes, the processes are only one aspect of interface definition. The complexity of interfaces, the multi-organizational project team, and incomplete project documentation prevent individual project parties (e.g., designers or contractors) from accurately defining all types of interfaces. The underlying problem is the lack of standardized interface categorization and definition for various interfaces that need to be defined.

Defining and categorizing interfaces is a very important step in the creation of the IOM (Interface Object Model) framework. Studies on interface categorization and definition have been conducted by several researchers (Laan et al. 2000, Critsinelis 2001, Pavitt and Gibb 2003). These studies have laid an invaluable foundation for this research. In the following, existing interface categorizations and definitions are discussed.

Internal versus External Interfaces: In general, interfaces in a construction project can be divided into the internal interfaces and the external interfaces. There is not a single standard about how such a categorization is determined. When contractual relationships are emphasized, interfaces within a single contract or scope of work are called internal. Normally, internal interfaces are much easier to handle because a single team is involved and the ownership and responsibility are clear. External interfaces occur between contracts or scopes of work. Managing them becomes difficult, especially when a large number of contractors or parties are involved. It is most important to clarify every external interface with involved subcontractors and precisely define their responsibilities.

Besides this general categorization of interfaces, other more specific interface categories are summarized in Table 2-1, followed by detailed explanations and comparisons.

Table 2-1: Definitions of Previously Defined Interface Categories in the Literature

Source	Interface Categories	Descriptions
Pavitt and Gibb (2003)	Physical	The actual, physical connections between two or more building elements or components.
	Contractual	Interfaces between the work packages normally associated with specialist contractors when work elements are grouped into distinct work packages.
	Organizational	Interactions between various parties involved in a construction project from its initial conception to its final handover.
Critsinelis (2001)	Intrinsic	Related to the physical links existing in an established production system concept among the various components.
	Discipline	Related to the areas of knowledge necessary to engineer and develop studies, analyses, designs, investigations and developments sufficient and necessary for the concept, and detailed engineering of the production system and its components.
	Project	Driven by the contracting strategy, existing among contractors, subcontractors, vendors and any external provider, with regard to their scope of work, schedule and responsibilities.
Lann et al. (2000)	Functional	Relations between the sub-functions (The main function is decomposed into sub-functions allocated to the responsible organizational segments).
	Physical	Interfaces between physical sub-systems.
	Organizational	Relationship between organizational segments that must be managed (the top-level requirements, as derived from the project objectives, are allocated to the organizational segments).

Pavitt and Gibb (2003) divided project interfaces into three main categories: physical, contractual, and organizational. These categories are discussed below:

Physical Interfaces: These interfaces are "the actual, physical connections between two or more building elements or components." They are inevitable in any construction projects and the easiest to be noticed. The failure at physical interfaces directly leads to the project failure with respect to the final product of building. Normally, the number and the complexity of such interfaces are mainly determined by the detailing design as well as the contemporary techniques of manufacturing or construction.

Contractual Interfaces: Occur where there is the grouping together of work elements into distinct work packages to suit the design information availability or the GC's program.

Contractual interfaces are created between workpackages normally associated with specialist contractors. In the meantime, packaging the work elements also causes additional physical interfaces resulting from separate subcontracts.

Organizational Interfaces: These interfaces consist of interactions between various parties involved in a construction project. Interfaces between different divisions within a single organization are also included.

This categorization includes most, if not all, types of interfaces people can recognize in construction. Pavitt and Gibb (2003) also clarified the important interactive relationship among the defined interface types during a project decision-making phase. As shown in Figure 2-1, such an interaction greatly complicates the project IM system.

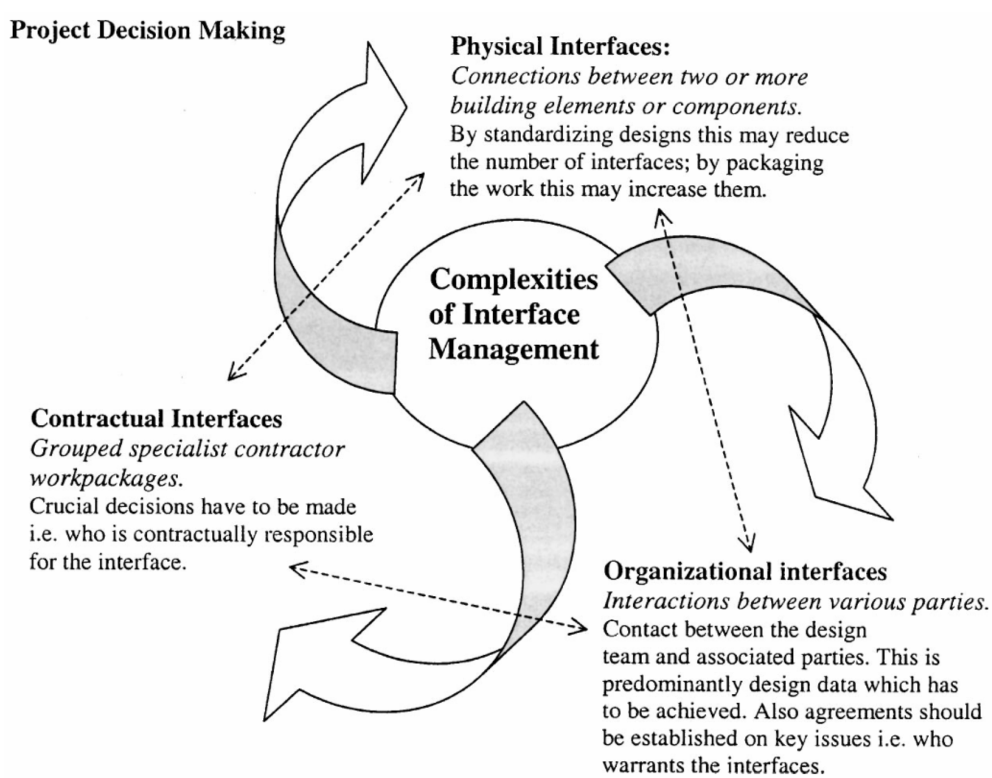


Figure 2-1: Complexities of IM (Pavitt and Gibb 2003, with permission from ASCE)

Critsinelis (2001) pointed out that interfaces were often complex and varied in level, criticality and nature in offshore construction. Accordingly, three inter-related interface categories were defined as:

Intrinsic Interface: "Related to the physical links existing in an established production system concept among the various components." Based on such a description, the intrinsic interface appears closely equivalent to the above-introduced physical interface.

Discipline Interface: "Related to the areas of knowledge necessary to engineer and develop studies, analyses, designs, investigations and developments sufficient and necessary for the concept, and detailed engineering of the production system and its components." Without this description, the term "*discipline interface*" creates confusion. It may be regarded as a general interface among disciplines (or trades), which does not remain at the knowledge level.

Project Interface: "Driven by the contracting strategy, existing among contractors, subcontractors, vendors and any external provider, with regard to their scope of work, schedule and responsibilities." According to the description, this category may be equal to the afore-mentioned contractual interface.

Laan et al. (2000) revealed that interfaces of a transport infrastructure project can be identified as completely as possible by viewing the system from three perspectives, which lead to three decompositions: 1) functional decomposition, 2) physical decomposition, and 3) the top-level requirement decomposition. The physical decomposition helps identify physical interfaces. The top-level requirement decomposition facilitates the representation of organizational interfaces because relevant requirements are located to the organizational segments. The functional decomposition generates a new concept—the functional interface. This interface is not defined in the two categorizations previously mentioned.

Functional Interface: According to Laan et al. (2000), the functional decomposition is the decomposition of functions necessary for the performance of the main function; then relations between the sub-functions are the functional interfaces. It is further stated that the sub-functions are allocated to the responsible organizational segments. Thus the functional interfaces also contain contractual interfaces when sub-functions are grouped into separate workpackages and subcontracted out. In addition, when defining the responsibilities allocated to the "operator" contract and the "systems" contract, Laan et al. (2000) indicated that "these have the character of functional interfaces, as they consist of the functional requirements for the infrastructure, and the restrictions of the infrastructure upon the operators." This description includes functional requirements presented by one system upon another system (systems performance requirements) into the functional interfaces. This conceptual extension greatly contributes to housing research because incorporating systems' functional requirements into IM consideration will lead to the improvement of the whole house performance.

According to the above discussions, different perspectives that are used to decompose a project vary the interface types to be defined. Pavitt and Gibb (2003) decompose the project into workpackages based on "Work Breakdown Structure (WBS)." Contractual interfaces are thus defined as grouped specialist contractor workpackages. Laan et al. (2000) decompose the project based on functions and then invent the functional interfaces. Some researchers think that the functional decomposition method is superior to the traditional WBS method. Their arguments will be discussed later in this chapter.

In both research and practice, it is hard for people to follow the strict and complete interface categorization when they approach interface issues. They often recognize where interface issues usually occur and then start from there for improvement. Such scattered improvements make some progress in IM. But the overall project performance remains poor because of other unattended interface issues. In the following subsections, individual IM approaches are reviewed, most of which comprise an identification of interface issues as well as their potential causes. This information helps in understanding the nature and characteristics of interfaces and reveals the most common interface issues in construction.

2.4.2 Physical Interfaces between Building Components

In the building construction industry, physical interface issues have led to frequent assembly conflicts that severely delayed the project schedule and compromised long term performance as well. As a result, researchers have shown growing interest in studying and solving physical interface issues. Among all research efforts that have been made, two representative works that focus on how to record and utilize physical interface information are reviewed.

2.4.2.1 CladdISS for Windows and Cladding System

Led by Alistair Gibb, a team at Loughborough University carried out **CladdISS,** a U.K. government funded research project aimed to develop standardized interface strategies for the windows and cladding system. In this research project, physical interfaces in building façade projects have been extensively investigated.

The building envelope normally faces a great number of the most challenging interface issues during design, manufacture, construction as well as O & M of the building. The issues include interfaces between different cladding types and between the cladding and the frame, roof, building services (e.g., mechanical, electrical services), internal systems (e.g., walls, floors, and ceilings), and secondary components such as sun shades, cleaning equipment, handrails, signs, and flagpoles (Pavitt and Gibb 1999; Pavitt et al. 2001; Pavitt and Gibb 2003). This research project has identified 12 key areas for improving IM in building facade projects. They are listed in descending order of importance as follows:

- *Identify the interface responsibility as early as possible;*
- *Appoint the specialist contractor earlier;*
- *Ensure that there is a greater understanding of all tolerances;*
- *Ensure that there is a greater understanding of buildability;*
- *Develop tools that identify and aid interface management;*
- *Appoint cladding and frame contractors at the same time;*
- *Standardize interface designs;*
- *Reduce adversarial effects within the process;*
- *Risk assess designers' knowledge of cladding systems from previous projects;*
- *Improve programming and sequencing at site level;*
- *Eliminate the term "by others;"*
- *Ensure that all installers have attended approved training course*s. (Training must include interface issues and their influence on performance.)

Some of these key areas, including planning, scheduling, subcontracting, risk assessment, training, etc., are beyond the scope of physical interface management. This reveals that different types of interfaces or interface issues are interrelated and influence each other. Accordingly, IM should not only focus on targeted interface issues but also be able to deal with other related interface issues. In addition, the success of these measures significantly hinges on whether interfaces in those project areas are defined accurately and adequately. To optimize technical and managerial aspects of cladding interfaces, this research project develops an interactive software tool titled “CladdISS.” This tool implements four steps:

- Review IM strategy;
- Identify cladding types and other building elements;
- Classify interface profiles; and
- Consider key issues and actions.

A two-tier interface matrix (shown in Figure 2-2) becomes the hub of this software tool. It covers physical interfaces between common cladding types as well as physical interfaces between cladding and other key building components. This tool helps the contractors identify what interfaces exist in their building façade project.

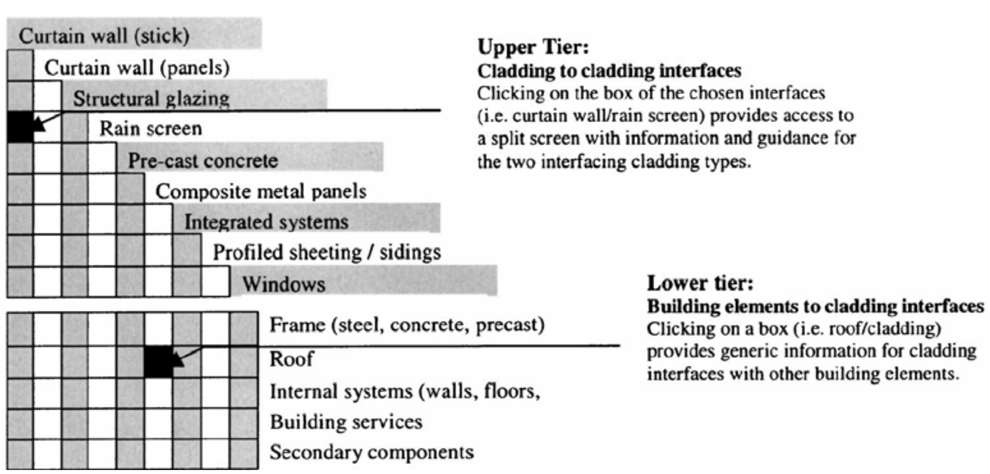


Figure 2-2: Cladding Interface Matrix (Pavitt and Gibb 2003, with permission from ASCE)

In addition to the matrix, typical interface drawings are provided. An example is shown in Figure 2-3, which illustrates what a particular interface comprises and what information needs to be collected and coordinated in interface design. This tool enhances people’s understanding of the joints/connections between facade components and standardizes the interface design process.

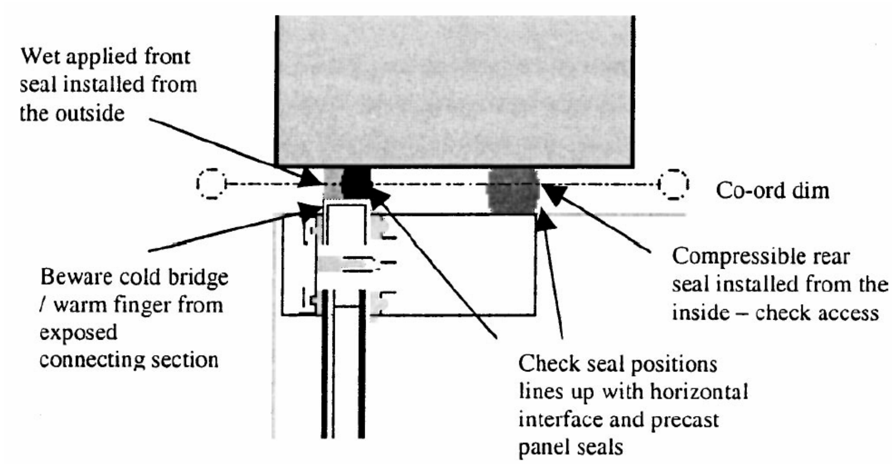


Figure 2-3: Typical Interface Drawing (Pavitt and Gibb 2003, with permission from ASCE)

The CladdISS strategy gives a good example of systematically approaching and solving physical interface problems for the windows and cladding system. It successfully presents and utilizes detailed physical interface information in the interface design process. However, for the proposed 12 key IM areas, adequate information support is not provided. As aforementioned, some of these areas are already beyond the scope of physical interface management. The needed information cannot be found in the matrix and drawings. Therefore, an effective way to present comprehensive information is needed for interfaces other than physical, such as contractual or organizational interfaces. Otherwise, achieving these management measures faces considerable difficulties due to lack of information. In addition, the strategy relies heavily on interface drawings that are graphics-based and do not carry any intelligence. This not only limits the interoperability and application of such information among a wide variety of non graphics-based construction management software but also lowers the opportunity for automatic analysis and coordination of interfaces.

2.4.2.2 Knowledge-Based System for Wooden Construction

Nakajima (1998) develops a Knowledge-Based System (KBS) for wooden construction. This system can create an assembly order and construction activities by using detailed design information—the descriptions of characteristics about building members, connections, and joints. These characteristics, divided into three types, are shown in Figure 2-4.

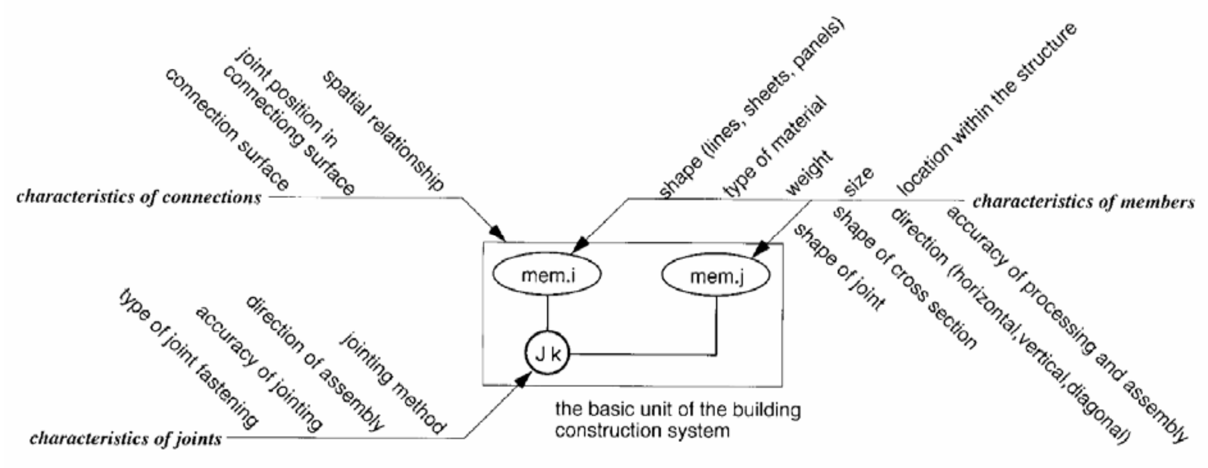


Figure 2-4: Characteristics of a Building Construction System (Nakajima 1998, with permission from Blackwell Publishing)

Some of these characteristics such as *spatial relationship*, *joint position in connection surface*, and *direction of assembly* are closely related to the assembly order. Other characteristics such as *shape of member*, *shape of cross section*, and *shape of joint* are related to the processing and fabrication activities. A building construction system, in Nakajima's view, is composed of units, each of which is defined as a single structure consisting of two members and one joint. Therefore, based on the descriptions of characteristics for those members and joints, the assembly order and construction activities for a building construction system can be determined.

In this research work, detailed characteristics of a joint were carefully studied and rules for generating the assembly order and activity procedures were summarized. Eventually, a construction schedule could be determined. This work provides an accurate way of presenting physical interfaces by focusing on the characteristics of building members, connections, and joints. The approach is useful for presenting simple physical interface information; but its ability to handle complex physical interfaces is unknown.

The example that Nakajima used to demonstrate KBS is fabricating wood building members manually and installing them piece-by-piece. This is a traditional way for housing construction where usually simple and single joint exists between two building members. Such a joint can be easily modeled by using the above approach. Nevertheless, current housing construction has already extensively used manufactured building components, such as roof trusses and floor trusses. In order to minimize the on-site labor requirement, some components are pre-assembled into larger components in the factory, e.g., a panelized wall. Sometimes, interrelated building components have even been integrated as complex systems (e.g., an integrated wall system in modular construction) before they are shipped to the job site. As a result, on-site connection of those components or systems becomes a complex process and multiple types of joints or interactions are involved. Under these circumstances, the construction methods and assembly procedures are distinctive. Nakajima's approach is unable to model and handle such complex interrelationships or interactions between building members. Research works taking into account up-to-date construction innovations should be provided.

2.4.3 Interfaces among Various Construction Parties

A construction project involves many participants. The multitude of project participants causes a large number of interfaces between them. Al-Hammad and other researchers have conducted extensive research about interface problems among various construction parties in Saudi Arabia. Their papers mainly discuss interface relationships between two parties, such as owners and contractors (Al-Hammad 1990), designers and contractors (Al-Hammad and Assaf 1992; Al-Mansouri 1998), GCs and subcontractors (Al-Hammad 1993; Hinze and Andres 1994), owners and maintenance contractors (Al-Hammad 1995), and owners and designers (Al-Hammad and Al-Hammad 1996).

In a conclusive paper, Al-Hammad (2000) identifies 19 main interface problems among various construction parties. These problems have been classified into four categories: financial problems, inadequate contract and specification, environmental problems, and other common problems. Strictly speaking, these problems (shown in Table 2-2) are not interface issues this research defines, but more likely reasons or factors causing various interface issues. As listed below, "*insufficient work drawing details*" may lead to assembly difficulties, errors, or conflicts between two building components. "*Delay in progress payment by owner*" may incur a poor working relationship as well as suspension of work in a project.

Table 2-2: Common Interface Problems from Construction Parties' Viewpoint (Al-Hammad 2000, with permission from ASCE)

Interface problems (1)	Responses					Mean (7)	Importance index (%) (8)	Rank (9)
	Very strongly affects (2)	Strongly affects (3)	Moderately affects (4)	Strongly doesn't affect (5)	Very strongly doesn't affect (6)			
Financial problems	**68**	**176**	**113**	**34**	**6**	**2.67**	**66.8**	**1**
Delay in progress payment by owner	26	39	31	5	1	2.82	70.6	3
Accuracy of project cost estimate	14	55	27	5	0	2.77	69.3	5
Owners low budget for construction relative to requirement	21	53	22	5	1	2.77	71.6	2
Prices change of materials and laborers during construction	7	29	33	19	4	2.07	51.6	17
Inadequate contract and specification	**71**	**206**	**193**	**39**	**0**	**2.61**	**65.3**	**2**
Insufficient working drawing details	13	39	43	7	0	2.57	64.2	3
Insufficient specification	11	44	41	6	0	2.59	64.7	9
Violating conditions of the contract	5	13	4	0	0	3.05	76.14	1
Poorly written contract	10	42	35	14	0	2.48	61.9	5
Change order	11	30	50	11	0	2.40	60.0	7
Environmental problems	**14**	**30**	**92**	**63**	**5.5**	**1.93**	**48.2**	**4**
Weather	4	11	49	36	2	1.79	44.9	19
Geological problems at site	10	19	43	27	3	2.06	51.5	16
Other common problems	**106**	**325**	**309**	**67**	**7**	**2.56**	**64.4**	**3**
Lack of communication between construction parties	10	38	47	7	0	2.54	63.5	10
Slowness of owner in decision making	13	47	32	8	1	2.62	65.6	2
Delay in finish of project	9	38	42	13	0	2.42	60.5	18
Unavailability of professional construction management	7	28	48	17	2	2.2	55.2	15
Skills and productivity of laborers	15	40	43	40	0	2.65	66.2	13
Poor quality of work	18	52	28	3	1	2.81	70.3	4
Poorly done planning and scheduling	16	38	24	5	1	2.62	65.4	11
Unfamiliarity with local laws of related governmental agencies	18	44	27	10	2	2.65	66.3	14

A survey has identified the severity of these problems to the inter-party relationship. As shown in the table, among individual interface problems, "*violating conditions of the contract*" is ranked the highest. However, among four interface problem categories, "*financial problems*" has the severest impact on working relationships. This is because at the current stage project profit is still the final goal of most project participants. Besides interface problems listed in the questionnaire, the following issues including *long lead items*, approval *permits*, *shop drawing approval*, *material procurement*, and *lack of designer experience* have been added by survey respondents.

Under most circumstances, a construction project has a single GC, who subcontracts out the specialty construction work and manages subcontractors and interfaces between them and their work. For financial, schedule, or jobsite control reasons, an owner may sometimes enter into multiple construction contracts directly with trade subcontractors. Creating more complicated inter-party interfaces, this type of contracting method is very likely to lead to project budget and schedule overruns without proper pre-planning and execution. Kuprenas and Rosson

(2000) identify that questions of responsibility for contractors and disagreements about scopes of work are common problems. Interfaces between two trade contractors should be defined and clarified with respect to scope and responsibilities in the bid division descriptions. This can clear up future confusion about the ownership of such interfaces. Simultaneously, additional contracts may be required to pick up items omitted from trade contracts or missing items about interfaces. Shrive (1992) points out that the key for the successful delivery of such projects should be preplanning of scopes and responsibilities for the whole work and consideration of all contract interfaces before bidding.

2.4.4 Design-Construction Interface

The design-construction interface is another area drawing considerable research interest. Studies in manufacturing have shown that management of the interface between design and manufacturing is very important for achieving a higher level of manufacturing flexibility (Shirley 1987). In construction, enhancing management of the design-construction interface improves both design and construction.

The improvement of the design process becomes critical for ameliorating the design-construction interface. During the design phase, customer requirements, constructive considerations, and quality standards are defined and incorporated into construction drawings and technical specifications to guide construction activities. In practice, this important phase is conducted with little interaction between the design and construction teams, which leads to problems such as incomplete designs, lack of constructability, design errors, change orders, rework, construction delays, and waste (Alarcón and Mardones 1998). According to Fritschi (2002/03), in the design phase, causes of interface issues fall into four main groups: 1) no clear definition of tasks, 2) insufficient preparation work, 3) unsatisfactory information, and 4) poor communication.

Alarcón and Mardones (1998) consider design a flow within which inspection, moving, transformation and waiting for information, redesign due to errors, omissions, and uncertainty, etc. are all waste. Improvement and optimization of the design process can avoid value losses. The main design problems identified include poor design quality, lack of design standards, lack of constructability, and lack of coordination among specialties. In their research, a “House of

Quality” matrix is used to determine the effectiveness of various technical responses to 21 listed design defects. Two technical responses, “*work specification*” and “*drawing delivery schedule*,” are found to be effective in avoiding approximately 50% of the defects if properly applied.

It has been noticed that some new design concepts have greatly enhanced the quality of design and construction. For example, DFA and DFMA have successfully reduced the parts of a product and coordinated the physical interfaces between those parts. Boothroyd et al. (1994) raise three criteria, against which each part should be checked when it is added to the product during the assembly. These criteria include:

- During operation of the product, does the part move relative to all other parts already assembled?
- Must the part be of a different material than, or be isolated from, all other parts already assembled?
- Must the part be separate from all other parts already assembled because otherwise necessary assembly or disassembly of the separate parts would be impossible?

Austin et al. (1999) conclude that current building design planning practice gives little consideration to the interdisciplinary, iterative nature of the process. This leads to a compromised design process that contains inevitable cycles of rework together with associated time and cost penalties in both design and construction. Under this circumstance, the ADePT (Analytical Design Planning Technique) is proposed. This technique helps plan the design, enables work to be monitored on the basis of the production of information, and allows design to be fully integrated with the overall construction process. According to Austin et al. (1999), this technique comprises three stages as shown in Figure 2-5.

First, design activities and their information dependencies are represented in the process model built upon a modified version of IDEF0. The detailed design process is broken down into five main disciplines, then into building elements and systems, and ultimately into individual design tasks. Second, the ordering of design activities on the basis of their information requirements is displayed with a Dependency Structure Matrix (DSM). Third, iterative design tasks are partitioned in a DSM and a planning tool is used to generate an optimal schedule. This technique focuses on improving the design process by satisfying information dependencies among design activities in a more efficient way. It may be limited to projects where aesthetic value is minimal in design considerations.

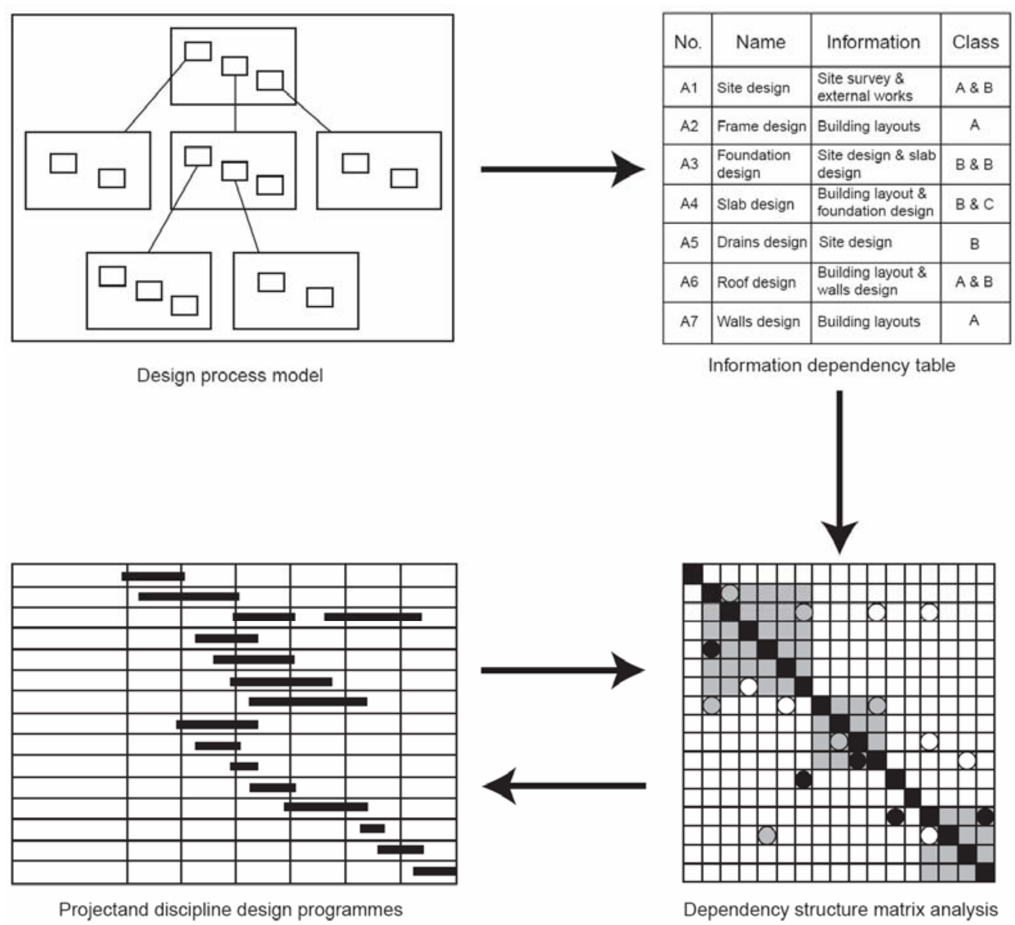


Figure 2-5: Analytical Design Planning Technique (AdePT) (Austin et al. 1999, with permission from Thomas Telford Ltd)

Other researchers have also made similar attempts to improve the design process. For instance, Chua et al. (2003) proposes a Process-Parameter-Interface (PPI) model to manage the design process of Architecture, Engineering, and Construction (AEC) projects. The model aims to improve design process scheduling by reducing information iterative loop and to enhance efficient collaboration. All research introduced above considers only activities purely related to the design development.

Khanzode et al. (2000) focus on creating information standards on the design-construction interface to improve the delivery of a construction project. The paper-based exchange of information between project participants is regarded as the main cause for redundancies, errors and omissions, duplication of information and effort, and difficulties in timely communicating changes in design. Those problems eventually lead to cost overruns and project delays. To overcome this weakness, a study was conducted to perform the following three research tasks: 1) monitor the information sharing between project participants in the structural steel delivery process, 2) clarify the limitations of the current process, and 3) prove how the new information standards help address some of these limitations.

In recent years, many companies employing integrated project delivery methods have emerged on the construction market. They offer a one-stop solution for the owner from in-house design to construction. Despite the increasing complexity of the firm and related risks, the Design-Build (DB) or Engineer-Procure-Construct (EPC) approach transfers the traditionally external design-construction interface inside the boundaries of a single firm. This shift has two merits. The first is to facilitate coordination between the designer and the contractor at an early stage, which results in savings, improvements, and reduced variations. The second is to significantly simplify contractual and organizational interfaces in a project (Sozen 1996).

Miles and Ballard (2002) indicate that design and construction are insufficiently integrated in all forms of project delivery currently on offer and design-construction interface problems are more critical for specialty contractors in modern fast-track projects. Their research proposal aims to reveal interface problems between mechanical design and construction, pursue improvements that accomplish the lean objectives of maximizing value and minimizing waste, and experimentally test those possible solutions. In their opinion, some “failures at the interface” are “systemic” and cannot be resolved simply by “working harder.” The ideal solution lies in a total restructuring of the delivery process around the creation of value and elimination of waste.

The proposed process modifications start from involving the key specialty contractors (including mechanical, electrical, drywall, and steel/concrete structure) in an initial process-restructuring group since this group incurs the greatest number of project coordination interfaces and workflow concurrency. Since design needs a lot of inter-craft coordination, it is very important in the restructuring process to define and structure design workpackaging before design progresses beyond the concept level. It is also crucial in the restructuring process to organize cross-functional teams. Fritschi (2002/03) combines several such tools as process management, visualization, selection of the project team members, and ways of team finding to assist the project manager with IM in the design process. Those tools as a whole cover many aspects of a construction project and approach the solution systematically.

Management of the interface between design and construction and the knowledge transfer between design and construction activities are regarded as two keys to reducing project delivery time, in particular for fast-track projects (Bogus et al., 2002). Relatively, CE concepts, principles, and methods could be adapted for use on the dynamic design-construction interface to overlap some traditionally sequential activities and therefore to reduce project delivery time. However, the degree to which design or construction activities can be overlapped is decided by the nature of the information exchange between those activities.

Based on the information dependency relationship among activities, Prasad (1996) defines four types of activity relationship: dependent, semi-independent, independent, and interdependent. Only independent activities can be overlapped with no risk of delay or rework; overlapping the other three relationship types of activities may cause associated risk. Bogus et al. (2002) propose a method for overlapping design and construction activities, reconfiguring the design-construction interface, and finally generating an ideal overlap schedule for a fast-track project. The core of their model is the use of DSM (Figure 2-6) to find out activity relationships and partition the activities needing backward flow of information.

As shown in Figure 2-6b, their DSM is enhanced by rating the task characteristics of evolution and sensitivity, which are ranked from "1" to "4." For example, "1" denotes fast evolution of upstream task and low sensitivity of downstream task to changes in upstream task; "4" denotes slow evolution of upstream task and high sensitivity of downstream task to changes in upstream task. Chen et al. (2003) use a similar methodology in the proposed IFIPM (Information Flow Integrated Process Modeling) to achieve an efficient and streamlined flow of information in the construction planning stage and finally to generate an improved CPM schedule for both design and construction activities.

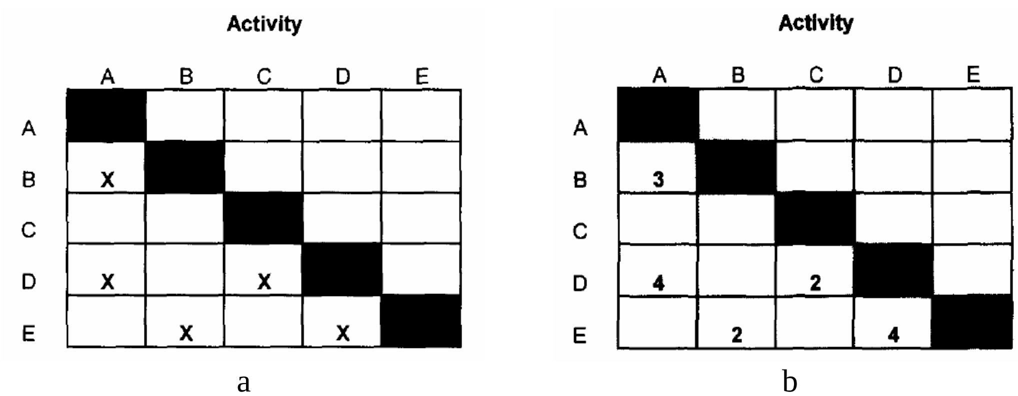


Figure 2-6: a) Partitioned Design Structure Matrix; b) Modified Information Matrix (Bogus et al. 2002, with permission from ASCE)

2.4.5 Contractual Interface

One of the widely employed forms of work structuring is WBS, which divides a project into elements according to customary contracting and craft divisions. The 16 CSI (Construction Specification Institute) divisions (including sitework, concrete, metals, wood and plastics, etc.) provide a common method of classification for WBS. Based on a defined WBS, distinguished work scopes are separately awarded to different subcontractors who are responsible for the delivery of such elements as foundations, masonry, pre-cast concrete walls, windows and doors, and insulation. Actually, the assumptions behind WBS may not be realistic because work scope is not divisible into independent elements. Project elements are commonly interdependent, according to Ballard et al. (2001). For example, external masonry walls and windows are closely interrelated since the windows have to be embedded into the external walls. However, in practice, they are usually subcontracted out to different contractors.

Miles and Ballard (2002) critique the traditional WBS. From their point of view, facilities are composed of subsystems and functionalities that have crossed traditional contract and craft boundaries. Successful performance of a subsystem design and construction normally involves a team of players. As an example, the building enclosure/envelope is one of the typical building subsystems. It consists of many interdependent components (e.g., roof, masonry wall, windows, insulation, waterproofing), which are produced and installed by different craft trades. The construction quality and the future performance of the building envelope are determined by integrated performance of all involved contractors. However, the current delivery process and WBS overlook the relationship between either these components or the involved contractors. During the design and construction of a subsystem, serious interface problems among different crafts happen very often. Poor workpackaging results in an excessive amount of interdependency among workpackages, and increases the potential delays (O'Connor et al. 1987).

Based on the TFV (Task/Flow/Value) concept of production, Ballard et al. (2001) propose a guide for generating ends-means hierarchies—moving from desired ends to actionable means—for the production. This guide provides an alternative to WBS and aids in the design of a more reasonable production system as expected by the lean philosophy. Miles and Ballard (2002) point out that workpackages should be structured around facility subsystems and functionalities in order to precisely define all the interfaces in a subsystem or function. Consequently, workpackages may be single-trade or multi-trade related and subcontracting should be organized in a way that facilitates IM. The formation of Cross Functional Teams in construction is proposed.

Cross Functional Team is now considered a basic requirement for a successful business. In a new era of systemic innovation, it becomes very important for an organization to be cross-functionally excellent. In addition to being good at the technological aspects, the organization should maintain complementary expertise in other aspects of their business, such as manufacturing, distribution, human resources, marketing, and customer relationships (Kotelnikov 2004). In the manufacturing industry, the application of cross functional teams has had some success. The most well known cases, as indicated by Kotelnikov (2004), are General Electric (GE) and Hewlett-Packard.

In the construction industry, middle or large-sized builders are cross-functional teams that are composed of personnel from design, construction, marketing, management, etc. A temporarily organized project team is also a cross functional team which involves a variety of stakeholders: owner, operator, designers, contractors, major suppliers, and regulators. For the building design, a cross functional team should consist of specialties for each of the building subsystems: foundation, superstructure, skin, HVAC (Heating, Ventilating and Air Conditioning), lighting and power, controls, interiors, etc. When the design is accomplished, according to Miles and Ballard (2002), the input from various parties is needed to properly construct the workpackages and write the Package Definition Document. Figure 2-7 illustrates the basic structure of a cross-functional team in construction, the organizational foundation upon which the process improvement is based.

