School of Construction Management and Engineering

The influence of design-production management at the pre-production stage for major international projects in Korea

by

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Abstract

Construction projects are increasing in size, scale, and complexity. Large scale construction projects (LSP) in Korea use international joint venture design teams (JVDT), which results in another layer of complexity into project delivery. Contractors experience unexpected design-production interface problems throughout the production stage that requires fast resolution to ensure the project meets completion deadlines. Korean contractors engaged on LSPs carry responsibility for both the design and production under the Korean regulatory system; hence design management at the bid and pre-production stage is used to manage the interface between design and production. Design management has focused upon the design stage to co-ordinate and control the design sequence there is a need for the contractor to have more practical and production-oriented design management, which could be implemented from the contractor's perspective through the production stage.

The research considers how design-production management can help as a system in the pre-production stage of LSP in Korea and set out considering that any international arrangement adds complexity because of the different cultures and technologies and joint venture agreements make the organisation of the project and more complex. Based on these insights, complexity theory was adopted as an underpinning theory of this research to develop a contractor-led design-production process map (DMPM), which highlights the interface management between design and production activities using system dynamics modelling and simulations.

In the procedure of developing the DMPM, 43 design-production management

(DM) factors obtained by questionnaire survey and semi-structured interviews (pilot survey) are analysed using statistical methods. With factor analysis, all DM factors were categorised into 6 factor groups (Information management, Design coordination, International JVDT, Support production stage, Large-scale project, and Korean feature). The importance-priority analysis, preference, and interrelationships of the DM factors are analysed and causal loop diagram and system dynamics modelling was undertaken. According to importance value and interrelationships of DM factors, system dynamics modelling was formulated and explicit performances were presented by graphic from and numeric values. After different model verifications including suitability and compatibility tests, DMPM was developed based on the optimal modelling and simulation result of system dynamics.

Research was carried out in order to reduce contractors' design-related risk during production stage in international LSPs in Korea. With the insight that complex interconnected project components between design and production should be managed integrative, developed DMPM should be implemented from early pre-production stage from the contractors' perspective. Thereby, contractors can estimate suitable bid amounts and reduce design risks caused by design errors and changes, more practically, can manage different design-related issues such as diversified construction standards, various building codes, cultural gap, and different working processes from early pre-production stage.

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Last, but not least, I dedicate my thesis to my beloved parents.

Declaration

‘I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.’

…………………………………..…….. Seoung-wook Whang

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List of Symbols and Acronyms

AEC …………………………….……. Architecture, engineering, and construction

BOQ …………………………………………………………..... Bills of quantity

BS ……………………………………………………………..... British standard

BIM ……………………………………….... Building information modelling

BIPV …………………………….…. Building integrated photovoltaic system

BREEAM ………… Building research establishment environmental assessment methodology

CHP ………………………………………….…... Combined heat and power

CP ……………………………………………………………….. Critical path

DM ………………………………………..... Design-production management

DMPM ………………………….. Design-production management process map

DRB …………………………………………….….. Dispute resolution board

FMS ……………………………...…. Facility management support system

GBCC …………………………………... Green building certification criteria

GDP ………………………………………………… Gross domestic product

GFA ……………………………………………………….…. Gross floor area

HVAC …………………………..…. Heating, ventilating and air conditioning

IPA ……………………………………….... Importance-performance analysis

IPM ………………………………………….…… Importance-priority matrix

IBC ………………………………………….….... International building code

ICC …………………………………….….….. International code council

IOS ……………………...…… International Organization for Standardization

Md ……………………………………………………………….. Man-days (Md)

NFPA ………………………………………. National fire protection association

JVDT …………………………………………….... Joint venture design team

LSP ……………………………………………………...… Large-scale project

LEED …………………….…. Leadership in energy and environmental design

SPSS ………………………………….....… Package for the Social Sciences

PEP……………………………………………………..….Project execution plan

PQ ……………………………………………………...…… Pre-qualification

PMIS …………………………………. Project management information system

PIP ………………………………………………… Project implementation plan

PPP …………………………………………...… Public private partnership

RAM ……………………………………..... Responsibility assignment matrix

RFP …………………………………………………….. Request for proposal

RIBA ……………………………………...… Royal Institute of British Architect

VE ………………………………………………….…… Value engineering

Publications and Presentations

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- S.W. Whang, and R. Flanagan, (2015), Minimisation of risk exposure at the pre-production stage through the use of contractor-led design management, Procs 31st Annual ARCOM Conference, 7-9 September 2015, Lincoln, UK, Association of Researchers in Construction Management, 155-164.
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CHAPTER 1 INTRODUCTION

1.1 Background

The research focuses upon large-scale projects in Korea where design is undertaken by an international joint venture design team. It considers the design and production interface issues at the bid, post-contract award, and pre-production stages. Large-scale construction projects (LSP) in Korea are increasing in size and scale, frequently using international joint venture design teams (JVDT), to undertake architectural design and structural, mechanical, plumbing, and electrical engineering design. Joint ventures are notoriously difficult to organize, manage, and deal with efficiently and effectively. They involve consultants from different countries with different technical competencies. Individuals or companies choose to enter joint ventures in order to share strengths, minimize risks, and increase competitive advantages.

An international joint venture design team is a team comprising an architect, structural engineer, mechanical and electrical services engineer, cost consultant, and any other specialist consultant assembled by the owner to undertake the design delivery and production of the proposed project. Such a design team is coordinated by the lead consultant or project manager and may include local (Korean) companies. The contractual relationship of each consultant is connected directly with the owner unless the design teams decide to form a joint venture company for project delivery, although this is not usual, because of liability issues.

Large-scale construction projects involve increasing complexity because of the desire for innovative and exciting design solutions to be built safer, faster, and greener. Due to increasing design risk passed to the construction stage, the contractor needs to pay more attention at the bid, in post-contract award planning, and in the pre-production stages to manage the interfaces between design and production (Song *et al.*, 2009). Formulating a bid, which is then developed into the tender offer, is one of the most important tasks for the contractor. If the tender price is wrong, the site production team will struggle to bring the project to a satisfactory financial conclusion. Tendering involves producing a bid price and a construction duration that the contractor must adhere to, and deliver with an acceptable level of profit.

The research considers the role of design management in the process. Designers and design engineers focus upon aesthetics, form, function, and structural and environmental integrity, whereas contractors focus upon resources, production methods, process and sequence as well as managing systems. The two approaches must be complementary (Hegazy et al., 2001; Hossaina and Chua, 2014), yet the design team receives little education and training in production processes. The contractors often require the architect or designers to recognise the sequence, method, and production process in the design process. Design-production management is an important tool for the contractor to understand the managing of resources effectively during the production stage.

Design management is an important discipline used by design consultants to manage the design process and the flow of information to ensure design continuity and collaboration amongst the consultants. Contractors in Korea have adopted design management principles to help manage the relationship and interface between design and production[1]. This research focuses upon how design-production management can help as a system at the pre-production stage of large-scale projects in Korea[2], where an international joint venture design team is responsible for the design. The reason that international joint venture design teams are chosen is that increasingly, they are being used to design innovative and exciting solutions for Korean large-scale projects. Clients' commission international design teams with the belief that they bring both new and innovative design solutions, and also prestige to the project. Korean contractors must understand and manage these teams at the production stage.

Three points are important in managing large-scale construction projects in Korea involving international joint venture design team (JVDTs):

- Firstly, any international arrangement adds complexity because of the different cultures, language, organisational differences, regulatory systems, codes and standards, and technologies.

- Secondly, joint venture agreements make the organisation and control more complex, particularly where many parties are involved.

- Thirdly, design for large-scale construction projects is a very complex processes, it is necessary to co-ordinate many specialist and information

[1] The term design-production management is used throughout the thesis.

[2] For the purpose of brevity, Korea is used throughout the thesis to denote the Republic of Korea, which is South Korea.

technology skills to deliver the project. The term complexity is probably too simplistic; design is intricate, complicated, interdependent, entangled, tortuous, convoluted, iterative and non-linear in nature.

Figure 1.1 shows diagrammatically the sequence of design and production with the risk and complexity through the various stages, including the risk at the tender stage, and at the pre-production post-contract award stage.

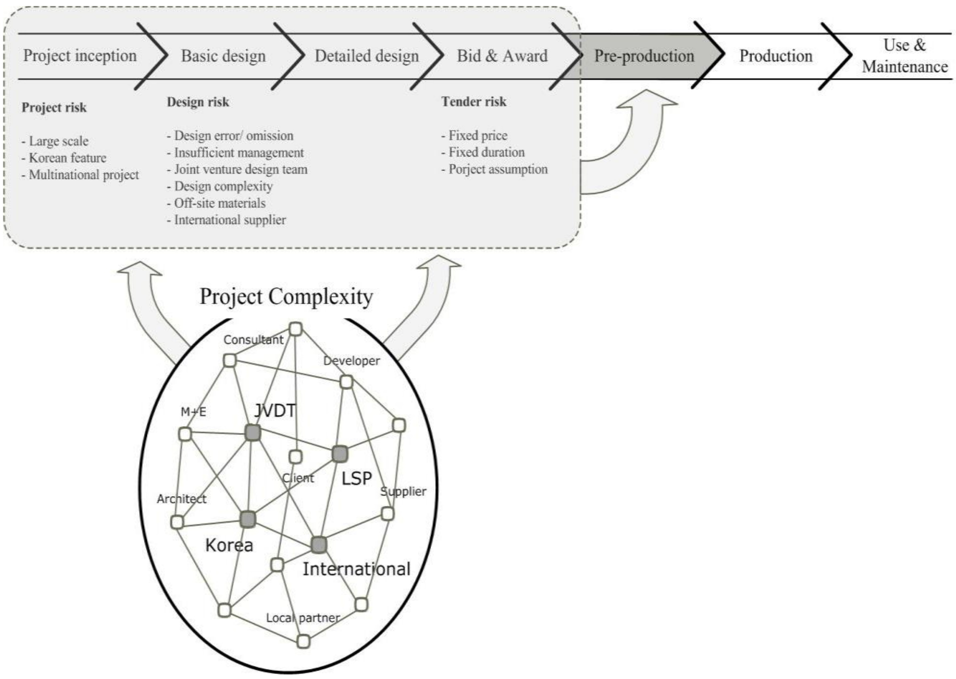

Figure 1.1 Project risk and uncertainty at pre-production stage

For example, a US based architectural company appointed to the joint venture, may have a CAD system that will not necessarily be compatible with Korean enterprises, nor will it have familiarity with Korean codes and standards, planning and code approvals, and regulations. Whilst there may be a local Korean design practice appointed to obtain code approvals, the interface between the US design firm, the Korean design firm, the general contractor, and specialist contractors requires a common communication and careful management. This research recognized this diversity of technology, codes, standards, and culture as a component of complex system. By adopting complexity theory as the underpinning theory of this research, complex interactions and interdependences between project components are modelled and simulated by a systems approach (system dynamics).

The motivation for the research has been the challenge faced by Korean contractors, who have often suffered significant financial losses when building large-scale construction projects in Korea designed by international joint venture design teams. Therefore, the research focuses upon how design-production management can help contractors in the pre-production stage following the contract award.

1.2 Background to the research topic area

There is a need for the development of a systematic approach using design-production management process map (DMPM) at the pre-production stage of the project, by modelling the complexity and interdependence of the data and information embodied in the initial project documents. The underpinning theory is based upon understanding complex systems and interdependence, by using systems thinking and cognitive mapping in order to demonstrate how design-production management can help improve construction performance and project profit.

Design management normally uses established processes to help the design team when they are at the design stage of a project to coordinate and manage the various disciplines engaged in the design process. However, because of the special features of the Korean construction sector, design management is used by the contractors to help in production stage by ensuring the sequencing, interaction, and flow of information from the design into production (Bea *et al.*, 2006). Design-production management involves managing complexity. Efforts to define the complexity of large-scale construction projects often refer back to systems theory, the idea that an organisation or a project can be treated as a complex system of interacting components (Vidal and Marle, 2008).

Large-scale construction projects incorporate many design elements that require unique and innovative structural, mechanical, electrical, and environmental systems (Aminmansour and Moon, 2010). These design technologies involve convergence between diverse professional disciplines (Wakisaka *et al.*, 2000; Lu *et al.*, 2015). In addition, large-scale construction projects have used international joint venture design teams to produce the concept and scheme design in Korea, which has resulted in a complex arrangement for the delivery of the design information. Due to project complexity, the profitability of large-scale construction project has been problematic for Korean construction enterprises who have underestimated the cost of project delivery at the bid stage (Laryea and Hughes, 2008; Owen *et al.*, 2010). Unlike the traditional concept of design management which focuses on design output and design process, design-production management concentrates more on interconnecting issues between the design information and production or assembly from the contractor's perspective as seen in Figure 1.2.

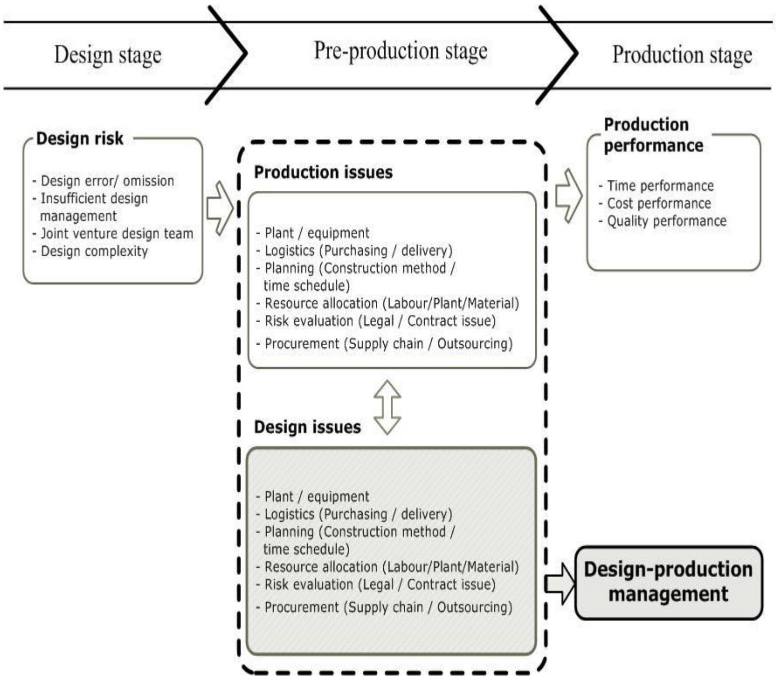

Figure 1.2 Concept of pre-production management

The literature review showed that research on design management has focused upon the management of a design solution from the perspective of the design team, to ensure timely and relevant design information. Insufficient attention has been paid to the design information and design management to help the contractor at the pre-production stage (Tzortzopoulos and Cooper, 2007; Song *et al.*, 2009). The pre-production stage is crucial to the contractor, who has already committed the enterprise to deliver the project for the accepted tender price and construction duration. The contractor needs to convert design information into production information at the pre-production stage (See Figure 1.3); the reason the management gap exists is because of time pressures to pre-order key materials, to resource the project, and to ensure there is sufficient information to commence production. Most importantly, the design team does not see the pre-production stage as critical because they have completed production drawings for the tender process and their fee payment milestones relate to the bid being received. The pre-production[3] stage has received little attention from the research community.

There is limited literature regarding design management from the contractor's perspective, and most studies focus on the design process or phase rather than the production phase from a contractor's perspective (see Anderson *et al.*, 2005; Tzortzopoulos and Cooper, 2007; Emmitt, 2010).

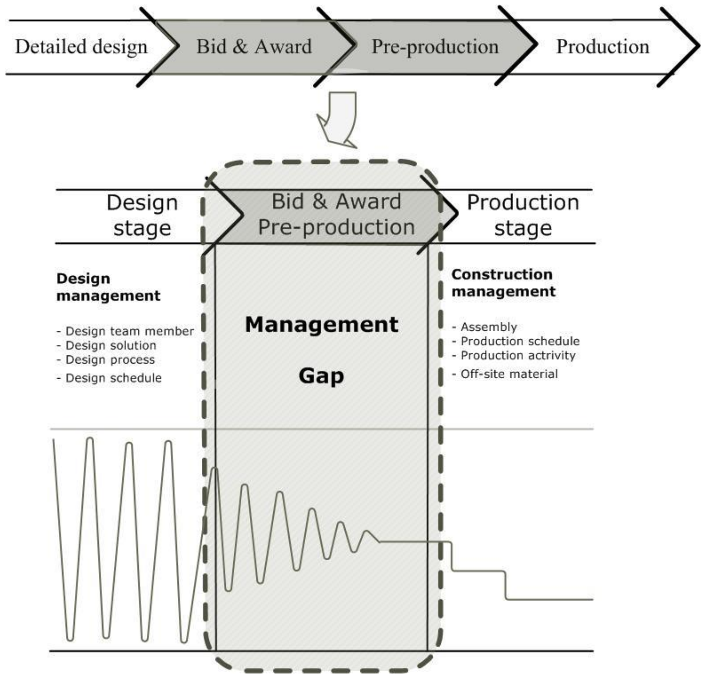

Figure 1.3 Insufficient attention on pre-production stage

[3] For this research, pre-production is the stage following the award of the project, the signing of the contract, and the stage prior to construction commencing on site. It involves the assembly of the construction team, the pre-ordering of materials, resource planning, and the planning of production prior to work commencing on site.

Korean large-scale construction projects tend to be designed and engineered by international joint venture design teams where a reputable foreign design company collaborates with local partners. Many successful design strategies involve foreign design teams, which provide a concept and schematic design, and then hand the design over to local partners to obtain detailed statutory approvals and construction documents. An international joint venture design team is influenced by the different cultural and language barriers, time zones, work process, technical standards, and building codes making effective design collaboration challenging. Collaboration between the foreign and local partners often fails because each party concentrates on their own project delivery milestones without consideration of how their counterparts conduct their tasks; this can result in unnecessary rework and design change on site. The integration challenge in an international joint venture design team is greatest when processes are in reciprocal interdependence. Particularly in complex projects, the actions of each design party must be mutually adjusted to those of the actions of other design or engineering parties.

Thus, international joint venture design teams rely heavily upon the contractor to respond to unexpected design-related problems caused by inadequate design information during the production stage, because, being a part of a joint venture design team, each design part cannot deal with these reciprocal intertwined design problems between design team members. Even if the contractors assume that all design information passed from the joint venture design team at the pre-production stage will be reliable and accurate, they should prepare appropriate methods to manage design-related problems during the production stage, otherwise these design problems can influence the entire production schedule. The literature review revealed very limited research that considers how design-production management from the contractor's perspective can be used from the early project stage to improve project performance.

1.3 Problem statements

***Statement 1*:** Complexity and interdependence are an integral part of the fundamental issues in the management of design information for large-scale construction projects in Korea undertaken by international joint venture design teams (JVDTs) in collaboration with Korean design organisations. Such complexity requires management at the interface between design and production in order to reduce uncertainty and manage the risk of project cost and budget overrun. Systems/ tools are required that can help in the management of the design production interface for use at the bid, post-contract award and pre-production stage.

***Statement 2*:** Design management has evolved as a systems approach using a recognised technique/discipline to manage design information for the design output and team members through design and into production.

***Statement 3*:** The bid, post-contract award, and pre-production stage are the most important stage for any contractor. Poor decision-making at these stages will lead to losses and disruption, yet design-production management systems pay little attention to the requirements at these stages from the contractor's perspective.

1.3.1 Discussion of the problem statements

Large-scale construction projects undertaken by international JVDTs are often more complex technically and managerially because of long project periods and the complicated interfaces. Decision-making, planning, and management are typically multi-actor processes involving multiple stakeholders (Flyvberg 2014). All system factors (here LSP construction components) are closely related to each other and have interdependence. It is difficult to manage and implement using traditional management techniques, because the relationships between the factors of production are interdependent, interconnected, and nonlinear. Even if the internal management process is set up perfectly, lots of external factors such as long-lead delivery items, delivery systems, off-site material inventory control, and international specialty works contractors who are not familiar with local (Korean) work practices, will seriously impact the entire project management process (Maylor *et al.*, 2008).

Technology and design are often non-standard leading to uniqueness bias. Experience, technology, and system processes cannot fully control the complicated intertwined internal and external factors (Jaafari, 2008). Important systems methodologies have been developed over the years. 'Hard' system thinking is highly appropriate for mechanical systems, but not as useful when people are the key elements in the design, operation and delivery of the system. The problem is that people are unpredictable in their behaviour (Remington and Pollack, 2007). Since the mid-80s, importance of 'soft' system thinking, including complexity theory and system dynamics, has increased (Blockley and Godfrey, 2000; Wiig et al., 2014). 'Soft' system thinking has the ability to cope with uncertainty and other problems such as management competency, human perceptions/judgement, bias, and differences in culture and value systems (Yeo, 1993; Aslani *et al*., 2014). Complexity theory is gaining prominence because it has considerable scope to provide insight into the systemic nature of managing complex projects (Nota and Aiello, 2014). Construction projects are complex in nature (He et al., 2015; Qazi et al., 2016). A large number of entities with a high level of nonlinear interactivity characterises most large-scale construction projects; they exhibit different characteristics and multiple kinds of systems such as hierarchy, interconnectedness, control, communication, emergence and adaptiveness. Thus, a systematic approach based on complexity theory is a reaction to projects running over time and over budget.

Design-production management evolved to reduce and integrate the gap between design and production. The design-production manager is a systems integrator; ensuring information and timing are part of the design delivery process. It has normally been led by the architect or a specialist consultant. Both architect and contractor focus upon construction and engineering phases using a wide range of building material specification in the management processes (Koskela *et al.*, 2002; Emmitt, 2014). The contractor must consider the temporary works design requirements and all the technical details of production.

In the Korean construction industry, contractors usually have their own design management team within the organisation; the design management team works with the production engineers to focus on production sequencing, methods, and logistics. However, such design management teams have little or no involvement in the design process. Information is a key part of the production requirements, having the right information at the right time and in the right sequence. Hence, they adjust and organize all design information produced by the design team for efficient and cost effective production. The contractor is looking for efficiencies, with off-site pre-fabrication wherever possible and optimisation of the work packages. The contractor breaks the project into a sequence of work with a work breakdown structure, taking account of the specialist work packages. The design team focus upon the finished product, rather than the production process.

Many large-scale construction projects (LSPs) in Korea are procured using the traditional design-bid-build approach. In this method of procurement, the contractor is appointed after design completion, although the design is rarely complete. Contractors have no choice but to review and examine all design information such as drawings, bills of quantity (BOQ), and specifications at the post-contract award and pre-production stage. The involvement of international JVDTs gives another layer of complexity and design risk to contractors at the production stage. Even if they have particular experience and knowledge of the design of LSPs, managing the interfaces between different production processes and materials used in Korea, the legislation, and cultural differences all increase the contractor's design-production interface risk during the site production stage. For a large-scale construction project in Korea designed by an international JVDT, there are different pressures, often not fully understood by the Korean contractors at the bid stage of a project. Separation of design and production by the design-bid-build procurement process makes the collaboration of design and construction knowledge more difficult, as well as diminishing the opportunity for contractors to influence the design output from the initial project stage (design stage). It is very difficult for the contractor to produce an accurate tender price and investigate appropriate construction methods according to the available design information within the short bidding period. Without a detailed design review, neither establishment of s specific construction plan, nor accurate cost estimation is achieved. Moreover, contractors should manage unpredictable interdependencies and changing conditions during the production stage.

The NEDC report (1987) stated that more than 50% of issues on sites are caused by poor design management, yet design management as a discipline has been slow to evolve. Design errors and omissions occur because design elements and construction technologies are interdependent and interconnected in contemporary large-scale construction projects (LSPs). An LSP is composed of different purposes, functions, and systems within one project such as a mass urban regeneration, airport project, and high-rise building project. According to project purpose and scale, different design, building technologies, structural or evacuation system, work process, and legislation are integrated intricately (Hameria and Nitterb, 2002). An enormous amount of design, material, plant, technical, and system information are poured into the production stage. Thus, insufficient design-production management can become a serious cause of design changes or rework throughout the production stages, and these iterative works impact on the overall project performance. Early involvement of a design-production management process could be a key factor in reducing project uncertainty and promoting efficiency. The production team has specialized training, in-depth knowledge of construction materials, production methods, and enough practical experience. A new approach is needed to manage the design-production interface.

1.4 Aim and objectives

*1.4.1 **Aim***

The main aim is to develop a design-production management process mapping approach for design-production management from the contractor's perspective for the construction of large-scale projects in Korea, which involve international joint venture design teams. This would improve the accuracy and reliability of the bid, post-contract award planning and pre-production stages prior to construction commencement on site.

1.4.2 Objectives

The research objectives are to:

1. Understand complexity theory and the interdependency of complex systems and how these influence large-scale construction projects involving international joint venture design teams.

2. Consider the characteristics of the Korean construction sector and how the construction environment shapes the procurement and delivery process in Korea.

3. Investigate the organizational and managerial characteristics of international joint venture design teams.

4. Produce a process map suitable for use at the bid, post contract award, and pre-production stages of a project by investigating the design-production management (DM) factors from the contractor's perspective, using a system

dynamics approach.

5. Validate the effectiveness of the process map and optimize the process map.

1.5 Research scope

The research takes a deductive approach using quantitative and qualitative information. It focuses on the development of a design-production management process map (DMPM) from the contractor's perspective for the pre-production stage of Korean large-scale projects involving international joint venture design teams.

1. ***Design-production management*** – The research focuses on design-production management as a project management methods. Interface management between design and production is very critical. However, its importance is often overlooked by both the design team and the contractor. Developing a process map may be useful to understand different interfaces and manage design-production elements.

2. ***Contractor's perspective*** - Conventionally, design management has been carried out by architects or specialist consultants from the design perspective, rather than the contractor's. Contractors must manage the design information to reduce design-related risks on site due to the increasing scale and complexity of contemporary LSPs. As there has been insufficient attention from academic researchers, design-production management from the contractor's perspective will be a contribution to the body of knowledge.

3. ***Pre-production stage*** - The design stage has been identified as a major source

of problems for the subsequent production stages (Koskela *et al.*, 2002; Emmitt, 2014). Design errors and omissions should be reviewed and corrected before commencing construction. Because these design-related problems impact on both design elements and relevant production activities, inadequate and inappropriate design-production elements should be managed at an early stage. If they are revised in the pre-production stage before starting of construction, negative impacts on the entire project performance can be significantly reduced.

4. ***LSP designed by international JVDT*** – Large-scale construction projects (LSPs) by their nature are high value, high risk, and highly complex, because of the large number of specialist collaborators, with many different design elements, technologies, and systems. This diversity makes LSPs more complex. Moreover, involvement of international joint venture design teams gives projects another level of complexity because of the different technical practices and work process adopted from different countries.

5. ***In Korea*** - Korea is a growing market for large-scale construction projects (Swickerath and Tillson, 2011), with a number of large-scale construction projects being planned and developed. In spite of diverse experiences on the construction of large-scale projects worldwide, the Korean construction sector has insufficient soft skills such as design, consultants, and management. By application of a design-production management process map (DMPM), Korean contractors can achieve advantages in management performance reducing project complexity and design risks.

1.6 Research approach

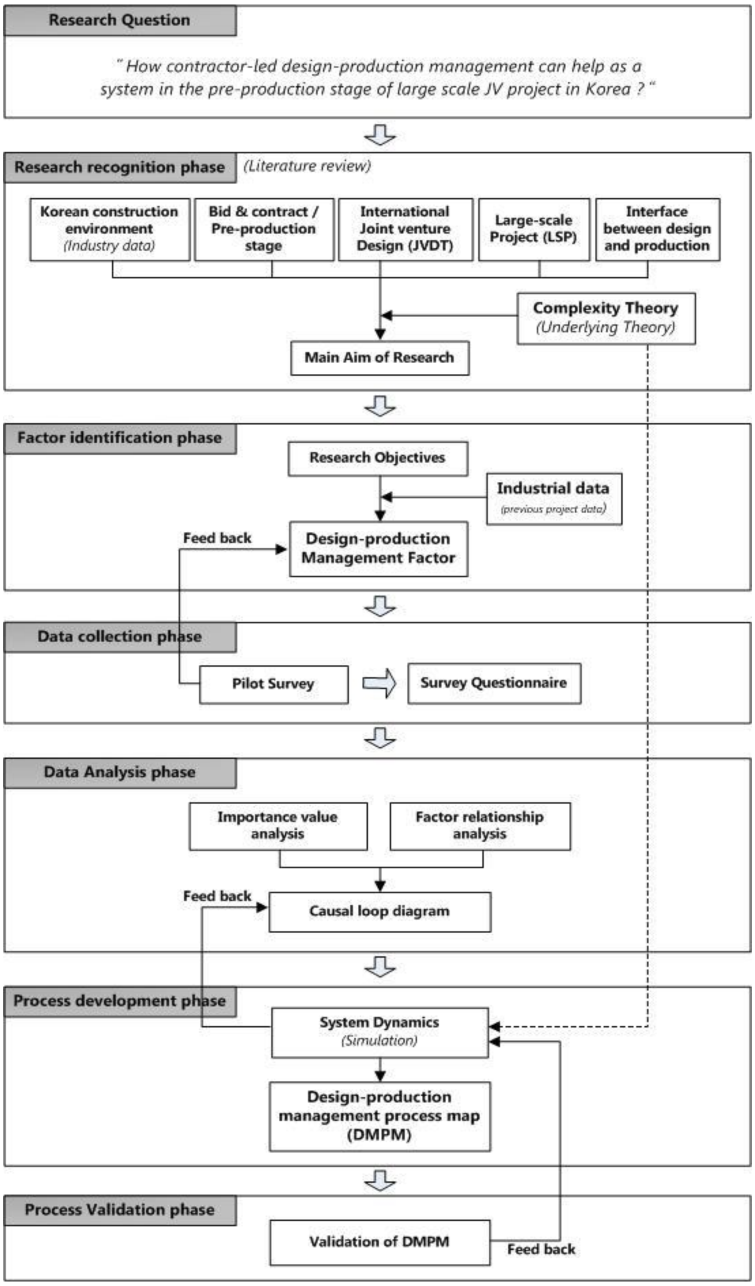

Figure 1.4 Research flow

Figure 1.4 shows the research sequence. The research is structured into six parts.