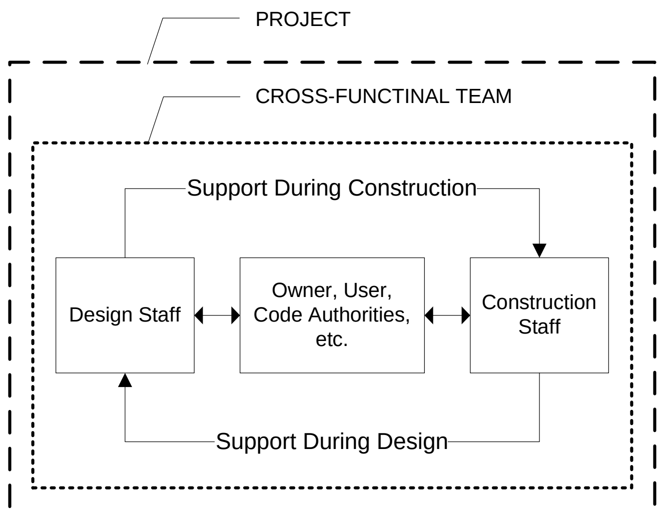


Figure 2-7: A Cross Functional Team (Miles and Ballard 2002, with permission from World Scientific Publishing Company)

Hybrid called cross-trained trades stem from the concept of cross functional teams. The residential construction site is extremely cramped for multidisciplinary trades to work on. Under such circumstances, cross-trained trades can well understand interfaces they will face in their boundaries and cooperate better while working together. Being trained in the relationship of their particular work to the performance of the whole house, involved subcontractors work like a single contractor who is more capable of handling interfaces within subsystems. IBACOS (Integrated Building and Construction Solutions) Corporation is experimenting with cross-trained trades that are organized as the grounds team, superstructure team, envelope/enclosure team, and systems/finishes team. The attempt aims to reduce the negative influence on subsystems caused by discrete teams (O’Brien, Wakefield, and Beliveau 2000).

2.4.6 Systems Approaches

In the literature, systems approaches such as the "*building systems*" and "*systems integration*" have been employed in construction. These approaches are related to the interface issues and IM.

2.4.6.1 Systems Engineering

Diverse systems approaches employed in different industry domains usually originated from *systems engineering* (also called *systems design engineering),* which was initiated around the time of World War II when large or highly complex engineering projects, e.g., the development of a new airliner or warship, were often broken down into stages and managed throughout the entire life of the product or system (from concept, design, production, operation to disposal). There, interface design and specification were required to enable the pieces of the system to interoperate.

Systems engineering can be defined as "the application of engineering to solutions of a complete problem in its full environment by systematic assembly and matching of parts in the context of the lifetime use of the system" (http://www.ichnet.org/glossary.htm). Applied in offshore construction, systems engineering represents an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, performance, test, manufacturing, cost and schedule, training and support, and disposal. Systems engineering integrates all the disciplines and specialty groups into a team effort that forms a structured development process (INCOSE 2004). In what follows, several systems engineering applications are reviewed and their close relationship with IM is depicted.

2.4.6.2 Systems Engineering Approach for Dynamic IM

In construction, interface coordinators or interface managers may be appointed to handle interface issues. Their experience and performance make big differences in the project outcome. With the increasing complexity of construction projects, those personnel's performance fluctuates.

The systems engineering method has been applied to managing interfaces of a transport infrastructure project in Netherlands. According to Laan et al. (2000), the project was complex both in size and in the number of internal and external interfaces. There were seven large Design-Construction contracts for the civil sub-structure and connections with the existing infrastructure, one Design-Build-Finance-Maintain contract for the rail systems, and a public tendered contract with a Train Operation Company. The complexity of this project made IM there a very challenging task.

After studying the complicated relationships between those contracts and their products or services, Laan et al. (2000) reached a conclusion; i.e., when a project is built from different contracts, these contracts have to be integrated based on systems integration and IM must be established in the contracts in a way that they can work together effectively and efficiently. The proposed systems engineering approach comprises seven aspects of IM presented below:

- Development of a structured specification tree where interface requirements between the systems are clearly stated;
- Scenario analysis;
- IM including interface identification, interface definition, and interface verification and control;
- Configuration management;
- Risk management;
- Verification activities; and
- Preparation of the “Systems” contract.

In addition, a series of matrices were used to effectively represent complex interface relationships including functional interfaces existing between systems contracts. All discovered interfaces were prioritized based on an overall risk analysis. During the design and construction phases, interfaces became highly dynamic. The dominant decision criterion for interface management and control was based on the system functionality. In the end, it was indicated that this case also showed that systems engineering principles and methods had to be employed flexibly according to the needs of the project and the environment (including the culture).

2.4.6.3 Building Systems

"*Building Systems*" is an approach to industrializing the building process by using the basic problem solving strategy of the general systems theory. It was adopted in the 1950s and 1960s. According to Sullivan (1980), the general systems strategy starts with the analysis of a particular system, or situation, in terms of the "whole," and then works toward the specific considerations of the "particular" parts. For example, the whole building system consists of many components and segments that represent a set of related tasks. The physical system itself is only one component within a larger and more complex process. The development of such a physical system within the context of the holistic understanding of that larger system or process constitutes the "systems approach."

In a building system, individual manufacturers supply a number of interactive subsystems (structure, atmosphere, vertical skin, plumbing, etc.) or components. It becomes very important for the subcontractors of the interfacing subsystems to cooperatively develop their proposal. Otherwise, extensive fitting and adjustments in the field will be required. For this reason, adequate cooperation on the part of independent subsystem bidders must be guaranteed. In addition, all other tasks including architectural planning, design, scheduling, as well as a contractual system have to suit the needs of the component manufacturers and subcontractors (Sullivan 1980).

There were several important systems building approaches in the past, including the CLASP (Consortium for Local Authority Special Program) system in the U.K., the SCSD (School Component Systems Development) project in the U.S., and the SEF (Study for Educational Facilities) project in Canada (Sullivan 1980). In SEF, the interface-oriented bidding process and subcontracting strategy were first employed to enhance coordination between interrelated subsystem providers and to minimize incompatibility.

In the systems approach, the extensive use of standardized, interchangeable prefabricated building components to form subsystems was assumed to help industrialization. But in practice, four critical interface problems often occurred. First, component systems were often "closed," which were difficult for interconnection with systems made by other manufacturers. Second, separately produced components caused serious problems on dimensional coordination. Third, functional performance was hard to achieve by simple combination of different components. It was a real challenge for the involved parties to enhance cooperation and coordination during the phases of design, planning, manufacturing, and construction. Fourth, conventional housing systems integration considers building subsystems separately. The interrelationship between different but connective subsystems is ignored. The lack of coordination between subsystems leads to uninformed design, lack of prototyping, absence of production simulation, and lack of understanding of the consequences of the field modification on performance (O'Brien, Wakefield, and Beliveau 2000).

The building systems approach achieved some success in educational building systems where performance-based and dimensionally coordinated building components were used in an open system. However, numerous problems still existed and need better solutions. In addition, this approach was seldom applied in housing construction, which limits its benefits in practice.

2.4.6.4 Systems Integration in Housing Construction

The customer requirements for any product have greatly increased in recent decades. There is no exception for a built facility (e.g., a building). However, differing from other types of industry products, the performance of a building is difficult to define and evaluate due to lack of clear standards and criteria for evaluation. The progress toward improvement in the building construction industry is slower than that in other industries. To catch up, whole-house research has been conducted in recent years.

The latest effort toward whole-house design and construction is made by Partnership for Advancing Technology in Housing (PATH). In the relevant research, "whole-house" design has been closely linked to the application of "systems engineering" principles. According to PATH (2003), the house is considered a system "in which specific products, materials and construction methods that may involve just one part of the house can have impacts throughout the house." Therefore, improvement efforts are focused on avoiding negative interactions and capitalizing on synergies or positive interactions in the design phases.

As indicated before, a building is composed of many subsystems. These subsystems are physically interrelated; changes to one subsystem influence the performance of many other subsystems. The practice in systems integration in housing still mainly considers each major building subsystem separately. Recently, researchers began to discuss a high level of integration, a real "optimization." In the funded HUD project "Industrializing the Residential Construction Site" conducted at Virginia Tech, systems integration was considered one of the most important means to enhance industrialization. Five primary areas interdependent in practice were defined. Their influence on housing construction is presented as follows (O'Brien, Wakefield, and Beliveau 2000):

- *Information integration:* Making the many pieces of information used by homebuilders accessible as one data source
- *Physical integration:* Making the many parts fit together as one
- *Performance integration:* Making the many systems perform as one
- *Production integration:* Conducting the many processes as one
- *Operation integration:* Operating the many subsystems as one

Systems integration can greatly increase the number of interfaces to be considered in the design, construction, and operation stages. Except physical interfaces that have been considered by the industry, other interfaces such as performance and operational interfaces are totally new concepts to the industry. This raises the complexity of interface issues in construction and makes them difficult to manage and control. Without clearly defining the newly emerging interfaces and their influence, the industry does not know where such interfaces exist and how to manage them based on certain rules.

"Optimization" across subsystems is complex in many aspects. The PATH research points out that "optimization" needs a series of performance metrics for each subsystem, a mathematical understanding of their relationships, and the ability to convert these performance metrics into economic terms. In addition, the approach must also be compatible with involved specialized product manufacturers and construction trades. The PATH roadmap, therefore, defines the whole-house design as follows (PATH 2003):

- Integrating various subsystems or components to optimize design and operation
- Integrating functions of various components or subsystems in a home
- Modifying the management approach and/or other processes to simplify the schedule, reduce negative interdependencies, and simplify construction

- Expanding the use of factory-built assemblies including whole-building systems.

2.5 INFORMATION MODELING FOR INTERFACES AND IM

IT (Information Technology) can work as a facilitator for IM, especially in complex building projects. Accurate information modeling is very important in the process of applying advanced technologies to the creation, management, and use of interface information. Existing information modeling methods have achieved some success in modeling interface information. However, the limitations of those methods have largely restricted the applications of the modeled information.

2.5.1 3D/4D Visualization

IT applications, in particular 3D/4D visualization techniques, are helpful for avoiding and resolving interface problems. Visualization helps not only knowledge discovery in construction but also helps the designer examine and understand the interrelationship between design parameters, especially in the multi-disciplinary environment (Rafiq 2003). Better visualization makes it possible to quickly test appearances and consistency of dimensions. 3D construction models aim to help the contractor put a project together and foresee interface conflicts before they happen on the jobsite.

4D technologies combine 3D CAD models with construction activities to analyze and visualize many aspects of a construction project, from the 3D design of a project to the sequence of construction to the relationships among schedule, cost and resource available. The underlying 3D model and schedule model are based on object-oriented concepts; the users can query their content and relationships (Emerging Construction Technologies 2000). The objective of 3D/4D visualization is to verify constructability and reveal schedule conflicts (Danso-Amoako et al. 2003).

Contractors usually have difficulties in coordinating 2D drawings from each specialty to minimize or eliminate conflicts on the jobsite. Such 2D drawings do not contain visualized information. They also contain no required intelligence and analysis environment to support the rapid and integrated design and construction of facilities. In contrast, 3D/4D visualization facilitates the understanding of the relationship between production elements and various construction activities, and therefore helps improve activity sequencing, constructability, and workflow for subcontractors (Emerging Construction Technologies 2000).

Danso-Amoako et al. (2003) propose a framework for the development of a point-n-click interface for construction visualization focusing more on how pieces and components fit together (i.e., constructability) rather than schedule conflicts. This interface is a browser-like and user-friendly environment where users just click, point, drag, mouse-over, etc. A global view of the proposed interface system consists of the following processes:

- User request;
- Query from proposed engine to a standard CAD package;
- CAD package response to query; and
- Proposed engine's response to user interface (browser)

Nevertheless, 3D/4D CAD is still not effectively employed in practice due to some barriers. Danso-Amoako et al. (2003) examine the concept of 3D/4D CAD computer visualization and analyze some of the most likely reasons for this anomaly. First of all, one major problem in migrating from 2D to 3D construction visualization is how to determine the level of detail to be shown in the model. Apparently, the GC and subcontractors request detail at different levels. Second, the lack of industry level standardization causes problems. 4D models are built in an ad hoc manner without a methodology guiding their generation. Third, the transfer efficiency between 2D drawings to 3D modeling production is low. Fourth, it still remains unclear about how 3D models can be properly used on the jobsite since 3D models are normally available only for the single-user desktop environment (Danso-Amoako et al. 2003; Emerging Construction Technologies 2000).

2.5.2 Object-Oriented CAD and Supporting Modeling Methods

It is difficult for a single design company or contractor to support any significant software development except a common software basis to be used for different applications (Serén et al. 1993). Although Computer Aided Design (CAD) has been widely accepted and employed in the industry since the 1980s, its applications are still restricted to generating 2D or 3D architectural and constructional drawings. 2D drawings are composed of lines and shapes without any intelligence about what the lines and shapes represent. 3D geometric models include shapes, lines and points, and three-dimensional components. Although making building objects more visible, 3D models do not carry intelligence about other properties of these objects (Jonathan Cohen and Associates 2004). As a result, comprehensive and efficient coordination via computer programming is impossible.

In practice, the most acceptable format for information transmission is paper-based. 2D blueprints are exchanged between different parties and used on the jobsite. With the development of Internet technology for sharing data digitally in the 1990s, CAD drawings can now be easily shared electronically. However, the lack of a shared project model still limits the usage of such electronic drawings that do not carry more information than the paper-based version. For example, specialty subcontractors, who conduct detailing design on their scopes of work, normally generate their own shop drawings (for fabrication and installation) based on the paper drawings or electronic drawings they received. They have to request further information from architects and other contractors for their detailed design since the information carried by CAD files is very limited.

Object-oriented CAD is a new idea for modeling physical objects such as building components. Specifically, these components are represented as objects containing the physical geometry as well as many other kinds of attributes including shape, behavior, code and performance data, transport requirements, cost, information related to construction means, methods and schedule, maintenance, and facilities management (Jonathan Cohen and Associates 2004). Object-oriented CAD facilitates the generation of a shared project model to which participants would have real-time access throughout the life of the project and can contribute their own knowledge while using information supplied by others. There are some successful applications, such as ArchiCAD and DDSPartner by Graphisoft, based on an object-oriented CAD system. These applications aim to achieve intelligent data exchange between architecture building models and building services.

Several modeling methods are used to implement the function of object-oriented CAD. Jonathan Cohen and Associates (2004) describes the following three models:

Parametric model: It visualizes the relationship between building elements. When a variable is changed, its influence on related elements is seen by automatically regenerating the model. The model is constantly responsive to changes and offers a degree of flexibility and coordination previously unavailable.

Procedural model: It adds some special ability to the model. For example, the model can prevent incompatible elements from being placed adjacent to each other.

Generative model: It creates geometries that satisfy the requirements and rules set by the user. These models greatly help interface coordination between building components from different perspectives.

Currently, there exist two streams for developing an intelligent CAD. One is to give the system powerful problem-solving ability. This can be achieved by developing a **Self Contained Expert System** (SCES). The other is to place the emphasis on understanding the designer's intention. Studies have been conducted to find out prerequisite requirements for developing these two streams (Marghitu et al. 1993; Marghitu et al. 1994). Through studying one of the most powerful advanced CAD systems—Pro/ENGINEER—solutions for several classes of CAD problems in the areas of specification, design, assembly, diagnosis, monitoring, control, debugging, and instruction, were found (Mills et al. 1992).

The possibility of applying the object-oriented approach to the construction industry has been extensively discussed. Researchers have presented various application tools and models, such as OOCAD (Object-Oriented CAD) tool, Object-Oriented Product Model, and OSCONCAD (Open Systems for Construction CAD) model (Scherer and Katranuschkov 1993; Serén et al. 1993; Marir et al. 1998).

O'Brien, Wakefield, and Beliveau (2000) indicate that the object-oriented CAD tools can help physical and performance integration by rationalizing all subsystems, i.e., drawing all required components and finding the most efficient method to connect like-subsystem components. The program can therefore automatically check for physical collisions between subsystems. For example, object-oriented CAD-based physical integration tools can be employed to the interface between adjacent subsystems (e.g., plumbing and framing) during the design phase. The same position-checking and interference-detection tools can be utilized to verify the relationships among components and subcomponents of a subsystem. All these applications are greatly helpful for IM in big projects, because as project complexities increase, the consistency of physical interfaces becomes intractable for an interface coordinator/manager.

However, object-oriented CAD systems remain rooted to building graphics due to their graphics-based CAD foundations. This creates a limitation that prevents object-oriented CAD systems from being fully optimized for creating and managing information about a building (AutoDesk, Inc. 2002). Therefore, the evolution of object-oriented CAD will continue with the development of building information modeling solutions that add the management of relationships between building components (AutoDesk, Inc. 2002).

2.5.3 Industry Foundation Classes (IFCs)

Even with many IT tools available, it is still difficult for project participants to effectively communicate and share information with one another. They should have a common interpretation of construction design objects. The project specification is a document that characterizes the products and specifies the processes. However, with the development of various computer applications assisting design, construction and project management, common construction objects or management contents may be displayed differently in those computer applications. "Interoperability," therefore, becomes very important for the open sharing of information between different hardware or software applications in use.

Interoperability requires that concepts which are common between different software applications are understood to be common and declared accordingly (Wix and Liebich 1997). The International Alliance for Interoperability (IAI), a public organization open to any member of the building industry, was first formed in 1994 and became a global organization later in 1996. The IAI aims to specify how the "things" (doors, walls, fans, etc.) that could occur in a building are represented electronically. The IFC object model has been released to provide an environment of interoperability among IFC-compliant software applications in the AEC/FM (Architecture, Engineering, and Construction/Facilities Management) industry. For example, the CAD and building simulation software can automatically acquire and exchange building geometry and other building data from project models created with IFC-compliant CAD software without loss of accuracy (Bazjanac and Crawley 1997). This makes it possible for intelligent interface-conflict checking programs to work based on existing data.

The IFC uses the object modeling terminology, for example, *class* and *object*. In the IFC, a range of things that have common characteristics are called a *class*, which can be represented by a specification. Each instance of its use is called an *object*. The IFC, composed of a series of specifications, represents a data structure supporting an electronic project model which is useful in sharing data across applications (IAI 1999a). That is to say, the IFC defines a single, object-oriented data model of buildings. This data model is the basis for any recommended applications.

IFC-based objects allow AEC/FM professionals to share a project model, yet allow each profession to define its own view of the objects contained in that model. The subsequent applications are always able to read and understand the characteristics defined by preceding professionals and add information to the object. This keeps the data consistent and coordinated through different applications. Furthermore, the shared data can continue to evolve during the whole process of a project (IAI 1999a). When other professionals share electronic information about characteristics and function requirements of an object recorded in IFC-compliant applications, physical and functional interfaces between building components or subsystems could be properly coordinated and handled.

Figure 2-8 illustrates the architecture of the IFC object model. There are four conceptual layers using a strict referencing hierarchy. Those layers are explained as follows:

Resource layer: Resources here can be characterized as general purpose or low level concepts or objects that do not rely on any other classes in the model for their existence with a few exceptions. All resources represent individual business concepts (IAI 1999b).

Core layer: There are two components. The kernel provides all the basic concepts required for IFC models within the scope of the current IFC release and determines the model structure and decomposition. A set of core extensions provide extensions or specifications of concepts defined in the Kernel (IAI 1999b). Wix and Liebich (1997) emphasize the importance of the classification of decomposition strategies since decomposition brings a basic functionality into the IFC definition. Three categories of decomposition are defined as: functional decomposition, constructive decomposition, and geometric decomposition. The decomposition methodology for each category can be effectively explained through examples.

Interoperability layer: This layer provides the provision of modules defining concepts or objects to two or more domain/application models (IAI 1999b).

Domain/Applications layer: Domain/Application models provide further model detail within the scope requirements for an AEC/FM domain process or a type of application. Each model is a separate one, such as a model for architecture or a model for HVAC work. All these models can use or reference any class defined in the Core and Independent Resource layers (IAI 1999b).

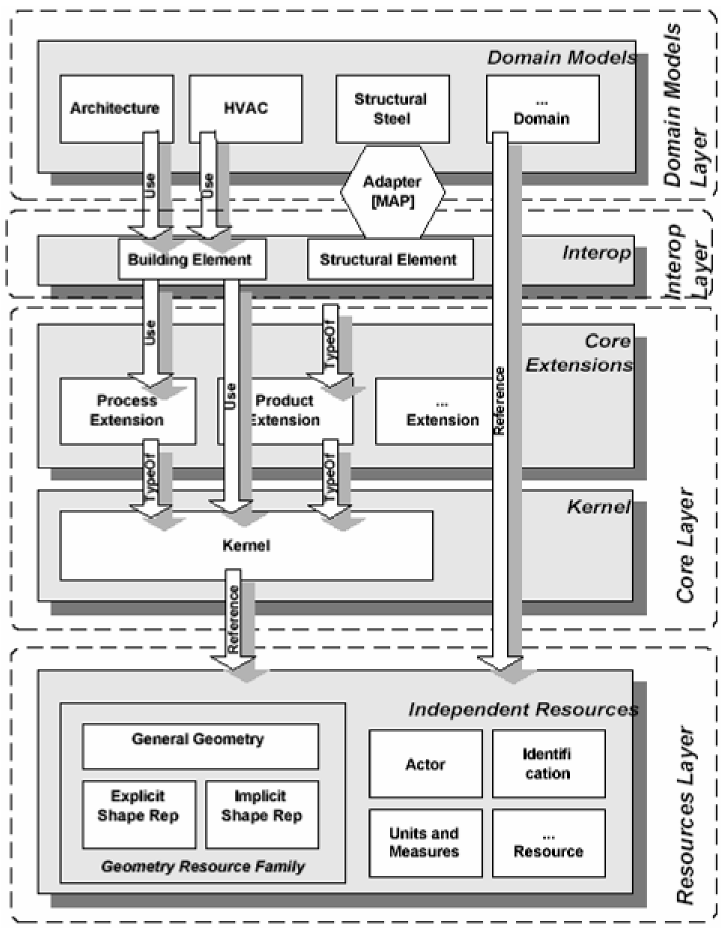


Figure 2-8: IFC Object Model Architecture (Wix and Liebich 1997, with permission from CIB)

The IAI (1999a) has set up important representatives of information for the development of the IFC, such as classes, objects, attributes (information about the class or its interface), relationships (occurring between classes), interfaces, the object model, process diagrams, usage scenarios, and test cases. These concepts are very useful for this research to accurately define the building components and find ways to represent interface information.

The IFC object model improves AEC information presentation in product models in many aspects. For example, it defines model elements, functional roles, and systems separately so that an element can assume multiple roles and/or be the member of multiple systems. It also allows applications to capture design intent (space requirements, space adjacency, and connectivity between elements) and design constraints (coordination of design grids, complex geometric relationships, alignment with offset, code constraints, etc.). The IFC model and its extension successfully build a platform that empowers various application developers through access to a very large constituency of end users and compatible applications (IAI 1999b).

Even though the IFC has established a comprehensive project object model, some limitations do exist. The latest version IFC2x3 (IFC2x Edition 3) has improved some aspects of Version 2.0—the previous release. It still maintains the scope of IFC2.0. As a result, discussion here is mainly based on a review of IFC2.0. For the purpose of this research, two questions are raised during review of the IFC specification. Are those elements, attributes, relationships, etc. defined in the IFC capable of modeling all types of interfaces or providing complete interface information for IM? And, is the IFC providing standardized interface representation for the use of multi-disciplines or a variety of project participants?

IFC2.0 itself states limitations for some key object model concepts, some of which are related to interfaces. For instance, IFC2.0 only supports point connections for connections between model elements. It is said that future release would add connections at edges and surfaces. Another example is that IFC2.0 defines relationships between IFC objects. But the relationship types are very limited. Only five categories are defined so far: *containment* (both physical and conceptual), *grouping*, *connectivity*, *constraint*, and *resource*. Although the IFC provides an environment of interoperability for information in a building and a building project, its capability of modeling multiple types of interfaces is poor. Therefore, this research proposes a completely new way of interface modeling by defining interfaces as distinct objects instead of using the limited functionality of traditional relationships. This approach will implement existing concepts of the IFC for representing the building and project components in the IOM framework.

2.5.4 Building Information Modeling (BIM)

The BIM is a new tool used in the AEC/FM industry. The Building Information Model (BIM) is not simply a 3D virtual model of a facility; it is an open standards-based repository of digital information for the facility being designed, built, operated, and maintained through its entire life cycle. The current BIM is based on traditional geometry-based CAD, object-oriented CAD, and parametric building modeling technologies. It provides intelligent project information (incorporating non-graphic information such as material descriptions and specifications, cost and schedule information, and construction methods) about building components; it is also capable of coordinating related elements when a variable (drawing parameter or building design information parameter including the structural load, component attribute, thermal property, weight, etc.) is changed.

Currently, the main implementation of parametric modeling is in geometry (Eastman 1999). This can be seen through the application the BIM. The geometrical information carried by each modeled building component helps coordinate the space conflicts in the building design process, which is also the main benefit of the BIM. For example, the new General Motors (GM) Lansing Delta Township (LDT) Assembly Plant was built 5-8% under budget and 25% ahead of schedule by the aid of a well developed BIM (Mitchell 2006). According to Mitchell (2006), while Ghafari (an architectural and engineering firm specialized in auto plan design) created the basic building framework, contractors were uploading and updating information about the components they were designing, fabricating, and installing into the BIM. Most of the space conflicts (as shown in Figure 2-9) had already been identified within the model before the engineer working on 2D drawings found some issues. Over 12 months, more than 10,000 interferences were identified and resolved in this project.

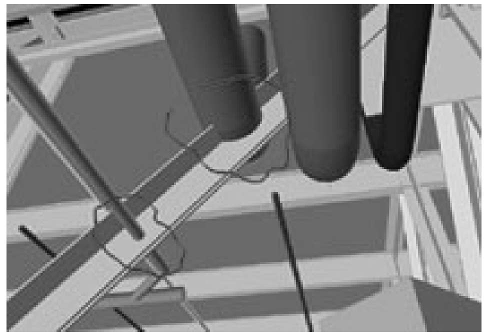


Figure 2-9: Conflicts Identified in a BIM (Engineering News-Record (ENR), with permission from ENR)

The BIM benefits have been recognized by the industry. According to Hagan (2005), who heads the Project Knowledge Center of the GSA (General Services Administration), starting from fiscal year 2006, the BIM must be included as part of the work proposal if AEC firms want to work with the GSA. However, some barriers to the model implementation should be noted. In the GM LDT plant project, the lack of trust in 3D data, the rigid CAD standard, the variety of subcontractor specialty software, and the requirement for paper plan submissions for design review are not in compliance with BIM approaches (Sawyer 2005b).

The BIM is often associated with the IFC object model, which provides the data structure for representing information used in the BIM. As indicated earlier, the IFC has some limitations in presenting comprehensive interface information. Therefore, the BIM is also limited in its capability of modeling and managing various interfaces, which are divided into different categories. Specifically, in the current product modeling methods, building components carry most of the intelligent information about themselves and interfaces are simply modeled as types of relationships. As a result, comprehensive interface information is missing in the BIM and project decision-making.

The aforementioned space conflicts are only one type of interface issue. With no conflicts in space, the inappropriate boundary conditions (complex interface attributes) may still fail the physical connections or functional commitments between related components. For example, an inappropriate method of applying sealant to a joint or improper curing time when temperature varies may cause the seal to fail. This interface information is usually not modeled in the BIM. Also, information supporting and helping control of interface related design, project planning and scheduling, manufacturing, construction and assembly, and facility management is not available in the BIM. What information influences the interfaces has not been accurately identified in the literature. In practice, various interface failures occur, such as delayed interface handling due to inclement weather conditions or poorly organized workplace interfaces. Most of the time, it is the interface condition that triggers the subsequent installation of related building components. For example, the equipment cannot be placed on a poured-in-place concrete base whose curing time has not been completed.

In practice, the current BIMs do help IM to some degree. With the continuous development of the BIM, schedule, cost, and other project information will be incorporated and extensively used for interface coordination and management. However, the interface modeling capability of BIMs still needs major improvement due to the data structure limitation.

2.5.5 Unified Modeling Language (UML)

UML originated in 1995 and is a general-purpose, standard specification language for modeling software systems. It can also be used for business modeling and modeling of other non-software systems. UML supports most existing object-oriented development processes. UML models can be directly used to generate code and test cases. Nowadays, within the OMG (Object Management Group), a non-profit computer industry specification consortium, UML is the most-used specification (UML 2005).

UML captures information about the static structure as well as the dynamic behavior of a system. The static structure defines the kinds of objects important to a system and to its implementation as well as the relationships among the objects; the dynamic behavior defines the history of objects over time and the communications among objects to accomplish the goal. Interactions are shown in sequence and communication diagrams (Rumbaugh et al. 1999).

UML is a very large modeling language with multiple views. It is capable of modeling systems from a more comprehensive perspective. UML 2.0 defines 13 types of diagrams falling into three categories (Table 2-3). As shown in the table, six diagram types represent static application structure; three diagram types represent general types of behavior; and the remaining four types represent different aspects of interactions (OMG 2005). Due to the existence of various views and diagrams, UML can be applied very flexibly to ensure that it is always the most appropriate modeling form being chosen for a particular condition. Therefore, UML is chosen by this research to model interfaces and interface objects in a systems engineering approach. The static view of UML will be extensively used while other viewpoints will also be applied under certain circumstances.

Table 2-3: UML Model Categories

Category	**Diagrams**
Structure Diagrams	The Class Diagram, Object Diagram, Component Diagram, Composite Structure Diagram, Package Diagram, and Deployment Diagram
Behavior Diagrams	The Use Case Diagram, Activity Diagram, and State Machine Diagram
Interaction Diagrams	The Sequence Diagram (Scenario Diagram), Communication Diagram, Timing Diagram, and Interaction Overview Diagram

Any precise model must first define the key concepts from the application as well as their internal properties and relationships to each other. Figure 2-10 is an example of the most commonly used class diagram of UML models. Other useful diagrams will be introduced later where they are used in interface modeling.

In this type of diagram, the application concepts are modeled as *classes*. Each class describes discrete object types that contain information and communication to implement behavior. Such information is modeled as *attributes* while the behavior they perform is modeled as *operations*. In a static view, UML can model different kinds of relationships: *generalization*, *association*, *constraints*, *dependency relationships*, *interfaces*, as well as *include* and *extend dependencies* of use cases. In UML, the term *interface* defines an externally visible behavior. It is used to represent one type of relationship between its model components, and therefore does not refer to the same “interface” that this research is studying. The *Interfaces*, *data types*, *use cases*, and *signals* are called *classifiers in* UML (Rumbaugh et al. 1999).

The aforementioned UML capabilities can be of great benefit to this research in modeling interface information, related project and building components, and their relationships.

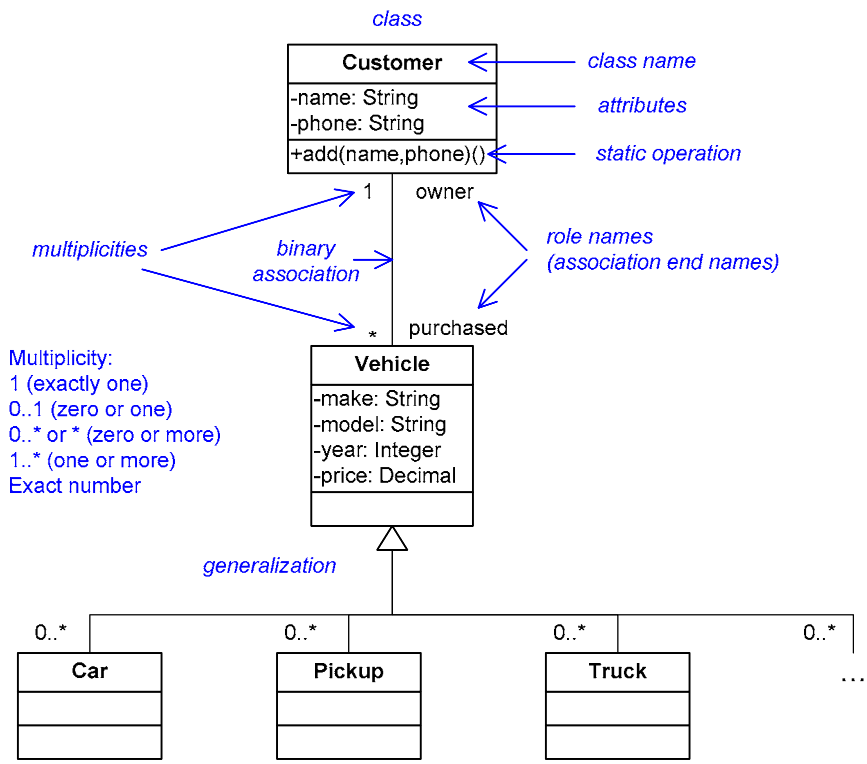


Figure 2-10: An Example of a Class Diagram

CHAPTER 3: INTERFACE-RELATED BUILT ENVIRONMENT ANALYSIS

This chapter presents an interface-related built environment analysis that adopts an innovative multi-perspective approach to systematically exploring the comprehensive cause factors of interface issues. Six interrelated perspectives are defined as: *People/Participants*, *Methods/Processes*, *Resources*, *Documentation*, *Project Management*, and *Environment*. In this chapter, the identified cause factors are further converted into a series of interface management and control elements to help develop the Interface Object Model (IOM) framework and systematic model-based interface management (IM) strategy. This IM strategy aims to manage diverse types of interfaces as a whole in a more efficient and effective way. This chapter adds a holistic view of interface issues to the existing body of knowledge. It also lays a theoretical foundation for practitioners and researchers seeking all-around IM solutions.

3.1 A MULTI-PERSPECTIVE APPROACH

Although some interface issues and their potential causes have already been disclosed in the literature review, they are scattered and only represent viewpoints of their authors who are concerned with specific problems. A systematic study of various interface issues in a broad construction setting has never been performed. As a result, comprehensive causes of interface issues still remain obscure. It is impossible for researchers to find universally applicable IM solutions without establishing a comprehensive understanding of interface issues. In this research, a multi-perspective approach is developed to analyze the interface-related built environment for exploring the comprehensive cause factors of interface issues.

This approach adopts the method of the Cause & Effect (C&E) Diagram invented by Kaoru Ishikawa in 1968. It is a graphical tool that helps identify, sort, and display potential or real root causes (factors) of a specific effect, problem, or condition. As shown in Figure 3-1, this diagram displays causes based on their level of importance or detail by using a hierarchical, structured approach. The main cause areas are the main categories or branches of the C&E diagram. Other possible causes related to those categories or branches are attached to them as sub-branches—major causes. If necessary, minor causes and sub-factors will also be identified. Any minor cause, if applied to more than one major cause, will be displayed under both sub-branches. Those causes take effect directly or through interactions with other causes either under the same category or in different categories.

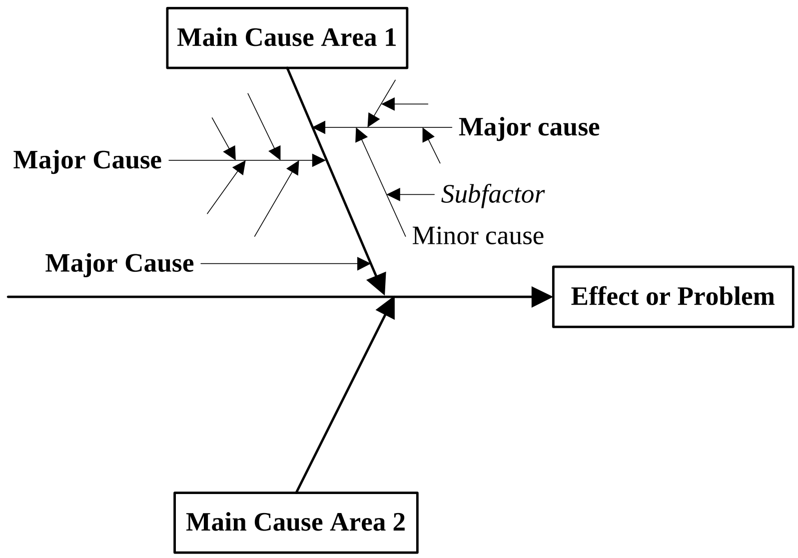


Figure 3-1: The Method of the Cause and Effect Diagram

This research investigates causes of interface issues from six interrelated perspectives including *People/Participants*, *Methods/Processes*, *Resources*, *Documentation*, *Project Management*, and *Environment*, which constitute the main categories of the C&E diagram as shown in Figure 3-2. These perspectives were determined by finding the key players that cause interface issues in a construction project. The players do not necessarily have to be people; they can be any entity that greatly affects a construction project such as the methods/processes people choose, the documentation that defines the product and the responsibilities of project participants, and the environment that affects the project processes and the people who are working there. From each perspective, the detailed cause factors for various interface issues are further explored. At times, the findings are run in numerous real-world construction scenarios to verify that they are real causes of interface issues. This ensures a practical and solid basis of the multi-perspective approach.

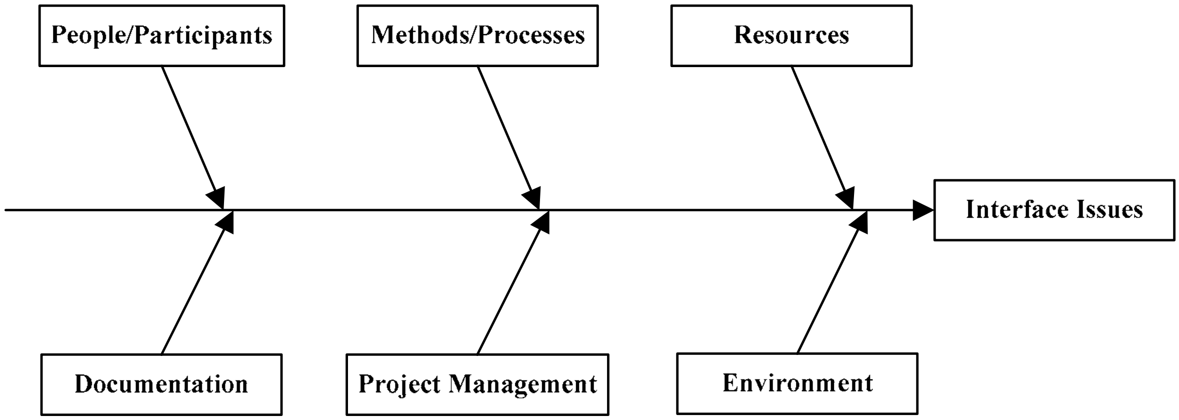


Figure 3-2: The C&E Structure of the Multi-Perspective Approach

Although these six categories are not of equal importance in their influences on interface issues, none of them can be ignored. The following sections explain each of these perspectives. Due to space limitations, the *People/Participants* perspective is discussed in the greatest detail while the other five perspectives are only briefly introduced.

3.2 PERSPECTIVE ONE: PEOPLE/PARTICIPANTS

People/Participants are actors of a construction project. Either individuals or organized parties perform certain activities that are necessary for completing a project. Such activities are more or less interrelated due to the activities themselves (dependent or concurrent activities) or the building products (components or subsystems) they yield. Interactions among different people/participants are unavoidable and need to be properly coordinated to prevent various conflicts and inferior project performance.

From the *People/Participants* perspective, the four major causes leading to interface issues, including *poor communication among parties*, *poor coordination among parties*, *poor decision-making*, and *financial problems*, are identified and shown as sub-branches of the main cause area in Figure 3-3. These problems are very common among different project parties. In the following subsections, these four major causes as well as their minor causes and sub-factors are illustrated and explained in detail.

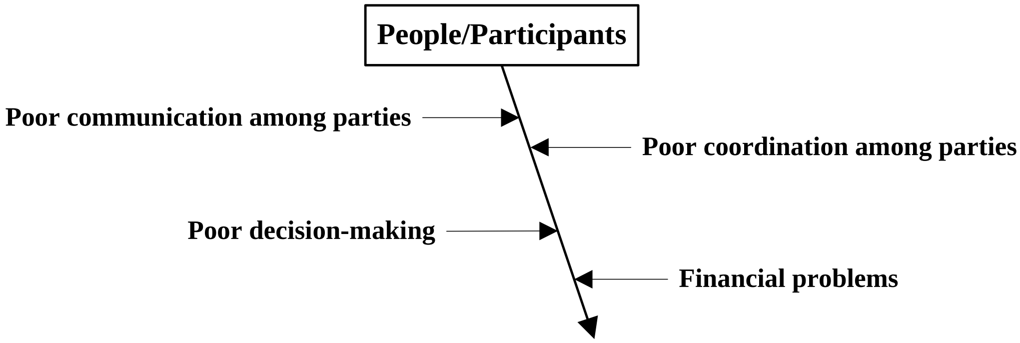


Figure 3-3: The Major Causes in the People/Participants Perspective

3.2.1 Poor Communication among Parties

Communication is the means of acquiring and transmitting information. A construction project involves many participants forming a temporary multi-organization, which cannot function effectively without good communication among people in it. Effective information exchange, especially in some information-intensive project phases (e.g., the design and assembly phases), is essential for project success. *Poor communication*, on the contrary, causes a wide variety of design errors, assembly conflicts, delays, and project failures, which reduce the overall performance of project participants as well as the quality of the final product.

Communication within the same party is usually much better performed than that across the boundary of parties. The latter becomes one of the major causes for interface issues. Figure 3-4 presents the two minor causes (with four sub-factors) that contribute to poor communication in a hierarchical structure. They are discussed below.

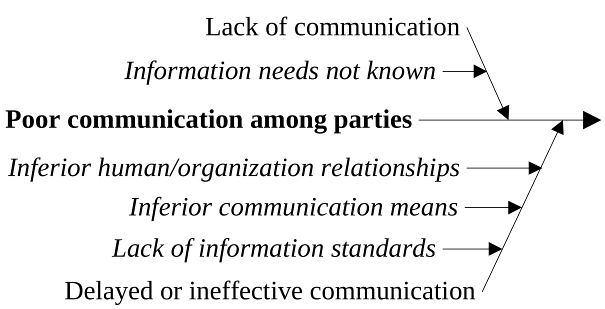


Figure 3-4: The Minor Causes and Sub-factors for Poor Communication

3.2.1.1 Lack of Communication

The *lack of communication* easily leads to poor communication among parties. *Unknown information needs* are the leading sub-factor. In general, there would be effective communication when people (information providers or information users) realize that information is needed for them to perform some function. Otherwise communication can hardly occur.

The industry knows well that subsequent activities usually need information from preceding activities. The "pushing" method has been used for years to communicate such information; i.e., people in preceding processes pass the information they think important to people involved in succeeding processes. Sometimes this mode works very well, sometimes not. The reason is two-fold. On one hand, the information dependency among parties is unclear when a project or project organization is complex. On the other hand, people who provide the information can hardly know the exact information needs of people who use the information. The "pushing" communication does transmit some useful information, but also passes on some redundant and misses some essential information. The resulting *lack of communication* has a negative effect on information-dependent activities.

It is critical for the involved personnel to make their information needs transparent to others at the earliest. Nevertheless, in industry practice, coordination among parties is insufficient, which greatly limits the communication for such information needs. "*Request for Information (RFI),*" becomes a widely used compensating method. Usually, a RFI is sent out immediately before that information is going to be used for an activity and the user expects a rapid response, which oftentimes cannot be accomplished. This incurs a potential error or delay for that activity, which may deteriorate the inter-party relationship.

3.2.1.2 Delayed or Ineffective Communication

At times, communications do happen, but they are delayed or ineffective due to one of three reasons:

First, *inferior human/organization relationships* prevent timely and effective communication because it takes time for people to determine whom they should contact and then to build a communication channel. Oftentimes, people involved in the inter-party communication are not direct information providers or users; under such circumstances, initial or further communications are required. This may result in delays or misunderstanding. In general, the most effective communication is conducted through the best human/organization relationships that are between people who directly generate or use the information.

Second, *inferior communication means* adversely affect communication. Fortunately, besides traditional communication means including mail, telephone, facsimile, and face-to-face meeting, new ways of communication such as electronic mail, instant message, voice/video conference, and World Wide Web enrich users' choices. Choosing the best means can make communication most efficient and effective.

Third, the *lack of information standards* lowers the quality of information generated and reduces the communication efficiency and subsequent information application. When information is not created based on the same standard(s), such as the format, accuracy, measurement unit, protocol, interface, etc., it can hardly be fully understood during communications. At the implementation stage, information may be unqualified or has to be converted. Very likely, errors are made, and some important information content is missing.

3.2.2 Poor Coordination among Parties

It is well known that a construction project has numerous participants who are more or less interrelated. Little or intensive coordination amongst them is required. Coordination is very critical in both design and construction to ensure compatibility between subsystems or components and to minimize conflicts in schedules, site activities, and resource utilization among different contractors. Coordination is also necessary between the design and construction parties for enhancing constructability. *Poor coordination among parties* results in various interface issues. Figure 3-5 illustrates the seven minor causes for poor coordination. They are discussed below respectively.

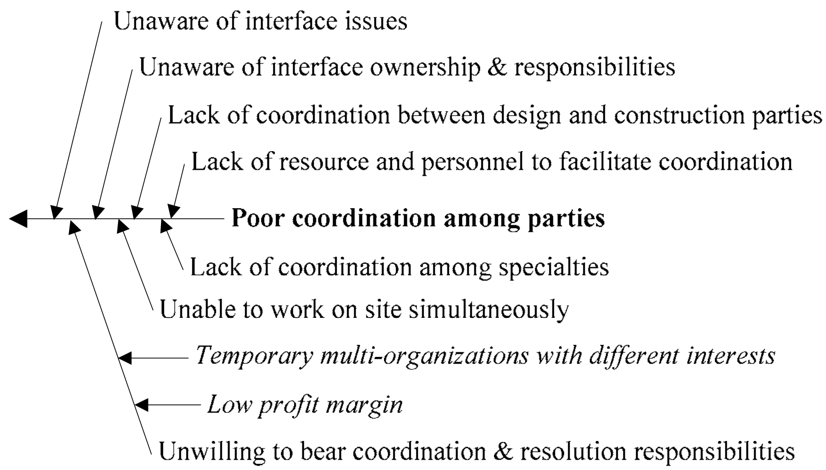


Figure 3-5: The Minor Causes for Poor Coordination

3.2.2.1 Unaware of Interface Issues

Interface issues are very new to the industry. Project participants, especially the designers, general contractor (GC), and specialty subcontractors are usually not familiar with these issues. Although they witness or experience numerous interface-related problems such as design and construction conflicts, delays, and low efficiency in assembly, they seldom categorize these problems as "*interface issues*" and rarely realize that close coordination through organizational boundaries could avoid and resolve most of these issues. As a result, interface-related coordination is minimally performed among different project parties.

3.2.2.2 Unaware of Interface Ownership & Responsibilities

Each interface may involve different parties. The ownership and responsibilities for an interface are neither clearly defined in project documents (e.g., contracts, specifications, drawings) nor specified by people who administrate the design and construction processes (e.g., the architect, GC's superintendent). It remains unclear who is responsible for coordination and what should be provided upon request during coordination. For example, in the shop drawings prepared by a specialty subcontractor, related building elements or components that are out of his scope are displayed and marked as "by others." Without specifying who the others are, it is hard for the specialty's field people to coordinate their work with the others'. This oftentimes leads to poor coordination on areas that are susceptible to interface issues. Pavitt and Gibb (2003) indicate that eliminating the term “by others” can improve coordination and minimize interface issues.

3.2.2.3 Lack of Coordination between Design and Construction Parties

The constructability of physical interfaces in a project needs to be verified through coordination between design and construction parties. In most project delivery methods, except Design-Build (DB) and Engineer-Procure-Construct (EPC), the design and construction parties enter into a project with separate and unrelated contracts that seldom explicate their coordination responsibilities; the *lack of coordination* has been a very common problem in the industry for years. The DB and EPC delivery methods make great progress by shifting the design-construction coordination into the scope of a single contract. Their influence is limited since they are still not the most widely applied delivery methods in the industry.

3.2.2.4 Lack of Resource and Personnel to Facilitate Coordination

IM has been a missing link of project management for a long time (Nooteboom 2004). In the industry, contractors usually lack a specialized interface coordinator to supervise interface coordination. Project management personnel are normally not experts in IM; their time is also occupied by other management activities. In addition, with the increasing project complexity, the total number of interfaces rises tremendously. Extra resources to facilitate IM are now not widely available, and insufficient as well. For example, there are no well-known interface databases or computer software for IM in the industry. As a result, IM performance is difficult to enhance.

3.2.2.5 Lack of Coordination among Specialties

Nowadays, many specialist contractors (also called specialty contractors) work on a jobsite as subcontractors. Besides mechanical, electrical, foundation, and excavation contractors, major materials or equipment suppliers who perform on-site installation are also regarded as specialty contractors. They provide one or more of the following types of services: 1) design input, 2) bulk materials supply, 3) components prefabrication/assembly, and 4) site erection services (Hsieh, 1998). Coordination among them is needed in very broad areas including design, work sequence, material and information flows, space allocation, and resource utilization to avoid and resolve various conflicts and ensure the quality and function of the built product.

In practice, there is no contracting relationship between specialties. Their respective contracts do not fully specify coordination responsibilities. Under most circumstances, specialties lack working experience and pre-established relationships with each other, which could have reminded them of potential coordination needs. If the architect and GC's superintendent do not recognize these issues and help initiate coordination among them, the *lack of coordination among specialties* occurs and causes critical interface issues.

3.2.2.6 Unable to Work on Site Simultaneously

Due to space limitations on a jobsite, work conducted by subcontractors usually follows a sequential order; i.e., one subcontractor starts to work right after another one finishes his work. This makes face-to-face, instant coordination between or among involved subcontractors impossible when there are conflicts between building components or subsystems. When the subsequent contractor faces conflicts, calling in the preceding one for coordination is also difficult.

3.2.2.7 Unwilling to Bear Coordination and Resolution Responsibilities

Subcontractors are usually unwilling to bear coordination and resolution responsibilities for potential or existing interface issues. One reason is that all subcontractors have their own interests. They are willing to make every effort to avoid their own mistakes that lead to financial penalty or loss of profit instead of considering the situation of others and conducting timely coordination for them. Another reason is that a low profit margin limits subcontractors' willingness and capability for coordination and resolution, which involves both time and cost.

3.2.3 Poor Decision-Making

Decision-making at various project stages influences a project delivery process and its final product. *Poor decision-making* increases design errors, change orders, conflicts, rework, and inter-party disputes in the design and construction phases, and easily causes time and cost overruns. It also lowers the quality and systems performance of the built facility. Figure 3-6 shows the five minor causes that contribute to poor decision-making.

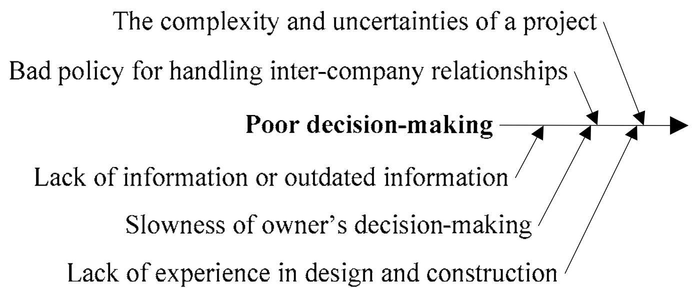


Figure 3-6: The Minor Causes for Poor Decision-Making

3.2.3.1 The Complexity and Uncertainties of a Project

Project complexity and uncertainties add great difficulty to the decision-making process. The complexity of spaces, functions, components, or systems of a built facility as well as the selected construction methods prevent decision-makers from reaching a good understanding of the project. This oftentimes leads them to bad decisions in selecting design approaches, building materials/components/systems, project delivery methods, subcontracting strategies, construction methods, work sequences, or equipment/tools. The resulting interface issues cause various project failures.

Uncertainties are usually unavoidable for any project. They normally relate to site geology, weather, market, individual human performance, and emergencies. Uncertain conditions in a project significantly increase the degree of difficulty in decision-making. Without taking them into careful consideration, decision-makers may reach some decisions that are not adaptable in an ever-changing environment. A wide variety of problems appear in interfaces between pre-defined project elements and these uncertain conditions.

3.2.3.2 Bad Policy for Handling Inter-Company Relationships

Inter-company relationship is very important to a construction project. It ensures timely communication and coordination as well as close cooperation among parties to streamline project processes and maximize interest of the entire organization. The relationship can be fostered or damaged with ease by decisions from any of participating parties. A company's policies implicitly affect its employees' decision-making by influencing their attitude and flexibility. An inappropriate policy, giving no emphasis to cooperation and reciprocity and passing risks on to other parties, leads to poor decision-making, which easily disrupts the inter-company relationship and effects serious interface issues.

3.2.3.3 Lack of Information or Outdated Information

In practice, decisions range from very simple to very complex. They can also be specific or general. Simple, general decisions may be made just based on the common sense or best practice the decision-makers have. To reach complex and/or more specific decisions, people need accurate and sufficient information, especially when they do not have initial experience with a "*decision situation.*" According to Sage (1992), decision-making is dependent upon many contingency variables such as the objectives, needs, constraints, alterableness, and environment. Accurate and sufficient information includes information verifying the real status of unsettled project conditions as well as information helping clarify the above-mentioned variables. The *lack of information or outdated information* probably delays the decision-making process or leads to poor decisions based on assumptions.

3.2.3.4 Slowness of Owner's Decision-Making

The owner's decision-making directly or indirectly affects many aspects of a construction project. Designers usually choose a very general design approach based on the owner's initial requirements. They also need the owner's decisions for developing a design in detail. If such decisions are late or absent, designers either postpone a design process or generate incomplete design documents. When the owner's decisions become available later, designers have to issue change orders to supplement or alter original design documents.

Also, the owner's decisions are needed by construction parties to make many of their own decisions. When the owner's decisions are delayed, affected construction parties have to put off their decision-making process or make poor decisions. This could incur various problems such as suspension of work, rework, and delay. Additionally, unexpected change orders from designers interrupt construction parties' planned activities and resource organization.

3.2.3.5 Lack of Experience in Design and Construction

An organization usually sets up some decision-making techniques and standard procedures for a decision-maker to follow. However, making good or bad decisions still depends greatly on the knowledge or experience of a decision-maker. In the design and construction phases, many design or construction related decisions are specific; e.g., where is the vapor barrier placed in a wall when a building in a hot and humid climate is designed or what is the right procedure to install a window into a wall opening? People lacking experience in building design and construction very likely make bad decisions under specific circumstances.

3.2.4 Financial Problems

Possible financial problems in a construction project include the owner's insolvency or non-payment, the contractor's underbids or cash flow problems, cost disputes between parties, etc. These problems impair project processes and cause low productivity, poor quality, suspension of work, delays, and disputes, some of which are typical interface issues. Actually, financial problems across the boundary of parties easily ruin inter-company relationships because the majority of project participants are pursuing monetary interest. Figure 3-7 presents the three minor causes for financial problems that result in interface issues.

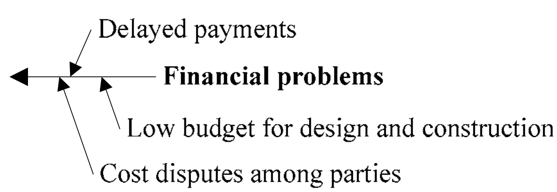


Figure 3-7: The Minor Causes for Financial Problems

3.2.4.1 Delayed Payments

All types of payments (especially progress payments) are critical for the paid parties to perform their duties continuously and consistently and to keep a project on schedule. On the contrary, delayed payments prevent the paid parties from performing their duties. For example, delayed progress payments from the owner cause difficulties for the affected contractors to purchase materials, pay their workers, suppliers and subcontractors, and run their organizations due to lack of funds. Interrupted material or equipment supply, suspension of work, and damaged inter-company relationships for communication, coordination, and cooperation lead to various interface issues. Delayed payments also damage mutual trust among parties; partnership is hard to establish.

3.2.4.2 Low Budget for Design and Construction

The owner assumes that a low budget for design and construction could save him money. He does not expect that this cost-cut may give rise to financial problems for both designers and contractors. These problems produce far-reaching effects on many aspects of design and construction. In the end, such a cost-cut comes at a high price to the project.

An insufficient budget in design, first, limits designers' capability to find a better design approach that is superior in many ways and helps achieve great savings for the owner in construction. Second, a low budget reduces the details designers can provide in drawings or specifications, which results in incomplete design. Third, a low budget makes designers unwilling to bear more liabilities for design coordination. In fact, early design coordination under the administration and supervision of designers is the most effective and efficient means to avoid future assembly conflicts between building components or subsystems.

Similarly, a low budget for construction also produces many construction related problems. Due to lack of funds, contractors hesitate to apply new technologies, which need initial investments and continuous training. They may not implement required safety programs and seldom provide adequate personal safety equipment for workers. They may hire unskilled labor, which not only provides poor workmanship but also has no experience in handling complex physical interfaces. Furthermore, contractors behave passively in communication, coordinate, and cooperation with other parties.

3.2.4.3 Cost Disputes among Parties

Avoiding disputes and potential litigation in a construction project is a common goal for all participating parties because a good relationship among them is an important factor leading to project success. It helps avoid disputes and possible lawsuits that take time and money from all the entangled parties. However, at times, disputes cannot be avoided since there are so many competing interests amongst involved parties including the owner, designers, suppliers, and contractors.

Cost disputes among parties may stem from poor estimates, underbids, change orders, cost overruns, delayed or non-payments, defective works, bad weather, problems in procuring materials and labor, on-site accidents, responsibilities for delays, or other causes. A dispute may produce an array of serious damages to a project including loss of productivity, suspension of work, extra work, delays, labor and materials escalation, loss of profit, economic loss, and increased overhead for both the jobsite and home office. It is worth mentioning that such damages may have a chain-breaking reaction from one affected party to other related parties, such as his subcontractors and contractors performing subsequent or dependent tasks. Due to space limitations, from the next section on, each perspective is only briefly discussed.

3.3 PERSPECTIVE TWO: METHODS/PROCESSES

Different design methods are employed to meet customer needs, manage the conformity of technical solutions, and plan and govern the design process. The selected design methods affect interfaces not only in design, but also in manufacturing, construction, operation and maintenance. Construction methods and processes are determined mainly on design documents though a certain degree of flexibility exists. The flexibility allows contractors to choose familiar and/or economical construction methods and processes for their scopes of work.

In general, construction methods determine the interfaces that appear in construction. For example, the stick-build housing construction method leads to a great number of simple types of physical interface among raw building materials on the jobsite. Inappropriate methods and processes may increase the uncontrollable interfaces on site and exacerbate the difficulty of IM. The cause factors of interface issues from the *Methods/Processes* perspective are illustrated in Figure 3-8. From this subsection on, each perspective is only briefly discussed; the selected cause factors that are very critical to interface issues or hard to understand are explained in detail.

The interdisciplinary nature of a project adds coordination needs among designers or specialty subcontractors to exchange interface parameter information. Besides the inadequacy of information, poorly sequenced information exchange among designers or specialty subcontractors complicates and delays the design process by producing *information iteration loops*. In addition, a less thorough understanding of interfaces between components or subsystems may result in design errors, low design constructability, and systems performance failures of the built facility. The lack of considerations for *modularity*, *standardization*, *component integration*, *manufacturing*, and *construction* in design increases the number and the complexity of interfaces.

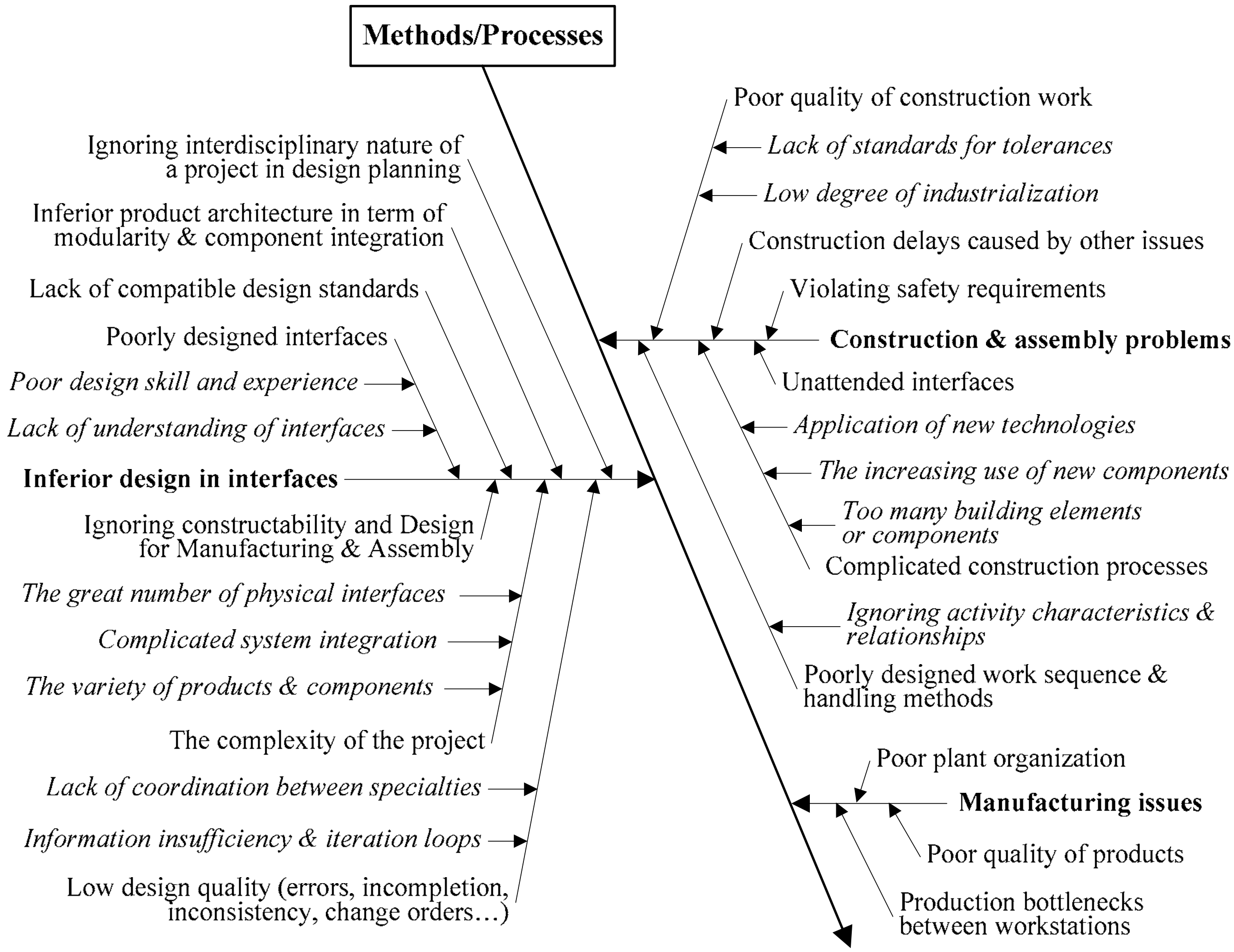


Figure 3-8: Interface Issue Cause Factors from the Methods/Processes Perspective

Manufacturers could face interface issues if they fail to choose proper manufacturing methods or to plan and organize related production processes that involve materials, machines, and laborers. *Poor plant organization* causes numerous conflicts in material or interim product movement (O'Brien, Wakefield, and Beliveau 2002). Interface issues between workstations or processes interrupt the smooth flow of production and compromise factory efficiency.

Complicated construction processes are one of the leading causes for *construction and assembly problems* due to the added complexity for activity planning, organization, coordination, and execution. The quality of interfaces would be largely impaired when the *quality of construction work* stays low; for example, uneven or inadequate application of sealant adversely affects the adhesive interface. Building elements or components constructed by different trades may not fit each other in dimension due to *lack of tolerance standards*. Interface conflicts are often caused by *poorly designed work sequences and handling methods*. Usually, concurrent or overlapping activities may face more interface issues in process than sequential activities.

3.4 PERSPECTIVE THREE: RESOURCES

The construction project delivery process has to be supported by various resources. Labor, materials, and equipment are traditional construction resources. This research also includes information and space as resources. As discussed above, accurate and sufficient information is a necessity for numerous activities in design and construction. Space availability is prerequisite for construction activities. In practice, resource-related interface issues are very common. The cause factors of interface issues from the *Resources* perspective are shown in Figure 3-9.

Labor issues are always concerns for contractors employing labor-intensive construction processes. However, these issues are critical as well for contractors who use a great number of pre-fabricated building products at the onsite assembly stage. *Low-skilled labor* more likely fails physical connections or functional commitments between factory-made products. Those workers also slow down the planned work progress and cause schedule conflicts and project delays. Occasionally, even the skilled labor, when *lacking cross-functional training*, may still be unable to handle complex physical or functional interfaces.

Workplace interface issues are caused by *insufficient space* or *space conflicts* among workers performing concurrent activities, material storage and movements, and operating equipment. Even when there are no visible conflicts, *poor site organization and maintenance* increases potential hazards, which is an example of workplace interface issues. Adequate preparation as well as proper workstation design and setup create the accessible interface between workers and their operating space or building elements; otherwise, construction activities have to be suspended until such an interface is ready.

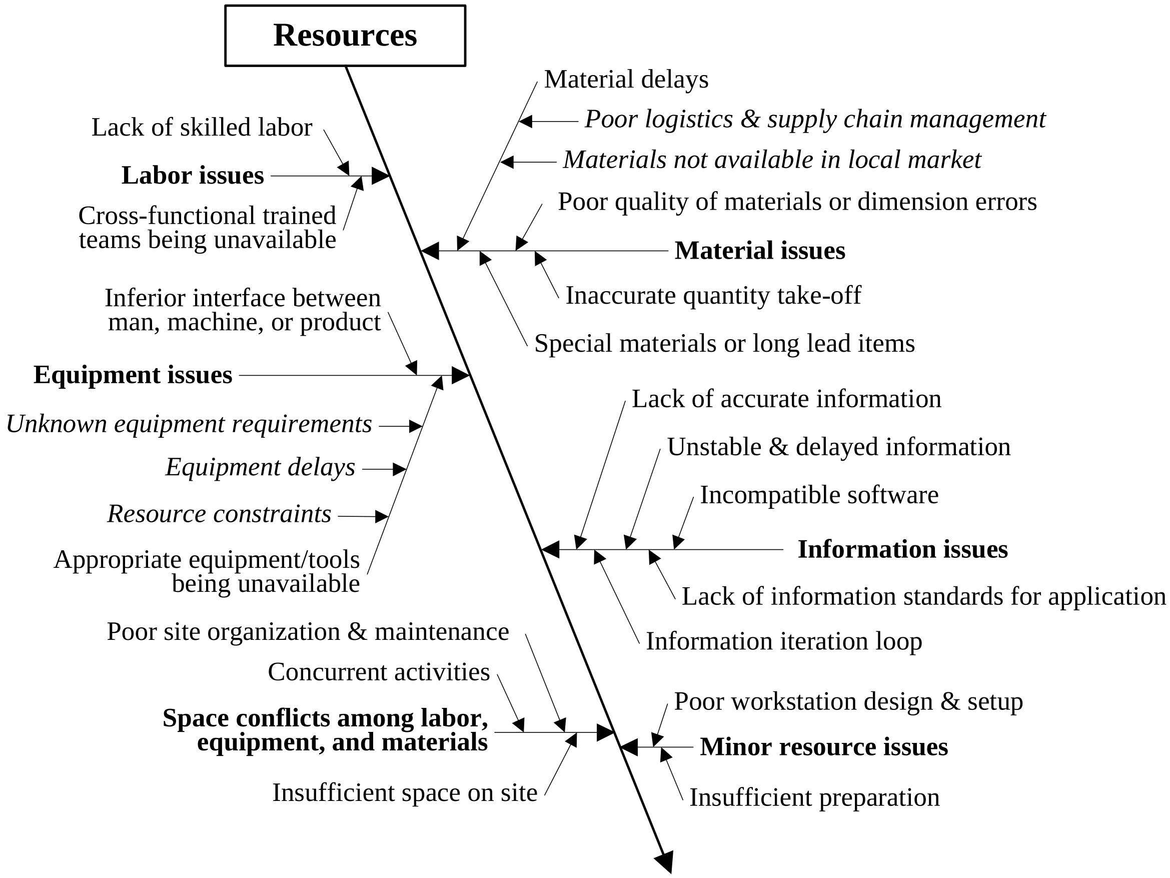


Figure 3-9: Interface Issue Cause Factors from the Resources Perspective

Poor quality of materials may directly fail physical connections between building components or interrupt such connections when defective materials need to be replaced. *Material delays*, especially special or long-lead items, lead to construction delays and other relevant interface issues. In addition, *appropriate equipment/tools being unavailable* or *inferior interfaces between man, machine, or product* lower the efficiency of handling physical interfaces and sometimes produce safety interface issues which are related to unsafe or hazardous working conditions or environment.

3.5 PERSPECTIVE FOUR: DOCUMENTATION

The importance of interface-related documentation can never be over-emphasized. Such documentation includes project specifications, drawings, contracts, purchase orders, change orders, project correspondence, etc. Other special interface documentation (interface register, interface O & M documents, etc.) may also be required. Interface-related documentation jointly clarifies characteristics of interfaces and defines responsibilities for involved parties. Inadequate or fragmented documentation leads to numerous omissions, confusions, incompatibilities, and disputes in the project delivery process. The cause factors from the *Documentation* perspective are shown in Figure 3-10.

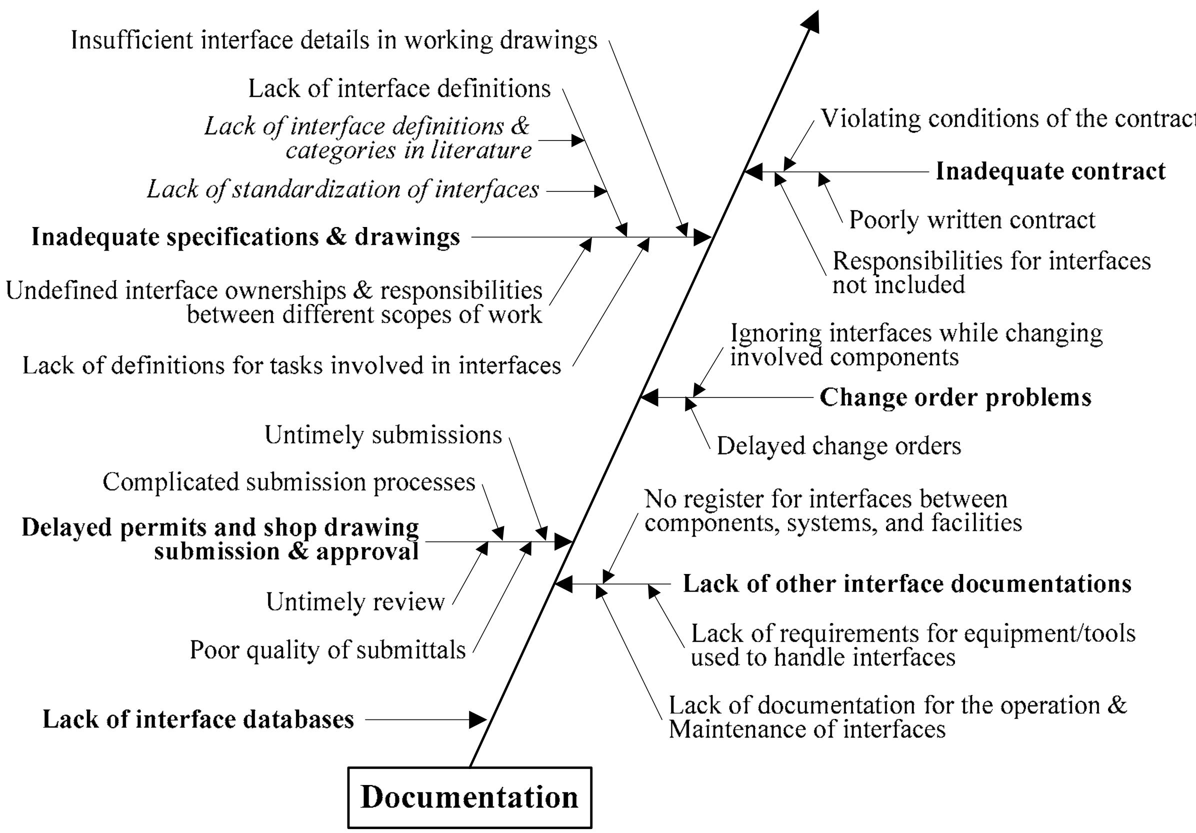


Figure 3-10: Interface Issue Cause Factors from the Documentation Perspective

There is still an unsettled debate about who is responsible for defining various interfaces in a project. With no clear answers, current *specifications* are inadequate with respect to interface definitions, standards, ownerships, and responsibilities. *Drawings* provided by specialty subcontractors are also short on detail concerning interfaces between their scopes of work and the others'. Present contract documents usually do not specify interfaces between contractors;

therefore, questions of responsibilities for contractors and disagreements about the scopes of work arise frequently. In fact, even before bidding, preplanning of scopes and responsibilities for the whole work and consideration of all contract interfaces should be given careful attention (Shrive 1992). Kuprenas and Rosson (2000) suggest that additional contracts may be required to pick up items omitted from trade contracts or missing items about interfaces.

The *shop-drawing submission and approval* process involves many participants. The process itself needs to have complex inter-party relationships well handled and requires a timely fashion to all transmission and review tasks. The *quality of submittals* should be guaranteed to minimize resubmission. This time-consuming process, if not run smoothly, will delay a contractor's design process, and further influence the subsequent procurement and construction process through interfaces among these processes.

Interface databases are rare in construction project information management. In the literature, a few interface query systems were proposed, such as CladdISS for technical and management aspects of cladding interfaces (Pavitt and Gibb 2003) and a *point-n-click* interface for construction visualization (Danso-Amoako et al. 2003). These works are either specially developed or still evolving. Therefore, when designers and contractors face unfamiliar interface problems, there are actually no external resources available for help. The quality and efficiency of interface design, handling, and management is low.

3.6 PERSPECTIVE FIVE: PROJECT MANAGEMENT

As indicated above, IM is indeed one aspect of project management. Poor IM lets many interfaces run out of control and leads to numerous interface issues. On the other hand, there are other aspects of project management, such as quality management, contract management, and resource management. Poorly managed subcontracting, planning and scheduling, quality control, resource allocation, etc. also lead to interface issues and increase the need for IM. The cause factors of interface issues from the *Project Management* perspective are summarized in Fig. 3-11.

Workpackaging and subcontracting create a great number of external interfaces that involve different contracting parties. Improperly separating work scopes and determining subcontracts incur built-in weaknesses in detailed design and subsequent construction, such as intensive information coordination, design information iteration loops, and complicated inter-party interfaces. The traditional **Work Breakdown Structure** (WBS) is regarded as the underlying cause (Miles and Ballard 2002).

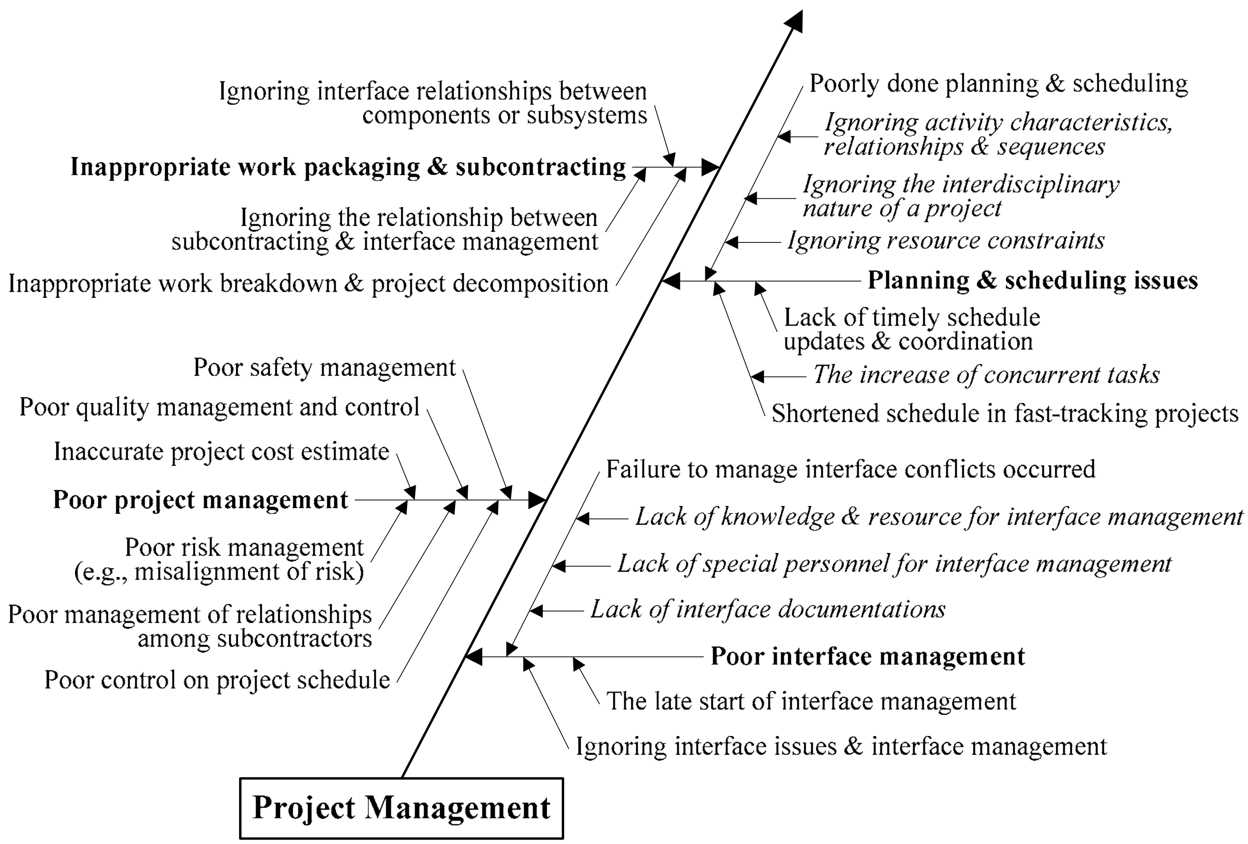


Figure 3-11: Interface Issue Cause Factors from the Project Management Perspective

3.7 PERSPECTIVE SIX: ENVIRONMENT

The term "*environment*" in this research refers to the broad environment setting of a construction project. It includes not only weather and geological conditions of the jobsite, but also local regulations, building codes and trade union practices, materials and labor availability on the local market, and cultural diversity. An integrated working environment on site is also included. The cause factors of interface issues from the *Environment* perspective are displayed in Figure 3-12.

Inclement weather and unexpected *geological problems at site* are common environmental factors that should be taken into consideration in a construction project. These unfavorable conditions interrupt well-planned construction-related interfaces concerning affected building components or processes. For example, heavy rain and the accumulated water could delay the process of pouring foundation walls. *Diverse local regulations, building codes and trade union practices* make it hard for contractors to practice nationwide. Culture was and is still not considered an environmental factor in construction. But its significance has started to be noticed by practitioners and researchers. *Cultural diversity* increases the difficulties in communication, coordination and cooperation among construction people.