The main research flow is organized into three stages:

- The data identification stage.
- Data collection and the analysis stage.
- The process development and validation stage with simulation using the process map.

The data identification stage consists of a literature review, an understanding of the underlying theory, and factor identification. In this stage, problems of design-production elements and limitations of existing design management process in Korean large-scale projects designed by international joint venture design team are reviewed. Then based on the underlying theory, including complexity theory and the interdependency of complex systems, diverse design-production management factors are obtained from the literature review and industrial reports.

A pilot survey including a semi-structured interview was undertaken with six Korean construction experts to understand the contractors' attitude towards design-production management and to establish the survey questionnaire using their practical knowledge and experience. The research questionnaire was formulated and influenced by the pilot survey results.

Highly ranking critical design-production management factors and interrelationships between factors were determined from the results of the questionnaire survey. The importance value of individual factors and the degree of interrelationship between them were identified; a causal loop diagram and system dynamics model was created from the results. After repeated simulations, an optimized and balanced design-production management process map (DMPM) is established. Then effectiveness and reliability of the process map is validated to correspond to different project performance targets.

1.7 Thesis structure

Chapter one outlines the research problem, the need for the research, aims and objectives, and relevance.

Chapter two introduces the characteristics of large-scale projects and their delivery in Korea. Because large-scale projects and the Korean construction industry have developed rapidly within a short period, understanding current large-scale projects and the Korean construction industry is important. Sustainable and advanced building technologies and materials, which constitute a large-scale project, were reviewed in order to understand the distinct contractor systems in Korea.

Chapter three presents complexity theory as an underpinning theory of the research. Through the study of complexity theory, complicated individual behaviours can be explained and understood. In addition, with the application of complexity theory as a fundamental knowledge for large-scale projects, different unpredictable and chaotic interactions are established as a systematic causality map.

Chapter four focuses on presenting the literature on design management in construction projects. Changing roles of design management in design and production were identified, and multi-conceptual perspectives on design-production management from the contractor's perspective, critical factors, and international projects are presented. This contributed to the development of the research question and hypotheses.

Chapter five describes the research design and execution of the research methodology. The research philosophy, strategy, and applied techniques are described. Research data obtained by questionnaire surveys were analysed using different statistical analyses, and then system dynamics was used to establish the design management process and its validation. The validation aspect of the methodology is presented.

Chapter six focuses on data collection and the survey results. A questionnaire survey was conducted by Korean construction experts to identify critical design management factors. Prior to distribution of the questionnaire survey, a pilot survey was conducted to test the clarity and relevance of the questionnaire. Based on the collected survey results, critical design management factors were analysed using factor analysis and importance-priority analysis.

Chapter seven focuses on investigation of factor interrelationship. Based on analysed factor interrelationships, a causal loop diagram was established. A system dynamics model was established using causal loop diagrams and the results of the questionnaire survey.

Chapter eight concentrates on validation and simulation of the system dynamics model. In the previous chapter, a reference model of system dynamics was established. This chapter validates this reference model in order to create an optimal model through numerous system dynamics simulations. Based on the simulated results of the optimal model, a design-production management process map (DMPM) was established. The simulation outputs provide major parameters that are used for the establishment of the DMPM.

Chapter nine summarises the research work. The achievement of the aim and objectives of the research were examined, presenting conclusions, research contribution on body of knowledge, and recommendations for future research.

CHAPTER 2 CHARACTERISTICS OF LARGE-SCALE BUILDING PROJECTS

2.1 Introduction

Within the scope of this research, a building project is defined as; "a set of processes, consisting of coordinated and controlled activities with starting and ending dates, which require people and other resources (capital, information, services, materials, machinery and auxiliary equipment), gathered in a temporary organization so as to meet pre-determined goals and to create a unique result." A building project is a transformation process of an investment decision into an operationally effective physical reality that should ensure profitability for the construction enterprise.

A project has two genetic features; uniqueness, while the result is unique, regardless of the presence of repetitive elements, and temporary, in that it has a finite duration (Lewis, 1995; Cleland and King, 2007; Guerra et al., 2009; Echeverria, 2011). A project is a temporary effort undertaken to create a product, service or result (PMI, 2015). Construction projects are very complicated businesses because of their singular features with high levels of complexity, uncertainty and uniqueness (CIOB, 2014).

Large-scale construction projects are known for their complexity, large size, high costs, and long periods for design, approvals, and production. They influence the communities, economy, and environment of regions, and even the whole country. The size and complexity affects the project costs. On mega projects, the construction cost can exceeds one billion US dollars. Some have time frames that exceed five years. Contemporary construction projects and large-scale projects use off-site manufacturing techniques with pre-fabricated components, which can involve specialist-fixing teams working to high tolerances. Advanced management systems and integrated information management systems must be used to co-ordinate and control the specialist teams and the site production team to ensure they have the correct design information for efficient site production; this presents new challenges (Schipporeit, 2000; Sha'ar et al., 2016; Yan and Luo, 2016). Most LSPs use advanced building technologies, innovative materials and structural systems reflecting regional and cultural characteristics. This chapter focuses on two characteristics of LSPs. Firstly, the general characteristics and secondly, the distinct characteristics when using Korean standards.

2.2 Large-scale project delivery in Korea

Due to their distinct characteristics and symbolism, most large-scale construction projects have been by the public as landmarks, reflecting certain regions or the country as a whole. The development of LSPs has always been recognized as an indicator of the technical and economic progress of a country. They are considered an iconic expression of cultural maturity expressed by the design, scale, function, and concepts. Korea gained international recognition in the 1990s as an advanced nation that was attempting to be at the forefront of technological change. The demand for office space, more spacious housing and massive infrastructure changes created an increasing need for LSPs (Cho and Chung, 2011).

2.2.1 Present large-scale projects in Korea

Korean companies are becoming leading players in the global market for LSPs both as a client and contractor. According to the Council on Tall Buildings and Urban Habitat (CTBUH, 2011), over ten years, the amount of Korean large-scale (over 150m high) buildings has increased from 9 to 124. Diverse large-scale construction projects include super skyscrapers (over 100 storeys), a new air-port, high-speed railways, and resort complexes. A unique feature of the Korean economy is the large conglomerates, chaebols[4] such as Hyundai and Samsung. They are diverse, very large and are very influential with a strong balance sheet. They develop LSPs for their head offices or commercial real estate a statue symbol of their wealth and scale. The high demand for LSPs is expected to continue for some time (CTBUH, 2011).

High-density mixed-use developments are another major trend within LSPs in Korea, such as offices, commercial, residential, and entertainment buildings (Cho and Chung, 2011). The history of mixed-use development in Korea is not a long

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[4] Chaebol are large, conglomerate family-controlled firms in South Korea characterized by strong ties with government agencies. They are typically global multinationals and own numerous international enterprises; they are often controlled by a chairman with power over all the operations. They have been at the heart of Korea's rapid industrial development over many years, and tower over almost every area of business: from stockbroking to theme parks; from supermarkets to heavy weapons. When South Korea's economy was small and predominantly agricultural in the mid-20th century, the government was in full support of chaebols to help rapidly increase the competitiveness of Korean industry and increase the size of the industry. Nowadays chaebols such as Hyundai, Samsung and LG have played a very significant role in social community and politics as well as in the economy and industry.

one it is a rapidly increasing trend in the LSP market. Of the most recent 100 LSPs in Korea, completed or under construction, 71 are mixed-use. Most of them are developed for residential or commercial purposes. These large and high-density projects create a new market in which mixed-use projects acts as a significant branding and marketing tool for different building materials and maintaining services provided by the other subsidiary companies of the chaebols (Swickerath and Tillson, 2011). Major chaebol construction companies have shifted their business target to development of high-density mixed-use developments. Super high-rise buildings have been completed and developed using mixed-use, with at least 65 storeys - see in Table 2.1.

Project	Location	Storeys	Height(m)	Stage
Hyundai Business centre	Seoul	110	550	Under planning
Lotte jamsil super tower	Seoul	112	556	Completed
Song-do Trade tower	In-Chen	65	305	Completed
Chung-ra city tower	In-Chen	110	453	Construction approval
Haeundea I-Park	Busan	72	298	Completed
Haeundea Zenith Tower	Busan	80	301	Completed
Busan Lotte super tower	Busan	107	510	Under construction
Haeundea LCT	Busan	101	412	Construction approval
World business centre	Busan	108	560	Under planning

Table 2.1. High density and high-rise mixed-use development in Korea

The characteristic of the projects shown Table 2.1 is that they all involve chaebol companies, with international joint venture design teams. They have innovative design and technical solutions.

Some projects are developed by chaebol groups as their head office, e.g. the Hyundai business centre (110 storeys) and the Lotte Jamsil super tower (112 storeys). Other commercial and residential real estate developments are: Haeundea I-Park (72 storeys); Haeundea Zenith Tower (80 storeys), and; Haeundea LCT (101 storeys).

2.2.2 Involvement of international joint venture design teams in Korea

The current global construction market is blurring the concept of national boundaries. With the trend of internationalization, enlargement, and increasingly large complex projects, the global architecture, engineering, and construction (AEC) industry has shifted toward multi-national cooperation in order to win major projects. Large-scale and complex buildings have been designed using international collaboration, in the design and engineering sectors. Korean contractors are experienced in international LSPs. With this experiences and knowledge of the technology used in different international large-scale construction projects (LSPs), Korean contractors have carried out diverse LSPs including the Petronas twin towers, the Taipei World Financial Centre and the Burj Khalifa. However, domestic architectural and engineering consulting firms do not have either the innovative design approach, or the technical knowledge to deliver exciting, innovative and outstanding design solutions on their own.

Since the introduction of LSPs in the late 1960s, collaboration with international design teams was inevitable in Korea, because at that time, most domestic design companies did not have the knowledge and experience to carry out the projects.

Collaboration with international companies provided opportunities for domestic companies to learn and gain experience. They could learn advanced design techniques, digital modelling and management systems from their international partners. The international partners gain understanding of local building codes by collaborating with local partners. Korean clients want exciting, innovative designs by appointing international design teams with a reputation for leading edge design solutions (Bea *et al.*, 2006). In LSPs, the international design partners undertake the schematic and concept designs; the local partners develop the working drawings and detailed designs in order to obtain approvals and seek bids (Choo et al, 2004; Mahmoud-Jouini et al., 2016). Korean building codes and regulations reflect the climatic conditions, and special requirements of the country. International designers need the technical support of local partners to fully understand the regulatory environment and to meet the local registration requirements.

An international joint venture is often described as the joining together of two or more business partners from separate jurisdictions to exchange resources, share risks, and divide rewards from a joint enterprise. However, international design joint ventures are a collaborative venture, where the companies collaborate under the joint venture to deliver a design solution. In essence, one company, usually the architectural design practice in building, or the engineering design practice in engineering projects acts as the lead partner in the joint venture. The reason that design joint ventures are different to the traditional business joint ventures concerns the professional registration requirements, and the liability insurance requirements. A professional indemnity policy covers the individual and the practice for negligence, when in a joint venture arrangement there must be special insurances to cover the joint venture for professional negligence. This can lead to a complex web of insurances being required to cover all the members of the joint venture.

The performance of any international project joint venture is requires effective and efficient communication, and co-operation between different project participants (Yan and Luo, 2016). Language, location, culture, specialist skills and the regulatory system will have an influence. The problems in managing joint ventures stem from one cause: there is more than one parent. The owners, unlike the shareholders of a large, publicly owned corporation, are visible and powerful, whereas in a joint venture, there is shared ownership (Killing, 1982). International joint venture design teams are complex to manage, because LSP building design relies on the integration of advanced design and engineering solutions with many specialists involved. An international joint venture design team is a temporary organisation where two or more distinct legal organisations collaborate to deliver a project. The selection of the IJV team is based on specialist knowledge, or on relationships. Frequently the IJV will be appointed after winning a successful design competition.

Korean clients often finance the continuation of their LSPs through the pre-sale of the real estate before the commencement of building construction. Chaebol contractors can sell the property on behalf of client, because they are well known to potential customers and seen as reliable, especially as they are a subsidiary of the larger chaebol group. Customers rely on the contractor's production ability and managing knowledge. They also rely more on the competencies of the contractor's design delivery team than the architect, designer, and other engineers throughout the project. Clients and contractors have to increase the initial pre-sale rate to ensure a stable cash flow. Clients and contractors prefer using renowned international joint venture design teams (JVDTs) as it can add status and value to the project.

2.2.3 Exclusivity in the Korean construction industry

The Korean construction industry accounts for 14.7% of total gross domestic product (GDP) (KOSIS, 2014). The total value of construction work orders is about £106 billion. The construction industry employs about 1.07 million people and accounts for 7.3% of the total industrial workers (KOSIS, 2014). The Korean construction market was fully opened up to the world between 1994 and 1998 following the Uruguay Round[5] agreement. However, due to government policies favourable to local companies, large contractors belonging to chaebol groups have more of a competitive advantage than foreign contractors. This is partly because when foreign contractors bid on public projects in Korea (38% of the total domestic market), they have to prove their record of accomplishment of projects in Korea in order to pass the pre-qualification (PQ) test. This is one reason why international construction companies find it difficult to win construction work in Korea; it is an invisible barrier to entry. Compared to the other three emerging

[5] The Uruguay round was the 8th in the multilateral trade negotiations (MTN) conducted within the framework of the General Agreement on Tariffs and Trade (GATT).

Asian countries; Taiwan, Hong Kong, and Singapore, the number of international construction companies working in Korea is a fifth lower than the average (Sachs *et al.*, 2004). There are few registered overseas contractors operating in Korea.

A barrier also exists in the domestic construction and engineering sectors. Before 2008, specialty contractors could not tender directly for any project. They could only be awarded the project through a general contractor, thus not making contract with the client directly. However, in terms of the LSP market, project award to contractors on their own is still almost impossible. All multi-use buildings over 16 storeys should be carried out by the general contractor only and not the client themselves or a specialty contractor. In addition, all large-scale projects need enormous amounts of initial capital to start the project. Due to the payment guarantees by the general contractors, clients can receive project financing from a bank or investors. Although it is one of the biggest project risks, Korean general contractors can manage it by themselves. Therefore, influence and competitiveness of general contractors is quite strong in the Korean LSP market.

2.2.4 Distinct characteristics of the Korean construction sector

The Korean construction industry is linked to other domestic industries such as manufacturing, heavy equipment, and the real estate sector through the chaebols. To increase economic growth and competitiveness in the global export market, the government has supported large chaebols such as Samsung and Hyundai through the provision of work. Improving infrastructure directly benefits all sectors of the economy for leading to rapid economic growth (Kisline, 2012).

These large companies all have a diverse portfolio of goods and services as well as a sophisticated ownership structure. For example, the Samsung group, which is a well-known electronic manufacturer worldwide, operates several different businesses covering hotels, department stores, heavy equipment manufacturers, contractors, architects, engineering firms, building materials and a financial company. Even if these companies take the position of joint stock companies, they belong to only one strong leader and founder family. It makes large interconnected companies more effective through use of quick decision-making and strong leadership. Far more than just a "company," Samsung is a determining standard in the social service sector, urban form and improving the quality of life in Korea.