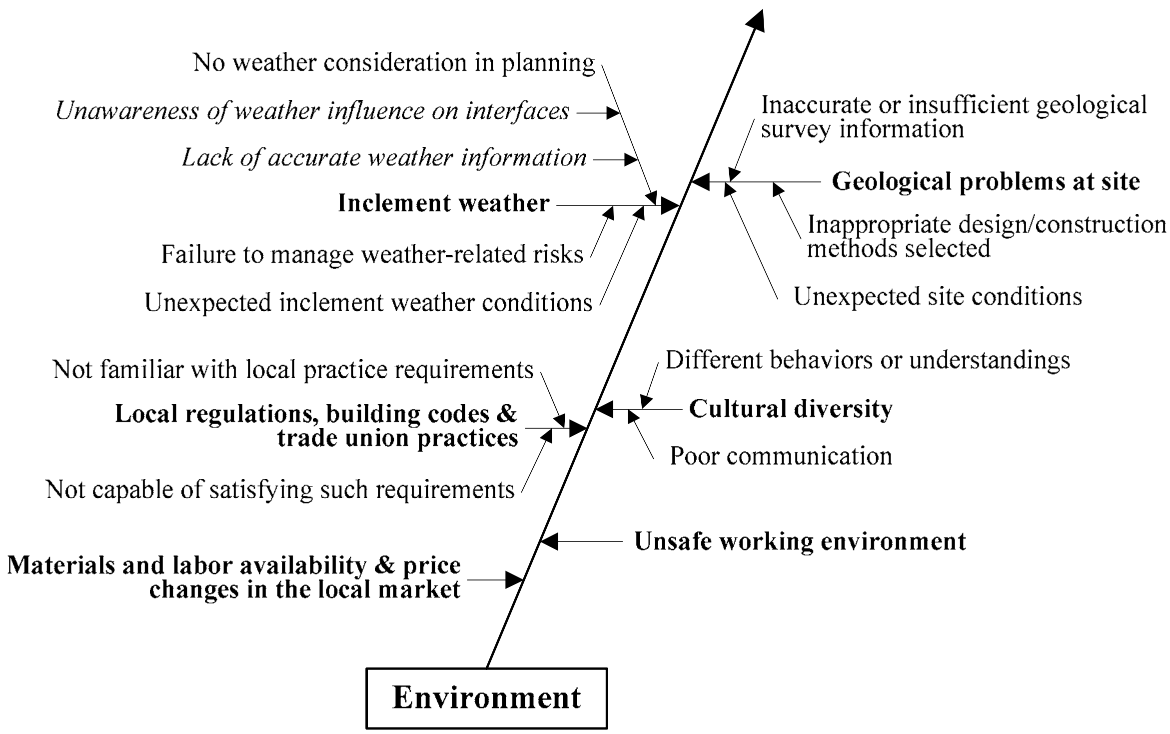


Figure 3-12: Interface Issue Cause Factors from the Environment Perspective

3.8 FINDINGS AND OUTCOMES

The multi-perspective approach has established some important findings and achievements:

First of all, this approach successfully performs an interface-related analysis of the current built environment and presents a holistic view of what causes interface issues. The cause factors identified under the six perspectives are very useful. They can be directly converted into success factors for managing interfaces in construction projects or be further analyzed based on different needs; e.g., the factor analysis and multiple regression performed by researchers at Hongkong

Polytechnic University to study Design-Build (Chan et al. 2001) and partnering (Chan et al. 2004) in construction projects. On the other hand, the cause factors can also be summarized into a series of interface management and control elements for future use.

Figure 3-13 shows one example of how the interface management and control elements can be generated from the cause factors under the *People/Participants* category. The process uses a method much like the *content analysis* methodology that can study the properties of textual information. Through studying the cause factors, interface management and control elements are summarized. The elements are either the key words of the cause factors (e.g., "*information need*" is the key words of the cause factor *unknown information needs*), or the descriptive names representing the project entities (e.g., "*interface awareness*" is the descriptive name of the cause factor *unaware of interface issues*). All the defined elements are displayed in the affinity diagram that can organize and present a large amount of data into logical categories.

In the process, if two or more elements can be identified from one cause factor, all of them are listed to avoid missing any useful points. If the same element is generated later from another factor, it is also recorded in the diagram. This means that one element could lead to interface issues in different circumstances. Here, only two levels are shown under the main category as any third level elements are merged into the second level. In Figure 3-14, six affinity diagrams are used to display the interface management and control elements for the six main cause categories respectively. These elements greatly facilitate the development of the *Interface Object Hierarchy* in the proposed Interface Object Model (IOM) framework.

Secondly, the findings of the multi-perspective approach implicate that managing interfaces is not a simple task, but that it requires a systems approach. Various project entities involved in the cause factors or in the summarized elements are actually interrelated, such as *construction quality* and *skill* of labor. They need to be properly managed and controlled within an IM system to avoid, minimize, and resolve all kinds of potential interface issues. Those entities also spread into the entire project delivery process (from design, construction, to O & M) and have gone far beyond their original boundaries. Therefore, individual project management aspects including IM should be integrated to maximize their performance so as to enable a dynamic and well-coordinated construction system—the final goal of IM.

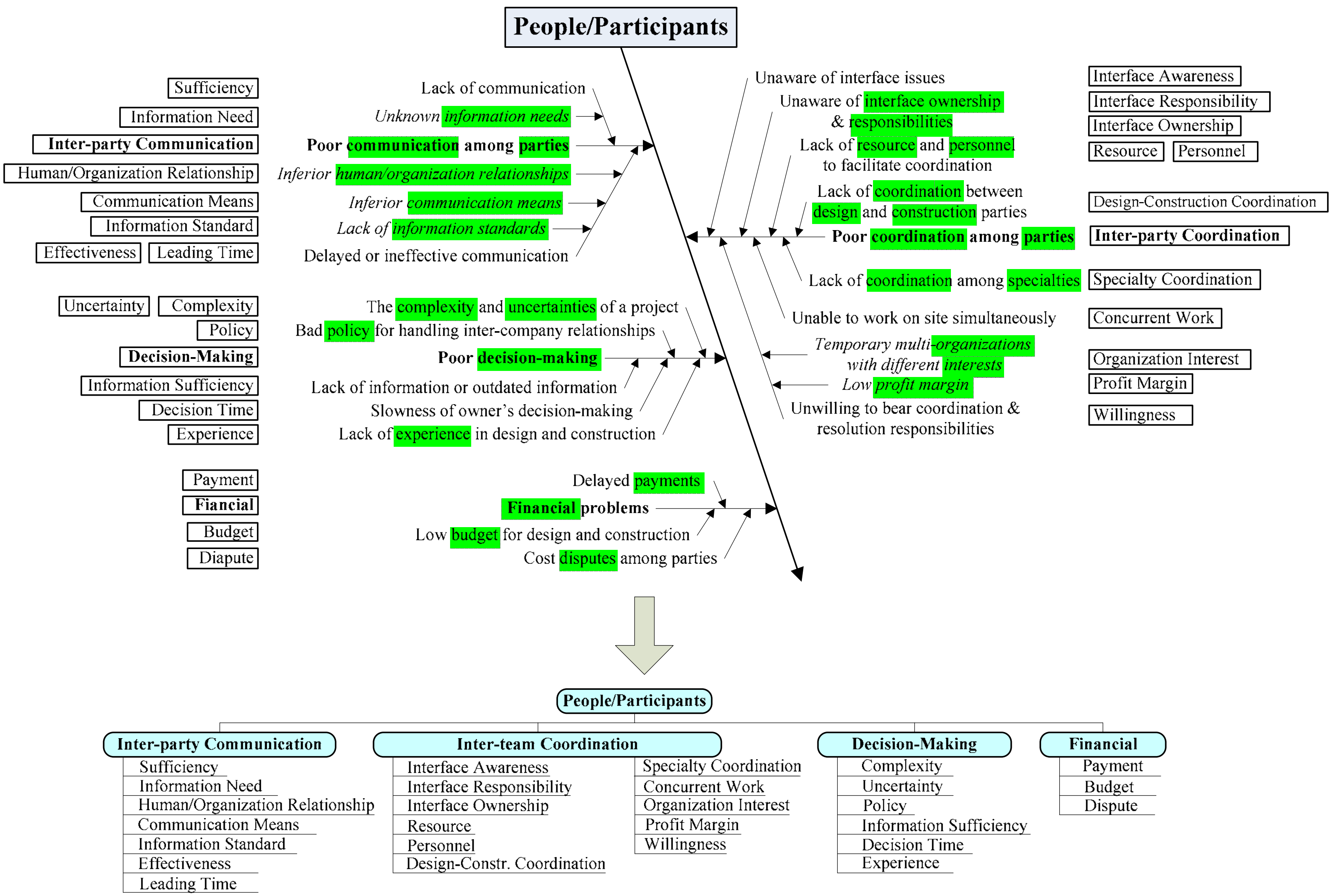


Figure 3-13: The Generation of Interface Management and Control Elements for the People/Participants Category

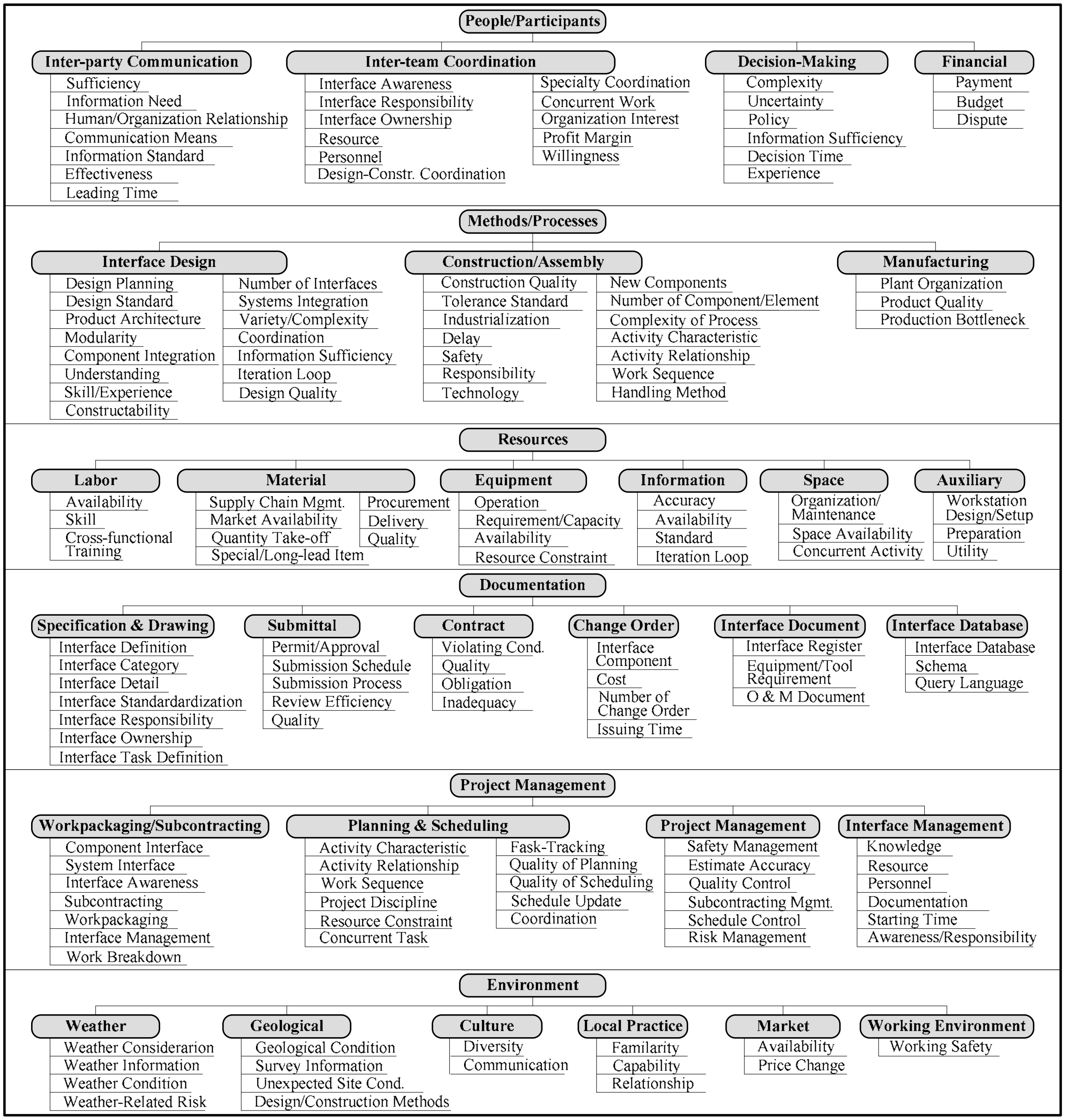


Figure 3-14: Potential Elements for Interface Management and Control

As shown in Figure 3-15, IM, though an individual project management aspect, also extends over the scopes of other traditional project management aspects (cost, contract, communication, resource, time, process, safety/risk, and quality). Through IM (the core of project management), all the management aspects can be integrated as a coordinated system.

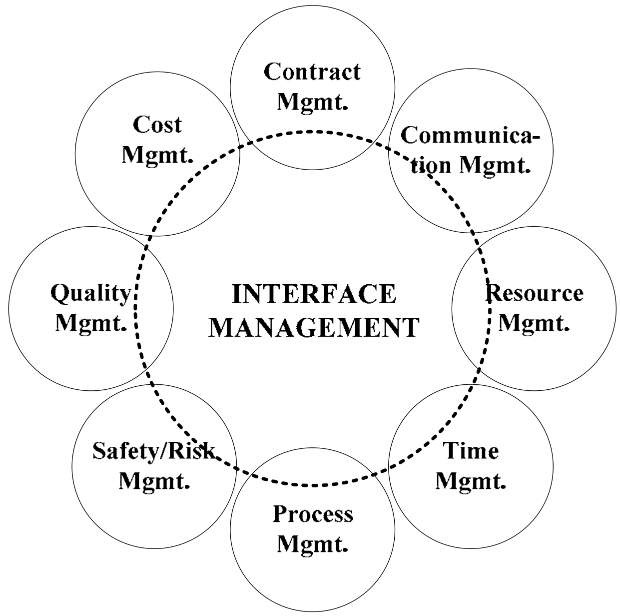


Figure 3-15: Systems Approach: Integrated Interface Management

In conclusion, the multi-perspective approach provides a theoretical base for seeking all-around IM solutions. Specifically, it helps deeper understanding of interface issues and their causes. Based on this understanding, the goal of IM can be determined and the specific interface management and control elements can be identified. Future research can develop all-around IM solutions.

CHAPTER 4: INTERFACE OBJECT MODEL FRAMEWORK

As discussed in Chapter 1, the large number of interfaces in a construction project and their complexity easily make the most capable personnel fail in their responsibilities for interface management (IM). IT implementation becomes the most effective way to record, track, check, coordinate, and control complex interfaces within the computer integrated construction environment. Modeling interfaces is regarded as the first step toward seeking appropriate IT solutions for managing interface issues. The proposed Interface Object Model (IOM) identifies applicable interface modeling objects, incorporates them into a well-structured, hierarchical data structure, and defines data dependencies for implementation. It is the basis for modeling numerous complex interfaces in construction projects and establishing interface databases that can be widely used by the industry. This chapter presents a comprehensive IOM framework, based on which further development of the IOM can be carried out in future research.

4.1 INTRODUCTION TO THE IOM

The IOM is proposed to be the basis for modeling numerous complex interfaces in construction projects. The following subsections explain what the IOM is in three steps.

4.1.1 What is a Model?

The term *model* can be explained as a simple description or representation of a structure or system. Presented in a general language, a model can be understood with ease and transformed accurately between different systems or disciplines. There are many well-developed graphic languages (e.g., the IDEF0, Express-G, and UML) available for modeling. In terms of the IFC, the *model* means a formal specification of requirements that can be used by software authors to create compliant software applications (IAI, 1999a). In this case, a model is used to communicate requirements.

Modeling is considered a very good methodology to monitor reality, standardize or simplify systems or a structure, explore and resolve potential problems, and finally instruct relevant operations. Kartam et al. (1994) indicate that the development of valid, credible models should be a logic precursor to automation.

4.1.2 What is an Object Model?

Different types of models can be created to fulfill specific purposes in designing, analyzing, and implementing a system. The most commonly used models in the AEC/FM industry are *process models*, *information models*, and *object models*.

A *process model* mainly describes the tasks or activities performed within a system or a process. For example, the Integrated Building Process Model (IBM) developed by Chung (1989) leads to a hierarchical breakdown of the building process. Sometimes, process models also show how and what information needs to be communicated between tasks or activities. For instance, the IDEF0 model published by the U.S. Air Force in 1981 successfully displays information dependencies between processes.

Due to the importance of information flows in a process or system, *information models* are created to mainly describe different types of information required by a system. For example, the Building Project Model (BPM) developed by Luiten (1994) integrates product, activity, and resource information for the purpose of computer-aided design for construction.

An *object model* can be explained as a representation of the structure of information and the relationship between that information and other information. As aforementioned, the IFC object model is defined as a representation of the information content and structure that needs to be exchanged or shared for "things" occurring in the AEC/FM industry. It presents the classes as well as their interfaces, attributes and relationships in a composite representation (IAI, 1999a). An object model can therefore be understood as a special kind of information model.

4.1.3 What is the IOM?

The proposed IOM is an object model and therefore in many aspects similar to other object models (e.g., the IFC). However, the IOM is a special outcome of this research for the purpose of modeling the information content, structure and dynamic response of events related to interfaces. Taking it one step further, the IOM is designed to represent the data structure of applicable interface objects (the smallest, applicable interface modeling units) and the relationship between such objects and building or project components. In implementation, any interface between building or project components can be accurately modeled by using one or more such modeling units.

4.1.3.1 An Object View of Interfaces

This research initiates the interface modeling method that models interfaces as objects. This method is based on an *object* view of interfaces. The following comparison explains in detail this view's advantages in interface modeling.

Traditionally, interfaces are viewed and modeled as relationships or dependencies between two entities (Figure 4-1) in many commonly used modeling languages in the construction field, such as Express, Express-G, and the IDEFs. Such relationships or dependencies contain limited information for a model to operate. Hence, operations and processes based on these models make it difficult to achieve the expected performance.

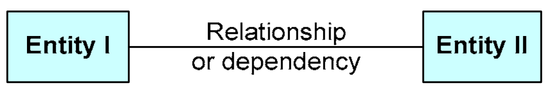


Figure 4-1: The Conventional View of an Interface

The innovative *object* view considers interfaces controllable interface objects (Figure 4-2). These objects are not only property collectors; they also contain operations sometimes also referred as methods. Therefore, they can react to events in the object environment and trigger specific interface handling processes as well. Based on this concept, interface management, control, and handling becomes more effective and efficient.

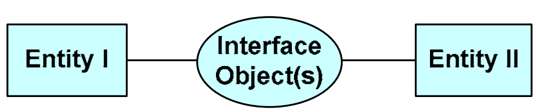


Figure 4-2: The Innovative View of an Interface

4.1.3.2 Important Modeling Concepts in the IOM

Two concepts—*class* and *object*—are very important in the proposed IOM. They are the commonly used terms in object models. This research adopts their definitions made in UML. A *class* is defined as "the descriptor for a set of objects that share the same attributes, operations, methods, relationships, and behavior." The concept of class is either real world element (e.g., door and window) or can just contain algorithmic and computer implementation concepts. Relatively, an *object* is an *instance* of a class, a concrete manifestation of an abstract description (Rumbaugh et al, 1999).

Although what the IOM is modeling is often referred to as interface objects, they are actually represented through classes of the real-world interface objects (instances) in a data structure. Each interface object class in the IOM denotes a set of real-world interface objects that have the same attributes, operations, methods, etc. The types of attributes and the brief descriptions of operations, methods, etc. are listed within an interface object class in the IOM but not ever specified there. During implementation, such an interface object class will be instantiated and become a real-world instance. Then, all properties will be specified in the greatest detail. The benefits of using classes in a data model are notable, such as the inheritance that allows classes to inherit from higher level classes (superclasses), the easiness to extend the model without re-inventing the superstructure, etc.

4.2 INTRODUCTION TO THE IOM FRAMEWORK

It is commonly thought that the model framework is very similar to or the same as the model architecture. However, this research gives more meaning to the model framework. It is believed that a model framework is needed before future research can accurately and fully develop a proposed model. For that model, the framework usually performs some of the following functions:

- Setting the baseline,
- Describing the entire structure,
- Revealing model components and their relationship,
- Showing modeling methods to be applied, or
- Leaving spaces for future development and extensions.

Such a framework explains how individual model components are incorporated into a well-structured system to perform the proposed function, and thus greatly enhances the comprehension of future model developers.

This research aims to develop a framework for the proposed IOM instead of fully developing the object model itself. Nevertheless, in order to provide adequate information and precise directions for future development, what this research creates is a comprehensive model framework that already includes some model developments as either examples or detailed sub-models for framework components. The following section introduces the architecture of the IOM framework, based on which the specific and then comprehensive framework elements are developed step by step.

4.3 ARCHITECTURE OF THE IOM FRAMEWORK

Figure 4-3 illustrates the architecture of the IOM framework.

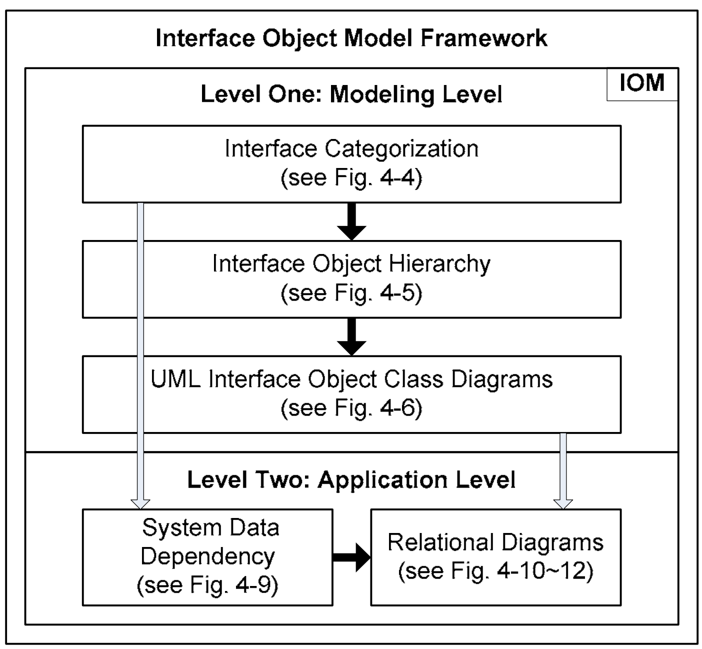


Figure 4-3: Architecture of the IOM Framework

In this framework, basically two levels exist. Level One, the *Modeling Level*, represents the intrinsic IOM developed as a class model. It has three major modeling stages—*Interface Categorization*, *Interface Object Hierarchy*, and finally *UML Interface Object Class Diagrams.* These components display interface objects in their hierarchy and structure. Level two of the IOM framework, the *Application Level,* includes two major model components—*System Data*

Dependency and *Relational Diagrams.* These components identify both general and specified data dependencies in the real world AEC/FM setting as an application of level one.

The most significant part of the framework is level one where interface objects are broken down based on several categories and other classifications. Indeed, applicable interface objects are the essence of the IOM. The modeling stages of level one are of different depth of abstraction. The last stage (*UML Interface Object Class Diagrams*) includes a special descriptive language, where all interface objects are properly specified and therefore ready for the *Application Level*.

Also, the *Application Level* is split into two stages. The first stage, *System Data Dependency*, looks at applications on a higher level of abstraction and can in fact be used with the first stage of the IOM. The second stage, *Relational Diagrams,* will be derived from the first stage structure using the IOM defined in stage three of the *Modeling Level*. Within each level, a solid arrow that connects two model components denotes a consecutive modeling step. The hollow arrow, however, represents an application relationship between the two levels of the framework; i.e., how model components of level two will find their hierarchical models in level one.

4.4 FRAMEWORK DEVELOPMENT

According to the architecture presented above, the framework development consists of two parts: 1) developing a class model at the *Modeling Level* and 2) developing a relation model at the *Application Level.* There are five model components in total. For the comprehensive IOM framework, most of these model components are only partially developed but structured with future extensions in mind. In the following, their development processes and examples are presented respectively.

4.4.1 Interface Categorization

Class models can be considered the core of object-oriented development and design. A proper approach to their development is essential. In this research, a general interface object categorization is urgently needed in the development of the class model. Without a categorization, the development of *Interface Object Hierarchy* lacks a fundamental data structure because various interface objects should be defined according to specific categories and kept under them for modeling and management. Therefore, such a categorization should be created in the very beginning of the framework development. Fortunately, the interfaces and interface objects can share a proper categorization.

In Chapter 2, this research has reviewed several types of interface categorizations made by different researchers. These categorizations are all generic. Due to the different authorship, some categories in different categorizations are actually identical according to their definitions such as *Physical Interface* and *Intrinsic Interface*, or *Contractual Interface* and *Project Interface*; some other categories, for instance, *Functional Interface* and *Contractual Interface*, overlap to some extent. Actually, all these categorizations are neither complete nor sufficient for this research. On the one hand, some categories like *Discipline Interface* or *Functional Interface* are not specified by either examples or precise definitions, and hence are hard to understand and apply; on the other hand, for many critical interfaces existing in the industry, it is hard to find any category to fit them in. Therefore, the IOM framework should make its own specific and accurate interface categorization, and then allow this categorization to be shared by the interface objects in the development of the *Interface Object Hierarchy*.

This research chooses an approach that categorizes interfaces based on their characteristics. Hence, the interface objects are also categorized according to their characteristics. The reasons are two-fold. First, this approach is very helpful for object-oriented modeling to accurately identify and categorize interface objects. Second, during implementation, people can easily decide which interface object(s) should be used for modeling an interface; this is because when people notice or experience an interface, its characteristics are most visible and some of them can even be directly perceived. In this research, important characteristics distinguishing different types of interfaces are *physical*, *functional*, *performance*, *operation*, and other *activity* characteristics. Accordingly, the five main interface categories are identified as *physical*, *functional*, *contractual*, *organizational*, and *resource* interfaces (shown in Figure 4-4). Their definitions in broad construction settings are explained below. Simple categorization at a higher level is beneficial to a hierarchical data structure. By using broad construction settings as the background, the data model can be structured and developed more generically for wide applications.

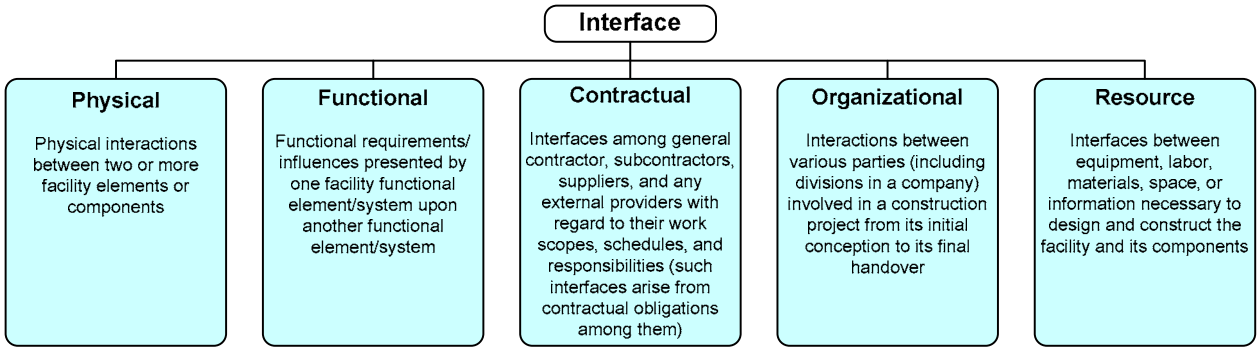


Figure 4-4: Interface Categorization

4.4.1.1 Category One: Physical Interface

This category comprises physical interactions between two or more facility elements or components in any built facility (buildings, plants, bridges, roads, and other structures). Such interactions include physical contacts, connections, as well as spatial relationships. Facility elements—building elements in broad construction settings—usually refer to raw construction materials; one piece of lumber or one sheet of wallpaper can be called a facility element. Using primary elements is unavoidable when traditional construction methods are applied. For example, 2x4 lumber is the primary facility element for housing construction in the stick-build method. Facility components—building components in broad construction settings—are manufacturing products that are delivered to the job site as assemblies of raw construction materials. Those components, such as roof/floor trusses, wall panels, or pre-cast bridge decks, are now widely used in construction. Using factory-made components greatly reduces the number of physical interfaces in a construction jobsite compared with using primary elements. However, the interface complexity may increase because more primary elements might be involved in the physical interface between two single components.

4.4.1.2 Category Two: Functional Interface

This category contains functional requirements/influences presented by one facility functional element or system upon another functional element or system. A functional element is a facility element or component either performing at least one function or having one influence on something. For example, a window is a functional element performing several functions, such as protecting the interior, providing daylight, and preventing heat loss or heat gain. A functional system is much easier to understand, e.g., the HVAC (Heating, Ventilation, and Air Conditioning) system performing heating, ventilating, or air conditioning for a building.

Functional requirement and *functional influence* are two interrelated aspects of a single interaction. In other words, it is the influence that leads to the requirement being raised. Here is one example. If element A receives some bad influence(s) from element B and therefore cannot function properly, the requirement(s) of A will be given to B to reduce the negative influence(s). Taking a building as the example, functional interactions within it consist of several functioning aspects, including *structural*, *humidity*, *thermal*, *acoustic*, *visual/lighting*, and *air quality/health*.

4.4.1.3 Category Three: Contractual Interface

This category represents interactions among the general contractor (GC), subcontractors, suppliers, and any external providers with regard to their scopes of work, schedules, and responsibilities for construction. These parties usually have contractual relationships among each other. Most of them (e.g., specialty subcontractors) are involved in certain workpackages that are interrelated in building the facility. Therefore, contractual interfaces should comply with pre-defined contractual obligations and simultaneously ensure that other types of interfaces (e.g., physical, functional) across different scopes of work can be performed successfully. Three major characteristics that distinguish this category from others are defined below:

- The described interactions are between parties that mainly are involved in the construction stage, though the specialty subcontractors also perform some detailed design tasks.
- Parties involved are bound by contracts and therefore have to perform their contractual obligations or duties defined by such contracts.
- Products or services those parties (except those GCs who only manage a project) provide are (or belong to) individual workpackages and somewhat interrelated in the construction system on the jobsite. Therefore they have to be carefully coordinated to avoid conflicts and incompatibilities.

4.4.1.4 Category Four: Organizational Interface

This category includes interactions between various parties (including different divisions within one party) in a construction project from its conception to final handover. The wide variety of parties include the owner, designers, contractors and suppliers, operation & maintenance contractors, labor associations, government agencies, and the public, community, or neighborhood (if affected). Interfaces qualifying for the *contractual interface* category are excluded.

Between most of these parties, for example, designers and government agencies, contractors and the community, or designers and contractors (in traditional delivery environments), there is no contracting relationship. Therefore, organizational interfaces among parties are harder to organize and achieve due to lack of obligation. Also, the connections or interactions between them are complex. They are of many different types, such as administration, cooperation, supervision, inspection, regulation, and consultation. Within this category, the most challenging interfaces are between the designers and associated contractors. Through these interfaces, a large amount of design data needs to be accurately transformed into construction operations.

4.4.1.5 Category Five: Resource Interface

This category involves interactions between equipment, labor, materials, space, or information that are necessary for the design and construction of the facility and its components. *Resource* is an evolving concept that has been gradually enriched with new contents since it appeared in construction. Besides labor, equipment, and materials, the most recently added contents are space and information. In this category, equipment includes not only traditional construction tools/equipment but also communication, computing, and simulation tools/equipment (both hardware and software). Information consists of project-related information, internal and external databases, and knowledge/experiences widely available (e.g., on the "Web"). Accordingly, resource interactions may include utility, space and information sharing, safety, learning, operating, environmental influence, interoperability, etc.

According to the previous discussion, the interfaces and interface objects can share one categorization when appropriate. Thus the above five interface categories become the basis for determining interface object categories in the development of the *Interface Object Hierarchy*.

4.4.2 Interface Object Hierarchy

The *Interface Object Hierarchy* is a very important model component in the IOM framework. It develops the hierarchy of interface objects that enables the generation of *UML Interface Object Class Diagrams*.

Before the development of the *Interface Object Hierarchy*, a small adjustment is made—to combine the *contractual* and *organizational* categories into a single one to hold relevant interface objects. Although these two categories are distinguishable in construction practice, they are all about inter-party interactions; thus a large part of such interactions are of the same kinds, e.g., communicating, coordinating, submitting, supervising, and contracting. Merging them successfully prevents duplicate interface objects from being listed twice in the IOM but simultaneously ensures that such objects are still available and easy to locate during implementation.

The *Interface Object Hierarchy* is developed as a diagram that aims at exploring applicable interface objects step by step and displaying both the breakdown process and its final result in a well-organized hierarchical structure. The diagram starts from the main interface object categories, then continues to several levels of subcategories, and finally proceeds to applicable interface objects. Subcategories are created to aid the breakdown process and help users locate interface objects they need during modeling. The breakdown process is carried out cautiously by carefully studying the potential characteristics of all kinds of existing interfaces, finding the most applicable classification principles, collecting numerous possible scenarios for identifying subcategories and interface objects, and determining a proper application level for applicable interface objects. Figure 4-5 shows an *Interface Object Hierarchy* diagram developed by this research.

There are four interface object categories: *physical*, *functional*, *contractual/organizational*, and *resource*. Due to the complexity of interfaces, it is very time-consuming to develop an accurate, multi-category, and applicable object hierarchy diagram. Therefore, this research develops only the *physical interface* category into the final application level as a solid example, which shows how the breakdown process can be performed and what interface objects can be identified.

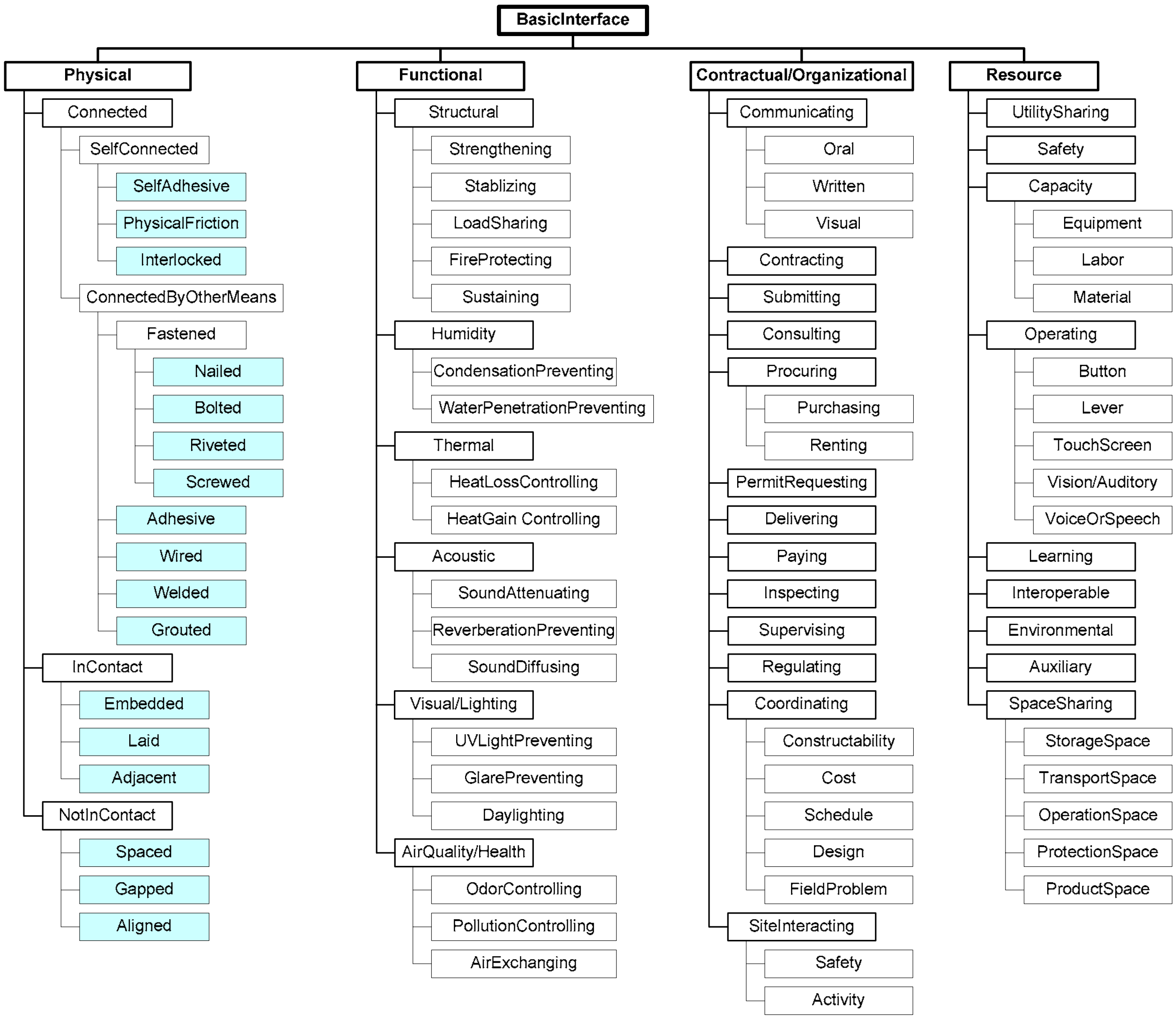


Figure 4-5: Interface Object Hierarchy

For the fully developed *physical interface* category, the longest breakdown path reaches the fifth level, such as `Physical-Connected-ConnectedByOtherMeans-Fastened-Nailed`. Seventeen applicable interface objects, including `SelfAdhesive`, `PhysicalFriction`, `Nailed`, `Gapped`, etc., are identified and displayed in the shaded boxes. Names for all the categories, subcategories, and objects are created using the `UpperCamelCase` convention. This fully developed branch is used to create a real *UML Physical Interface Object Class Diagram*, where the data structure of this category is presented and explained in a greater detail.

For the other three categories, this research develops them just into the third interim levels—more indicatory subcategories which may not be 100 percent accurate and can be revised in their future development. Even at an interim level, it can be seen that the data structure already becomes very complex. To accurately determine subcategories and applicable interface objects is extremely difficult. In the previous chapter, this research summarized a series of interface management and control elements from the multi-perspective view of interface issues (the well-developed C&E diagram). These elements, at the very detailed level, are greatly helpful for this and future research to determine lower level interface object subcategories and applicable interface objects in the IOM.

4.4.3 UML Interface Object Class Diagrams

The *UML Interface Object Class Diagrams* present detailed information for interface objects in a standardized format. UML class diagrams are capable of including different types of detailed information for the defined classes because several compartments, e.g., attributes, operations with methods, or responsibilities, can be attached to a single class box according to the needs. On the other hand, these diagrams are IT applicable since UML graphical representations stemming from modeling language bundles can be automatically converted into code in a wide range of commonly used software development tools such as C#, C++, and VB.

In the IOM, the *Interface Object Hierarchy* diagram can be fully transformed into a series of UML class diagrams. Usually, each interface object category (including its sub-levels) will be converted into a single UML diagram. Such a diagram may contain many classes and subclasses with comprehensive information. If necessary, it will be easier to maintain child diagrams that are more readable for users. These child diagrams can always be merged back into a single UML diagram.

In the transformation process, the main category, subcategories, and objects in the *Interface Object Hierarchy* Diagram become classes into which various detailed information is added. Their hierarchical relationship is replaced by the *generalization* relationship in UML—a sort of superclass-subclass relationship. This relationship allows a subclass to inherit attributes from its superclass while still having additional, special attributes of its own. Thus, information is gradually added into the diagram during transformation: The general information is added to the superclass and more specific information is given to the subclass. Consequently, the whole transformation becomes easier; information is distributed more evenly; and the generated UML diagram is well balanced.

Figure 4-6 displays a *UML Physical Interface Object Class Diagram*. Here, classes at five levels are clearly displayed and information on attributes and operations for interface objects is properly incorporated into relevant classes as compartments. If necessary, further information, such as responsibilities, can also be added to those classes. In the diagram, notes explaining specific classes are added wherever needed. The end-tier, applicable interface object classes, are highlighted and can be easily located during application. This comprehensive example can be a guide for future research to transfer the other three categories into UML class diagrams. In the following, the basic data structure and specific classes of this UML diagram are explained in greater detail.

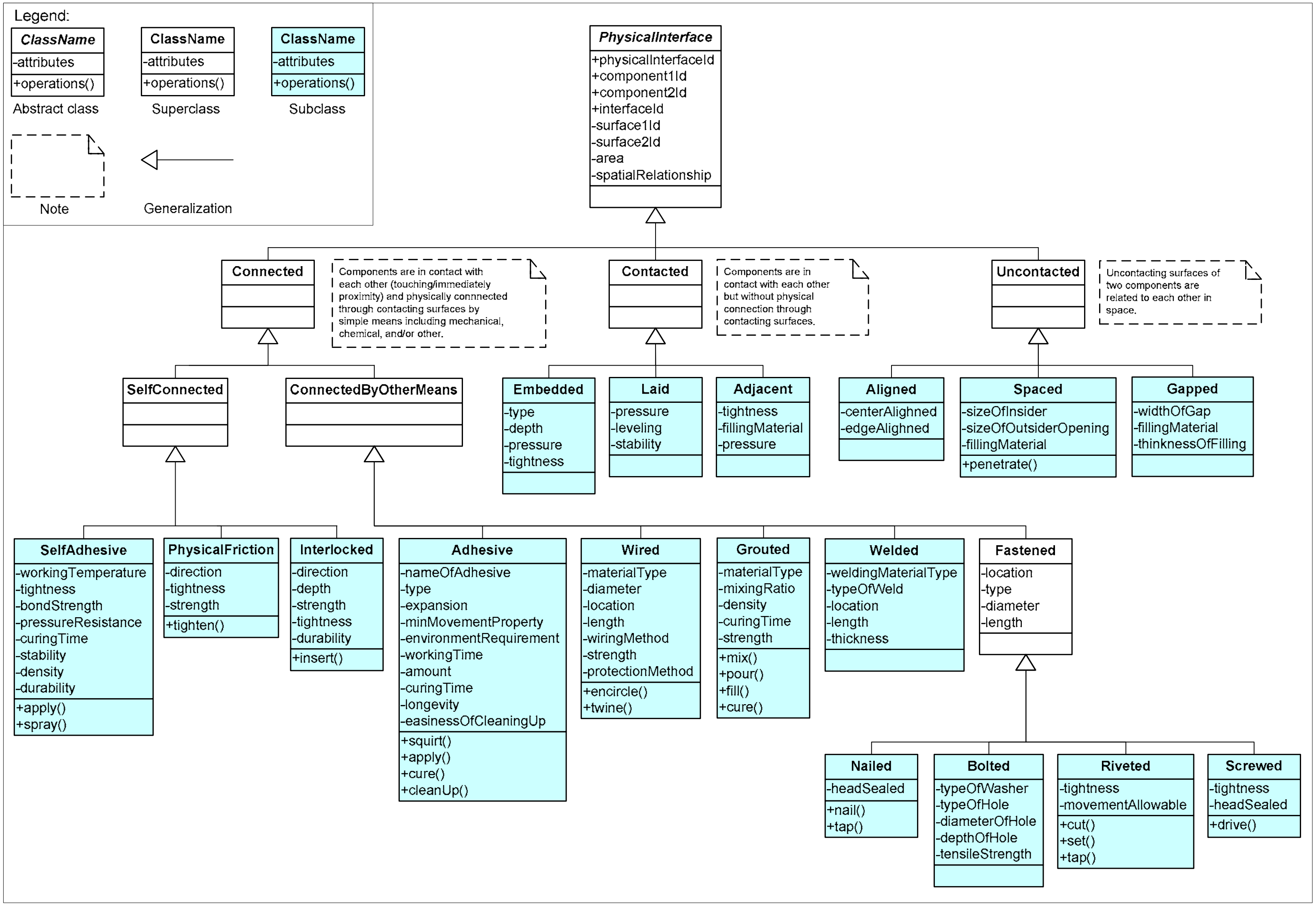


Figure 4-6: UML Physical Interface Object Class Diagram

4.4.3.1 Data Structure

In the diagram, the highest superclass is called *PhysicalInterface*, which has three child classes: 1) *Connected*, 2) *InContact*, and 3) *NotInContact*. Each has its definition and scope. In UML, an italic class name represents an abstract class which cannot be directly instantiated; then the concrete subclass(es) will be needed for instantiation. Here, *PhysicalInterface* is an abstract class, as well as *Connected*, *InContact* and *NotInContact* classes.

Under the *InContact* and *NotInContact* subcategories, six end-tier applicable interface object classes including Embedded, Laid, Adjacent, Aligned, Spaced, and Gapped are identified. Under the *Connected* subcategory, two situations appear: *SelfConnected* and *ConnectedByOtherMeans*. The former consists of three applicable interface object classes: SelfAdhesive, PhysicalFriction, and Interlocked. The latter comprises four applicable interface object classes (Adhesive, Wired, Grouted, and Welded) and one further category—*Fastened*, which contains another four applicable interface object classes, namely Nailed, Bolted, Riveted, and Screwed.

By the aid of such a step-by-step categorization, the data structure for physical interface is well established and displayed. What types of properties/attributes need to be defined for each applicable interface object class is also depicted along the breakdown path. To help future developers and users better understand the UML class diagram, examples taken from some transition classes and end-tier applicable interface object classes need to be given to explain how these classes are defined and what the UML notations stand for.

Prior to presenting these examples, two concepts that are required for interface object implementation need to be introduced first. They are s*imple interface* and *reference interface*. In general, a *simple interface* refers to the simplest type of interface interaction, which can be represented by any interface object defined in the *Interface Object Hierarchy* diagram or *UML Interface Object Class Diagrams*. A *reference interface* refers to a complex type of interface interaction, which comprises several simplest interface objects (simple interfaces) and additional components. In physical interface modeling, each type of physical interaction between two or more facility elements or components can either be a *simple interface* or a r*eference interface* based on its physical characteristics. These two concepts are discussed further below.

4.4.3.2 Simple Interface and Reference Interface

In physical interface modeling, a *simple interface* refers to the simplest type of physical interaction between two facility elements or components. Interface objects presented in the physical interface object category and the corresponding UML physical interface object class diagram are all simple physical interfaces, but at different levels. No matter whether the two facility elements or components are connected, in contact, or not in contact with each other, this type of interaction does not involve any additional component that needs to be specially designed and manufactured for accomplishing the function required by the interaction. Common fasteners, adhesives, and other simple mechanical or chemical means of connection are not considered additional components. The simple interface is most elementary for modeling physical interactions. It is also a required component for any *reference interface*.

A *reference interface* is more complex than a simple interface. In addition to simple interfaces, it needs some additional component(s) for connecting two facility elements or components. The additional components, such as masonry wall ties, are called *interface components*. They exclude fasteners, adhesives, and other simple connecting materials. Usually, interface components are added for connecting two facility elements or components through surfaces that are not in contact with each other. This distinguishes a *reference interface* from the *connected by other means* interface.

In physical interface modeling, a reference interface, when used, becomes a complex type of interface object which holds several simple physical interface objects and additional interface component(s). This is explained later within the *Relational Diagrams*.

4.4.3.3 Physical Interface Object Classes

In the following, several physical interface object class examples are presented and explained in detail. The first example is the *PhysicalInterface* object class.

The *PhysicalInterface* is an abstract class that may not have direct instances. Its UML notation is shown in Figure 4-7.

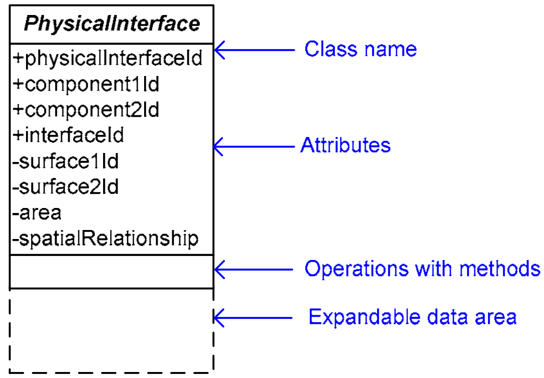


Figure 4-7: Physical Interface Class

The definition of *physical interface* was presented earlier in this chapter. Here, the discussion focuses on several attributes defined in the *Attributes* compartment attached to the class name box. The names of attributes are created by using the lowerCamelCase Convention. In the IOM framework, the list of attributes for any class is just an example and may not be of the completeness required by real-world modeling.

physicalInterfaceID: Multiple types of physical interactions between two facility elements or components are regarded as one single physical interface and assigned with a unique physical interface ID for modeling and tracking purposes. Each type of interaction will then be modeled by using a specific simple interface (an interface object) or a reference interface comprising simple interfaces and additional interface component(s). Finally, a physical interface is modeled as an aggregation of simple interface(s) and/or reference interface(s).

component1Id and *component2Id*: Indicate which facility elements or components are involved with this physical interface. It is common to take two facility elements or components into consideration at a time.

interfaceId: As mentioned above, one single physical interface that consists of multiple types of physical interactions is assigned a unique physical interface ID. Therefore, to distinguish each type of interaction within this interface, a specific interface ID is given to each interface object used to model this interface. Here, the *interfaceId* can also be called *simpleInterfaceId*, which is different from a *referenceInterfaceId* employed later in the *Relational Diagrams*.

surface1Id and *surface2Id*: Indicating which surfaces of elements or components are involved with a specific interface object.

Besides the attributes compartment, there are expandable data areas for the *Operations with Methods* compartment, *Responsibilities* compartment, etc. Important object-oriented interface information can always be added into the class according to the data needs.

The *Connected* interface object class represents a type of physical interaction in which two facility elements or components are in contact with each other (touching or in immediate proximity) and physically connected through the contacting surfaces by simple means including mechanical, chemical, and/or other. There are two types of connected interface: One is *self connected* and the other is *connected by other means*. Their names are self-explanatory. Here, the `SelfAdhesive` interface object class (as shown in Figure 4-8) is explained in detail as an applicable interface object class example.

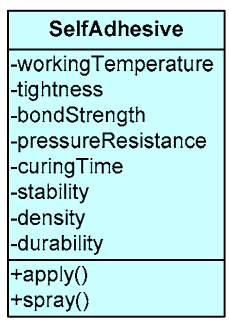


Figure 4-8: Self_Adhesive Class

This is a concrete class which can have its instances. Examples are interfaces between self-adhesive construction materials (e.g., wallpaper, tile, aluminum sheet, and spray foam insulation) and their base materials (e.g., tile, drywall, polyethylene, and steel). There are eight important attributes including *working temperature*, *tightness*, *bond strength*, *pressure resistance*, *curing time*, *stability*, *density*, and *durability*. These attributes need to be accurately specified and strictly followed during the interface handling process to ensure a quality self adhesive interface. The operations may include *apply*, *spray*, or other activities.

The *InContact* interface object class refers to a type of situation where two facility elements or components are in contact with each other but without a physical connection through the contacting surfaces. For example, a pre-cast foundation wall rests on compacted gravel, or two pieces of pavement tiles are placed adjacently. There are no permanent physical connections existing to bond the two elements or components together.

The *NotInContact* interface object class represents a type of condition where two facility elements or components are related to each other in space but not in contact. The two elements or components may be aligned in space (Aligned); one may contain the other (Spaced); or a constant gap may be kept between them (Gapped). For example, a corridor represents a gapped interface between two parallel walls.

4.4.4 System Data Dependency

In IOM implementation, a critical issue exists; i.e., how interface objects identified in the IOM can be used to model real-world interfaces in their construction contexts. A method to map interface objects into construction settings of numerous interfaces should be found. In this research, relational models at Level Two are created to perform such a mapping function.

Level Two, the *Application Level*, comprises two major model components: *System Data Dependency* and *Relational Diagrams*. Both of them use UML static view class models, which can describe the vocabulary of a system and specify structural relationships within it. The first model component, *System Data Dependency*, shows the entire structure of the construction project system and how the identified interface object categories fit into this structure. This UML diagram is greatly simplified to display only the highest-level classes in the hierarchies of both the system and the interface objects. It also serves as a parent diagram at Level Two to hold the second-stage child relational diagrams.

It is apparent that the highest-level interface object classes are the main categories of interface objects presented previously. For the construction project system to be modeled, one question comes to the fore. What are the highest-level classes most necessary for this system?

In the literature, there are many project information models that have a hierarchical structure. In those models, key project contents or entities are illustrated at a higher level. Froese

(1992) develops the General Construction Object Model (GenCOM) to improve the integration of project management tools by using object-oriented models of construction projects. This model defines the high-level object classes or entities as: *activity*, *component*, *method*, *action*, *resource*, and *project participant*. The relationships among these object classes are also specified. Luiten et al. (1993) define the conceptual Information Reference Model for AEC (IRMA). The central concept is the *project object*, which consists of four major classes: *product*, *contract*, *activity*, and *resource* (including *agent*). These high-level project object classes or entities are referred to when a *System Data Dependency* is created in the IOM framework.

Figure 4-9 is a *System Data Dependency* diagram presented in UML. The high-level object classes of the construction project system are defined as: *built facility*, *facility component*, *process activity*, *people/participant*, and *resource*. The *facility component* object class plays an important role in the model. It is located at the center of the model and connects other object classes or entities with it. Process activities are performed by people/participants to construct or handle facility components. Resources are used to conduct process activities. With the aid of these relationships, the modeled information is integrated as a complete system and can be easily incorporated into other building product models where project information is also organized around facility components. In the diagram, the high-level interface objects—*PhysicalInterface*, *FunctionalInterface*, *Contractual/OrganizationalInterface*, and *ResourceInterface*—are properly incorporated into the model.

It is very important for the IOM framework to have the *System Data Dependency* diagram well developed. This is because this diagram can be used to derive specific project or facility components that are essential, constituent elements of the *Relational Diagrams* introduced below. In addition, this diagram shows which category or categories of interface objects are related to these components. The *System Data Dependency* acts as the parent diagram for relational diagrams that present lower level details.

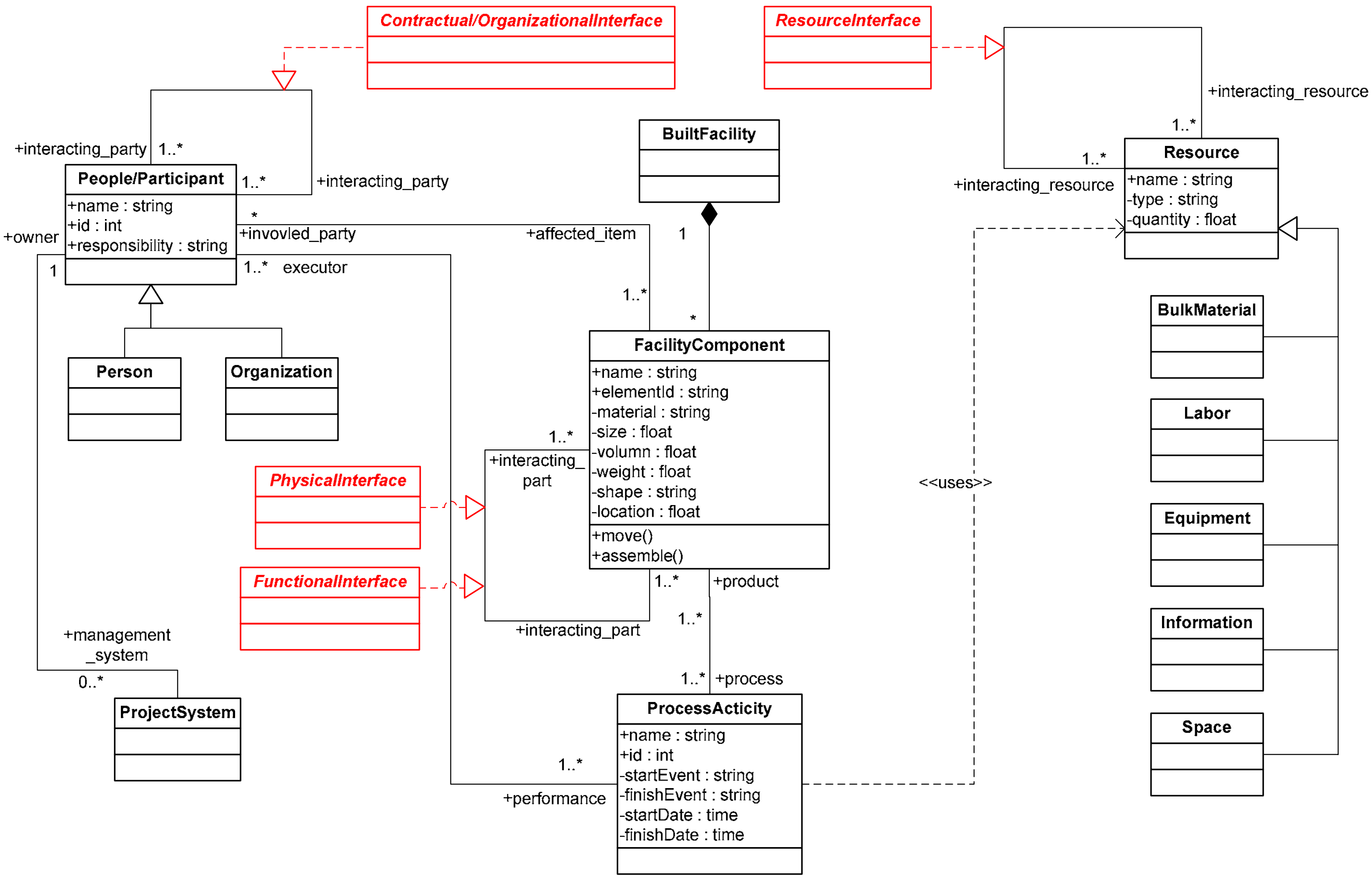


Figure 4-9: System Data Dependency

4.4.5 Relational Diagrams

The *Relational Diagrams* comprise another group of UML diagrams. Most of them describe data dependencies between specific facility or project components and their appropriate interface objects in selected construction contexts. These contexts can be diverse project conditions that are compatible with selected project delivery methods or construction methods. The facility or project components at a detailed level are derived from the major project objects or entities displayed in the *System Data Dependency*. Based on the needs of interface modeling, proper interface objects are selected to fit into specific construction contexts.

Figure 4-10 illustrates the data dependency (contextual relationship) between the physical interface objects and facility components. This is one of the simplest types of data dependency in the IOM. In the diagram, the *association* classifier connecting two classes is capable of specifying data dependencies and consequently increases the model applicability. The highlighted object classes belong to the scope of interface modeling (proposed by this research) while the other classes should be modeled in building product models currently existing in the industry. As shown here, any physical interface can be modeled as an aggregation of simple interface(s) and/or reference interface(s), and any reference interface is composed of simple interfaces and additional interface component(s). Each reference interface is specified by an attribute—*reference interface ID.*

Compared with the data dependency between the physical interface objects and facility components, data dependencies between other types of interface objects and related project components are more complex to model. The identified cause factors (in Chapter 3) can be used to create numerous detailed project scenarios where both project components and the involved interfaces are illustrated to a certain degree. Relational models can be created to incorporate relevant interface objects into such project scenarios and precisely depict the relationships or dependencies between them. Based on these relational models, interface modeling can be performed and further used to help the management and control of various interface issues described in those project scenarios.

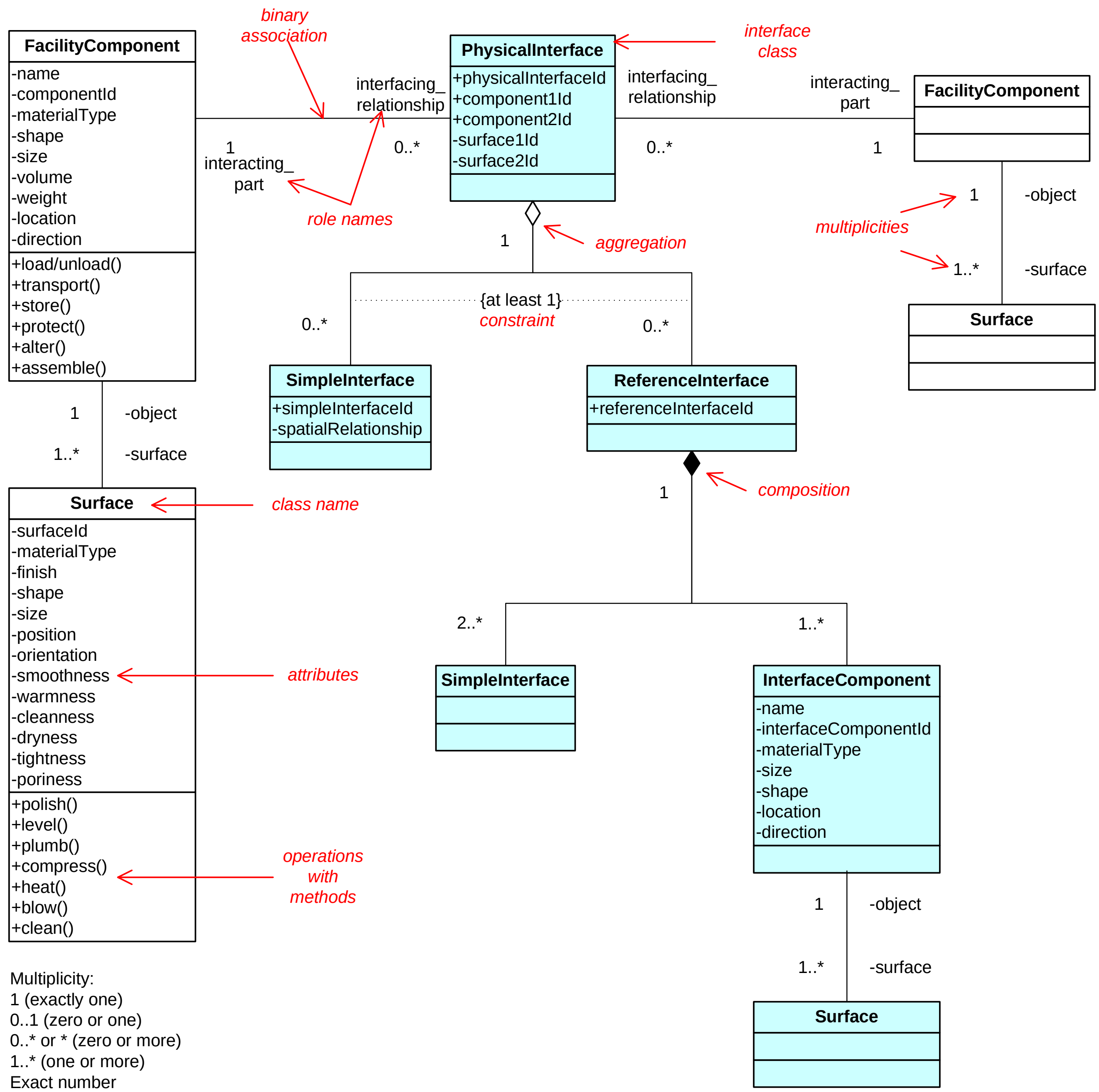


Figure 4-10: Data Dependency Between Physical Interface Objects and Facility Components

In this model component, there also are other relational diagrams that aim to illustrate complex types of interface objects (reference interfaces) comprising several simple types of interface objects (simple interfaces). There is not a superclass-subclass relationship between a complex type of interface object and related simple types of interface objects. Due to their complex nature, class models at Level One cannot capture them. Such complex types of interface objects exist widely in interface modeling. They represent real-world interface relationships that repeatedly appear in construction projects. These complex types of interface objects need to be defined prior to interface modeling. If generalized as object modeling patterns, they can greatly increase the speed of modeling common real-world interfaces.

Here, two relational diagrams are presented to illustrate the reference interface type for physical interface modeling. Figure 4-11 shows a simple type of reference interface, which consists of two simple interfaces and one interface component—the additional component used to connect the two facility elements or components. A real-world example given here is the physical interface between a door panel and a door frame. When the door is hinged to the frame, the first and second basic interfaces in the diagram can all be modeled by the `Screwed` interface object and the interface component is the hinge.

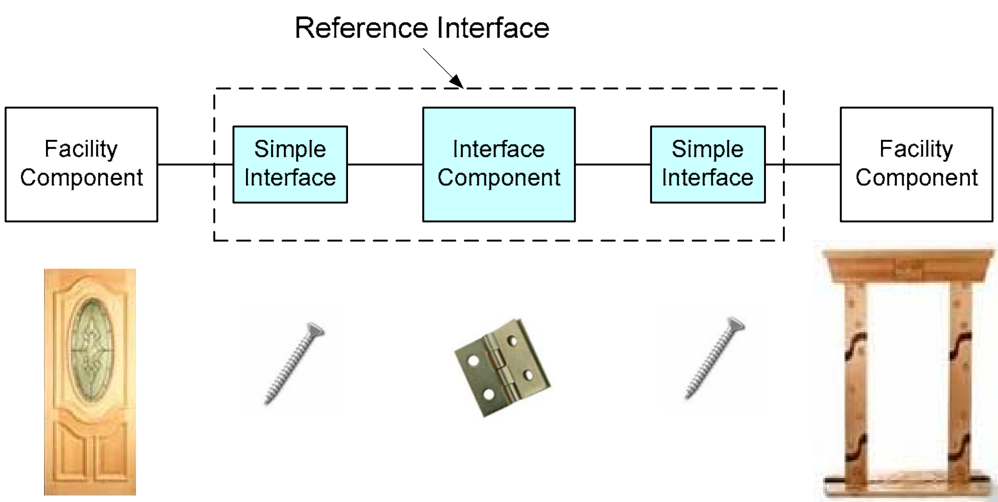


Figure 4-11: The Simple Type of Reference Interface

Figure 4-12 shows a compound type of reference interface, which comprises a chain of simple interfaces and interface components. A real-world example will be given in the next chapter during the model validation.

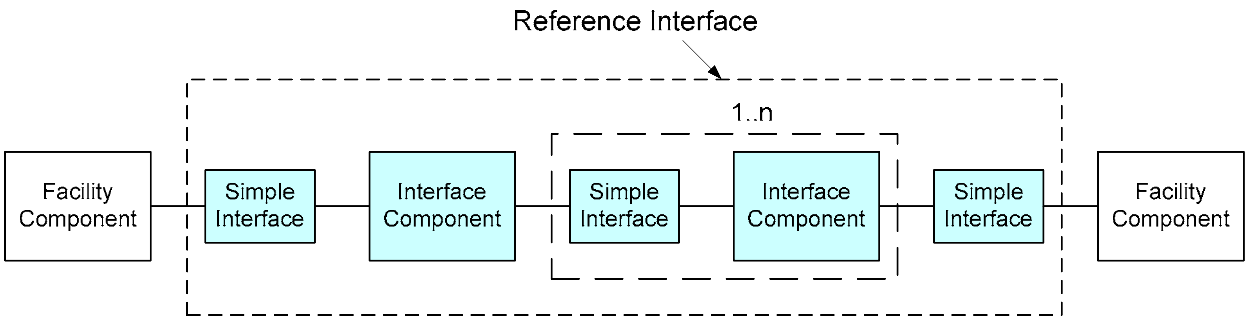


Figure 4-12: The Compound Type of Reference Interface

During implementation, users can freely choose some of these relational diagrams whose contexts are compatible with project conditions that they are going to model. Furthermore, users can also create their own relational diagrams based on any unique project conditions that they are facing.

Up to now, the development processes, sub-models, and examples for all the model components have been presented. Figure 4-13 shows a graphic view of the IOM framework as a whole. Here, each model component is illustrated by the corresponding diagram(s) developed by this research. The comprehensive framework provides not only guidelines for continued development but also precise examples showing what the developed model components may look like. Those detailed examples are very helpful for the model validation conducted in Chapter 5.

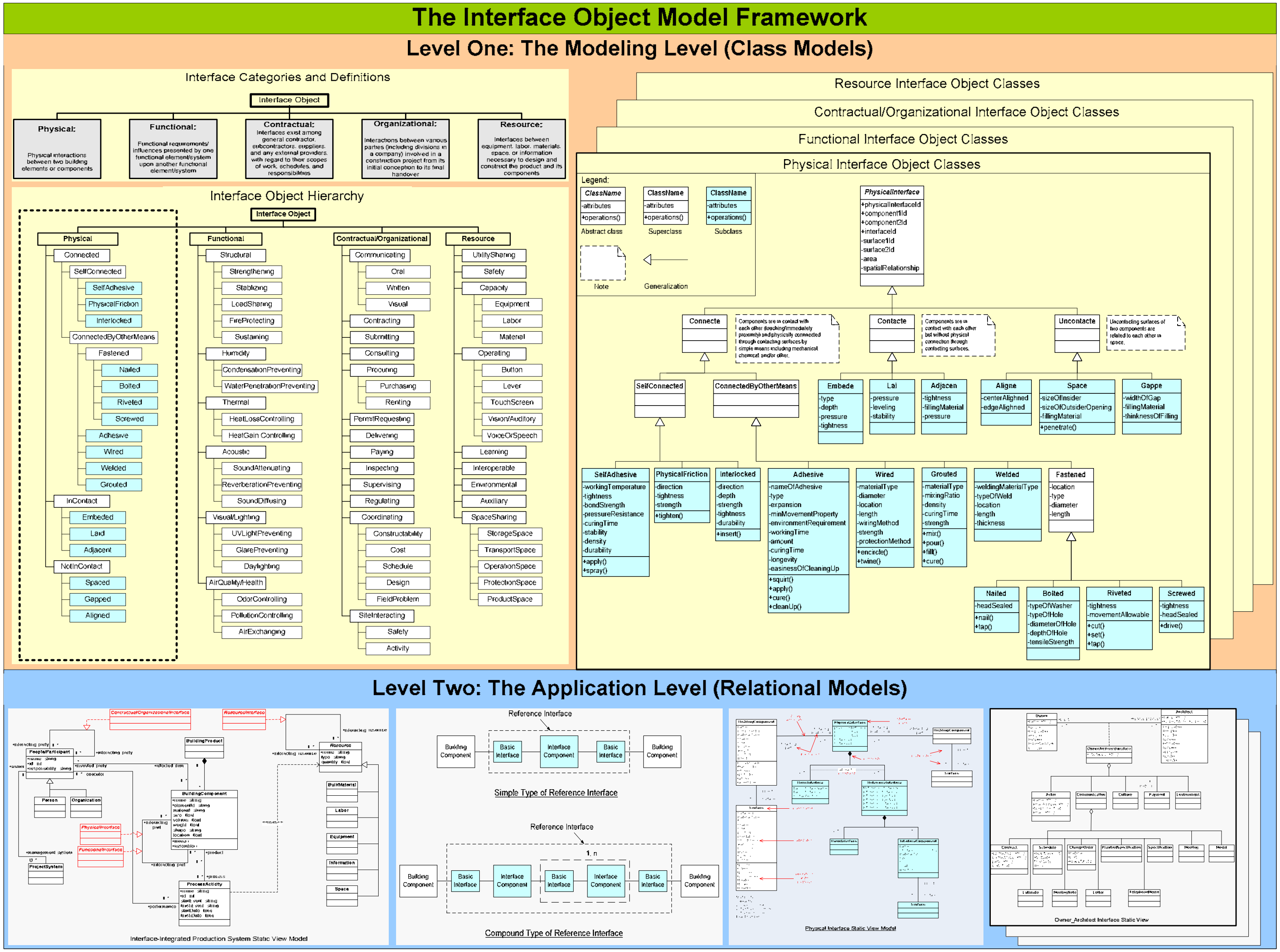


Figure 4-13: The Comprehensive IOM Framework

CHAPTER 5: INTERFACE OBJECT MODEL VALIDATION

In this research, physical interface modeling is chosen for validating the proposed IOM (Interface Object Model). This chapter first presents a decision-making model, which helps the user decide which physical interface object(s) should be used for modeling specific physical interfaces, and demonstrates how the decision-making process and detailed physical interface modeling can be performed. Then this chapter introduces the U.S. housing construction process and related interfaces. The focus is located on two complete construction processes. Based on the physical conditions occurring in these two processes, physical interface modeling is performed and presented to validate: 1) how the proposed interface modeling method works in complete construction processes under real-world conditions and 2) how effective the fully developed applicable physical interface objects are for the modeling.

5.1 THE DECISION-MAKING MODEL

The IOM validation implements two procedures:

- A decision-making model is first built and used to determine the appropriate physical interface object subcategories as well as applicable interface objects for modeling physical conditions.
- Physical interface modeling is performed in two complete construction processes. The modeling validates that various types of real-world physical interfaces can be modeled by using interface object classes identified in the IOM framework.

In this section, a decision-making model is presented. Then, a decision-making process is demonstrated by running one decision-making scenario. Finally, two modeling examples are given to illustrate how specific interface information can be added to instantiate the selected interface object classes.

5.1.1 The Decision-Making Model for Physical Interface Modeling

As shown in Figure 5-1, the decision-making model is actually a flow chart which displays a standardized decision-making process. The process involves six if-then scenarios and five possible outcomes. Those scenarios are “decisions,” each of which contains a Yes/No question usually leading to two arrows coming out of it, one corresponding to Yes, and one corresponding to No. For the physical condition to be modeled, the possible outcome of decision-making is the selection of one or more physical interface object subcategories among `NotInContact`, `Reference`, `Connected`, and `InContact` interfaces, and/or `Null` (i.e., the physical condition is not counted as a physical interface and only need be controlled by its geometrical information). How the decision-making process can be performed is explained in the next subsection.

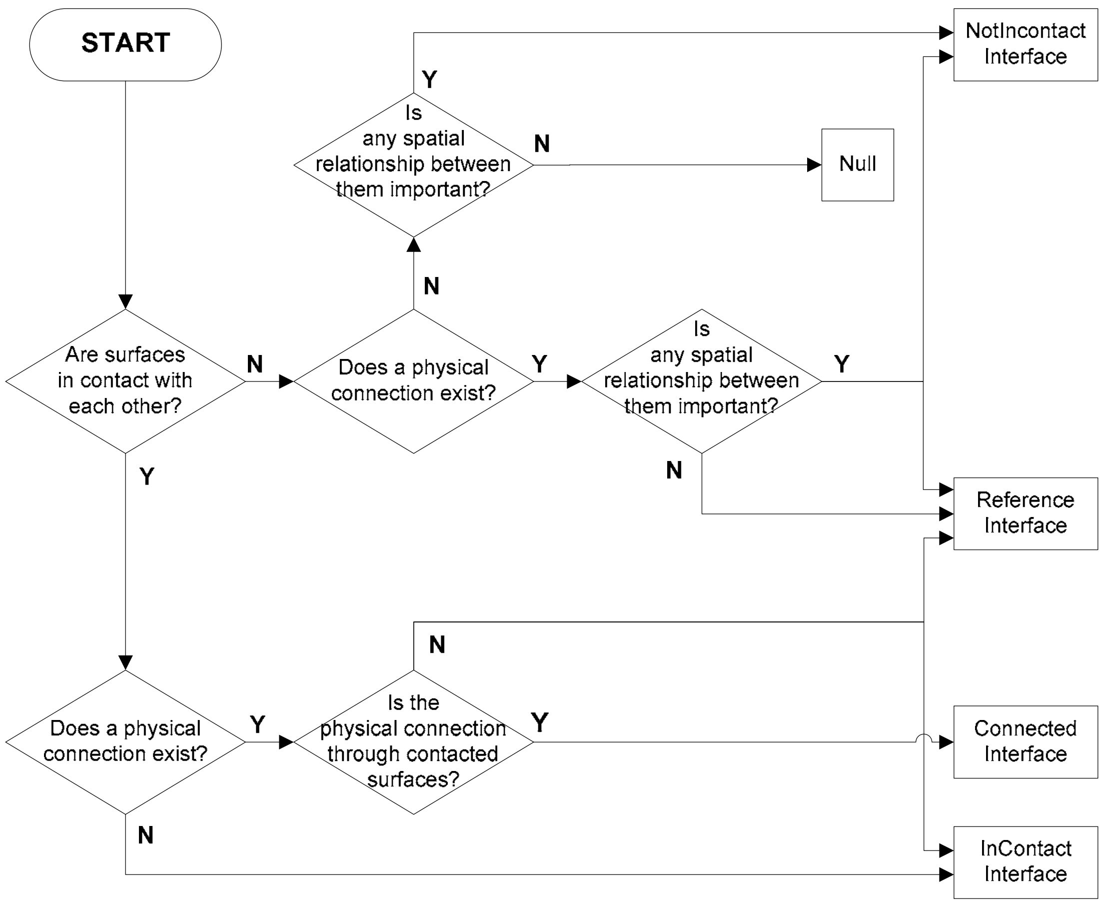


Figure 5-1: The Decision-Making Model for Physical Interface Modeling

5.1.2 A Decision-Making Scenario

In Figure 5-2, for demonstration purposes, physical interface object subcategories are given picture symbols to enhance understanding. All specific, applicable interface object classes identified in the IOM framework are listed near their subcategories. One decision-making scenario is run here to show how to select the appropriate interface objects for modeling a specified physical condition.

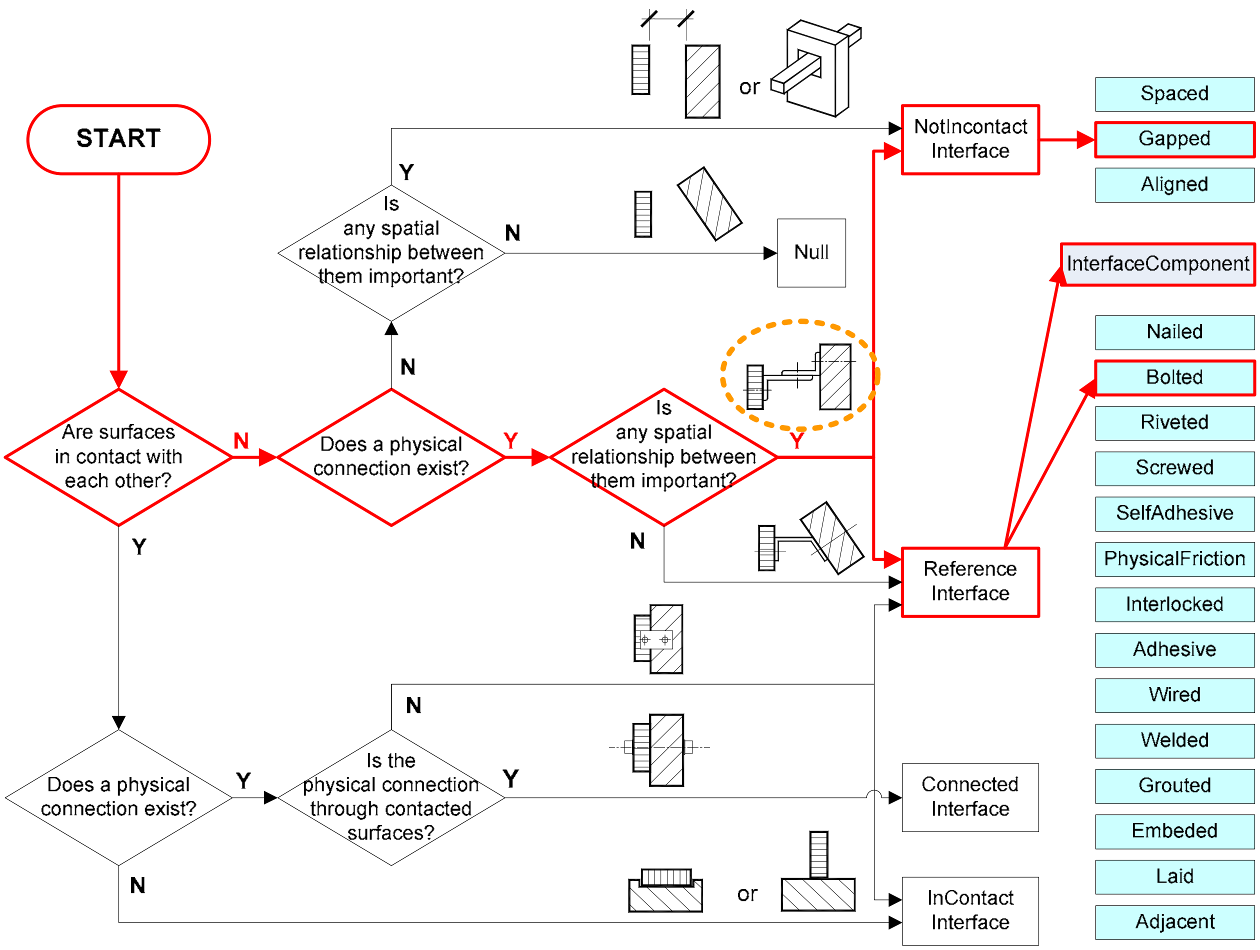


Figure 5-2: A Decision-Making Scenario

In the scenario, the physical condition in the dashed ellipse is chosen for demonstration. The decision-making process starts by asking the question: "Are surfaces (of the two facility elements/components) in contact with each other?" Apparently, the answer is "No," which leads to another question: "Does a physical connection exist?" According to the condition displayed, the answer should be "Yes," which results in the third test: "Is any spatial relationship between them important?" It can be seen that these two elements/components are put in parallel. The gap between them is very important and needs to be controlled, so the decision is “Yes,” which finally points to the `NotInContact` and `Reference` interface subcategories.