Large Korean construction enterprises in the chaebol group, went overseas, initially to the Middle East to construct transportation, power, and oil and gas projects. Chaebol construction companies have a significant impact on not only the construction industry, but also other related industries in Korea and overseas.

Being involved in a wide range of businesses is a very distinctive characteristic of Korean contractors. Contractors have expanded their business boundaries to land development, property sale and facility management. The best example is the Haeundae I-Park project, developed and constructed by the Hyundai Development Company, one of the large chaebol groups in Korea. The project is 511,805 square meters high-density mixed-use development project, which includes three high-rise residential and commercial towers (66, 72, and 46 storeys) with 1,631 units (Swickerath and Tillson, 2011). The Hyundai Development Company was the client, the investor, the developer, project manager, and contractor for the project. It also has various affiliates including building material manufacturers and suppliers, property sellers and facility management. With professional knowledge and organization in the field, contractors control the whole project among different subsidiary and affiliate companies, each with their own interest and purpose. This configuration necessitates simultaneous management and project organization on both the client's side and the contractor's side (Swickerath and Tillson, 2011).

Even if large contractor just constructs the building not involved in development, financial investor such as bank allows project finance based on payment guarantee from contractor instead of developer. Finance sector trusts the contractors belonging to large conglomerate**;** they have a strong balance sheet and can call upon financial resources. The client will accept the VE proposal and design changes from a contractor in order to retain the name of the large conglomerate for property sale (Acharya et al., 2006).

Chaebol are typically global multinationals and own numerous international enterprises, controlled by a chairman with power over all the operations. The term is often used in a context similar to that of the English word "conglomerate". There are several dozen large Korean family-controlled corporate groups, which fall under this definition. The chaebol dominated the industrial sector and were especially prevalent in manufacturing, trading, and heavy industries. Construction and real estate investment are an integral business within the chaebol business enterprises. In contrast, medium sized and small firms have a relatively weak equity, technology, qualified engineers, and management capacity (Seo and Kim, 2012). The chaebol contractors have strong balance sheets because they can leverage their purchasing power across different business divisions. The financier and investors have confidence in the technical and financial ability of the contractor to deliver the project. This has implications for the management of design and production risk, and the ability to maximise profitability. The responsibility and authority of the contractor is very strong throughout the change of the project methods of procurement (BS 8534, 2011). New methods of procurement such as Design-build, Turnkey, Engineer Procure Construct (EPC), two stage tendering, and PPP have emerged as new approaches single point responsibility and authority is increasing. Asia is conservative with its regulatory systems; it is slowly introducing the new methods of procurement. The important issue is the allocation of risk; many Asian clients prefer to give the construction responsibility to the contractor. The traditional concept of design management and role of design management is changing. Unlike the traditional approach to design management where only the design process and out-put are considered, design production management focusses on how project information and data is integrated and processed during the construction phase.

The government established policies and procurement systems to improve the competitiveness of the construction industry and to increase market size. At the beginning of the project, the client will contract with just the general contractor, who will enter into contracts with the sub-contractors and specialists. Hence, all project responsibilities and authorities focus mainly on general contractors, even the design elements. General contractors have the most efficient organizations, the most experience, and the most technical capability throughout the project process not only during production, but also in financing, approval and sales. Clients give them more authority and responsibility than is usual in a client-contractor relationship. Despite the architect and consultant make a contract directly with the client not the contractor, they will follow the contractor's working process throughout the project. Once the design is completed and handed over, the architects and designers often become involved in other projects. In Korea, most design consultants focus upon pre-contract services and are less involved in post-contract construction. This means the design should be 90% complete at the tender stage, whereas in reality because of a lack of available information, the design is less than 90% complete at the tender stage. When unexpected design-related problems occur post-tender pre-construction on site, contractors do not have sufficient professional support from the design team consultants such as architect and designer (Sebastian, 2005; Walker, 2015; Sha'ar et al., 2016). Local design partners find it difficult to handle the problems without the technical support from contractors or foreign design partners, especially when the client or contractor requires the design changes.

The contract for professional services between the client and the international joint venture partners will stipulate roles, responsibilities, and fees payable to whom, and at what stage. The fee proposal will establish the design responsibilities. This can create problems because the design team is asked to undertake design services requested by the contractor, without recognition of the commensurate cost to the joint venture partners.

In Korea, when problems occur during the production stage, the client or supervisors tend to focus the blame/responsibility on the contractor, even if the problems are not the contractor's fault; this is partly a function of the Korean system of responsibility being placed with the contractor. This is distinctive characteristic of the Korean construction sector that differs from other construction industries. Sometimes the contractor's responsibility is taken more seriously than the architect's responsibility, even in design issues. Therefore, the contractor should be competent in construction methods, engineering technology as well as management skills. After design completion and handover, the designers may be involved in other projects, leaving the contractor without sufficient design team support during production (Ng and Skitmore, 2002; Lee *et al.*, 2005). The contractor must ensure a suitable design-production management (DM) process is in place to prevent and solve design-related problems during the production stage. This is established according to the company's capabilities, structure and organization. Moreover, the contractor also plays the role of a coordinator between JVDTs throughout the production stage in order to solve complex and unexpected design issues such as design changes or value engineering (VE) (Pheng and Leong, 2000; Hossaina and Chua, 2014). Contractors have no choice but to promote strong leadership and coordination skills to ensure the project's success. These strong leadership and coordination skills have distinctive characteristics of the role, critical to the competitiveness of Korean contractors.

2.2.5 Design-production management from the contractor's perspective

Despite the increasing complexity and quality standards of construction projects, less time and lower budgets is allocated to designing, bidding, planning, and construction (Ng and Skitmore, 2002). Tzortzopoulos and Cooper (2007), state designers aim to reduce their direct costs for professional services, and are less concerned with reducing the overall construction costs. They are more interested in design of the building form and function rather than the practical considerations of the production process. Hence, when contractors are handed the project documents from the design team there are often hidden design risks. Contractors do not always fully appreciate the design quality that comes from the design stage. Designers often concentrate on their design tasks without considering other aspects of production, which can result in unnecessary rework when on site. In many Korean large-scale projects, international JVDTs tend to rely on the contractor to respond quickly to unexpected design-related problems on site. The international JVDTs consists of design team members from different countries, they take design responsibilities, but want the contractor to take responsibility to sort out the practical issues when the project is on site (Sebastian, 2002; Sha'ar et al., 2016). At the initial production stage, appropriate design support and decisive responses from JVDTs are difficult to achieve. This is because the concept design has been completed by international JVDT and the local partners conduct detail design. Both design parties believe that they are not responsible for the design support at the initial pre-production stage. International architects may think that because they have already handed over their basic designs to the contractor that the design stage is over and the contractor should deal with any minor design problems. They may also believe that local partners who have the same culture and language as the contractor would be better at handling minor design issues. On the other hand, local design partners have different opinions to their international partners. They believe that if the contractor highlights the design problems at the pre-production stage, these are the responsibility of the international designer to resolve. A contract for professional services is a commercial contract with milestones and responsibilities, the JVDT will endeavour to ensure they make cover their costs and make a profit.

During the production stage, many design changes occur, either due to increase in scope of the work, client requested changes, statutory requirements, or unexpected events. Design production management plays a role between production and design to ensure the contractor, the specialty contractors, and all the supply chain have sufficient information to enable them to work efficiently and effectively. Therefore, Korean contractors play a role as construction manager and a design manager simultaneously. This allows for a collaborative process with the client. Contractors support the JVDTs to solve complicated design issues by applying their practical experience, knowledge, and technologies ensuring that innovative or unprecedented design solutions are both feasible and cost effective.

The large chaebol groups have their own construction company as well as diverse subsidiary companies in the construction industry including developers, manufacturers, equipment, and construction materials as part of their business. LSPs allow these companies to create an exclusive and stable market for their goods and services.

When a parent company attempts to develop a LSP, they consider how their various subsidiary companies fit into this project. If a chaebol group plans to develop a high-density mixed-use project, they will consider how the subsidiary companies will be involved. They attempt to achieve the business goal as project partners in the development of a large-scale project. They seek design or material changes to supply material or equipment that they produce or handle (Kim and

Kown, 2005). The client may sometimes ask the contractor to amend the design or material to incorporate the components and materials. These types of requests for design changes should be dealt with by the JVDT. However, in Korea, such requests are focused on the contractor, which is the affiliate company. The requests are reviewed and managed by the contractor's design management team. If design-production interface elements are not managed, the project may suffer from unnecessary design changes and re-work which can have a serious impact on the construction costs and duration. An example in the research is the extensive us of off-site pre-fabrication wherever possible. The Korean construction industry is undergoing rapid change with more off-site pre-fabrication and manufacturing that is driven by computer aided manufacturing systems. Such systems need standardised components and modular approaches. Converting a bespoke design into a manufacturing system is costly, and time consuming. The manufacturing plant needs close contact with the site production team to ensure the design is not compromised. The design team needs to work closely with the production team. Thus, contractor's design management plays the role as an intermediary between the client's project manager, the design team, and the contractor. Unlike the role of design management, the role is required in order to control and coordinate different between various affiliates regarding building material, construction equipment, interior design, or property sale.

The Korean contractor has a much wider role and more responsibility than a contractor in the UK or USA, because of the ultimate responsibility for the product. The contractor works throughout the construction phase as a design manager, construction manager, time manager, quality manager, safety manager, logistics manager, plant manager, and production manager, responsible for co-ordinating and controlling the multifarious specialist work packages. The contractor must have competencies to fulfil these roles as well as analyse the design-production elements, which may have arisen from the acceptance of affiliate company's requests to reduce unexpected design risk. This means the contractor must manage all stages of the project from the contractors' perspective as well as the clients' perspective (Swickerath and Tillson, 2011) and establish an appropriate design-production management process at the pre-production stage.

CHAPTER 3 THE CHANGING ROLE OF DESIGN MANAGEMENT IN DESIGN AND PRODUCTION

3.1 Introduction

This chapter focuses on the changing role of design management in contemporary international built environment. The literature review focused upon design-production management issues in complex projects. The aim is to reach a holistic understanding of changing role of design management. There are four main issues:

1. The role of design management is evolving, with the contractor taking a more active role in managing the design process during the production phases.
2. Large-scale projects are very complex, because of their scale and the large number of parties involved.
3. The traditional separation of design and production is more pronounced when international joint venture design teams are involved. They can be impacted upon by different culture, processes, and standards.
4. There is need for a new way of managing complexity at the production stage.

3.2 Complexity in construction projects

3.2.1 Increasing complexity

The concept of complexity is now being used more practically in different industrial sectors including the architecture, engineering, and construction (AEC) industry, particularly in large construction projects where many different experts and decision-maker are interdependent (Luhman and Boje, 2001; Robertson and Combs, 2014). Any LSP is a dynamic system in which the decision-making environment is complex and influenced by:

(i) the number of elements/packages in the system,

(ii) the number of connections between them and their interdependence,

(iii) the presence or absence of random variation,

(iv) the degree to which uncertainties affect the behaviour of the system (Mackinnon and Wearing, 1980).

To this, list can be added the number of controllable and uncontrollable events influencing the system. For example, the weather is uncontrollable, and political events can have an impact on large project. This all adds to the complexity of control, and the need to manage effectively the interfaces, particularly between design and production. Careful management is required to monitor the dynamic changes that occur through the project.

A construction project may be one of the most complex undertakings in any industry because of all the stakeholders involved, ranging from the client, the consultants, the contractor, specialty contractors, and the supply chain. The project must meet the regulatory standards, and be compliant with all the governmental codes.

A project evolves and develops over time as more information becomes available. The personnel/team changes as a project develops, and experience is gained during production (Vidal and Marle, 2008). Complexity in construction projects is a frequently occurring aspect of the AEC industry that makes it difficult to understand, foresee, and keep control of its overall behaviour, even when given complete information about the project system.

Complexity is not new, but it is increasing in construction projects, because of the increasing size and budget. Questions have been raised over how complexity can be managed in an appropriate way considering the reasons for complexity such as structural, dynamic, and interactive project components (Owens *et al.*, 2011). Participants of large-scale projects have different cultures and work processes that add to the complexity particularly where there is an international joint venture design team responsible for the design delivery. Vidal and Marle (2008) found that because participants involved in a project have different perspectives, individual characteristics are likely to influence how complexity is perceived - for example, differences in views between a specialist and a generalist. Naderpajouh and Hastak (2014) focused on the underlying factors of complexity, they identified a project is being composed of technological complexity, and organisational complexity. They regard them as the core components of project complexity. They believed that project complexity could be managed within a project system when differentiation can be recognized amongst a number of varied complex elements, e.g. tasks, participants, and interdependence or connectivity the degree of interrelatedness between these elements. Some authors distinguish between technical complexity (complexity with regard to the project's technical system), and social complexity (complexity with regard to the social system, such as the constellation of players involved (Cleland and King, 1983).

Carver (2017) presented his view that there are three types of complexity: structural complexity, emergent complexity, and socio-political complexity. Structural complexity involves the scale of the work on the project. A project is structurally complex when it has many stakeholders, work streams or other elements.

Emergent complexity encompasses projects where there are a number of unforeseen issues or where the situation is unknowable at the outset, as is the case with most construction projects. For example, increases to the price of steel in a construction project or stakeholders who were not identified at the outset suddenly needing to be included.

Socio political complexity is where the project suffers from hidden agendas and lots of politics. Dealing with socio complexity is the most difficult because of the unstructured nature of the issues.

Culture can add to complexity. One important key to leading and working with multi-cultural teams is to understand how context factors into all communication. Hall (1976) observed that communication in certain cultures, whether spoken or written, is a very direct and concise exercise. There is great reliance on numbers, statistics, and completeness of information. These cultures would be nervous about conducting business on a handshake. They prefer documenting agreements in detail to avoid different interpretations later, depending on context. Even if the agreement is reached via a phone conversation, the points would be put in writing at the first opportunity. These are the "low context" cultures, because they emphasize the clearly spelled content of the message, and the surrounding context would have a low priority. Hall described cultures found to be low-context include German, Swiss, American, Canadian, British and Scandinavian, as well as the cultures these societies influenced.

At the other extreme are the cultures in which the succinct, explicit message, whether spoken or written, does not communicate the entire picture. For completeness, context must be considered, it contains rich supplemental information. Hall classified these as "high-context" cultures in which individuals consider not just the message but also implied meaning, non-verbal cues, surrounding relationships, trust rather than numbers: the holistic picture. High-context cultures include Chinese, Korean, Japanese, Indian, Arabic, Brazilian, French and Spanish. Working on joint ventures with high-context stakeholders can result in misinterpretation of the expectation on delivery.

Consideration must be given to the differences between the controllable and uncontrollable factors that influence complexity. The weather is uncontrollable, yet it affects production on the job site. Allowances are made at the bid stage for inclement weather, but exceptionally inclement weather or unforeseen events such as floods or hurricane will delay the project and create problems with meeting production schedules.

In the traditional approach to project management, solutions to project complexity are the decomposition of an organization in order to undertake a detailed segmentalised investigation of all internal project components, such as technical, structural, organizational aspects. Academia and construction industry practitioners have tried to find management solutions to manage complexity within projects from inside the system. In the AEC industry, new layers of complexities are continuously evolving from the outside.

Due to the increase in large-scale projects implemented by JVDTs, complex external elements are becoming more involved in construction projects. The new layers of complexity, including different design standards, building codes, new building materials, legal systems, rules on bribery and corruption, and environmental criteria etc., seriously increase the complexity of the project delivery process. Management in one area of design or production cannot control these complex interconnected elements between design and production aspects. Complicated elements can cause unexpected re-work or design changes during the production stage. These complex external elements need to be integrated collaboratively with existing internal elements, they need to be managed at the early project stages.

The literature indicates that in the AEC industry, the importance of collaboration or integration between internal and external project elements is becoming even more significant. Owens *et al.* (2011) states that projects are influenced more by external elements than by internal project elements such as technical engineering, construction methods and management tools. In order to implement a complex project, contractors need to be able to optimize the available project components (experts, equipment, and resources) under unknown constraints whilst accommodating the changes from outside such as new financing partners or unexpected political risks. Migliaccio *et al.* (2008) investigated different project delivery methods for complex projects, especially for design-build and public private partnership (PPP) projects, to address rapidly changing external factors. They developed a new framework to cope with complex external elements caused by multinational participants including JVDTs, off-site resources, and multiple types of procurement systems. The framework is conceptual and not been validated in practice.

3.2.2 Complexity in international large-scale project

Comprehensive and detailed understanding of the characteristics of international large-scale construction projects (LSP) will help to understand better the impact of complexity. Projects can fail due to being unable to manage complexity and the speed and nature of changes (Hallowell and Toole, 2009). Complex LSPs often lead to having to incorporate different processes and state of the art technology into the project. The participants have more diverse approaches to the design of a project from a variety of fields and organizations. Large scale and multinational projects will increase the number of advanced technologies, experts, materials, and processes to the project. Some project components are likely to be sourced internationally for large-scale project: this will present challenges to the production team because of language and familiarity with the products and components. Unexpected risks caused by the uncertainties, can lead the project into another dimension of complexity. (Egginton, 1996; Yan and Luo, 2016).

Because LSPs include different functions and purposes in a single project, many building technologies and processes are united and interact with each other such as certain wall technology integrated with solar and ventilation technologies. Moreover, with the development of off-site and innovative building materials, contemporary LSPs require complicated and elaborate processes to manage the interfaces between in-situ and off-site building components. Unlike normal building projects where each individual engineering sector (e.g. structural, electrical, mechanical work) is conducted within their specialized area, all decision-making, execution, and even subordinate production activities are interconnected between the previous and next steps. This occurs even if they are not directly related to the construction process of the LSP (Gray and Hughes, 2001). In addition, LSPs, particularly designed by international JVDTs, tend to produce a high degree of organizational complexity and an increase in complexity (Gidado, 1996; Lu, 2015). Because most of these complex aspects of LSPs should be perceived, discussed, and dealt with at the pre-production stage, the degree of complexity of which contractors should manage at the early stage is very high when considering the short period time for the pre-production stage. Design information should be reviewed and checked at the pre-production stage within a short time period. Using only basic design information such as drawing, specification and bills of quantity post contract award, the project team must order suitable building material and construction equipment and establish project execution plan (PEP). The appropriateness and feasibility of design, integration with various production activities and different international building codes should be reviewed (Doloi, 2010; Ahern et al., 2014). Therefore, in contemporary project management, contractor is required to have practical design-related knowledge and experience in order to cope with the changing characteristics of a project. Compared to traditional design management where the contractor's design management team have focused on how to manage the design information and related production stages, changing design management to concentrate on how to integrate design and construction technologies in the design.

The multinational aspect is another layer of complexity in LSPs. Because all participants have different objectives, working practices, building codes, and culture, complexity in these international LSPs is increasing. Every company and country has their own operational and management systems, and working practice. This disparate processing gap will be integrated as time goes on (Schneider, 1995; Golini et al., 2015). However, despite the effort of international organizations in order to integrate the different project elements such as the International Organization for Standardization (ISO) 9000 or British standard (BS) 5750, problems concerning how international joint venture design teams (JVDTs) should work and communicate in complex project teams and how LSPs are designed and delivered effectively still remain (Yan and Luo, 2016).

Many experts must carry out their tasks in complex interfaces between design and management or design and construction. In terms of multinational LSPs, collaboration with different design areas is critical because LSPs rely heavily on the integration of different design and engineering parts such as structure, electronics and heating, ventilating and air conditioning (HAVC), which have different operational criteria. In contemporary complex project, because of the rapid development of advance construction technologies, design must rely on engineering solution, rather than architectural aesthetics. Advanced technology can be defined as complex design and manufacturing solutions that involve specialist knowledge and skills. They can involve "first of a kind" technology, where untried technologies are used for the first time (Finon and Roques, 2008). Using first of a kind technology will increase the complexity of project delivery because of the increase in uncertainty and risk. One of the changed roles of design management is the control the interfaces between engineering technologies and architectural design. The issue in design management is how to incorporate the latest construction technology into architectural design. If these complex project components are not appropriately managed through integration between the design and engineering elements, projects can result in degraded design quality and construction delays, which are the main reasons for unnecessary design change or rework during the construction phase (Kim and Kown, 2005). These complexities cannot be avoided, but have become as critical to projects, particularly designs by international JVDTs. Thus, in order to deal with these complexities, integrated design management processes should be implemented from the early production stage.

3.3 Design management in the construction industry

Construction projects including multinational LSPs are not merely a matter of engineering and technology. They are essentially a management enterprise because different project components including capital, experts, materials, procurement, processes, and construction methods are intertwined very complex (Vidal and Marle, 2008). Unlike normal construction projects, all project implementation processes should be managed by well-organized design management processes in contemporary LSPs (Ahern, 2013). It has direct or indirect influence on all production activities and construction stages, so it should integrate various disciplines.

3.3.1 Integrated design management

Traditional design management can be divided into two parts. The first part focuses on organizing the design team for outstanding design solutions and the second part aims to develop improved design processes or systems (Tzortzopoulos and Cooper, 2007). Design management is involved throughout the design phases. From the project feasibility study via schematic design to the working drawing stage, design management is mainly about the management of the design team's activities, process, and outputs from an architectural or engineering consultancy (Hales, 1993; Andersen *et al.*, 2005). In terms of design solution, design management focuses on how to create optimal design output within a limited time. However, it is developed focusing on only the design team and processes without consideration of the practical issues at the production stages (Song *et al.*, 2009).

Every project involves thousands of decisions as well as needing long production duration sometimes over several years. The increase of the project scale and complexity makes the concept of design management an important one across the different disciplines. In particular, when a complex design involves specialist contractors that will be responsible for the design and installation phases, coordination with the principal designer is important to ensure compliance with the design ethos. Naturally, collaborative and integrated approaches have emerged as a critical form of effective design management of construction projects. McDonnell and Lloyd (2014) pointed out the role of the architect for the collaboration of designer and other professionals, while Albogamy and Dawood (2015) suggested an effective relationship between the client and design team. They all insisted that recently the collaboration or integration of the main project participants by one organization is one of critical project implementation such as joint venture, design-build, and partnering. Because various design, technology, engineering, and material issues are discussed from the initial stage of the project and all discussed issues are materialized by drawing and design documents, integration and knowledge sharing between the architect and other experts is crucial.

In spite of different research on collaborative and integrative design management amongst design teams or project teams, the focussing of management competency on only the design team or stage may give a limited impact on the whole project performance. The trend shift in design management is not only management for design itself, but also integrated management for all design-related production issues using a process model. In contemporary construction projects, particularly large-scale construction projects (LSPs) that need a long duration, enormous project components, and different experts, all design-related production activities are implemented using appropriate design management process models. Practically, even if different management models are being used (the RIBA Plan of Work by Royal Institute of British Architect is mostly used (RIBA, 2013)), there is still a variety of research being developed in the academic field and industry. Because contractors implement integrated design management process models from the pre-production stage, they should consider all design-production issues including those listed below:

- Interference management between detailed design and constructability;
- Supply chain management for long lead and long distance items;
- Detailed information management of subsidiary components and materials;
- An implementation plan of assembly between the off-site and in-situ production;
- A value engineering management plan during the production stage;
- A reflection on the vender and manufacture's detailed design information;
- An in-depth review of all project documents in the pre-production stage;
- Information transfers and a storage plan;
- Construct ability simulation;
- IT application plan.

Chua *et al.* (2003) focused on design parameter interfaces in order to create a design management process. In complex LSPs, each design parameter has its own explicit features, so it is recognized that interface management between design parameters is an essential factor for the appropriate design process model. Parraguez *et al*. (2015) suggested effective data process for design management. Not only designer or project team, but also all related staffs on site should be able to access all kinds of project information. All information is transferred and stored based on design management process model. Various researchers (Bryde et al., 2013; Schwalbe, 2015) have suggested that effective information transfer can bring about potential benefits including the effectiveness of sharing design concepts, the recognition of changed design, automatic issue of critical reports, and distribution of information procedures. Through this information transfer system, all design information can be transferred efficiently from the design stage to the production stage without omission or misunderstanding in spite of several design changes (Parraguez et al., 2015).

These design management models tend to focus on managing the internal components such as production processes or supply chains, which are already considered critical and complex. In line with these features, different management process models have been developed and used such as the RIBA Plan of Work by Royal Institute of British Architect, the first version of the RIBA Plan of Work was published in 2007 (RIBA, 2007). However, project complexity is increasing due to international aspects and joint venture aspects. Indeed, because increasing funds and high-level designs and technologies are essential in the development of LSPs, the involvement of multinational design teams, engineers, technologies, and working processes is inevitable. Thus, sufficient design management of LSPs involving international JVDTs, as well as a wide and in-depth understanding of the international environment is crucial.

3.3.2 Design management in an international environment

Even if diverse integrative systems are developed to increase efficiency and productivity, there are still differences in working processes, communication, building codes, and regulation for each construction industry. Each company and country has their own way of working and determining how these disparate entities will interact and perform is often left to trial and error. These differences among countries and cultures could result in critical problems in contemporary international LSPs. According to Sebastian (2003), practical problems often occurring during the construction stage in multinational projects are:

- Delay of design-related decision making due to lack of co-ordination amongst international joint venture design teams (JVDTs).
- Uncertainty of the work scope on design change during the construction phase.
- Lack of understanding in a cross-cultural environment.
- Decrease in work efficiency due to the language barrier and difference in work process.
- Lack of mutual trust and respect of ability or faithfulness between participants.
- Mutual inconsistency of computational programs for design and managing tasks.
- Increase of drawing errors and mismatch due to inconsistent drawing style and code.

Multi-cultural management

It is evident from phenomenology that people see differences within different cultures. Schneider (1995) suggested that cultural diversity is one of the most critical challenges in current international LSPs. It is becoming increasingly apparent that success in international projects requires an appreciation of what culture means and what the practical impacts of different cultures are on projects.

Project participants may also have different faiths, assumptions, and behavioural norms, which can cause conflicts between multi-national team members.

Pheng and Leong (2000) and Webb (2015) focused on project management in East Asian culture, in which relationships between team members are quite important. They insisted that confrontations are avoided and human relationships are highly valued. In contrast, personal relationships in Western culture are less important when doing business. In East Asian cultures, where status is very important, talking about problems directly with a person in public is avoided so as not to embarrass the person or downgrade their status. In a similar context, Chen and Partington (2004) and McFarlin and Sweeney (2014) looked at attitudes, particularly in projects and their organization in Asian countries. They explained that when a certain organization has a dispute because of a misunderstanding of a partner's culture, their attitude would act as an effective communication method. There is a tendency, in East Asian culture, to keep relations harmonious by not talking directly about problems.

Cultural problems often occur between Western and Asian partners. This is because their cultural background and social approaches are very different, and unnecessary arguments sometimes occur. According to Demirbag and Mirza (2000), when they have meetings about a certain issue in a project, Westerners usually implement tasks according to the written documents while Asian people tend to include oral discussions in the agenda. In many cases, this difference of perception can lead to unnecessary confusion. Particularly in international LSPs in Korea which involve different foreign architects, designers, suppliers, and contractors, culture-based arguments can make projects more complex due to misunderstandings of work scope, responsibility, and working processes. In addition, Asian construction sites such as in Korea, rarely actively express opinions, due to the characteristics of the organizational culture in which strong leadership is seen as more worthy than active expression of individual opinions (Kim and Kown, 2005). Thus, in the early stages, projects can quickly progress without any arguments amongst team members, but later on, may make the project more complex because of the lack of brainstorming or proactive suggestions. According to Bea *et al.* (2006), this unilateral leadership can seem quite arbitrary and problematic for Western colleagues.

In order to overcome these barriers between opposite cultures, Gorse and Emmitt (2003) and Browne (2016) concentrated on the communication between team members. In the construction industry, effective communication is required at multiple levels from strategic decision-making to day-to-day practical activities on site. They also perceived that words are a practical vehicle for communication; however even the same word may have a different meanings in different cultures. In East Asia, formality and attitude are sometimes a more significant element than words for communication; this is because people recognize the mutual respect of colleagues from their expression of attitude and formality. These factors are emotional; but they are essential for good communication in most cases.

More specifically, language barriers are one of the main causes of project complexity amongst project team members (Ochienga and Price, 2010). In a multi-cultural construction environment, English is the common language. Most documents, contract provisions, and drawings are generated in English in international projects. However, East Asian construction experts are still not familiar with English. Even if a lot of effort is put into effective communication, there is still no prompt for active mutual-communication between international project team members. This can be another critical factor in the increasing complexity of international LSPs. According to Lee (2008), only 28% of Korean partners respond immediately to requests of cooperation from foreign partners. This is quite a low level compared to the response of international partners (78%). He insisted that due to the lack of sufficient correspondence and information exchange caused by the language barrier, project complexity, including design changes or reworks, increases during the production stage.

LSPs are implemented based on international, diverse project participants who have different cultural backgrounds work together as a team. Understanding and managing the ways of behaving and communicating from different cultural backgrounds is essential in international projects. Except for these cultural aspects, technical diversity including different working processes, building codes, and construction standards are another critical factor of project complexity.

Global standard interfaces

For an international large-scale construction project (LSP) in which diverse technologies are intertwined, a realistic approach for design management is interface management between different working process and technical criteria.. According to Mira and Pinnington (2014), contractor needs to manage different project interfaces such as design criteria, building code and working practice between design and construction. Interface gaps can happen anytime on a project.

This inevitably can give serious and unexpected construction problem such as over cost and construction delay throughout production stage, contractor have to possess appropriate managing strategy to control these interfaces before project commencement. This managing strategy should comprehensively consider the production execution plan, also design-relevant issues.

Ng and Skitmore (2002) suggested that because of limited time frames and manpower, all the different design standards and technical criteria should be integrated perfectly before starting construction. In LSPs designed by international JVDTs, it is getting more difficult for contractors to find suitable solutions to manage the complex interfaces between different design standards. In spite of many meetings with international JVDTs at the pre-production stage, design-related complexities caused by interface gaps among regulations or building codes cannot be integrated without systematic design management processes.