Under the `NotInContact` category, there are three identified physical interface objects. According to the selected condition, the interface object, `Gapped`, is chosen for modeling. When the `Reference` interface subcategory is involved, it means that additional interface components, in this case, two steel angles, are required. As displayed in Chapter 4, a reference interface should be modeled as a chain of simple interfaces and interface component(s). Here, `Bolted` is chosen to model the two simple interfaces among the facility elements/components and the steel angles. Figure 5-3 shows the modeling structure for this physical condition. Comprehensive interface information is not available at this stage.

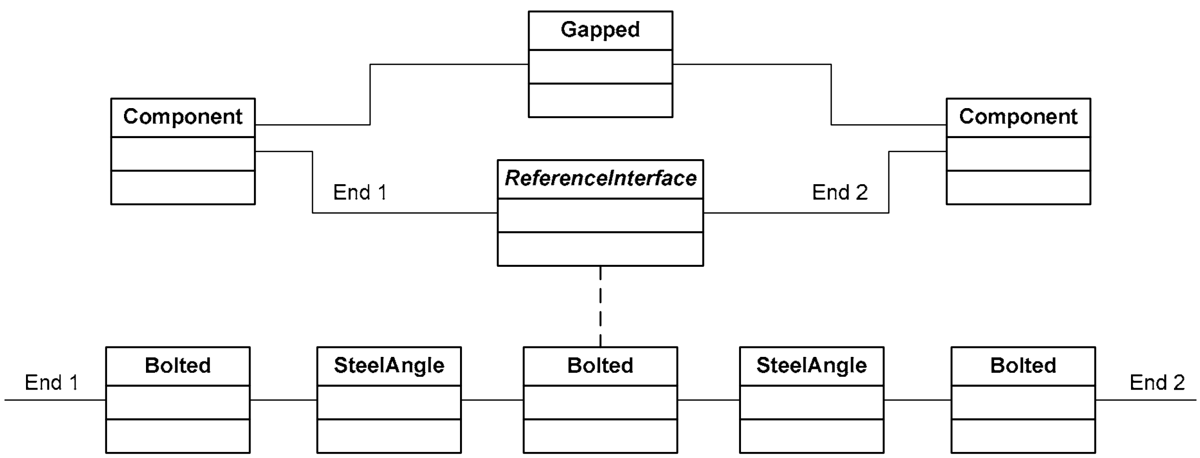


Figure 5-3: The Physical Interface Modeling Structure for the Selected Physical Condition

5.1.3 Interface Modeling Examples

In this subsection, two real-world physical interface examples chosen from a building façade project are presented for modeling. Detailed information displayed in the CAD drawings is added into the interface models for instantiation.

The CAD drawing of the first example (Figure 5-4) shows a bottom sectional detail illustrating how a piece of glass panel fits into a U-channel. There are two main facility elements or components. One is a 12mm thick clear glass panel; the other is a 3mm thick 40x34x40mm stainless steel U-channel. The other building materials involved include sealant, backer rod, and wood spacer. There are several wood spacers (300mm center to center) for each piece of glass panel. Backer rod is caulked in the two gaps between the glass panel and U-channel continuously. Sealant is applied on top. These materials are for filling purposes only, through which no permanent physical connection can be established. By following the decision-making process demonstrated above, the NotInContact interface object subcategory is first selected for modeling, then the Gapped interface object. In this research, the difference between the Gapped and Spaced interface objects is clearly defined:

- Gapped: The surface of a facility element or component is not in contact with the surface of another facility element or component, and a constant gap exists between these two surfaces. This gap needs to be specified in the design and also strictly executed and controlled during construction.
- Spaced: One facility element or component is providing a space to contain another facility element or component. No contact is required under most circumstances.

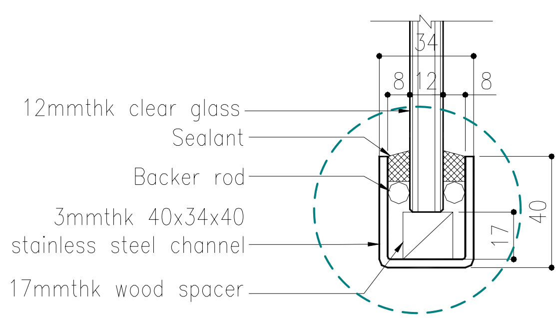


Figure 5-4: Glass Panel Bottom Sectional Detail

Accordingly, the interface modeling is performed and displayed in Figure 5-5. Properties of the glass panel and U-channel are neither listed nor specified here. This information should have been modeled in the concerning object-oriented building product model, where, however, operations with methods on these facility elements or components are usually not modeled. For the two interface objects, all properties including component ID, surface ID, area, spatial relationship, width of gap, filling material type, etc. are specified. Operations are also briefly described. This supplements the project information provided by the traditional building product model and helps automatic interface coordination and control. In this example, the two interface objects have the same type—`Gapped`. But their simple interface IDs, GP001 and GP002, are different, which helps distinguish one from the other.

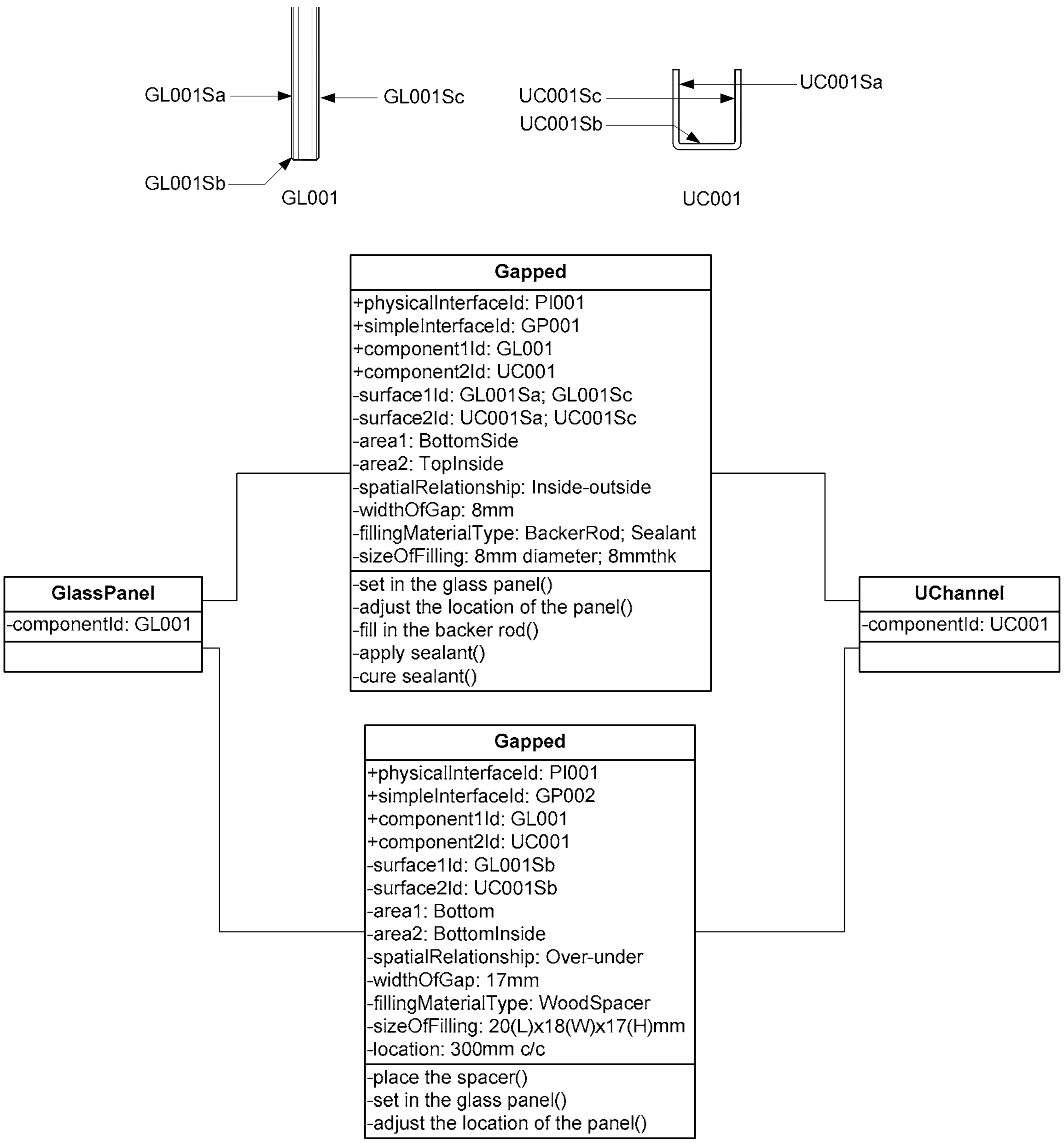


Figure 5-5: Interface Object Modeling Example I

The second example (Figure 5-6) shows how a piece of granite panel is attached to a concrete column. Besides the main facility components (the stone panel and the concrete column), additional components include 6x60mm stainless steel dowels and 55x35mm 30mm wide stainless steel bent angles. Usually, each piece of granite panel is restrained in four places, two at the top and two at the bottom. The dowels are inserted into pre-formed or onsite drilled mortises or holes positioned in the center of the thickness of the stone panel. These mortises or holes should be at least 75mm from any corner.

As shown in the CAD drawing, the restraint dowels are fixed into the holes by wood chips and the embedment is 25mm, greater than the minimum 20mm. Each bent angle has two slot holes to accommodate any deviations during construction. Once position is determined, the dowel is welded with the angle which is attached to the concrete column by one M10 expansion bolt. Those additional components as well as the expansion bolt are displayed in a 3D perspective view on the left of the diagram.

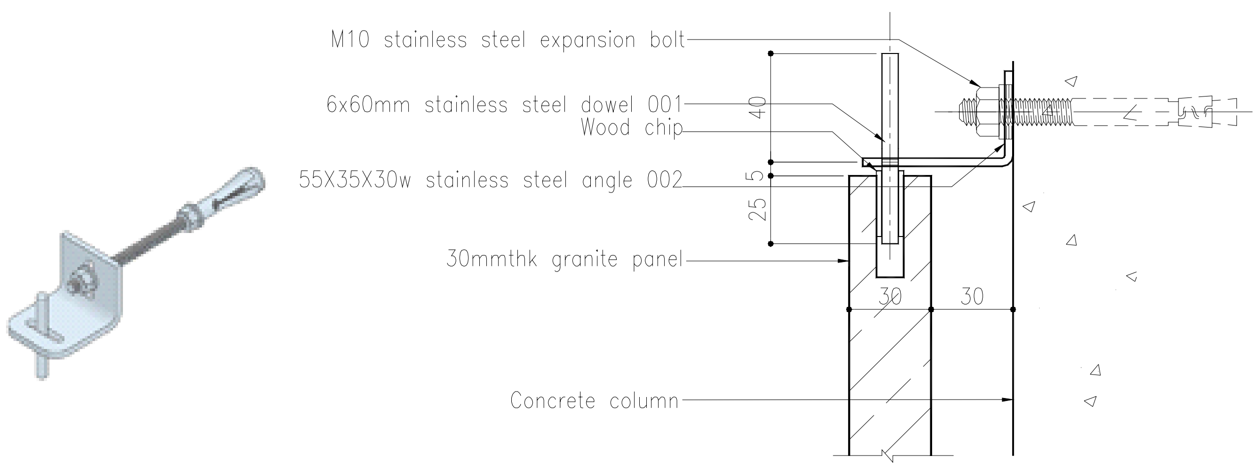


Figure 5-6: Granite Cladding Detail

According to the decision-making process, this physical interface can be modeled by one basic interface and one reference interface. The simple interface, referring to the constant 30mm gap between the granite panel and the concrete column, is modeled by the `Gapped` interface object. The reference interface, referring to the connection between the panel and the column through restraint fixings, is modeled using three simple interface objects (`Grouted`, `Welded`, and `Bolted`) and two additional interface components (the stainless steel dowel and the stainless steel angle). The expansion bolt is one type of standard fastener and belongs to the `Bolted` interface object; therefore it is not considered an individual interface component. The pertinent interface modeling is displayed in Figure 5-7.

These two examples successfully illustrated:

1) How the appropriate interface object subcategories and applicable interface objects for the selected physical condition can be determined through the proposed decision-making process.

2) How the graphic-based, detailed physical interface information can be modeled using the object-oriented modeling method.

Besides these individual examples, in the following, the IOM validation is performed in broad construction contexts—relatively complete construction processes. If the physical interface modeling is proven workable, it can be assumed that the other four types of interfaces can also be accurately modeled after relevant applicable interface objects are defined. Due to the complexity of the IOM validation in complete construction processes, the modeling only stays at a level where the applicable interface objects are identified but not instantiated by recording detailed project information.

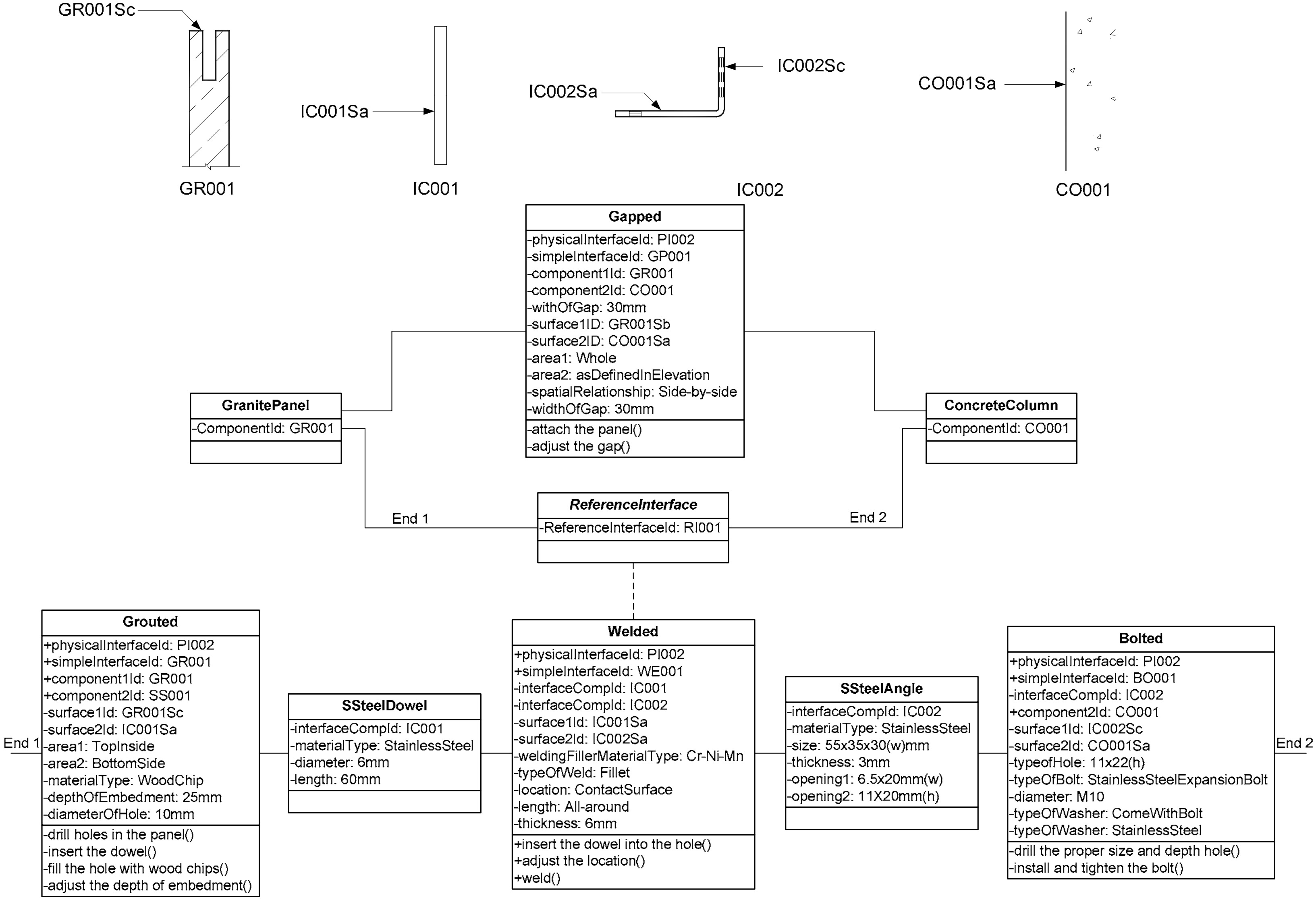


Figure 5-7: Interface Object Modeling Example II

5.2 IOM VALIDATION IN SELECTED HOUSING CONSTRUCTION PROCESSES

Although this research aims to deal with overall interface issues in general construction contexts, it chooses housing construction as its specific background for extended discussions, real-world examples, as well as model validations. The reasons are:

- Housing construction represents a large and very important portion of the U.S. construction industry.
- The homebuilding process is comparatively simpler than commercial construction. Interfaces are easier to identify and monitor. Homebuilding can be a paradigm for other complex types of construction.
- Due to the mass production of similar single-family houses and townhouses, IM strategies to be developed can be used repeatedly and widely. Timely and broad feedback can be obtained for future development.

5.2.1 The U.S. Housing Construction Process

As aforementioned, in the U.S. housing construction industry, *stick-build* is still the prevailing form of “industrialized” housing. This is a traditional craft-based homebuilding process, which is labor intensive, long lead-time, and subcontractor-based. Figure 5-8 models the operation of the stick-build homebuilding process in a UML use case diagram.

In this example, 27 sub-processes, from *Excavate Footer* to *Occupation*, were identified. They were performed in a sequence. There were 21 subcontractors in total hired to build a house. They entered the process at different points in time and conducted one or more sub-processes. For example, the excavation subcontractor excavated the footer first, and came back later for backfill. Sometimes, two subcontractors such as the framing subcontractor and lumber supplier performed the same sub-process. To keep a smooth production and avoid potential conflicts among them, close communication and coordination is essential.

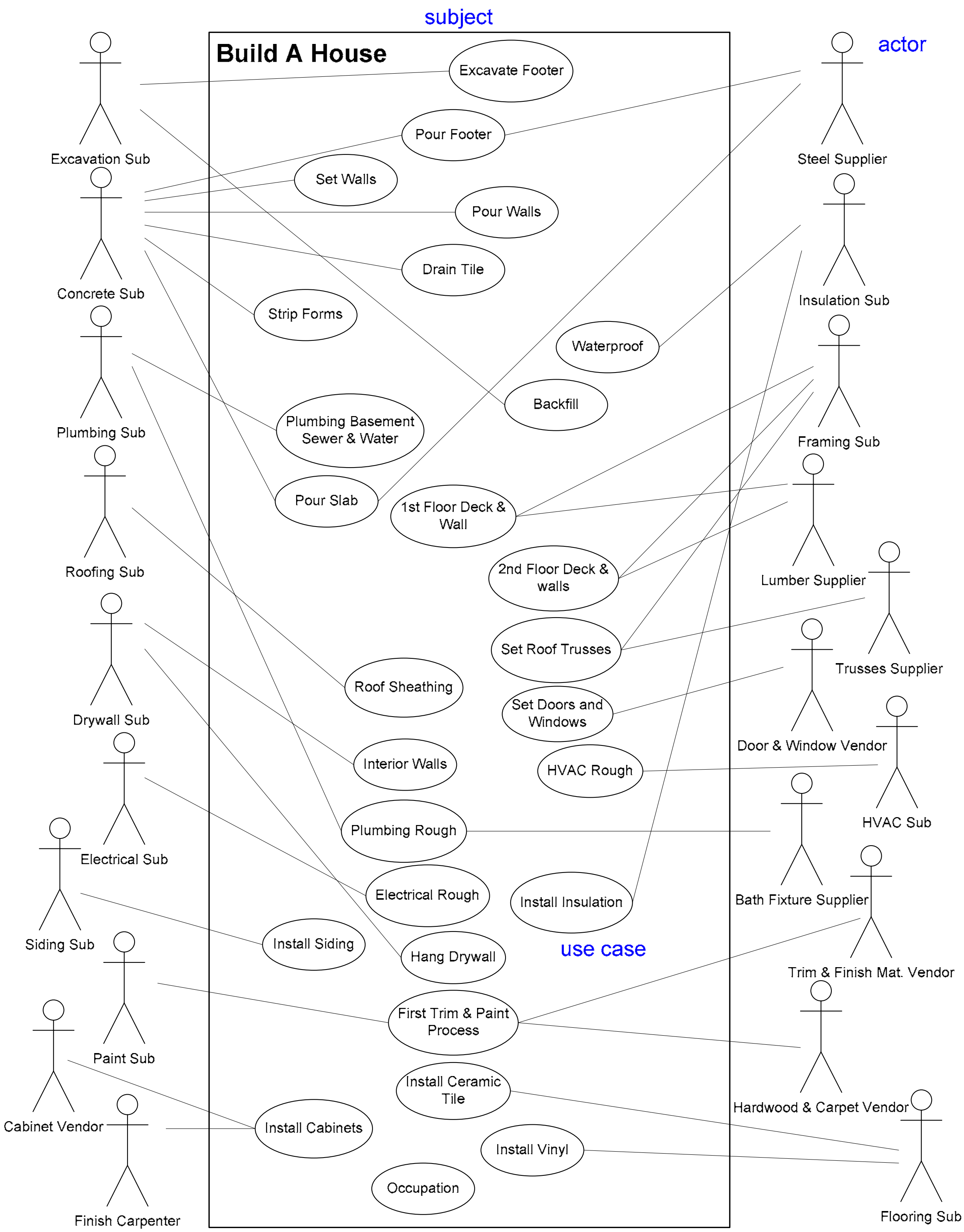


Figure 5-8: Use Case Diagram for the Operation of the Homebuilding Process

Figure 5-9 shows detailed interactions among the main project participants in a homebuilding process. Part of the information is derived from a project report by Lewendowski (2002). In the diagram, the participants were listed at the top of the diagram. They were the customer, builder's sales person, regional office, and superintendent, subcontractors, suppliers, regulators/inspectors, as well as a virtual participant—web schedule. From top to bottom, the project evolved over time. Seven project stages were specified as pre-construction, foundation & basement, framing, HVAC, plumbing & electric, interior & finishes, environment, and completion. Communications or interactions were monitored as arrows with specific descriptions, such as "*give the written house package*" or "*call to schedule the window and door placement*." As expected, the most intensive communication occurred between the superintendent and subcontractors. The innovative web schedule automatically responded to inquiries. To some degree, it helped reduce the coordination responsibilities the superintendent took, and therefore became a facilitator of close and instant communication and coordination.

In the traditional homebuilding process, a large number of physical interfaces occur. They are mainly among raw materials, such as concrete, steel, framing lumber, sheathing boards, etc. These interfaces are pretty simple and familiar to most construction people. As shown in Figure 5-10, a five-carpenter crew could handle the framing process with ease. Here, quality control was quite easy since interface operations were simple and physical interfaces were exposed in an open building system. Also a high flexibility for adjustment and correction existed. Therefore, technically, physical interface management and control in the traditional homebuilding process are not so hard to perform. The lack of IM is the main problem that leads to physical interface failures and poor quality of the house being built.

With the increasing use of manufactured building components and subsystems, it is assumed that the homebuilding process can be conducted more efficiently and the quality of the house being built should be greatly enhanced. Nevertheless, the reality is not that ideal. Numerous problems happen while handling physical interfaces between those components or subsystems.

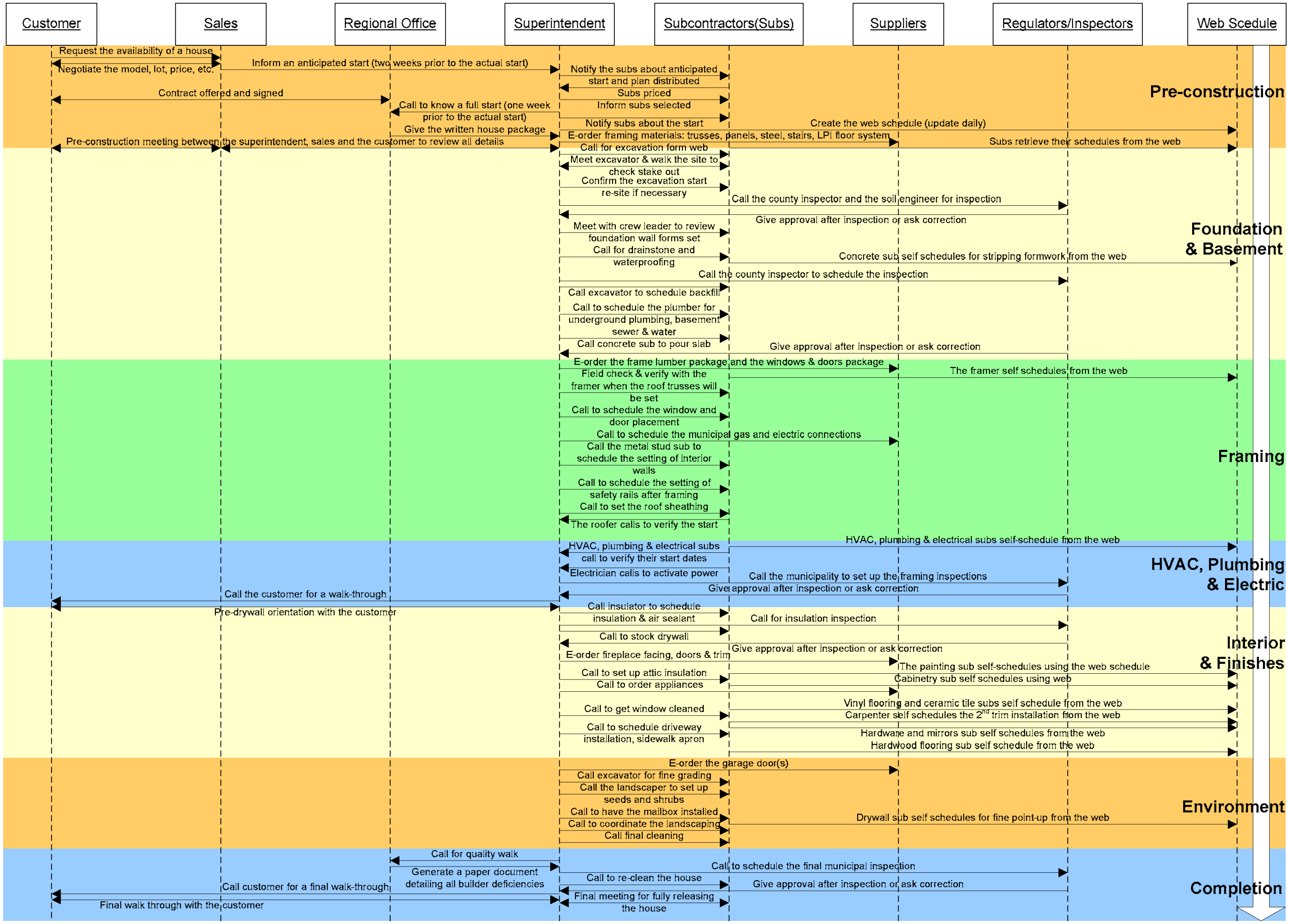


Figure 5-9: Sequence Diagram for Interactions Between Participants in a Homebuilding Process

Figure 5-10: “Stick-Build” Framing Process

Actually, factory-made components and subsystems increase the complexity of physical interfaces during installation. Both the superintendents and workers are not familiar with how to control those interfaces. In addition, the flexibility for adjustment is reduced compared with that in the stick-build process. As a result, numerous physical conflicts occur and the installation process is often times interrupted and delayed. Figure 5-11 displays some typical physical interface failures in the homebuilding process. These failures involve factory-made components, such as integrated wall panels, floor decks, roof trusses, and interior metal-framed walls.

This research performs physical interface object modeling mainly in two selected housing construction processes which involve a large number of factory-made building components. Here, the main purpose of IOM validation is to demonstrate that the identified physical interface objects are capable of modeling physical interfaces in complete construction processes. To keep the model simple, detailed information specifying each physical interface is not provided.

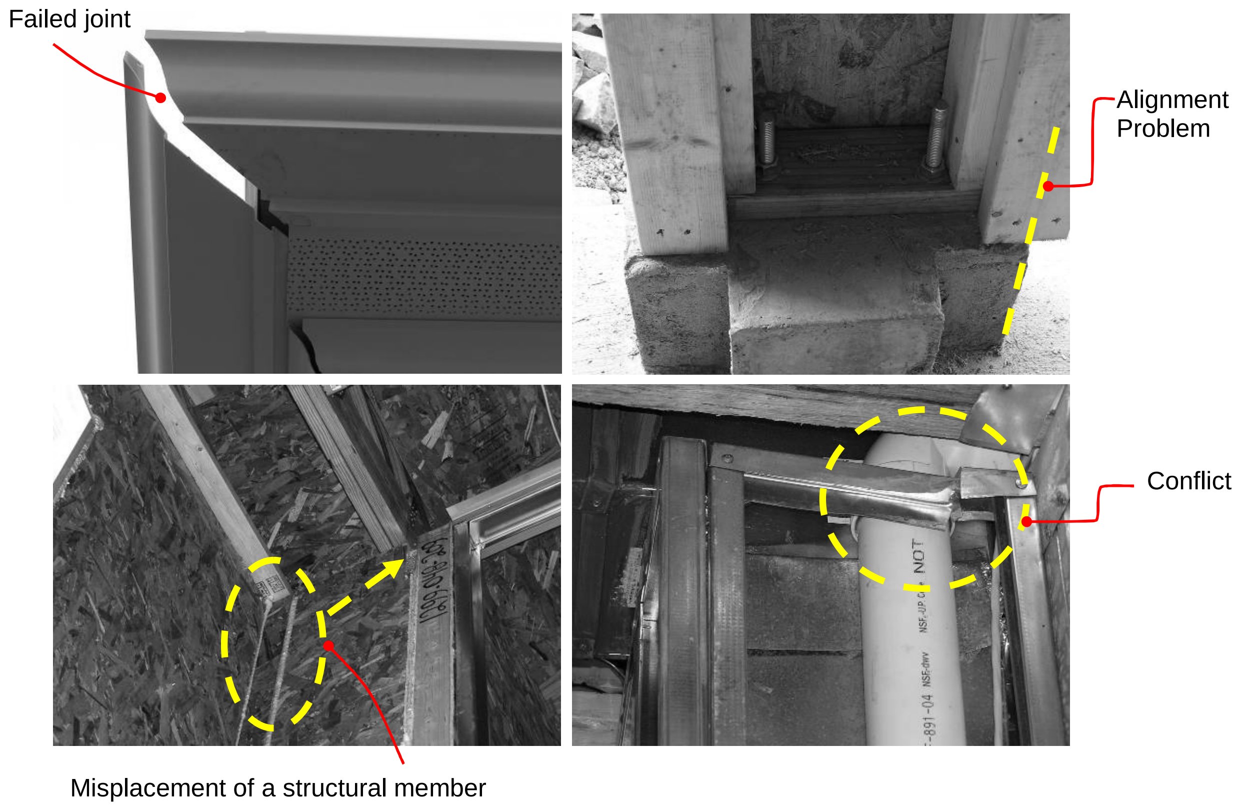


Figure 5-11 : Typical Physical Interface Failures

In the following subsections, the two selected housing construction processes, *foundation wall installation* and *componentized superstructure framing*, are briefly introduced. Interfaces within them, especially physical interfaces, are discussed respectively. Choosing the housing construction processes for validation does not limit the IOM's capability to model interfaces in any other type of construction. On the contrary, it facilitates better understanding and accurate application.

5.2.2 Foundation Wall Installation

To help the holistic understanding of foundation wall installation and componentized superstructure framing processes, this research conducted case studies in construction projects of a large national homebuilder. Figure 5-12 provides an overall structure of housing foundation and superstructure subsystems based on the author's observation and understanding.

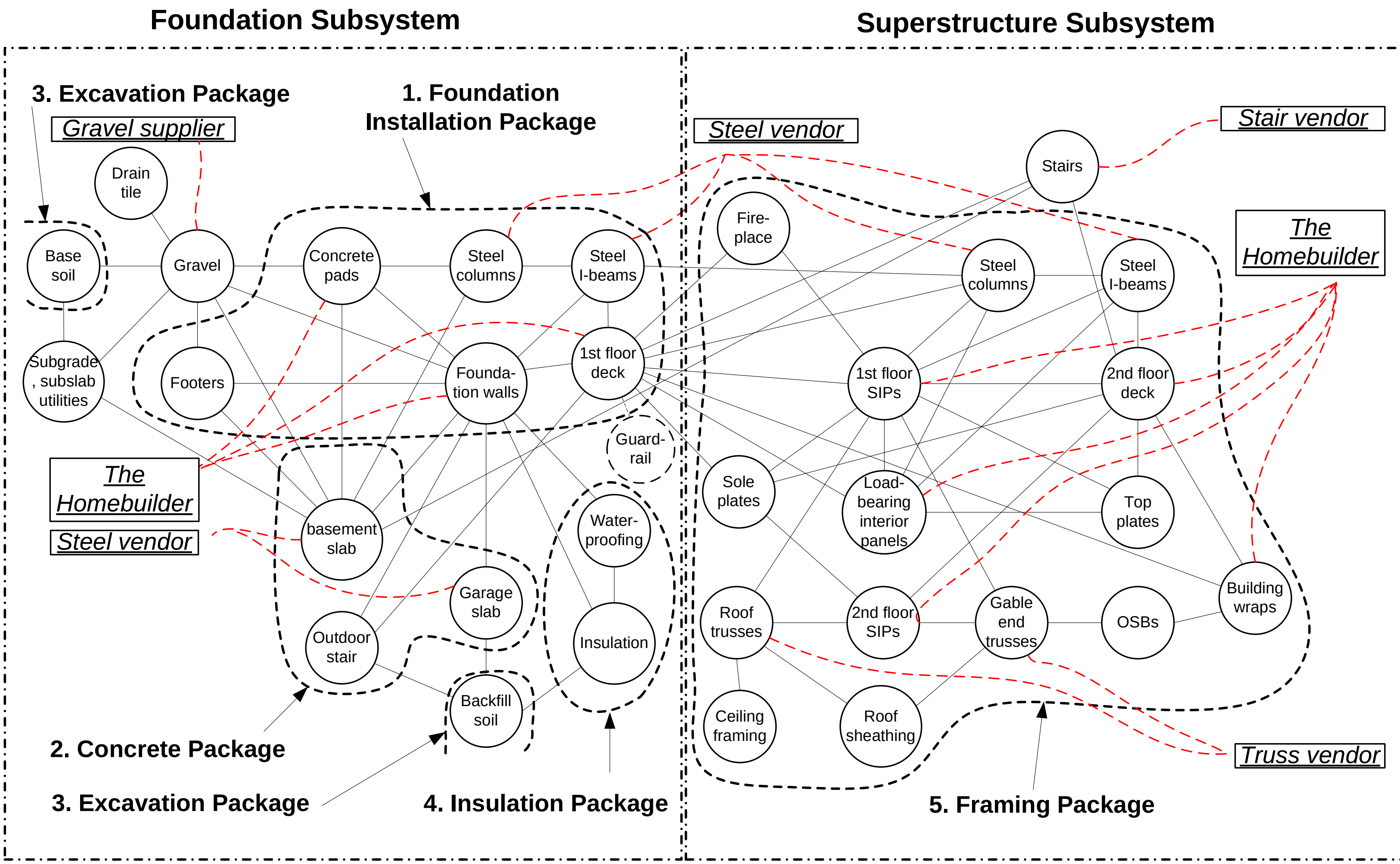


Figure 5-12: Overall Structure of Foundation and Superstructure Subsystems

In the diagram, facility elements and components in the foundation and superstructure subsystems are displayed in circles. Their physical interfaces are represented by solid lines. Areas marked by the dashed line denote workpackages awarded to different subcontractors or suppliers. By breaking interfaces and interface responsibilities, workpackaging creates the weak points of quality and increases the difficulties of coordination. In this chapter, discussions are restricted primarily to physical interfaces.

5.2.2.1 Foundation Wall Installation Process

The foundation wall installation process is within the scope of the *foundation installation package*. It represents onsite assembly of pre-cast high strength concrete foundation walls and the first floor decks. The foundation walls basically consist of an exterior face shell, a top ledger and a bottom ledge, and vertical studs every 610mm on center. The wall panels also integrate dampproofing, openings for small plumbing and electrical fixtures, windows, and doors. They can be quickly connected within a day with a higher precision than the traditional block or poured-in-place foundation walls. The pre-cast foundation walls require pre-cast concrete round footers and square pads instead of cast-in-place concrete footers. Once properly installed, the foundation system will be plumb, level, square and has fewer cold conduction and water leakage problems.

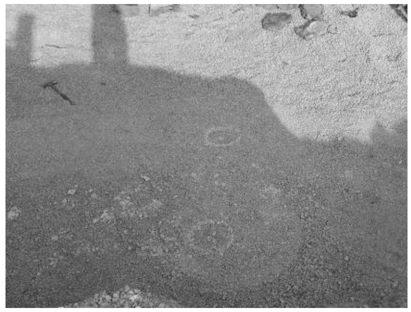
The installation can be started when foundation excavation has been completed and foundation drains, sub-grade and sub-slab utilities, and gravel (or crushed stone) are in place. The installation procedures are listed below and illustrated by photos:

Deliver pre-cast foundation walls to the job site by truck

Deliver footers to the job site

Set up the crane

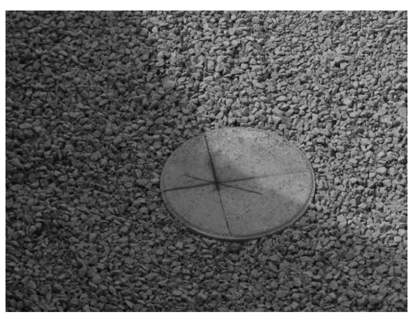
Mark the primary layout of the foundation and the location of footers



Tamp and level the gravel (or crushed stone)

Install footers and concrete pads

Mark the layout of the foundation



Lift the foundation walls into place piece by piece (starting from the corner panels)

Bolt the walls together by three 12.7x140mm galvanized standard grade bolts per connection

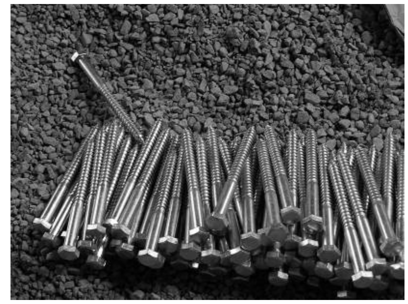
Install steel columns and I-beams

Apply polyurethane caulk to bond walls at joints

Apply polyurethane caulk on the upper surface of top ledgers and lift the first floor decks into place piece by piece

Adjust precision of the floor plan

Bolt the sill plate of floor decks and the top ledger of the wall panels with 15.9mm lag bolts placed 305mm on center



Nail floor decks together by adding additional lumber bracing below the floor decks

Install the temporary guardrail around the stair opening

5.2.2.2 IOM Validation

Based on the foundation subsystem structure and installation procedures presented above, the involved facility components and their established relationships are modeled by a UML diagram as shown in Figure 5-13. The floor decks and foundation walls, which are composed of facility elements or sub-components, are enriched with proper detail. The specific function that one component performs for the other related component is also summarized. As shown in the diagram, the most prevailing function is "*support*." For some facility components such as the floor decks and foundation walls, which also connect with themselves to form an assembly, their functions are defined as both "*component*" and "*assembly*." This model becomes the foundation for the interface model to be created for the foundation wall installation process.