In the global construction environment, Korea has maintained its own regulations and standards instead of adopting global standards such as the International Building Code (IBC) or International Code Council (ICC). According to Hong (2013), multi-national projects in Korea are designed and constructed based on Korean standards and building codes. Only minor building parts which do not have any specific Korean standards, are implemented using global criteria such as IBC or ICC. Rather, this utilization of diverse standards and criteria make LSPs more confusing and complex. No one can apply certain standards to any production activity during the construction stages with confidence. To support this, he used the Lotte Tower project as an example, which is the highest building project in Korea and is designed based on IBC and NFPA[6] by international JVDTs. Verifying that different building codes and detailed specification of off-site material are applied appropriately into construction drawings is one of the important roles in design management.

In the design process of Korean large-scale projects, initial basic designs are usually generated based on global standards by the international design team, and then later these basic designs are modified and Korean local design partners generate other detailed designs in order to fit Korean building codes and regulations. In many cases, during this design modification process, the original designs need to be changed according to Korean standards. This design specialization may be able to efficiently resolve the standard interface issue. However, because of this design specialization, design-related complexity is likely to increase with less consistency in both international and local design teams. Hong (2013) insisted that even if some modified parts and detailed design parts are minor, they can still seriously influence the total construction cost and period, if interfaces are insufficiently managed between the different criteria.

With increasing environmental interest, most Korean LSPs are designed to satisfy sustainable criteria. Except for the Korean sustainable building assessment; Green

[6] The National Fire Protection Association (NFPA) is a United States trade association, albeit with some international members, that creates and maintains private, copyrighted, standards and codes for usage and adoption by local governments. This includes publications from model building codes to the many on equipment utilized by firefighters while engaging in hazardous material responses, rescue responses, and some firefighting.

Building Certification Criteria (GBCC)[7], and international sustainable certifications such as BREEAM and LEED which are most famous sustainability assessment tools from around the world are also used in Korea (Alyamia and Rezgui, 2012; Lee, 2012). Kim and Kim (2011) suggested that sustainable materials and construction methods should correspond with global standards and Korean standards simultaneously. There are some problems in adopting global standards directly into the Korean construction industry. Some sustainable elements can be problematic in delivery and maintenance, if they are not distributed in Korea. In addition, other sustainable elements may need specialists from foreign countries to install them into the Korean environment. Even if international design teams consider these issues as problematic, they do not have detailed information on the distribution or delivery of the local sustainable elements (Bunz *et al.*, 2006).

In an international environment, design management has to respond to different design and construction aspects, from cultural differences and working process gaps to international criteria. In spite of a wide range of design managing tasks, all problematic design-related issues need to be controlled within a short period of time from the initial project stage. Thus, design management has no choice but to be implemented from the contractor's perspective throughout the production

[7] The Green Building Certification Criteria (GBCC) was developed by the Korean government as a sustainable building assessment to evaluate the environmental performance of buildings and promote green buildings in Korea. These criteria assess the entire building construction process and are also expected to promote technological development and the quality of competition in green building materials.

stages.

3.4 Design-production management

In complex projects, existing design process methods which focus on the design stages carried out by architects or design consultants cannot ensure sufficient design management (Macmillan *et al.*, 2002; Tzortzopoulos and Cooper, 2007). Although a number of major design process models have been developed based on design aspects and designers' perspectives, current design-production management (DM) needs more active involvement of contractors to generate a more complementary set of relationships between designers and specialists from consultancies, engineers, vendors, manufacturers and constructors (Andersen *et al.*, 2005; Tzortzopoulos and Cooper, 2007). In particular, in international large-scale projects, the contractor's role has been recognized as more critical in generating the practical design process and design management model, which is used throughout the production stages for optimal project performance.

3.4.1 Design-production management from the contractor's perspective

Contractor's design management is understood as the coordination and regulation of the building design process on site, resulting in the delivery of a high-quality building. It is quite different from the traditional concept of design management, because from the contractor's perspective, it is about how to erect the building using efficient design information and engineering knowledge while traditional design management is about how to plan and design the building effectively (Koskela *et al.*, 2002; McFarlin and Sweeney, 2014).

However, the explicit functions of design-production management from the contractor's perspective are less defined; there is little empirical research on design management from this perspective. Bibby (2003) and Emmitt (2010) noted that while there is a growing interest in design management within the AEC sector, a number of barriers interrupt the success of design management. These barriers are related to responsivity, who is in charge of the design process and output and who is leading the design management during the construction process. Tzortzopoulos and Cooper (2007) stated that there are still diverse issues relating to a lack of a design management role and disputes caused by insufficiently well-defined responsibilities between designers and contractors.

The research into contractors' design management began in the 1990s in accordance with the changing environment in favour of design-build procurement. Gray *et al.* (1994) pointed out the growing importance of contractor's design management in their seminal report (1994) and the book followed. Until now, design management has not sufficiently emphasized how contractors could manage the design process, or how contractors should organize and manage design information from the pre-production stage, or what barriers they would face. As well as this, the concept of the design management function has become much broader and less defined from the contractors' perspective (Anderson *et al.*, 2005). Those researchers into design management from the contractor's perspective (Gray *et al.*, 1994; Gray and Hughes, 2001; Tzortzopoulos and Cooper, 2007) pointed out that even if specialized design professionals and construction trades have made the delivery of many of the complex and massive construction projects possible, they also separate the design process from the contractor's work scope.

This separation hinders the integration between design and construction knowledge and diminishes the opportunity for contractors to influence the design processes (Mills and J. Glass, 2009; Song *et al.*, 2009).

Due to this separation, contractors have been struggling to control and keep their profit in increasing project scale and complexity. In order to avoid losing profit, construction industry is developing suitable management and procurement methods such as design-build, public-private partnership (PPP) and integrated project delivery (IPD) (McDonnell and Lloyd, 2014; Mira and Pinnington, 2014). In particular, different researches are carrying out on project management based on design and production elements on site. Various researchers have argued that due to the diversity of project procurement and increasing building technologies, management responsibility of contractors has raised in the design information and building materials (Emmitt, 2007; Sweis, 2014). Ng and Skitmore (2002) insisted that the systematic management of design aspects is essential for the development of large-scale construction projects (LSPs). They explained that contractors are in the best position to provide well-organized and stored management because they have empirical data on project availability and resource allocation, which links in with the design aspects in the production stages. Multinational LSPs frequently run over budget, over time, and fail to make acceptable profits for construction enterprises. Because the practice of LSPs requires special systems, materials, equipment, and techniques that necessitate sufficient integration between project elements, the understanding of systematic management is essential for the appropriate allocation of limited project resources (Warszawski, 2003; Aritua *et al.*, 2009; Ahern *et al.*, 2014).

Chan and Kumaraswamy (1995) found that balanced management between design and construction aspects could have positive results on the improvement of constructability during the production stage. They insisted that through an in-depth design review by the contractor, detailed designs including working drawings and shop drawings could be improved in advance without any design change or re-work. Indeed, in order to support the validity of their insistence, Chan and Kumaraswamy presented that construction productivity could be improved by 24% if the design process is managed appropriately before construction begins. Deane (2008) also looked at design management within the context of the contractor, which involves co-ordination between design process and different production activities to deliver high-quality performance, enabling the needs of the design, manufacturing, and construction processes to be met.

Recently, there has been research into more specific design-production issues carried out by contractors during the production stage. Austin *et al.* (1996) and Parraguez *et al*. (2015) focused on the sharing of detailed design information as an essential factor during the construction process. They insisted that the efficient flow of information between project participants from the architect via the site engineer to suppliers could have a positive and immediate response when unexpected design-related problems occur during construction. In a similar context, Walker and Walker (2012) investigated the importance of the contractor's early involvement. They argued that because contractors have practical experience regarding both design and production problems in previous projects, they are ultimately responsible for the co-ordination between the construction and design processes from the initial project stages. Song *et al.* (2009) also demonstrated the importance of early contractor involvement in the design process using the simulation of a construction schedule, which was conducted in four different construction stages. Hence, with the application of explicit design management, contractors can improve the performance value and reduce wasteful rework on site. Benefits from the involvement of a contractor's design management are increased by the improved schedule, cost, safety, and quality performance (Jergeas and Put, 2001; Gil *et al.*, 2004; Emmitt, 2010).

3.4.2 Design-Production managements on site

According to Ng and Skitmore (2002), due to the adaptation of advanced technologies, managing tools, and procurement systems, the production stage becomes the most critical but difficult stage in the whole project. At this stage, one needs to consider how the design aspects are to be integrated with advanced building technologies more than in any other project stage. Traditionally, in the production stage, design management has concerned with design changes and detailed design information. Design changes occur unexpectedly due to incomplete designs or in order to improve workability by changing some parts of the basic design. The important thing here is how to respond proactively and with flexibility to these issues. On the other hand, detailed design information has already been generated with plans on how to transfer and distribute the appropriate data on time and in person. It is about efficiency and accuracy. Even if both issues are design management aspects, they directly influence construction productivity and project performance.

Design management helps to analyse and integrate all design information into the production process. It ensures that the production process is not held up by lack of design information, or by poorly integrated design details. The blurring of the boundaries between design and production due to increasing complexity of building design, technology, and the use of advanced and specialised materials. The distinction between design and production has become more complex because of increasing specialisation in the delivery of work/trade packages on site, and the interdependence of the packages (Grilo et al., 2007; Emmitt, 2010). A design manager has in-depth knowledge in different construction technologies needs to control the integration between design and production.

Buildings are made up of a series of spaces with different functions and customised layouts, and physical systems that create different boundaries between spaces, with external appearances. Such systems require management of the interfaces between specialty items. An example is the way that the mechanical, electrical, communication and plumbing services are integrated into the structure. The supply chain with its layers of specialists must be engaged in a way that facilitates continual improvement rather than constant reinvention on a project. This means that the design must reflect the constraints of production involving both off-site pre-assembly and on site production. Design management is key to ensuring the project is well planned and meets the requirements for production, with sufficient lead times to order materials and to manufacture bespoke components.

Off-site component management

A wide range of parts used in building are made in factories and assembled on site. Off-site products involve transferring a significant portion of the construction operation from the construction site to more or less remote sites where individual components of buildings and structures are produced. The benefit of using off-site components is largely dependent on project specific conditions and the degree of integration with the on-site process (Blismas *et al.*, 2006). Many construction components have already been manufactured such as air-conditioning units, lumber, and piping. However, there are physical limitations in terms of spans, weight and size of off-site components that make certain options less desirable. The large majority of off-site components are assembled with other in-situ building components on site. Sometimes they do not have full roles in themselves. Thus, practical challenges are imposed on the methods of assembly in managing the materials and on the assembly process (Blismas *et al.*, 2005; Arif *et al.*, 2012).

Almutairi et al. (2016), suggests the lack of criteria and standardization between off-site and in-situ building materials is the main constraint in extending the use of off-site standardised volumetric and bespoke components. In order to extend the use of off-site components, all detailed design information, including shop drawings and specifications should be integrated before commencement of production activities. This is because assembly information of the off-site components should be merged with the detailed drawings later in the production stage, the appropriate criteria and guidelines that take into account off-site assembly are needed from the early stages onwards. Meiling *et al.* (2012) also pointed out that because it is very difficult to change the design after placing the order with the off-site manufacturer, appropriate assembly strategies and standardisation should be decided upon before the construction begins. It is apparent that the erection of a building would become more efficient if each component was produced and assembled according to pre-set standardisation, particularly the mechanical, electrical, and structural modular systems that make this possible (Pan *et al.*, 2005).

However, there are the other potential factors between off-site and in situ components that could cause instability. Because the detailed design information and product specifications are generated by the manufacturer or supplier, and not the architect or designer, contractors have to deal with different interfaces between heterogeneous building components during the production stages. To manage this wide range of assembly processes of building components, new design management approaches led by contractors are required, in which production processes of off-site components would be considered one of the most critical production processes for the contractor, supplier, and designer (Boyd *et al.*, 2013).

Contractor's early involvement

In construction projects, most of the critical decision-making that strongly influences entire project performance is determined at the early stages from the identification of project outlines and budget availability. In addition to this, practical production execution plans that deals with the evacuation or erection processes, long lead materials, HVAC installation, and even sustainable approaches are determined in the early pre-production stages (Fewings, 2005). The traditional procurement system makes it quite difficult for the contractor to have influence in the early stages (design process). Because contractors are selected through a competitive bidding system at the end of the design process, they have little input in the design process. Thus, traditionally the architect has played a design management role.

However, Gil *et al.* (2004) pointed out the lack of practical knowledge that architects have of the construction process. Although in construction projects the architect can be assigned to all design-related tasks, it is difficult to deal with different production activities on site even in relevant design. Architects who do not have grounded experience and knowledge of practical production activities closely connecting advanced building technologies may have problems in suitable decision-making based on of economic aspects, constructability, construction period and technologies (Anderson *et al.*, 2005). In the same context, Arditi *et al.* (2002), Alegre-Vidal *et al*. (2013) and Sha'ar *et al*. (2016) argued that design management without design experts in a project could cause serious problems such as a delayed schedule, rework, and disputes during the construction process. They also insisted that even if contractors cannot directly influence design concepts and output, they should be able to support architects or designers in order to generate detailed working drawings using their grounded experience from the early project stages.

Constructability is strongly affected by design management in a variety of ways, ranging from different assembly checklists, constructability reviews, building process simulations, and structure feasibility studies. The practical execution plan is always changing and being revised according to the characteristics of each project design (Doloi, 2008). Thus, in order to deal with different project features, the contractor's design management team needs to be involved from the early project stages such as the pre-production stage (Gray *et al.*, 1994). Through the comprehensive and detailed review of feasibility and constructability in the early involvement of contractors, they can generate production-oriented data or detailed information, which eventually allows them to avoid unexpected or overlooked design-related risks (Koskela *et al.*, 2002; Bryde *et al*., 2013).

Due to increasingly complex procurement and project scale, the boundaries of the design and construction sectors are disappearing. Diverse interfaces are managed on site between international and local construction teams, designs and production processes, and off-site and in-situ assembly methods. Because the integrated role of project management between the design and production process has increased, the early involvement of a design management team is not limited when improving schedule, cost, and quality performance (Jergeas and Put, 2001; Gil *et al.*, 2004).

3.4.3 The shifting role of design management

With the change of the overall environment in contemporary complex and international LSPs, the meaning of design management is broadening. In the past design managers needed in-depth expertise in design and construction processes to lead the design process successfully. Now, they need more collaborative and integrative competences to manage design-related aspects including using international joint venture design teams (JVDTs), off-site components, and the integration of various building codes. Because, there are enormous design-related project components involved in contemporary LSPs, it is difficult for design managers to control all project components, which are dealt with by experts in a wide variety of fields (Gray and Hughes, 2001). Instead of focusing on specialists and isolated design solutions, design management now deals with wider design-related aspects and integrated managing processes.