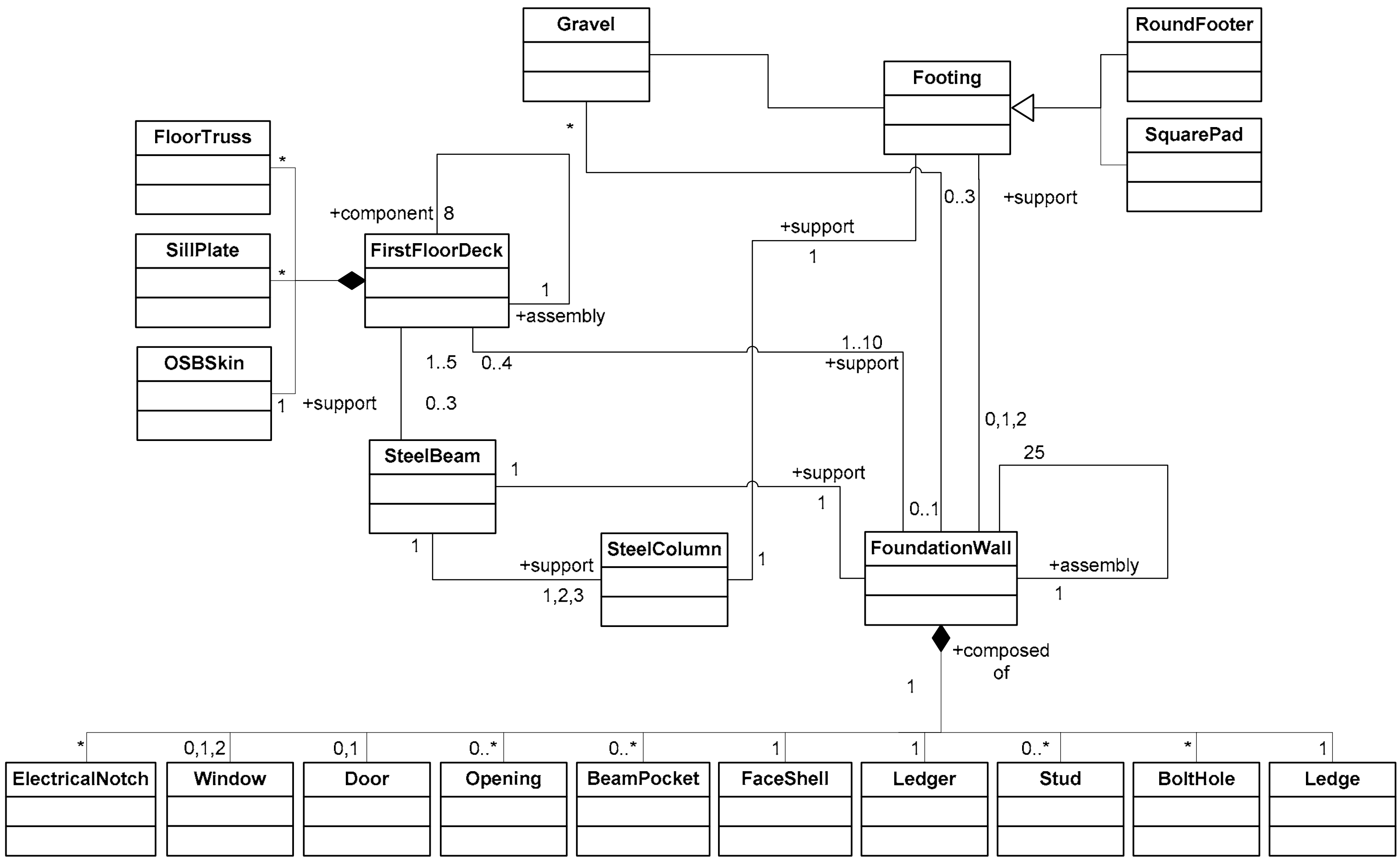


Figure 5-13: Facility Components and Their Relationships in Foundation Wall Installation

By running the decision-making model numerous times, this research is able to determine proper applicable interface objects for modeling all physical relationships occurring in the foundation wall installation process. Incorporating these interface objects with the UML model in Figure 5-13, this research generates an interface model for the foundation wall installation process. Here, two facility components do not point directly to each other. A kind of many-to-many objectified relationship, the interface object(s), is inserted between them. To keep the model readable for this validation, all of the interface objects (highlighted in the diagram) are not instantiated; i.e., no detailed information concerning attributes, operations with methods, etc. are added to them. The instantiation has to be done before this model can be implemented to coordinate and instruct the real-world construction.

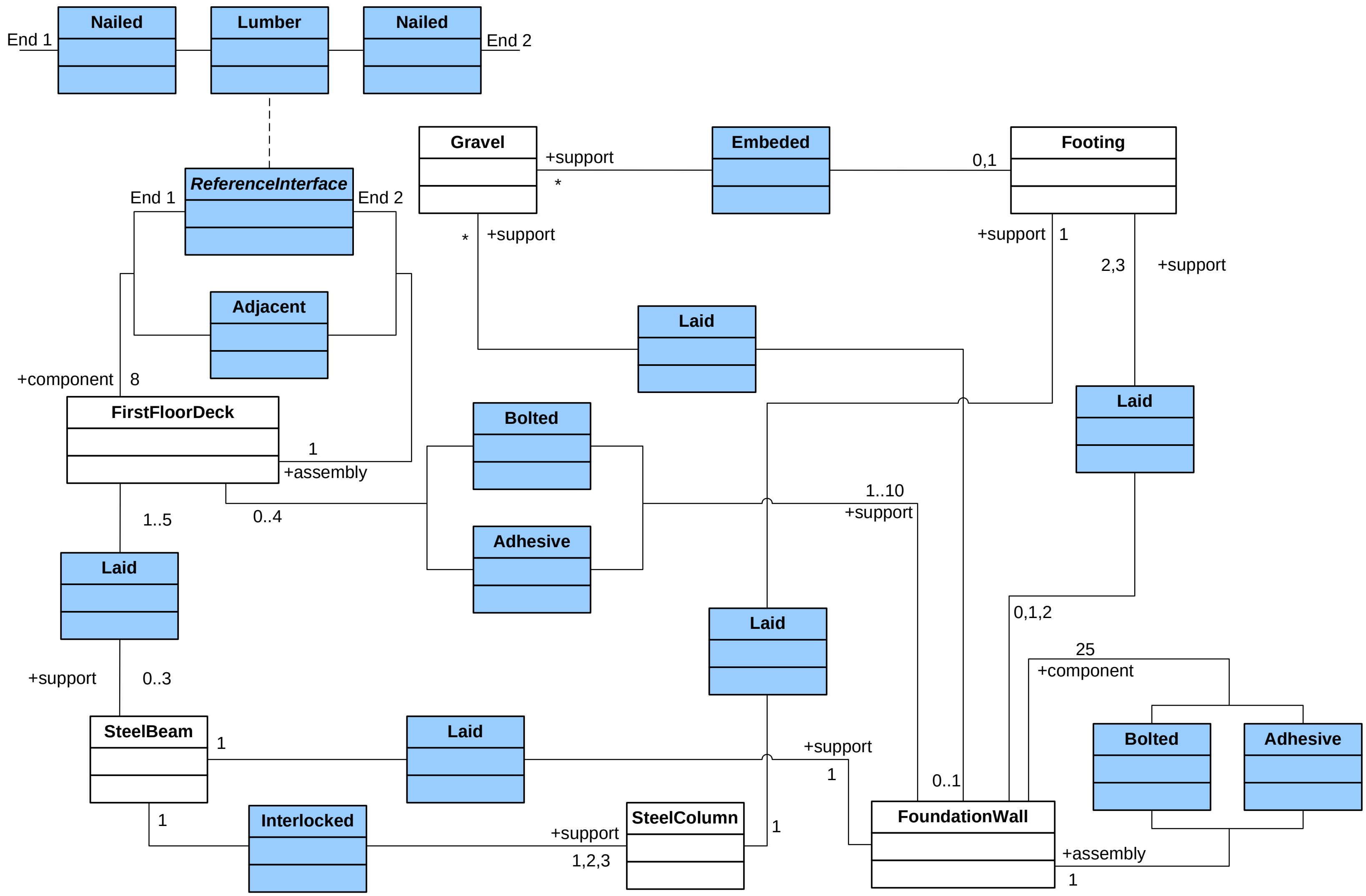


Figure 5-14: Interface Object Model for Foundation Wall Installation

5.2.3 Componentized Superstructure Framing

5.2.3.1 Componentized Superstructure Framing Process

The componentized superstructure framing process is within the scope of *framing package* in the superstructure subsystem. The process employs factory-made exterior integrated Structural Insulated Panels (SIPs), interior metal-framed panels, floor decks, roof trusses, and Oriented Strand Boards (OSBs). The integrated SIPs are a composite building material, which incorporates OSB structural skins, polystyrene or polyurethane foam insulation, doors, windows, electrical chase, and weatherproofing wrap. They offer better quality and performance than the traditional site framed walls due to being manufactured in the well-controlled factory environment. During installation, trained labor is required to handle complex physical interfaces among SIPs and other facility components. For a typical 3,000 square feet single-family house, the process normally takes three days for an eight-person crew and a crane to finish.

The framing process can be started after the foundation subsystem is finished. The framing procedures are listed below and illustrated by photos:

Deliver exterior wall panels, interior wall panels, floor decks, and other building materials to the jobsite by truck

Set up the crane

Nail the OSB sheathing on gable end trusses and attach building wraps (sometimes, eave trusses are attached to the gable ends)

Install the sole plates for the first floor wall panels

Apply sealant on the sole plate

Lift the first wall panel into place

Nail the panel with the sole plate

Install the temporary lumber bracing

Install other wall panels on the first floor piece by piece and nail or screw them together

Lift the stack of interior metal-framed walls onto the first floor

Install the metal-framed walls

Install the top plates on interior walls

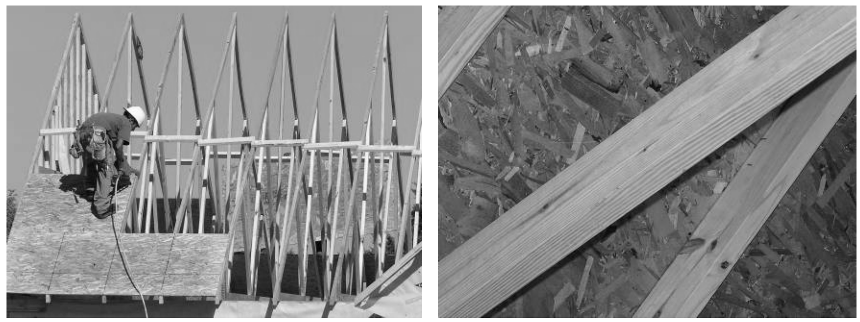
Install the first floor steel columns and beams

Lift the second floor decks into place

Install the second floor wall panels

Install the roof trusses (starting from the gable end)

Nail the roof sheathing on the trusses



Install final roof trusses and sheathing

Install wall panels for garage

5.2.3.2 IOM Validation

Based on the basic structure of the superstructure subsystem and the described installation procedures, a UML model (Figure 5-15) is generated to monitor the physical relationships among involved facility components and elements in this assembly process.

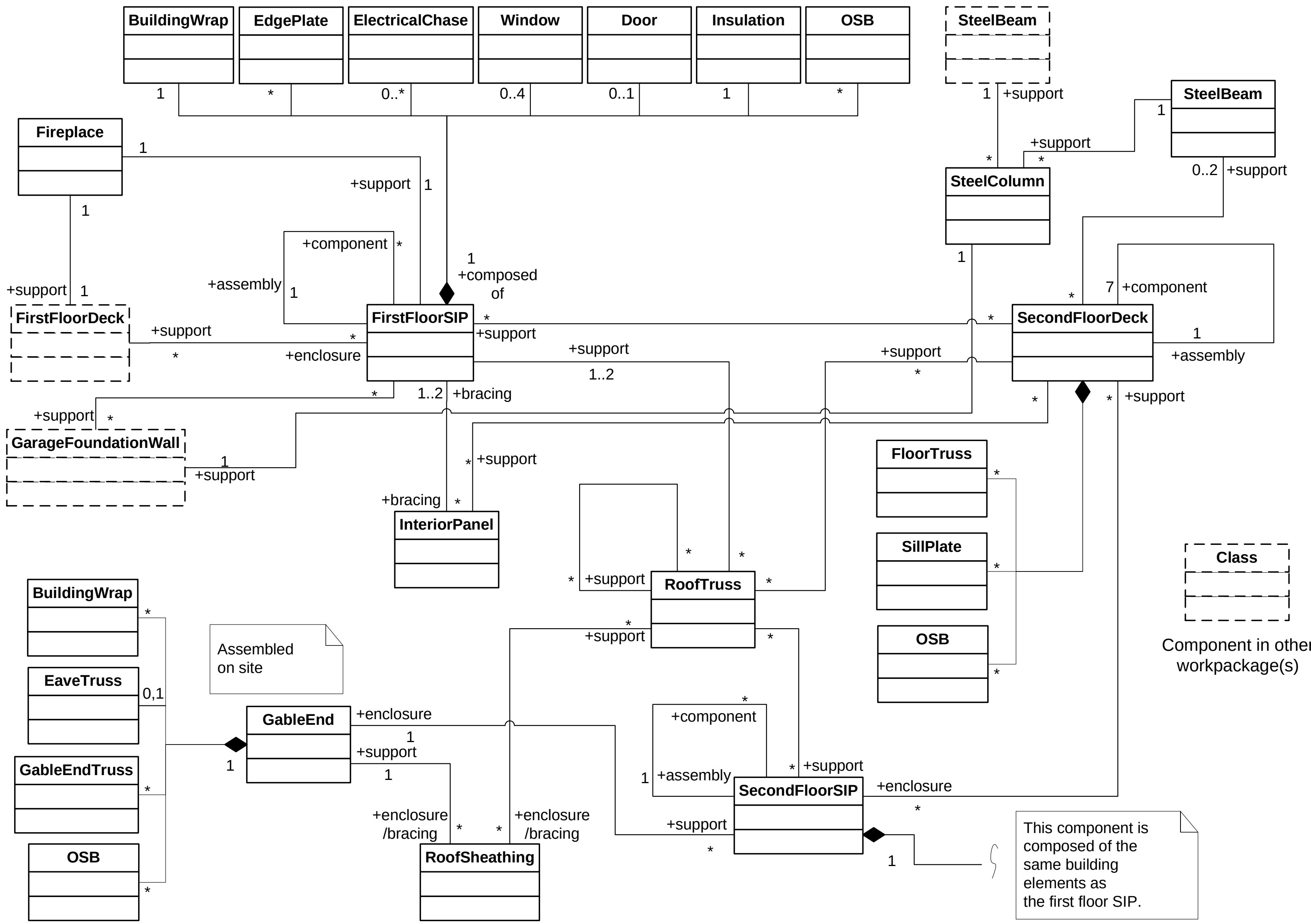


Figure 5-15: Facility Components and Their Relationships in Componentized Superstructure Framing

In this diagram, facility components in the componentized superstructure framing process are displayed as solid line class boxes. The facility components displayed in the dashed line boxes belong to other workpackage(s). Because the components in the presented process are closely related to these components, their relationships need to be modeled as well. There are three facility components—the (first or second floor) SIP, the second floor deck and the gable end—in the process that are composite building materials. The model also illustrates what they are composed of. Among them, the gable end is actually assembled on site in this case. However, it should be able to be assembled in the factory to save time and enhance quality. The truss is easily deformed on the job site if it is not stored properly.

Using the same interface modeling procedures as for the foundation wall installation, the physical interface modeling is performed for componentized superstructure framing. As shown in Figure 5-16, the interface objects in this model are also not instantiated for the sake of simplicity. However, their modeling capability is evident.

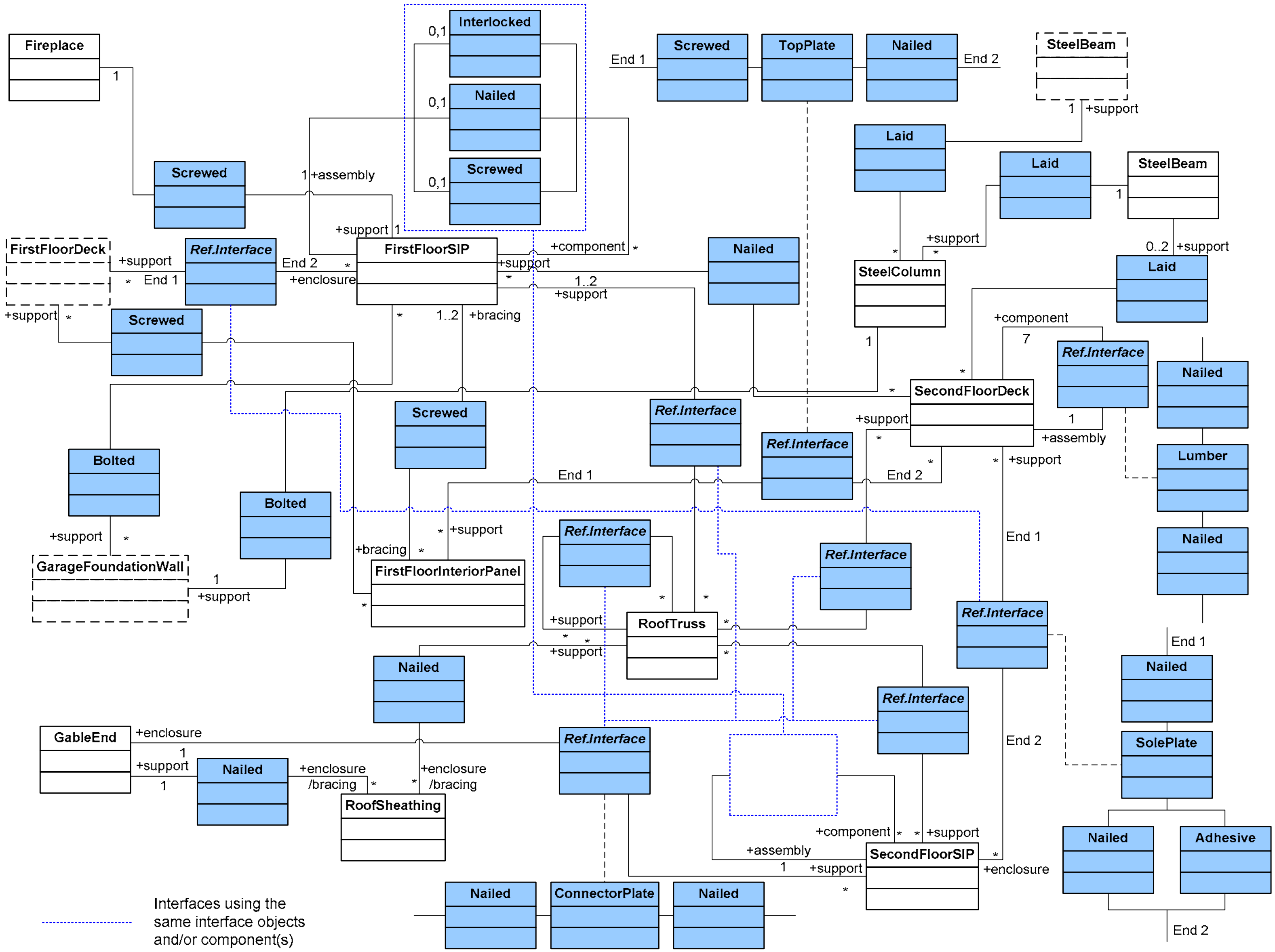


Figure 5-16: Interface Model for Componentized Superstructure Framing

5.3 BENEFITS AND POTENTIAL APPLICATIONS

The IOM data structure and interface object modeling method offer some benefits for presenting comprehensive interface information which can enhance current building information models (BIMs). Furthermore, potential model applications in the design and construction phases will greatly improve overall project performance. Further explanation is presented below.

Firstly, the IOM and related interface object modeling provide a unified presentation of interface information in the greatest detail. Through the validation of physical interface modeling in building façade project examples and completed housing construction processes, it can be proven that the proposed IOM works in real-world construction settings. Modeled interface information is more accurate, and can be easily stored, exchanged, and applied to IT applications.

Secondly, the IOM enhances the completeness of modeled interface information in two respects. On the one hand, it supplements the IFC object model, which is not capable of presenting comprehensive interface information due to lack of a data structure for interface information. The IOM is able to be seamlessly incorporated into the IFC as an added layer. As a result, all product models based on the IFC will be given the capability to model comprehensive interface information. On the other hand, through the concept of reference interface, the IOM can model additional interface components. This will provide an interface components material list for procurement. Such a list is often missed in current construction projects.

Thirdly—and perhaps the most significant future impact—this interface object modeling method allows interface analyses during the design and construction phases. These interface analyses, never existing before, can test different design solutions and the incorporated types of interfaces in design and construction against risk, cost, time, and any other management concerns. Potential applications may include but are not limited to:

- **A design tool for improving construction performance through interface optimization:** Physical interface modeling in the design phase can help track the total number of interfaces, the involved interface objects, and the additional interface components. Optimization can therefore be performed by minimizing the number and the complexity of physical interfaces in a project. Although the number is not a sole standard for judging the complexity of interfaces, it can provide very important information for such a judgment. For example, in the design phase, by selecting factory-made facility components instead of raw building materials, designers can effectively reduce the number of interfaces that need to be specially designed and executed later on the construction site. Consequently, interface related operations will be limited; quality control and IM can be easier.

- **A structural method to determine interface-friendly workpackaging and subcontracting**: Through interface object modeling, different types of interfaces between or in relation to two facility components can be monitored. According to the complexity of such interfaces, it will be determined whether these two components can be separately assigned to different workpackages and built by different contractors. Usually, interface-friendly workpackaging and subcontracting attempt not to break complex interfaces in construction projects. This can avoid intensive information coordination and interactions across boundaries of project participants.
- **An enhanced view for BIMs:** Interface object modeling adds detailed interface information to current BIMs for simulation and coordination. This greatly enhances the BIMs' completeness and capability of coordinating and controlling interfaces. Especially for visual 4D models which incorporate 3D CAD models with construction activities to display the construction progress over time, detailed interface information will help trigger sequential construction activities only when the prerequisite conditions for specific interfaces are satisfied. The enhanced simulation will provide more accurate project progress over time in the real-world construction setting or environment. Based on such models, the breadth and depth of coordination can be increased. Project performance in terms of interfaces will be optimized.

CHAPTER 6: SYSTEMATIC MODEL-BASED INTERFACE MANAGEMENT

This chapter presents a conceptual, systematic model-based interface management (IM) strategy for integrated project delivery (IPD), especially design-build that facilitates extensive interface information sharing, coordination, and provides the best opportunity for BIM approaches. This strategy provides a good foundation for creating an implementation environment for the proposed interface object modeling technique. Its development consists of three consecutive steps: 1) propose the main IM sub-processes that aim to deal with various types of interface issues in a complete project process; 2) develop the interface modeling core that combines the Interface Object Model (IOM) and the Building Information Modeling (BIM) approach; and 3) incorporate the modeling core into the project process for more effective and efficient IM. This chapter also briefly discusses how this IM strategy works in general and what specific functions the interface modeling core performs in the project process. This conceptual work needs further development for its implementation.

6.1 INTRODUCTION TO THE STRATEGY

As discussed earlier, in the literature, most of the proposed IM strategies and tools are aimed at resolving specific interface issues. Scattered improvements in the project processes do not significantly enhance overall project performance and the quality of the final product (the built facility) in terms of interfaces. This research proposes a systematic IM strategy that will make a difference. This strategy is presented as an integrated process flow chart.

The strategy employs *systems engineering* thinking. It aims to cover a complete project process (regarded as a project system) where sub-processes are interacting components; e.g., poorly performed preceding processes can adversely affect succeeding processes in some way(s). All of these sub-processes are contributing to overall project performance (e.g., against schedule and budget). On the other hand, different types of interfaces (*physical*, *functional*, *contractual*, *organizational*, and *resource* interfaces) in the system are interrelated. They should be coordinated and controlled as a whole to improve IM performance as well as overall project performance. That is to say, IM activities involved in different sub-processes are all very important and need to be performed at the same level of efficiency.

Due to the large number of interfaces and their complexity in a construction project, the strategy is IT oriented—extensively incorporating IT tools into the IM process. First, various interfaces with comprehensive interface information are accurately modeled using an object-oriented modeling language; this depends on the interface modeling core for which the IOM is the backbone. The core also relies on current BIM approaches to model facility components and related project information. Second, the modeled information is stored, coordinated, and implemented by appropriate IT tools that are seamlessly incorporated into the IM and project processes.

The strategy's goal can be achieved to its fullest potential when a project uses an IPD method (such as design-build or engineer-procure-construct) where IM can be performed and coordinated extensively due to the highest degree of integration of design, planning, manufacturing, and construction activities. Also, a design-build process, in which a BIM can be easily shared between design and construction professionals, can achieve greater benefits from BIM approaches (AutoDesk, Inc. 2002). In contrast, for the traditional project delivery (e.g., design-bid-build) or fast tracking methods, the strategy faces great difficulties due to lack of communication and coordination among parties who have no direct contracting relationships. Also, BIM approaches hardly work since the delivery process depends largely on subcontractor involvement during design development (Post 2006). However, if adequate communication and coordination can be achieved and subcontractors' design information can be incorporated into a BIM (Building Information Model) as early as possible, the strategy's benefits can still be realized. Successful IM will help achieve a win-win relationship among project participants as well as optimize overall project performance.

6.2 Conceptual Development

The conceptual development of the strategy is based on an IPD process, in particular, **design-build**. It implements three consecutive steps. These steps and their results are introduced in the following subsections.

6.2.1 IM Sub-Processes for a Complete Project Process

In practice, a typical design-build project delivery process may be composed of the following five main phases, namely *Project Definition and Conceptual Design*, *Detailed Design*, *Subcontract*, *Plan and Schedule*, and *Construction and Assembly*. IM is usually considered in the detailed design and construction and assembly phases. In this research, the proposed IM strategy aims to cover a complete project process that extends the traditional project delivery process into a sixth phase called *Operation, Maintenance, Retrofit, and Salvage*. These phases are introduced later in this chapter. Now, IM starts at the very beginning of the project—the project definition and conceptual design phase—and continues till the final operation, maintenance, retrofit, and salvage phase. Figure 6-1 shows the concept of the new IM strategy.

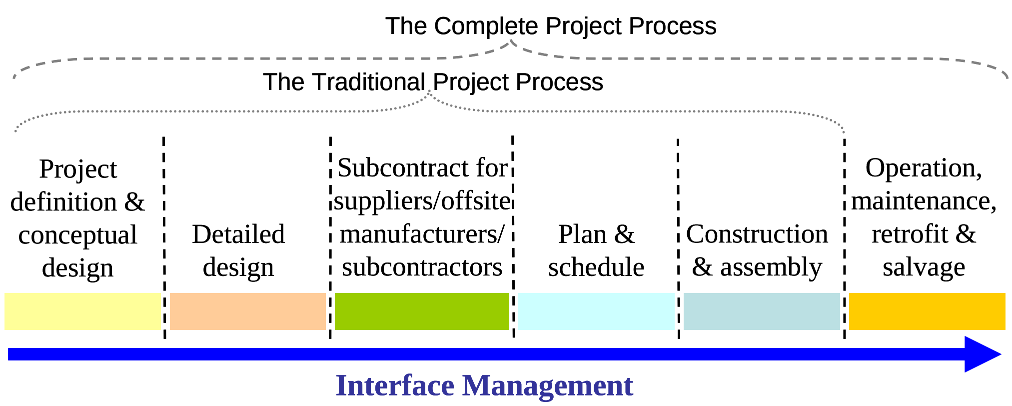


Figure 6-1: The New IM Strategy for a Complete Project Process

Through a literature review (Chapter 2) and an interface-related built environment analysis (Chapter 3), numerous interface issues in those project phases have already been revealed. The needs for IM can be envisioned. This research proposes several main IM sub-processes to meet such needs. These processes must be appropriately incorporated into the complete project process to improve IM performance. Figure 6-2 is an integrated project process flow chart that combines the proposed IM sub-processes with project sub-processes. The notations are explained in Table 6-1.

In the following, each of these project phases is briefly introduced, followed by a discussion of the IM needs and the proposed IM sub-processes in that phase.

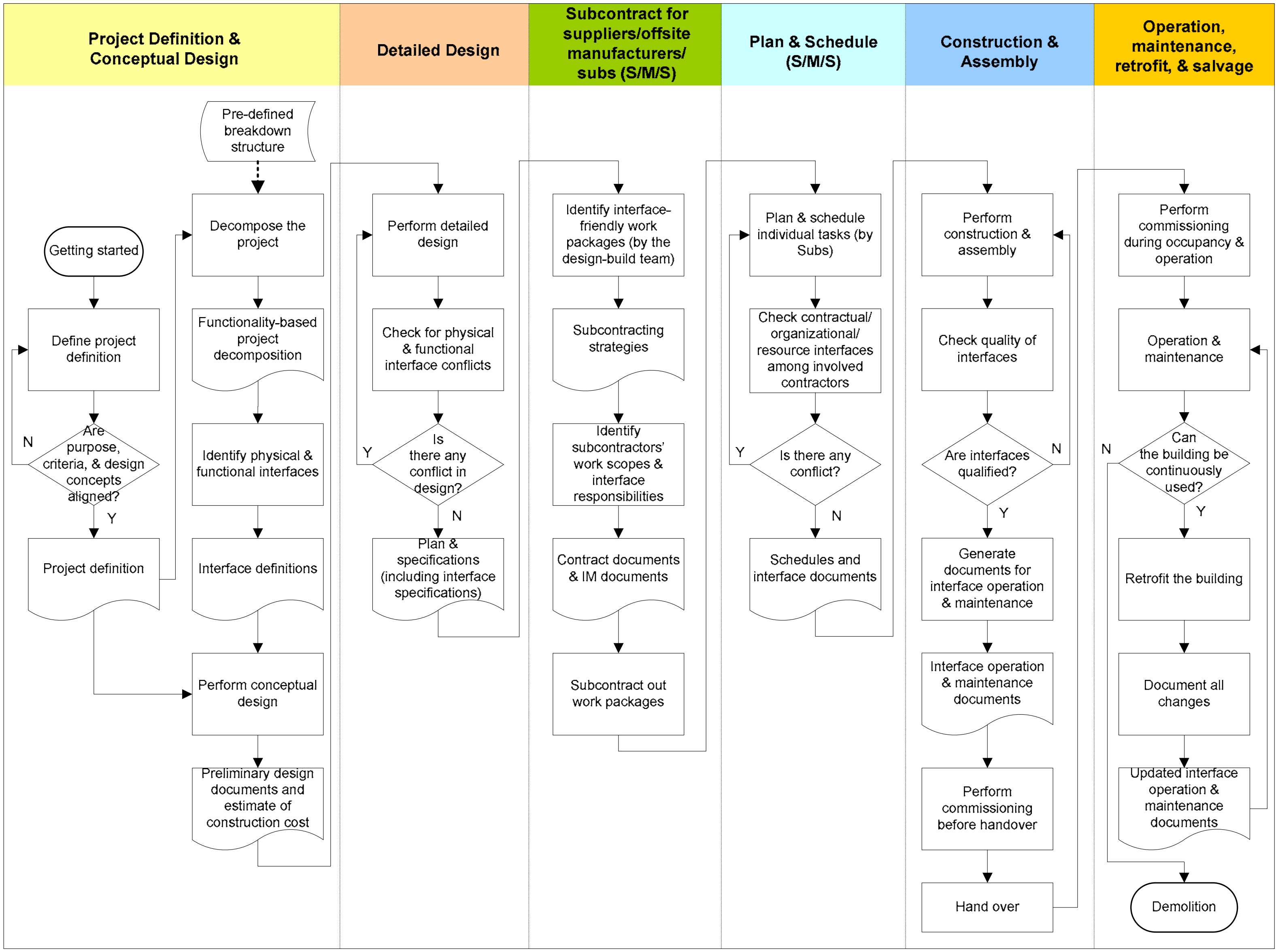


Figure 6-2: IM Sub-processes in a Complete Project Process

Table 6-1: Notations for the Process Flow Chart

Notation	Function
Getting started	Terminator (start and end)
→	Arrow (flow of control)
Hand over	Process
Is there any conflict in design?	Decision
Contract documents & IM documents	Document
Pre-defined breakdown structure	Stored data

6.2.1.1 Project Definition and Conceptual Design

This phase, also called *Schematic Design*, is the first step by a design-build team. Its main outcomes include the *project definition*, preliminary design documents, and primary estimate of construction cost.

In this phase, the project definition is extremely important for avoiding some inherent interface issues that may occur later in the detailed design, construction and assembly, and operation, maintenance, retrofit and salvage phases. As discussed previously, to achieve a lean design process or a lean project delivery system, a comprehensive project definition that aligns the project purpose, criteria and design concepts is needed in the project conception phase (Ballard and Zabelle 2000). Also, the project definition actually includes *interface definitions* that specify various interface relationships among facility or project components, such as the spatial relationship between functional facility areas, the orientation of the facility in the environment, as well as the special site features including roads, parking, communities, neighborhoods, etc. One example is presented below.

Cross infection control is a very important functional requirement for hospital design. This reflects on the selection of spatial relationships among involved areas, floor plan design for organizing patient flows, mechanical system types and zoning, etc. These requirements should be specified in the interface definitions, which enhance the conceptual design with better interface features. Hence, it becomes easier for the detailed design to satisfy such functional requirements. Since the lack of (or inadequate) interface definition may cause serious interface issues, the presence of interface definition is emphasized in the strategy.

In order to define main physical and functional interfaces in a facility more adequately and accurately, a decomposition of the facility is needed. This strategy proposes to use a pre-defined breakdown structure (functionality-based) because a decomposition based on systems or functions has been regarded superior to the traditional WBS in defining interfaces (Laan et al. 2000; Miles and Ballard 2002).

6.2.1.2 Detailed Design

This phase usually includes two sub-phases: *Design Development* and *Construction Documents*. In this phase, the approved schematic design is continuously developed to generate the detailed floor plans, elevations, sections, the specification outline defining materials, finishes, and facility elements/components/systems, as well as the updated construction cost estimate. After these documents are approved, comprehensive construction drawings and specifications are developed. During detailed design, all physical and functional interfaces should be carefully considered, accurately defined, and closely coordinated to ensure that construction documents are adequate, error-free, and constructible.

Based on such a need, a special IM sub-process for checking physical and functional interface conflicts is added into the detailed design phase. This sub-process may be aided by 3D visualization techniques, object-oriented CAD tools, or BIM approaches. The identified interface conflicts in design can be corrected automatically or manually. Simultaneously, the *interface specifications*, as one part of project specifications, are also provided. Here, IM performance of checking and correcting interface conflicts is highly dependent on the effectiveness of modeling and computer programming as well as the skill and experience of a design-build team.

6.2.1.3 Subcontract

At present, most construction projects are subcontractor-based. It is very common for 20 to 30 subcontractors to be employed on a single project, like the stick-build homebuilding process mentioned earlier, which involved 21 subcontractors. Also, the selected subcontractors may have no previous working experience with each other in handling similar construction projects. Their project performance varies and greatly affects the construction and assembly phase.

Prior to subcontracting, the project work scope is usually decomposed into facility elements and/or components based on the selected breakdown structure. Then these elements and/or components are regrouped into different workpackages that are ready for subcontracting. The subcontracting strategy has great influence on interfaces and IM. For example, a poor subcontracting strategy breaks the large number of physical and functional interfaces into different contracts, which leads to intensive coordination for interface parameter information (if subcontractors need to do some detailed design) and on-site activities. This further complicates the relationships among subcontractors and increases the difficulties in their operations. Therefore, this research considers subcontract a distinguishable project phase for IM.

The proposed strategy adopts the functionality-based breakdown structure used in the schematic design phase, and identifies interface-friendly workpackages for subcontracting; i.e., to keep the complex interfaces in a single contract and/or reduce the number of interfaces that may be broken into different contracts. On the other hand, during subcontracting, work scopes and specific interface responsibilities for subcontractors need to be precisely defined. This information should be written into contracts. If necessary, additional IM documents need to be provided for subcontractors to handle complex interfaces within or related to their scopes of work.

6.2.1.4 Plan and Schedule

The plan and schedule phase is right before the construction starts. According to Hendrickson and Au (2003), the involved tasks in this phase consist of:

- The selection of technology and construction method
- The definition of work tasks
- The estimation of required resources and durations for individual activities
- The identification of interactions among different work tasks
- The development of cost and time schedules

This phase provides a very good opportunity for the design-build team and subcontractors to establish their relationships and coordinate their construction plans and schedules. However, in practice, this opportunity is not fully utilized by project participants. Usually, their working relationships are relatively loose and coordination may stay only on the schedule level. In fact, a successfully conducted plan and schedule phase should be able to establish the best working relationships among participants prior to the real construction. These relationships include effective and efficient communication channels, clarified and accepted coordination responsibilities, and the willingness to share various resources and cooperate closely. Also, the success of this phase includes extensive coordination among participants' detailed construction plans and schedules. This avoids and minimizes potential construction related interface issues later.

The strategy proposes an IM sub-process to check contractual, organizational, and resource interfaces among involved contractors for potential conflicts. The purpose is to enhance their working relationships and optimize site organization, material supply, resource allocation, work sequence, and working environment for construction activities. The outcomes are the coordinated schedules and interface documents. It is worth noting that during construction the schedule coordination should be executed frequently among the updated schedules of subcontractors to determine the proper relationships among the real statuses of work progress.

6.2.1.5 Construction and Assembly

This phase is the constructing and/or assembly of facility elements, components, and subsystems on the jobsite according to construction documents. It is the most complex project phase due to the numerous parties involved and the ever-changing environments. On the other hand, interface conflicts in design, usually unnoticeable in the design phase, arise in construction. In addition, poor construction quality, material supply, resource utilization, schedule control, etc. can cause many defects or failures that increase construction costs and delays.

If potential interface conflicts in design, inter-party working relationship, construction plan and schedule are not identified, coordinated, and corrected in the previous project phases, the IM needs in the construction and assembly phase will become significantly more complex. It will be extremely difficult to perform IM successfully. Fortunately, the IM sub-processes added into those preceding phases have eliminated many potential interface issues and hence reduced the complexity of interfaces in the succeeding phases. As a result, interface management and control in this phase focus mainly on quality and safety control.

The IM sub-process—checking quality of interfaces—is integrated into this phase. Here, mainly physical interfaces (e.g., physical connections, spatial relationships, and construction methods) and resource interfaces (e.g., workplace organization, equipment operation, and environment) are checked. Any defects or failures need to be corrected. Then project commissioning before handover is employed to check functional interfaces for facility subsystems. Information obtained through commission may be used to form a good strategy for the formal operation after occupancy.

6.2.1.6 Operation, Maintenance, Retrofit, and Salvage

Conventionally, the operation, maintenance, retrofit, and salvage phase is not considered part of the project delivery process, or is included in a very limited way. It belongs to the scope of facility management. Nevertheless, many aspects of this phase are found to be related to the project delivery process in terms of interfaces. For example, the choice of building materials determines the life cycle of such materials for maintenance. The selection of facility subsystems and their functional interfaces decides the operation procedures and strategies to keep the energy efficiency of a facility. The quality of physical interfaces influences the frequency of repair and replacement of operational parts in a facility. Therefore, this research incorporates this phase into the complete project process for IM.

Besides the interface operation and maintenance (O & M) documents provided by the construction and assembly phase and the information obtained from the facility commissioning before handover, this phase is also dependent on a commissioning during occupancy and operation to find out the best operation strategy for optimizing systems performance and achieving energy efficiency. The facility subsystems (e.g., lighting system and mechanical system) may also be adapted during occupancy (due to changes in use) or retrofitted if needed. All the changes may alter interface O & M procedures, and therefore need to be documented. The updated interface O & M documents are usually generated for future use.

To achieve the best IM performance as well as overall project performance, all these IM sub-processes need to be performed effectively and efficiently. The aid of interface modeling and automatic interface coordination in the complete project process is necessary. The following subsection introduces how an interface modeling core is built based on the proposed IOM.

6.2.2 The Interface Modeling Core

The interface modeling core represents a powerful modeling engine for the systematic IM strategy. Several functions for this modeling core are defined as follows:

- Accurately model comprehensive interface information for various types of interfaces in construction projects
- Automatically check conflicts and coordinate interface information
- Quickly respond to queries for interface information and IM procedures
- Instantly give notice of IM needs for certain activities to the involved participants
- Generate comprehensive IM documents and guidelines

Based on these functional requirements, this research builds an interface modeling core. As shown in Figure 6-3, this modeling core combines the IOM and current BIM approaches. There are four important components: the *IOM*, the *Interface Databases*, the *Building Information Modeling Environment* (BIME), and the generated *Building Information Model* (BIM). How these model components are related to each other and how interface modeling can be performed are explained here.

A fully developed IOM will present the complete data structure and data dependencies for interface information. Based on the IOM, the interface databases (the structured collection of interface information) can be created. According to the research needs, the databases can be object-oriented; this feature acts as a bridge to connect the database world and the object-oriented programming world. The databases can also be XML-based; they store all the documents and data (from individual organizations' information resources) in one place for application. In practice, the interface databases can be provided by different sources. Servers are needed to provide database services to various computers or computer programs. Also, the IOM by itself can evolve into an interface modeling tool that incorporates the interface modeling application software with the IOM data model. It can access interface information from the databases. An IM handbook, as one main outcome, can be generated. This research, however, chooses to mainly utilize the powerful BIM approaches for interface modeling and coordination.

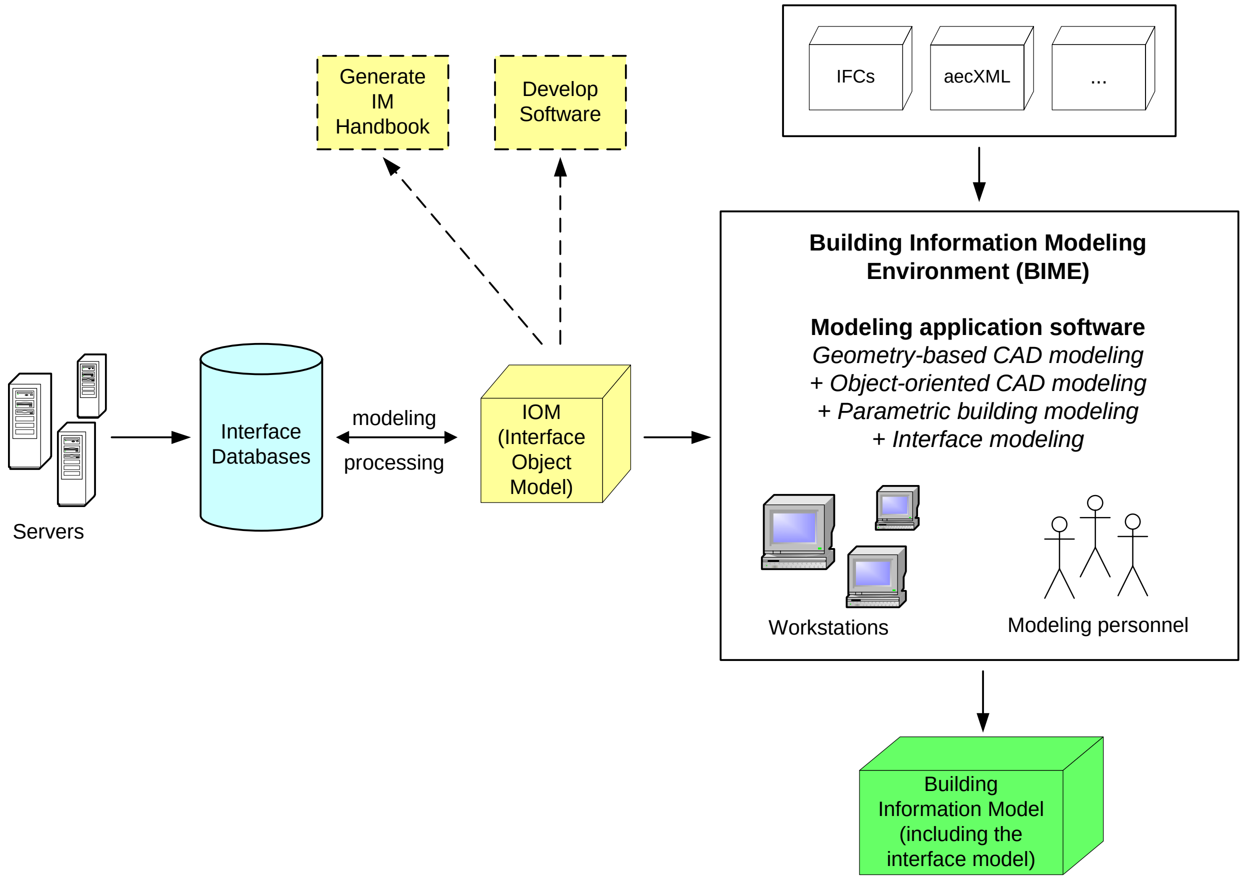


Figure 6-3: The Interface Modeling Core

The BIME integrates the current BIM environment with the interface object modeling technique. The current BIM environment consists of 1) the BIM application software (e.g., ArchiCAD, Bentley Architecture, or Autodesk Revit), 2) workstations, and 3) modeling personnel. It is based on the data structure provided by the IFC or other data models. The current BIM application software employs technologies of geometry-based CAD, object-oriented CAD, and parametric building modeling. The interface object modeling technique is added into the software as plug-ins or extensions.

The interface modeling can be performed during BIM (e.g., after two building components are modeled, their interface(s) is/are modeled right away) or after BIM (e.g., after all the building components are modeled, their interfaces are modeled together). During modeling, the BIME accesses the IOM and interface databases (through the IOM) for data structure and interface reference information. The generated BIM includes the traditional BIM and an interface model.

In the modeling core, the IOM acts as the backbone; the BIME is the kernel; and the generated BIM is a repository that holds complete, intelligent, multi-perspective project information including interface information. The enhanced BIM not only performs coordination functions but also provides compatible information for modeling, processing, operation, and decision-making. In the following subsection, this modeling core is incorporated into the IM integrated project process proposed above.

6.2.3 Systematic Model-Based IM

Early in this chapter, the proposed IM sub-processes are integrated into a complete project process for systematic IM. However, the effectiveness and efficiency of these IM sub-processes are questioned due to the complexity of interfaces and interface issues. The importance of interface modeling, automatic interface coordination and IT-aided IM is emphasized. Accordingly, an interface modeling core is created and presented. This subsection aims to incorporate the modeling core into the complete project process to assist IM. The incorporation should answer the following questions:

- When the interface modeling core should be incorporated into the systematic IM process;
- What project/IM sub-processes should be connected with the modeling core; and
- How the interface information flows between the modeling core and these sub-processes.

Figure 6-4 shows a new integrated process flow chart to illustrate the incorporation. The process flow chart includes the previous flow chart (shown in Figure 6-3) that presents how the proposed IM sub-processes are integrated into the complete project process. It also includes the simplified modeling core that shows the four model components only. The modeling core and project/IM sub-processes are connected by interface information flows, which are displayed as the dashed lines. The thick dashed lines represent information (to be modeled) flowing into the modeling core; the thinner dashed lines denote information (stored in the BIM and/or the IOM) that flows out of the modeling core to the corresponding sub-processes and will be implemented there. In the following section, how the IM strategy works in general and what specific functions the modeling core performs are discussed.

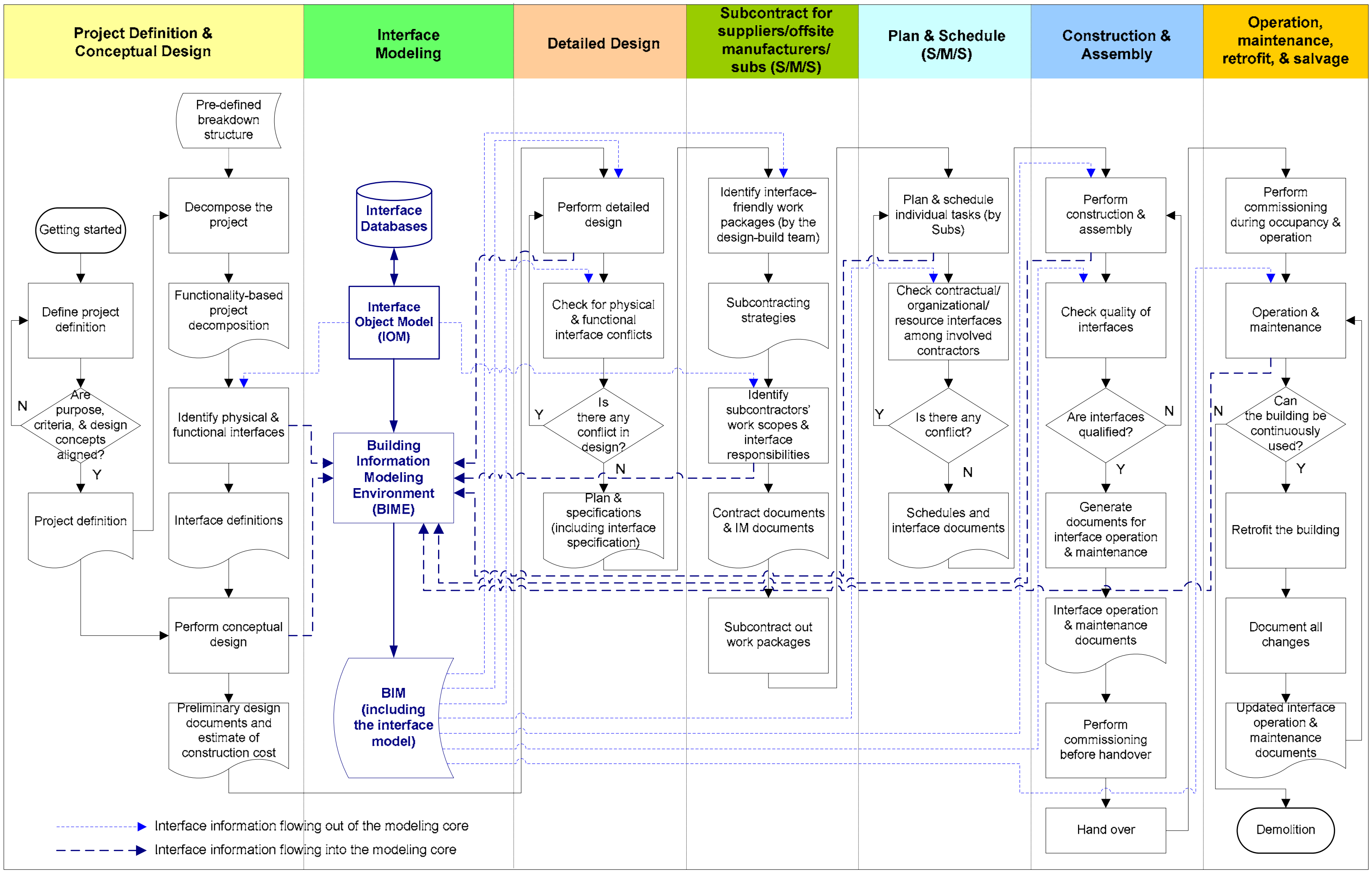


Figure 6-4: Systematic Model-Based IM Process Flow Chart

6.3 DISCUSSION OF APPLICATIONS

Up to now, the view of the systematic model-based IM strategy has been completed. The integrated process flow chart (shown in Figure 6-4) has successfully incorporated the proposed IM sub-processes and the interface modeling core into a complete project process that employs the design-build delivery method. In this section, how the IM strategy works in general and what specific functions the interface modeling core performs over time are discussed.

As shown in the flow chart, the modeling core is first used in the project definition and conceptual design phase to accurately define main physical and functional interfaces of a facility. At this stage, the BIM has not been built. Designers make queries to the IOM for interface definition information based on the type of facility to be designed, the environment the project faces, and the specific requirements from the client. Then, the IOM together with the connected interface databases provide compatible information to support this task.

The outcomes of this task are the *interface definitions*, which accurately define all the important physical and functional interfaces of a facility. The definitions are used to direct the subsequent conceptual design in the choice of facility plan, orientation, and/or MEP (mechanical, electrical, and plumbing) systems. Hence, the conceptual design can include all important interface features for design development performed later. The definition information is also incorporated into the IOM to enrich the connected databases and prepare the physical and functional interface modeling. During the task—performing conceptual design—the preliminary design information starts to be entered into the BIME for modeling. From now on, the BIM is built and will be updated continually as the project evolves over time. At this stage, information stored in the BIM can be used for energy analysis by using tools such as EnergyPlus. According to Khemlani (2006), the use of BIM in the schematic design phase can provide the platform for early integration of architectural, structural, and MEP designs.

The use of the modeling core in the detailed design phase starts with the task—performing detailed design. The design process is actually a modeling process. Information stored in the BIM directs design development, which, in turn, instantly records the design progress and updates the stored information. With the increasing use of BIM approaches in the industry, the design outcome will finally be a BIM that contains all the project information in an intelligent way and can generate all the needed design documents (e.g., plans, specifications) automatically.

The process can begin with designing/modeling facility components first, and then design/model interfaces among them. All parties involved in design (the architect, structural engineer, HVAC engineer, etc.) contribute their information to the same BIM and share it with others. After the design process is complete, interface conflicts in design can be visualized and coordinated in the BIM by using the parametric building modeling technology. In the future, if the procedural and generative building modeling technologies (introduced previously) can be applied, the interface modeling can be conducted with the component modeling. The benefit is: once the interface for a component is designed/modeled, other components without compatible interfaces cannot be added into the design/model. This improves the design quality and minimizes the coordination time. After all the conflicts in design are resolved, detailed design documents and related IM documents are generated by the BIM.

In the subcontracting phase, the modeling core is connected with the task—identifying interface-friendly workpackages. When a design-build team begins to identify workpackages and prepare subcontracting, the modeled interface information can help determine the interface-friendly workpackages. The process is explained here. First, the modeled physical and functional interfaces can be visualized in some ways in the BIM. So the complexity of such interfaces can be better understood by the team. During workpackaging, interface statuses are monitored, such as how many physical and functional interfaces are broken and how many interface objects are involved in each of those interfaces. Based on the information, the design-construction team can adjust his/her choice and finalize a better workpackaging and subcontracting strategy to simplify the interface relationships that the subcontractors will encounter in the future.

In the next step—to identify subcontractors' work scopes and interface responsibilities—besides interface information modeled in the BIM, information stored in the IOM or interface databases is also used to determine interface responsibilities for subcontractors. As a result, both the general and specific responsibilities can be identified. The information is reentered into the BIME for model updating. In addition, important interface resources, such as equipment, technologies, etc., are also modeled. Then, the BIM can generate comprehensive contracting and

IM documents for subcontractors. These documents include both general and specific interface information for construction operations as well as interface coordination and management.

After being awarded the contracts, subcontractors usually plan and schedule their tasks based on the project requirements and submit these documents for review and coordination. Traditionally, it is the design-build team's responsibility to coordinate these plans and schedules. This is a complicated and difficult process where all the relationships and influences among subcontractors' on-site activities should be carefully studied and understood. Schedule coordination is time-consuming due to the restricted work sequence, the availability of subcontractors, suppliers and their resources, the integrated environment that affects construction activities, etc.

In the strategy, this coordination process is assisted by the BIM. Firstly, plans and schedules are inputted into the BIME for modeling. Then the BIM that contains comprehensive interface information can extensively check contractual, organizational, and resource interfaces among involved contractors. Coordination may be directly performed in the BIM if other powerful scheduling tool(s) can be integrated into the BIME. After coordination, the updated schedules and IM documents are returned to subcontractors.

Coordination needs to be periodically performed while the schedules and project progress are updated over time. It is better to provide a web schedule that is also accessible by the subcontractors and suppliers. Through the web schedule, they can update their schedules and work progress on-line and get the new coordinated schedules on a timely basis. They also can see the work progress of the related contractors, so they can prepare in advance if any delays that affect their activities are about to occur.

The modeling core is also greatly helpful in the construction and assembly phase. Interface information stored in the BIM can be used by subcontractors to perform interface-related construction activities. In particular, the visualized model can help them understand relationships among facility components related to their scopes of work. As indicated by Sawyer (2005a), in the new GM LDT plant project introduced earlier, the BIM became a central tool of the meetings and subcontractors were always coming back and asking for more. On the other hand, contractual, organizational, and resource interface information can also help subcontractors deal with other project participants as well as organize the required resources and workplace interfaces. In addition, detailed information (interface attributes, operations, etc.) modeled in interface objects can be the most important references for subcontractors' interface operations and quality control.

After an interface is fulfilled, the interface status in the BIM is updated through the BIME. Then, the new BIM can be employed in checking quality of interfaces by inspectors. If inspections are all passed, interface O & M documents are finalized and handed over to the owner or owners' facility management personnel.

In the last project phase, the BIM can be used to determine interface O & M strategies. Systems performance (energy) simulation and evaluation for all proposed strategies can be conducted based on comprehensive functional interface information modeled in the BIM. Based on the results, the best strategy can be chosen. Physical interface O & M information can help determine when the operational parts in a facility need to be repaired or replaced and which types of new parts are compatible with the old facility system. The interface O & M data, records and best practice are entered into the BIME to update the BIM.

After a certain period of time, a facility will be retrofitted and some physical and functional interfaces will be changed. Accordingly, the O & M strategy needs to be adjusted to accommodate the changes. The above process will be performed once again. No matter how many times retrofits are conducted, the BIM is always updated to contain the history of and the latest interface information.

The use of the interface modeling core permeates the whole project process from beginning to end. The BIME supports uninterrupted exchanges of interface information with involved sub-processes and instantly updates the BIM to reflect real project status. The BIM can be implemented in different project/IM sub-processes for designing, constructing, coordinating and managing various interfaces. Accurate interface documents are also generated from the BIM to assist the IM process. This systematic model-based IM strategy is highly effective and efficient for handing a large number of interfaces in multi-disciplinary projects that employ IPD methods.

It is worth noting that this IM strategy is only conceptually developed. Future research should focus on developing the modeling core, specifying detailed IM procedures, and demonstrating the strategy via real-world applications.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 RESEARCH FINDINGS

Interface management (IM) is an emerging area of project management in the construction industry. It is extremely important for multi-disciplinary construction projects including infrastructure design and construction, sustainable development, and building construction. Properly managing interfaces among the client, developers, designers, contractors, government agencies, environments, or facility/project components, is essential to project success. This research helps establish the importance of IM in the construction industry, and inspires comprehensive interface-related research to be performed widely and promptly.

Specifically, this research aims to enhance the industry's overall project performance by improving interface modeling through systematic model-based IM. The most important contribution is the Interface Object Model (IOM) framework that presents the data structure and dependencies of interface information for object modeling. The following subsections conclude the main research findings (contributions).

7.1.1 A Multi-Perspective Analysis

This research conducted a multi-perspective analysis to explore comprehensive cause factors of interface issues in the current built environment. This analysis adopted the method of the *Cause-and-Effect* diagram and identified six interrelated perspectives (*People/Participants*, *Methods/Processes*, *Resources*, *Documentation*, *Project Management*, and *Environment*) as main cause areas. From these perspectives, 155 cause factors (including major causes, minor causes, and sub-factors) of various interface issues were explored and presented in a well-structured, hierarchical way. The cause factors can be directly converted into success factors for IM.

To represent the cause factors in a more applicable format, this research transformed them into a series of interface management and control elements within affinity diagrams. These elements were helpful in developing the *Interface Object Hierarchy* diagram for the proposed IOM framework, and can be used in future research in other ways as well. This multi-perspective approach contributed a holistic understanding of interface issues to the literature and built a theoretical foundation for researchers and practitioners to seek all-around IM solutions.

7.1.2 A Comprehensive IOM Framework

This research initiated an *object* view of interfaces, and defined a unified way of presenting interface information. Consequently, in the object-oriented modeling environment, interfaces become a collection of active objects that react to outside requests and automatically perform complex operations. These objects can play a very important role in model-based interface coordination, management, and operation.

To support the proposed interface object modeling, the data structure and dependencies of interface information were defined in an IOM framework. This framework consists of two levels. The *Modeling Level* presents the basic interface data structure in a hierarchy; the *Application Level* illustrates the data dependencies (contextual relationships) between interface information and other well-known project information. There are five model components within the framework, including *Interface Categorization*, *Interface Object Hierarchy*, *UML Interface Object Class Diagrams*, *System Data Dependency*, and *Relational Diagrams*. They have been developed into different levels based on the research needs.

This interface data model is the first in the literature. When fully developed in future research, the IOM will have broad applications in interface design, construction, and management. Specifically, it helps project participants build a comprehensive understanding of various interfaces within their scopes of work. It also helps create interface databases to improve future modeling and decision-making. Most importantly, accurate, standardized, and model-based interface information can be easily adopted by an IT-oriented IM process for managing and controlling a wide variety of interfaces in construction projects and preventing potential interface issues.

7.1.3 A Systematic Model-Based IM Strategy

This research conceptually developed a systematic model-based IM strategy that employs *systems engineering* thinking. The strategy targets all kinds of interface issues as a whole and covers a complete project process for IM. Due to the complexity of interface information and the difficulties in performing effective and efficient IM, an interface modeling core is created and incorporated into the project process. This modeling core, backed by the IOM and Building Information Modeling (BIM) approaches, can model and handle large amounts of interface information to improve IM performance as well as overall project performance in the construction industry. This strategy has established a good foundation for creating an implementation environment for the proposed interface object modeling.

7.1.4 IM Benefits

Effectively executed IM can be of great benefit to construction projects. Through this research development, potential IM benefits can be concluded as follows:

- Build a deep understanding of project complexity for project participants
- Optimize design in terms of quality, compatibility, constructability, cost, risk, and function to meet customer needs
- Improve project planning by avoiding, minimizing, or eliminating potentials for interface issues in advance
- Improve workpackaging and subcontracting to reduce project complexity and to avoid inherent interface issues
- Build and maintain desirable relationships and interaction channels among project participants to achieve timely communication, coordination, and cooperation
- Standardize handling processes and work flows for various types of interfaces in construction projects and reduce uncertainties
- Enable a dynamic and well-coordinated construction project delivery system when responding to changes
- Identify and record good practices in dealing with project complexity and reapply them in future projects

Much effort is required to fully achieve these IM benefits. The author of this dissertation plans to perform future research in the following directions, which will not only further develop this research into an application level but will also build valuable connections with other relevant efforts in the literature and in construction practice.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Considering the enormous variety of interfaces and the severity of interface issues in multi-disciplinary construction projects, the author believes that applications of this research are unlimited. However, despite the several aforementioned research findings (contributions), this research needs further development to achieve its full implementation. For the short term, the planned research will target four tasks.

7.2.1 Further Development of the IOM

The first task is to further develop the IOM into an application level and incorporate it into 3D or 4D BIM. The objective is to promote the IOM's implementation and simultaneously enhance BIM capabilities to model and coordinate various types of interfaces as well as to guide field interface operations. This task is most important and has the highest priority in the research plan.

At present, this research has studied modeling physical interfaces. A software prototype, which incorporates physical interface modeling with BIM approaches, needs to be built. In the prototype, the IOM's capabilities of modeling physical interfaces and directing the visualization of related interface handling procedures (as shown in Figure 7-1) will be tested. At the same time, ways of using the modeled information for design, construction, and project management and control will also be uncovered. The application will be to improve the componentized homebuilding process.

As presented in this dissertation, information that can be modeled in interface objects includes interface attributes, operations with methods, responsibilities, etc. This information supports various modeling functions of interface objects. In the planned research, potential field operations for those applicable physical interface objects will be accurately defined based on the knowledge of construction and the well-developed classification/taxonomy of construction operations (Everett 1994, Al-Masalha 2004). The operations will then be visualized and linked with corresponding interface objects. In response to outside requests, those interface objects will direct the model to display the linked visualization or simulation, which helps disclose potential conflicts and guide field operations to be performed in a more accurate and efficient way.

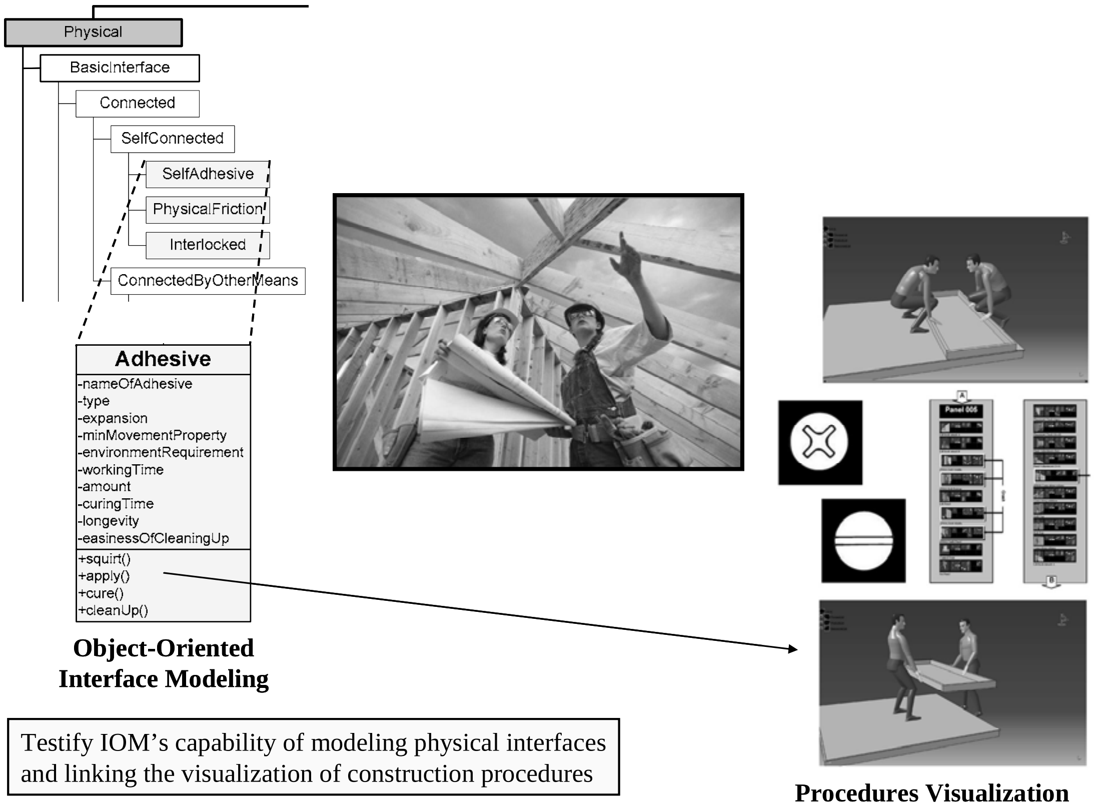


Figure 7-1: Interface Modeling Capabilities of the Prototype

At the early stage, the visualization will use an icon-based prototyping methodology that "develops a graphic heuristic for industrialized assembly and suggests a new taxonomy for designing construction operations and presenting those designs to the field" (Johnston et al. 2006). This method describes each operation/task in the still-frame animation format to enhance understanding. Within each activity frame, Operation, Component, and Resource windows hold constituent icons attributable to the operation/task. Those icons are active in task analysis and sequencing. This iconic construction language is still under development by Brendan Johnston, a Ph.D. candidate in the Building Construction Department at Virginia Polytechnic Institute and State University. However, its benefit to presenting interface operations can be envisioned.

After building this software prototype for physical interface modeling, future research will develop it to model other categories of interfaces from *functional*, *organizational/contractual*, to *resource* interfaces. Since applicable interface objects within these categories have not been defined in the current IOM framework, future work will first develop them into the applicable level and then find model applications for them. For example, functional interface modeling can be used to improve housing design by optimizing interrelationships of housing components or subsystems. Once complex interactions among components or subsystems are accurately modeled, performance optimization in the design process can be automatically performed (Figure 7-2).

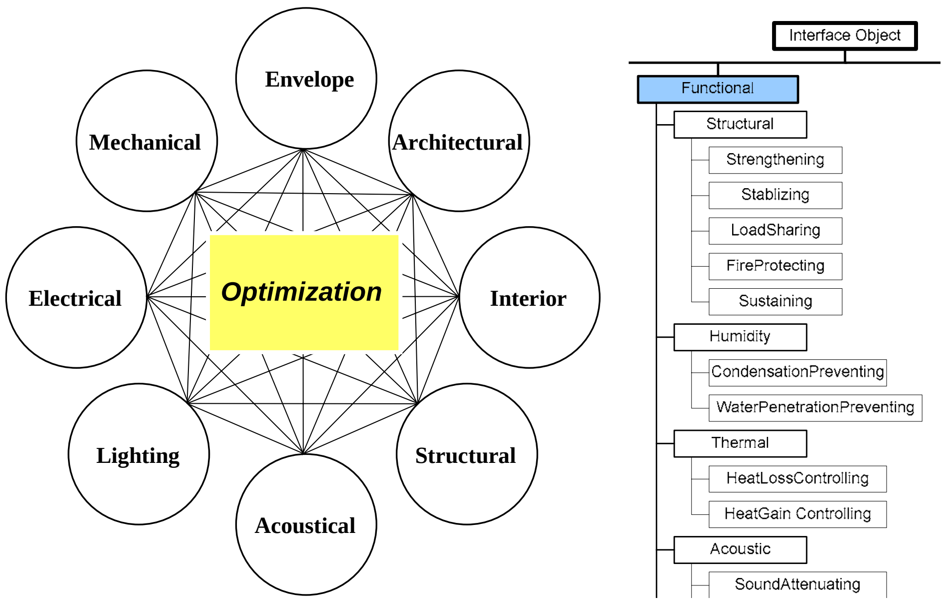


Figure 7-2: The Implementation in Systems Integration

After all the categories are fully developed into the applicable level and their implementations are found, the IOM's overall efficacy can be demonstrated. To fully develop this interface modeling concept and its applications, industry or academic partners may be needed.

7.2.2 Incorporation of the IOM with the IFC

The second task aims to incorporate the IOM into the IFC (Industry Foundation Class) object model. The IFC is a widely used data structure for BIM. In the IFC, very limited relationship object types are defined between facility or project components; this makes it not very capable of modeling various types of interfaces. The objective of this research task is to form a complete project data structure by supplementing the IFC with the IOM.

Figure 7-3 illustrates the IFC2x3 model architecture. The incorporation may start with defining the *interface resource* in the Resource Layer. The interface resource will include all the defined interface objects for other layers to implement. Then, the *Interface Management Domain* may be defined in the Domain Layer. There will also be other adjustments and additions for the Core and the Interoperability Layers to accommodate the IOM data structure. The complete incorporation procedures will be proposed in future research.

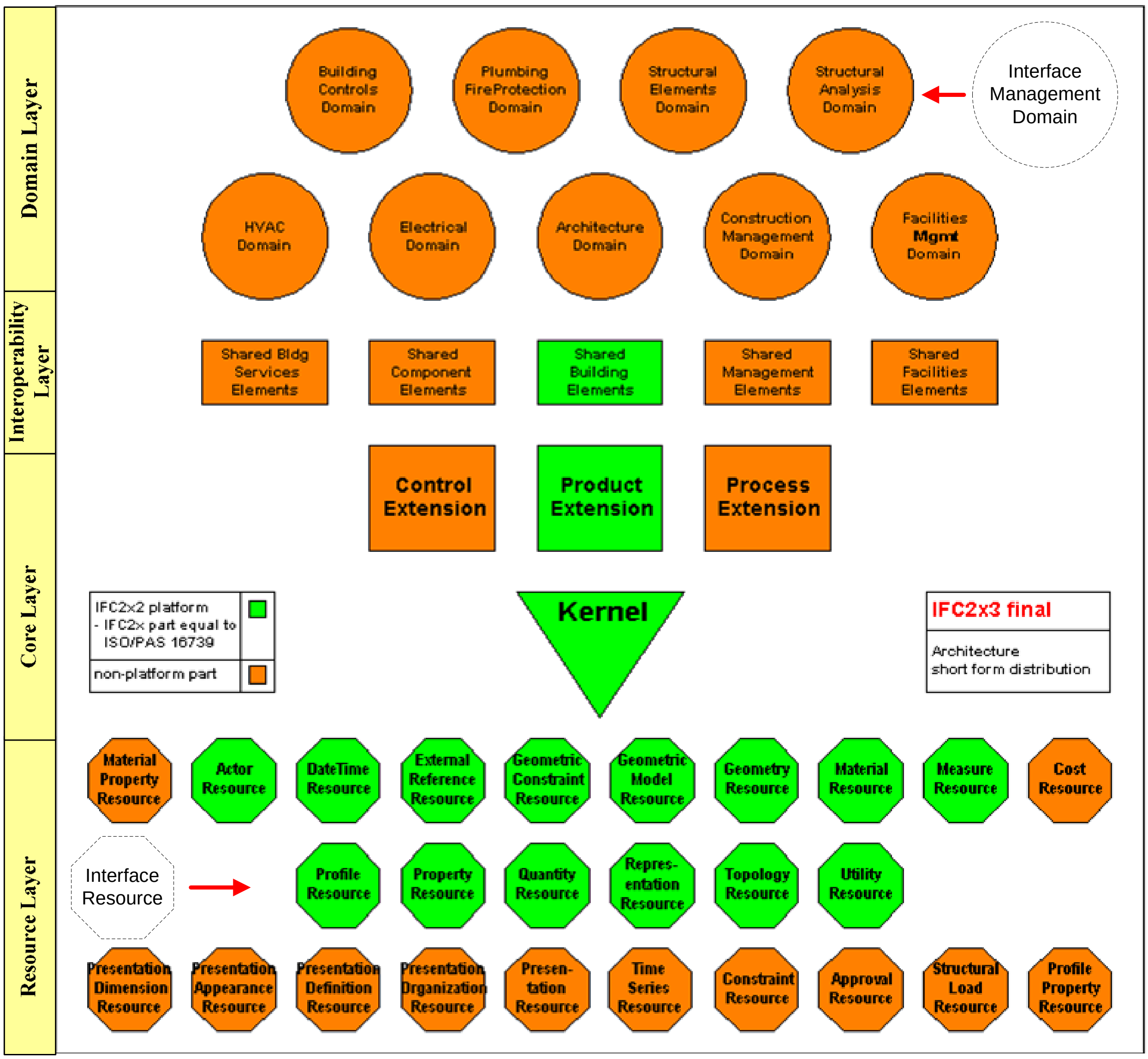


Figure 7-3: IFC Model Architecture (IAI 2006, with permission from IAI International Council)

After the model architecture is properly altered, the interface data structure (as exemplified below) can be added as a transparent layer into the IFC. The interface modeling capacity of a BIM, which is based on the enhanced project data structure, will be improved.

```
Interface
  ifcInterface
    ifcInterfaceObject
      ifcPhysicalInterface
        ifcConnected
          ifcAdhesive
          …
        ifcInContact
          ifcEmbeded
          …
        ifcNotInContact
          ifcSpaced
          …
      ifcFunctionalInterface
        …
```

7.2.3 Strategic Development of IM

The third task targets the strategic development of IM. This includes the full development of a systematic model-based IM strategy for Integrated Project Delivery (IPD). Chapter 6 presented only a concept of this strategy in an integrated process flow chart, which lacks detail for implementation. Also, the performance of proposed IM sub-processes needs to be demonstrated, such as how design and construction can be improved through interface analyses and how interface-friendly workpackages and subcontracting strategy can be defined for better IM.

If this strategy can be fully developed in an IPD environment, it can also be adapted for other project delivery environments such as design-bid-build or construction management. Future research will carry on this strategy's development in diverse project delivery environments and find more applications in the construction industry.

In addition, since the proposed IOM has an application potential beyond the construction domain, the strategy's implementation in other industry domains needs to be explored. The strategy can be developed based on the new needs revealed.

7.2.4 Incorporation of IM with Lean and Agile

Lean construction and agile project management (APM) are two emerging management philosophies in recent years. Their applications in construction face great challenges from a project's complexity. IM, managing and controlling interrelationships or interactions among elements of complex project systems, can help augment these two strategic approaches and facilitate the implementation of related techniques and methods in the dynamic built environment. This research considered IM a facilitator of lean and agile due to the overlapping scopes. Thus, the fourth task is to incorporate IM with lean construction and APM.

Specifically, interface databases to be developed can assist lean construction in understanding and dealing with the "physics" of production (physical issues) as well as project complexity (defined by Howell (1999) as the number of pieces or activities that can interact in a project system). The interface-friendly workpackaging and subcontracting (according to the functionality-based breakdown structure) as well as the coordinated project schedule can be used to enhance the Master Schedule in the Last Planner technique. IM can also help APM cope with human dynamics and achieve the high efficiency and effectiveness of small, self-organizing multi-disciplinary teams, as shown in Figure 7-4. Future work will focus on specific strategies of incorporating IM with lean construction and APM techniques.

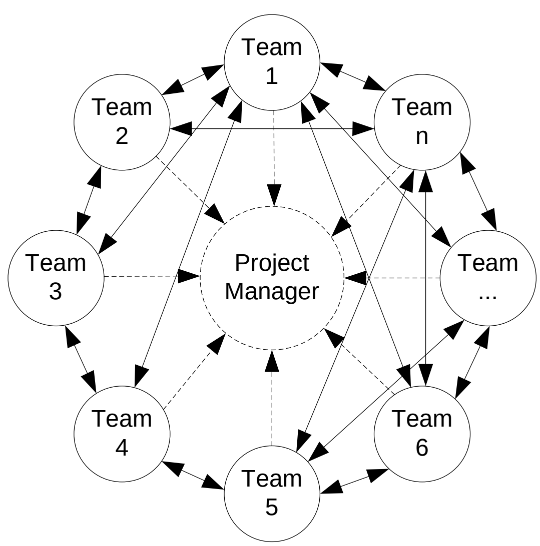


Figure 7-4: Self-Organizing Multi-Disciplinary Teams in APM

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VITA

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