According to Emmitt (2010), in design management, changes occur in different ways such as form, function and fit in order to conduct modern complex projects. Form relates to style; function concerns engineering, and; fit is the link between form and function. These basic patterns are integrated elaborately in the production stage. Thus, he insists that the role of design management is now a fundamental requirement to delivery high quality production (here, it means a construction project). In the past, the design manager who was often the architect, designer or consultants has been interested in the uniqueness of the building form and functional conveniences.

Recently, however, design managers take feasibility and the erection process into consideration more, instead of just the design aspects (Tzortzopoulos and Cooper, 2007). Appropriate recognition of the shifted role of design management, which focuses more on the integration of design-production elements, is essential. The production stage is dynamic, constantly changing and subjectively defined. In accordance with the changing building environment, integrated management approaches between design and production are required to deal with complex production stages.

Design change management

Design change involves the shift from the original design and facilities due to client requests in order to reduce construction costs or the contractor's proposals for an increase in construction productivity. It also includes the partial change of the contract due to inconsistencies between design and site conditions or inaccurate drawings. These changes need to be referred back to the design team and checked against critical design documents including planning approvals and the client's request for proposal (RFP) (Emmitt, 2007). Thus, most design changes in the production stage inevitably create cost and time over-runs. Design change does not only refer to the changes in building materials, design scope, and construction methods. It also comprises changes to all project aspects such as quality, environment, process, cost, risk, and stability in the construction phase.

Research has shown how design change or error impacts upon projects. According to Cusack (1992), design change within the contract documentation can contribute to a 5% increase in a project's contract value. Bijen (2003) revealed that design changes account for as much as 10% of the total cost in building and structural projects. Importantly, this increasing cost does not mean a direct building erection, because it is also inextricably linked to less tangible environmental or social costs. As such, design changes in the production stage should consider not only the construction process, but also subordinate elements including environmental aspects or supply chains according to design changes. Design change management is more construction-oriented than design management and can achieve a high performance when implemented from the contractor's perspective.

Construction, as a project-based practice, is particularly prone to a high degree of changes due to various reasons. Smith *et al.* (1999) and Han *et al*. (2013) recognized that design changes originate from either external or internal pressures that are being applied in the production process. At a more detailed level, Tombesi (2000) and Hindmarch *et al*. (2010) revealed that the majority of causes of design change are generated from construction activities. Construction-oriented design changes are often as bellows:

- *Unforeseen project circumstances* - For example, unexpected ground conditions or abrupt changes in environmental circumstance. These risks can be somewhat mitigated before practical commencement of the erection through experienced design managers having previous knowledge of this. However, the risks of the unexpected site conditions or project situations cannot be completely eliminated.
- *Client requests* – These are changes requested by clients and generally focuses on the business aspects such as a change of the basic plan including building gross floor area (GFA) or additional facilities. Therefore, design changes requested by a client often involve a wide range of construction rework.
- *Designer requests* - These tend to be related to the recognition of a critical design error that needs to be revised.
- *Contractor requests* - Requests related to production performance issues including the availability of materials and design feasibility. It is important to estimate and predict how much extra cost and time is needed for this design change.

Love *et al.* (2009), states that a large number of latent probabilities of design change occur due to design errors and omissions, which influence error-provoking activities taking place during the production stages. For example, under traditional procurement, competitive tendering can cause architects or design firms to commit these design errors, as they undertake their work for the lowest price. This low price makes it difficult for architects or design firms to undertake design audits, reviews and verifications before design delivery. Most of the design information including drawings and specification completed without careful review or verification inevitably lead to an incomplete design, which may need to be revised by the contractor. In this case, the incomplete designs would be sent to design team again to be reviewed and revised. However, in contemporary large-scale projects designed by international joint venture design teams (JVDTs), this can result in major disputes during the construction stage because the international design team will have already disbanded or probably be involved in another project (Love *et al.*, 2011).

Management of design changes between international JVDTs and contractor is one of the shifted roles of design management. Design information generated at the design stage, influences production. Particularly in contemporary large-scale and complex project, design change and subsequent re-work occur frequently. Construction-driven design changes are often linked to unsatisfactory site conditions that hinder good workmanship, material delivery, and plant operation. Even if these construction-driven causes cannot be handled through design change, they can be managed on site by the substitution of other material, production, and workmanship by the contractors. Conversely, design-driven causes including design errors, omissions, and invalid structural calculations can have a more serious impact on project cost and duration, because, unlike systems or building materials, designs cannot be replaced by substitutions (Sun *et al.*, 2006). Lopez and Love (2012) insisted that design-driven elements such as structural system have a bigger impact on increasing the project cost and period than the construction-driven element. They demonstrated their assertion by investigating 139 individual projects showing the extra project costs needed for design change during the construction stage.

Design change and subsequent re-work normally happens because of poor design information, but it may occurs due to the contractor's attempts to reduce construction costs. Even minor changes during the construction stage can be wasteful of resources or time: the majority of changes have significant cost implications. Changes tend to result in revisions or additional work as well as disruption to the workflow programme (Emmitt, 2007).

Thus, management of design changes is one of the main requirements in the role of design management. Consideration must be given how to analyse and propose a newly changed design in order to increase construction efficiency or reduce construction cost or period from the contractor's perspective. Detailed technical analyses is undertaken to review the impact of changes on the production process (Sun et al., 2006). Design changes have implications for other interconnected aspects of the project. Poor management causes various problems on site including disputes among project participants, loss of productivity as a result of reprogramming, unbalanced resource allocations, changes in cash flow, financial cost, and increased risk of coordination. Contractor's design management teams should estimate the practical effect of design changes using the experience of similar or previous projects, which consider not only the amount of re-design, project schedules and new erection methods, but also construction processes. Choo *et al.* (2004) and Mahmoud-Jouini *et al.* (2016) asserted that when there are design changes or construction re-work during construction stage, both design team and production team should understand the work process and tasks according to the changes.

Hindmarch *et al.* (2010) insisted that because of limited design specialists within contractor, it is difficult to allocate a suitable design management team in every project including looking at equivocal potential projects and whether they can award the project or not. Thereby, they suggested a systematic management tool to support contractors in design change processes. Sun *et al.* (2006) also insisted systematic management tools to manage design changes and re-works in construction process as a collective problem-solving process. In systematic management, newly approaches to design management can be optimized. It requires the sharing of tacit knowledge and explicit information between members of the production and design team to find the appropriate project execution method. In addition, this managing system can be used throughout the project execution to manage changes and to record a decision-making trail for later review and analysis. At the end of a project, all recorded design changes can be reviewed and analysed. This will help the design manager as well as all project participants to learn from any mistakes or identify responsibility for any extra cost or duration.

In joint venture design teams located in different locations, there is special need to ensure that the design is managed and co-ordinated across the team through the design stage, and into the production stage. Professional fees are sometimes lump sum fixed price, or fluctuating as a percentage of the construction price, and sometimes reimbursed on a cost plus basis. The fee for construction supervision is lower than the design fee, yet from the contractor's perspective, they see construction supervision as the critical phase. Design management must be driven by the contractor's team to ensure production schedules are kept on target. The special arrangement of international joint venture design teams must ensure there is sufficient in the design budget to ensure the contractor is not delayed by lack of information, or poorly co-ordinated design.

Value engineering management

Value engineering (VE)[8] is a one of the management tools used to carry out essential functions of a product, service or project to meet the lowest cost. Effective VE can facilitate a generation of new technologies and processes, which could improve the industry's productivity, profitability and competitiveness (Cheaha and Ting, 2005). VE has been widely practiced in the construction industry and has become an integral part of the development of civil infrastructure and large scale projects with an aim to produce innovative ideas and solutions for enhanced project value. This can be fulfilled through the use of advanced building materials, creative design, simplified construction processes, innovative erection methods, improved construction quality and safety, and minimal environmental impact.

According to Zhang *et al.* (2009), VE exercises have led to cost savings of 5-10%

[8] Value engineering (VE) is a systematic method used to improve the "value" of goods or products and services by using an examination of function. Value is defined as the ratio of function to cost. Either improving the function or reducing the cost can therefore increase value. One main aspect of value engineering is that basic functions should be preserved and reduced as a consequence of pursuing value improvements.

for a wide range of construction projects. Because construction projects are carried out under extreme conditions such as tight schedules, high complexity, and one-off production processes, there are latent opportunities for cost saving in comparison with other manufacturing industries. Pathirage *et al.* (2006) recognized the VE as a ratio of function to cost and consequently, by its application, project functions can be improved or construction costs can be reduced. They developed a matrix of the various project functions against their associated costs and revealed that project value is maximized by an optimal trade-off between the functions and their associated costs. Huan *et al*. (2015) emphasized that the close partnership between client and contractor is one of the essential elements for successful VE. Before production stage, mutual trust and a harmonious relationship between client and VE consultant is important. Once construction begins effective collaboration and cooperation between the client and project team is important. The performance of VE depends primarily on the effective working cooperation between the project team (contractor) and other project participants including client and VE consultant.

For a long time, designers or VE specialists have conducted VE studies and exercises at the design stage (Shen and Liu, 2003; Chen *et al.*, 2010). Most VE team members are part of the project design team or special VE consultants. However, at the construction stage VE is a production-oriented event in order to improve the value of facility as well as construction performance through the comprehensive analysis of the design document and construction implementation system. It involves gathering suitable information, searching for creative ideas, evaluating the promising alternatives, and proposing more cost effective alternatives (Huan et al., 2015).

Designers normally tend to use the same design approach they have already used to or well-known technologies. Although design outputs such as drawings, bills of quantity (BOQs), and specifications may be handed over to contractors without any serious errors or omission, there are still lots of areas of change for efficient construction productivities according to the contractor's special technologies and accumulated experience. From the contractor's perspective, VE exercises can be a practical way to reduce project cost and period. Particularly for clients and contractors, VE at the construction stage is perceived as the last chance to improve the quality of the facilities with the same or lower costs and duration (Assaf *et al.*, 2000; Chen *et al.*, 2010; Huan et al., 2015).

The more complex a project, the more likely VE is to be applied and have a practical input. Depending on the project period and complexity of the LSP, the contractor may have more options to apply elaborate and advanced technologies into the construction stage through VE. Zhang *et al.* (2009) insisted that VE should not be ruled out in the construction process. Contractor's practical experiences and expertise can ensure more innovative construction plans and methods. Improved construction logistics management can lead to substantial cost savings, better quality, and earlier project completion. After reviewing the project documentation and visiting the project site, the contractor can carry out VE exercises based on existing project resources including the most up to date budget, labour, and equipment data. In contemporary complex large-scale projects, contractors are required to have their own systematic design management tools due to the shift in the role of design management from design-oriented to production-oriented design. Based on accumulated design data and technical knowledge, the contractor's design-production management (DM) systems should handle individual design elements, which are connected with the construction process during VE exercises.

3.5 Summary

This chapter discusses changing role of design management in design and production phases from the contractor's perspective. With the increasing complexity in large-scale projects, international joint venture design teams and complicated interconnected project components create another layer of complexity to projects making it more difficult for contractors to manage different design-production elements. As these project components are complex and interconnected, contractors have to consider a wider range of design-production aspects, which are impacted by different cultures, working processes and technological standards. New approaches are needed to deal with complex and interconnected design-production elements from the contractor's perspective. The role of design management has shifted from design-oriented to production-oriented management.

The literature shows that design management has focused predominantly upon the design stage of a project, whereas the contractor post-tender is concerned with the interface between design and production, and ensuring no project delays caused by excessive design changes, or insufficient information. This is particularly important when international joint venture design teams are involved.

This research considers how a contractor can carry out the design-production management interface in complex multinational project by using design management. This chapter reviews and analyses relevant literature to consider how the role of design management is used to help to manage the production process on site more effectively. The next chapter deals with the complexity theory as the underpinning theory for the research in order to investigate whether complexity theory can be applied in contemporary large-scale and complexity project.

CHAPTER 4 UNDERPINNING THEORY

4.1 Introduction

This chapter presents the underpinning theory of the research, which is complexity theory. Chaos theory, from which complexity theory has developed, deals with non-linear relations that cannot be fitted into a simple linear law, taking the form of a statement of single cause and consequent effect. Complexity theory is gaining prominence because it has considerable scope to provide insight into the systemic nature of managing complex projects. Construction projects deal with chaos, complexity, discontinuity, non-linearity, and phase shift processes, as opposed to developmental processes with aspects of reality in which changes do not occur in a linear fashion. Understanding complexity is becoming more important particularly in large-scale project because of the difficulties associated with decision-making, where many parties are involved in activities/work packages that are interdependent over a finite time. These characteristics include high levels of interconnectedness, non-linearity, adaptiveness and emergence.

Important systems methodologies have been developed, such as soft systems methodology, system dynamics, complexity theory, interactive planning, and critical systems heuristics. The commitment of using a plurality of systems approaches together in combination is sometimes called critical systems thinking. System thinking mechanism and system dynamics are reviewed as principal research theories and subsidiary research methods of complexity theory. The complexity involved in LSPs developed by international JVDTs can be explained by system thinking. System dynamics is introduced as a solution to manage the contractor's risk and uncertainty at the bidding and pre-production stages.

4.2 Complexity theory

Complexity theory and science deals with complex systems; however, there is no precise and consensual definition of the concept of complexity (Morel and Ramanujam, 1999; Bertelsen, 2003; Wood and Gidado, 2008; Bawden and Robinson, 2015). Complexity science studies how relationships between parts give rise to the collective behaviours of a system and how the system interacts and forms relationships with its environment (Wood and Gidado, 2008). Such interactions are associated with the presence of feedback mechanisms in the system (Morel and Ramanujam, 1999; Bertelsen, 2003; Ramalingam et al., 2008).

Complexity science is in contrast to the classical science, widely practiced in the twentieth century, which makes philosophical assumptions, labelled as the traditional world view, including underlying assumptions of reductionism, objective observation, linear causation, entity as unit of analysis and others (Dent, 1999). The rise of complexity science has paralleled an increase in dissatisfaction with the traditional world view (Wood and Gidado, 2008). Complexity is a new science; it has developed new methods for studying regularities and an approach for studying the complexity of the world. Complexity science differs from traditional science (Wood and Gidado, 2008). Dent (1999) suggests that complexity science is a new way of thinking to solve modern issues.

Richardson (2008) stated that the overall message from the complexity science literature is that, instead of focussing on various parts of a system and how they function, there is a need to focus on the interaction between these parts, and how these relationships determine the identity, which is not limited merely to the parts, but the whole system.

Bertelsen (2003) describes construction as a complex system and explains that the general assumption of the construction process is that it is an ordered, linear phenomenon, which can be organised, planned and managed top down. The frequent failures to complete construction projects on time and schedule give rise to thinking that the process might not be as predictable as it may seem. Construction is a non-linear, complex and dynamic process. Baccarini (1996) proposed a definition of complexity of construction projects as consisting of many varied interrelated parts and can be operationalised in terms of differentiation and interdependency. He suggests that the definition can be applied to any project dimension such as organisation, technology, environment, information, decision-making and systems, with the need to identify the type of complexity being taken into consideration when referring to project complexity.

Information and communication technologies used for searching, forwarding, classifying and saving information have changed the world, making it more dynamic and complex. Business systems are open systems interconnecting with enormous relevant elements in a dynamic and continuously changing environment. Mankind has tried to understand these diverse dynamic changes. Diverse areas of research have tried to explain and understand the dynamic and complex phenomena in natural science such as physics and astronomy and use it in the social sciences including politics and sociology.

Complexity theory can provide insights into aspects of modern society and simplify complex systems. Complexity theory represents a growing body of interdisciplinary knowledge about the structure, behaviour and dynamics of change in a specific category of complex systems - open evolutionary systems in which the components are strongly interrelated, self-organising and dynamic. It has improved understanding of world stock markets, traffic systems, urban planning, airline networks, seismology, and virus research. Consideration of these phenomena through a lens of complexity theory has provided a platform for new approaches, processes and techniques (Aritua et al., 2009). Complex systems reflect the world's inherent irregularity. The real world is a world of complexity, of messiness, of change, flow and process. Social and natural phenomena occurring in the real world have similar features to those shown in complex theory as below:

- The type and number of influences on the phenomena are increasing. With rapid technical development, these influences include diverse social activities and worldwide economic affairs. Thus, the diversity of influence on the phenomena causes new and ever more complex dynamics.
- There are no solid rules governing the phenomena. It is difficult to form clear and uniform rules such as gravitation found in dynamics especially when applying this to human behaviour. As social communities develop, their desires increase causing the phenomena to change more rapidly.
- All entities involving social phenomena cause diverse effects on each

other. For example, the complex ecosystem within which all entities interact, sharing nutrients needed to sustain life whilst still adapting to a changing environment. In the economic sector, mutual interactions become one of the critical elements for business success and risk sharing.

Some of phenomena in complex system is not predictable, no matter how much is known about them. It is important to understand, how these elements interact and how the system adapts and changes throughout time. What looks chaotic may be predictable by understanding the patterns and rules of complex behaviour.

The world can be described as a system comprised of a large number of entities that display a high level of interactivity. The nature of this interactivity is mostly non-linear. Complex theory provides insights that help to create learning environments, making it worthwhile to pursue this line of thought.

In summary, complex systems are composed of a diversity of elements that interact with each other, mutually affect each other and in so doing generate behaviour for the system as a whole. The patterns of behaviour are not constant because when the system's environment changes, so does the behaviour of the system as a whole (Aritua et al., 2009). The system is thus constantly adapting to the conditions around it. In a complex system, linearity is not present because dependent of the starting conditions, minor changes and variations can lead to unexpected and dynamic effects that grow exponentially in magnitude over time.

Complexity theory is the underpinning theory for this research. Complexity theory can be used to explain the complex world and characteristics of complexity in construction industry including international LSP. Design and production involves the application of diverse high-technologies, professionals with technical competencies, complicated procurement systems, interconnected work processes, and increasing natural and political risks.

Complexity theory was used to understand and explain complex phenomena or dynamic changes in the fields of strategic and organizational management. In terms of the conventional Newtonian paradigm, complexity and disorder have not historically been the subject of academic research. This is because convention dictates most phenomena have a linear causal chain, where the results of the specific objects and phenomena can be predicted. Whereas, order and disorder are recognized as opposite concepts in the field of conventional science.

Complexity theory forms the basis that natural and social phenomena are so complex that accurate prediction is not possible (Bertalanffy, 1976). All elements of natural and social phenomena are interacting at the edge of chaos going beyond the border of the traditional Newtonian paradigm system. At this edge of chaos, small changes can have large unexpected results, with management activity emergent, rather than planned (Vidal and Marle, 2008). Complexity theory seeks to find and demonstrate the hidden laws within chaotic phenomena, which occur around the world. It is an alternative system of thinking and explaining complex social and natural phenomena.

The goal is to research the hidden patterns and interactions between objects within the current complex system. In the Newtonian paradigm, large or long term projects tend to be viewed as just more ‘complicated’ systems that can be planned and managed in the traditional way by the application of knowledge, skills, tools, and techniques to meet the project requirements. The challenge with LSP projects is that they are long-term, very complex, with high levels of interdependency, and many uncontrollable events such as the weather, bounded by a contractual system and codes and standards. In contrast, efforts to manage the complexity recognizing the natural feature of large and long term projects can be a form of empirical finding to solve the different problems caused by complexity (Maylor et al., 2008; Owen et al., 2011; Ahern et al., 2013).

Such complex systems consist of a number of interacting components, within which interactions show non-linear characteristics. Individual components seek their goal by cooperating and exchanging information within the system. The behaviour of one component has a random impact on the behaviour of many others, resulting in an unpredictable chaotic state. It is extremely sensitive to even small changes: the amount of change is amplified as time progresses. This characteristic is known as the butterfly effect. In conventional thinking systems, these uncontrolled and dynamic changes have been recognized as system errors. However, complexity theory accepts these as natural phenomena as well as being a necessary process for the deployment of systems (Walby, 2007).

Initial subtle changes make big differences laterally (Chen *et al.*, 2001). It is one of the main concepts of complexity theory and has been applied to different industrial and economic fields to investigate unpredictable phenomena (Manson, 2001; Chiva *et al*., 2014).

In a conventional system, researchers focus on the recognition of features and attributes of individual system components in order to understand the entire system. They believe that because most systems consist of a set of individual components, they can understand systems that are more complicated by looking at each component in detail. However, a complex system is dynamic in which behaviours of each component can generate chaotic new order from the stable orderly state. The system is developed by unpredictable interactions and the dynamics changes between independent components. Complexity theory aims to understand and predict the entire system by recognition of the interrelationship between system components and not individual attributes of these components (Chen *et al.,* 2001). Because there are complex non-linear relationships between the components affecting the entire system, management processes and decision support systems could also be viewed as dynamic systems.

4.2.1 Linear thinking vs System thinking

Large and complex projects can no longer be controlled or conducted effectively using conventional thinking mechanisms (Werhane, 2007). Modern industries, including the construction sector, are based on complex functions and the interdependence of sub-processes constituting the system. A decision-making system, which is suitable for a certain situation, may cause an unexpected error in another situation. This, the positive effect in the short term may have an adverse impact on the entire process in the long-term. Before the 21st century, these features were not perceived as critical. With the development of conventional linear thinking systems, most social phenomena can be explained and managed. For conventional linear thinking systems, problematic phenomena are able to be solved simply and quickly by the removal or improvement of the dominant problem area (Richmond, 1994; Jones, 2014).

Due to the rapidly changing environment and intertwined functions, conventional thinking systems no longer serve as the dominant thinking mechanisms. In order to understand and manage the complexity, new thinking systems are required that are more flexible and multifaceted. A new thinking mechanism has been invented as a new framework to replace the existing linear pattern of thought.

System thinking integrates individual components into the whole system, while the conventional linear thinking mechanism divides the components in the sequences to understand the whole system more easily (Waldrop, 1992; Pandey and Kumar, 2016). In systems thinking mechanisms, most social and environmental systems are recognized as having their own behaviour patterns and reactions. Mutual influences between individual subordinates increase, and make the whole system more complex (Kunze et al., 2016). In social phenomenon and industrial systems, the interdependences and correlations have increased over time, and remain changeable over time. System thinking mechanism alone cannot explain all social phenomena or industrial systems; system thinking is an approach to help decision-making, it is not the panacea. System thinking allows the whole process to and system can be understood from initial concept to completion, giving all participants wider perspective (Ahern et al., 2014). Using a system thinking mechanism, problematic situations that are recognized as system errors, and not ignored simply as errors. They are analysed from the comprehensive perspective whether there is any hidden rule or self-organization affecting the system process.

4.2.1.1 Linear thinking

Linear thinking is a conventional thinking mechanism, in which most phenomena and systems have only single and dominant causality among them. All phenomena are based on, Isaac Newton's understanding of the world. The way an apple falls down from the tree and the behaviour of the planets are predictable phenomena. All phenomena in nature seem to be predictable if they can put them into proper formulas. The general view of the linear thinking world is that it is an ordered and can be organized, subdivided and managed from top down. There is only one reason that problems occur. In the linear thinking system, the impact factor can be recognized as a single line from cause to effect, and the importance of these factors is always assumed to be unchanged (Groves *et al.*, 2008). For example, when asked to explain the reasons of the greenhouse effect, scientists doing research based on this linear thinking mechanism may investigate several causes, and then list these causes in order of importance to find the dominant cause instead of finding the mutually-influencing factors. Researchers would say that problem could be solved if the few dominant reasons at the top of the list of importance are improved upon.

Richmond (1994) called this mechanism "laundry list thinking", as well as pointing out that it was the dominant thinking system in society. Such thinking can lead to the following hypotheses:

- Causality flows only in a single direction.
- Factors constituting the whole system are interdependent.
- The relative importance of a factor is fixed between factors.

- The mechanisms of the factors are not critical influencers of the result.

Linear thinking mechanisms can be used to make decisions whilst having a monotonous perception of social phenomena and systems. This perspective of the social phenomena and systems is sometimes abandoned because there is no consideration of the effect of time. Linear thinking processes are undertaken regardless of timing and duration of the strategy, monotonous - see Figure 4.1. Diverse hidden impacts of interconnected time aspects and other system components tend to be ignored in the linear thinking mechanism, whereas system thinking makes the decision based upon many interacting parameters, some of which may be uncontrollable.

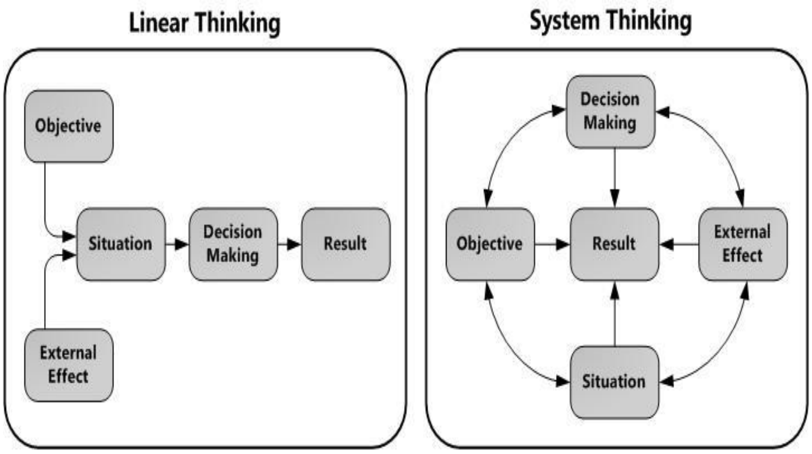

Figure 4.1 Linear thinking vs System thinking (Sterman, 2000)

Researchers of complexity theory have suggested using system thinking as an alternative framework (Cavaleri and Sterman, 1995; Maani and Cavana, 2007). System thinking has a feedback loop system and recognises the system is dynamic as seen in Figure 4.1, it makes systematic mechanisms more flexible and complementary.

4.2.1.2 System thinking

Most social phenomena are not linear and ordered but non-linear, complex and dynamic. Large-scale construction projects must be perceived as a complex system, operating on the edge of chaos. Dynamic control systems must cope with constant change and unforeseen events. A challenge on any construction project is to keep the information, planning and resourcing updated as situations change. The design team perceive a project as being the site production team undertaking construction in accordance with the drawings, specification, and contract conditions. They do not see the level of pre-planning, pre-ordering of key materials, the interaction of the specialist on-site and off-site delivery teams, the impact unforeseen events such as extreme weather conditions, or the resources required to deliver the project.

System thinking involves the organic integration of interrelated components. United components make up the whole system and each component conducts its own distinct objective within the system. Within the system components are mutually related and interdependent each other (Pala and Vennix, 2005). System thinking, unlike linear thinking, observes the interactions of the various processes and behaviours within the system based on holism. The basic components of system thinking are:

- “Dynamic thinking” which seeks to change problematic components according to their progress
- “Operational thinking” which aims to understand the actual phenomena

rather than simply having mathematical prediction

- "Feedback thinking" used for the recognition of the circular causality between components within a system (Richmond and Peterson, 1994).

These three ways of thinking keep the system's correlations balanced as seen in Figure 4.2.

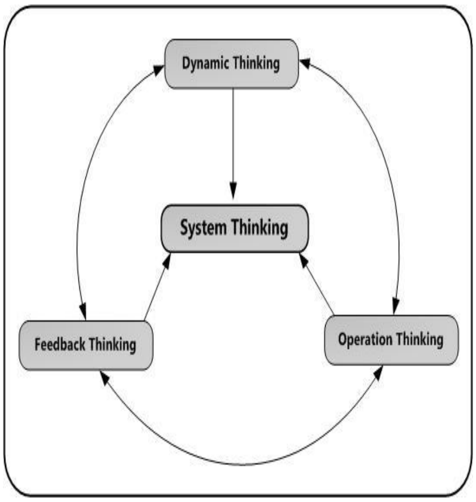

Figure 4.2 Interrelationship between basic system thinking components

Dynamic thinking is a way of thinking which investigates the behaviour patterns over a rather than looking at a problem at a specific point in time. This is where the behaviour patterns are formed over a long period of time rather than using short-term observations. If the behaviour patterns can be identified, systems can have long-term and contextual insights (Waldrop, 1992; Nian *et al.*, 2013). According to the progression of time, because the effect of a system component is measured by the interaction between components, systems can recognize the result of behaviour patterns more easily.

Operational thinking is a way of thinking in order to understand the working mechanisms of a system. It tries to be aware of why change happens and in what way it changes the system (Park and Peña-Morab, 2003; Shabanpour-Haghighi and Seifi, 2015). When a problem occurs within an operational thinking mechanism, the system focuses on how to recognize the operational process rather than just view the problematic pattern, reason, and influence.

Feedback thinking is when complex circular interconnections are made via integration of causalities between components. Feedback thinking is very likely to find the basic reasoning behind the problematic behaviours from the internal system structure instead of looking at the external effects. Using this perspective, circular feedback is caused by problematic changes and intertwined components within the system (Sterman, 2000; Aslania and Naaranoja, 2014). Because the problem is to be solved through the cooperation, the operation should increase the system's performance without using any external support.

These three ways of thinking are essential factors in understanding the main mechanisms within system thinking. Feedback thinking is important in system dynamics, because system dynamics is based on the integration of different feedback structures (Rodrigues and Bowers, 1996a; Jones, 2014).

The various causalities and effects from previous behaviour are called "Feedback loops". If there is no feedback loop in the system dynamics model, the system is too simple and fragile. The reason for any unexpected result and behaviour is that the system consists of diverse feedback loops and the relationships between feedback loops are not easy to predict. Researchers of complexity theory have utilized system dynamics as a critical research tool in understanding and predicting complex systems. With the utilization of systems dynamics that has a powerful analytical function, the system can be redesigned and modified based on the feedback loop structure.

4.2.1.3 Change of thinking mechanism in construction industry

The construction process is an assembly-like process which is complicated and dynamic. It is undertaken in changing and uncontrollable weather conditions, with a work force that is disparate and formed of temporary teams brought together to deliver a project, that is not fully designed at the outset. The main cause of project failure in the construction process is the tendency to understand the entire process in order, which is reflected in the underlying management-as-planning and dispatch theories as found by Koskela and Howell (2002).

Many design teams, and contractors consider construction projects as ordered and simple - thus predictable – phenomenon, which can be divided into contracts, phases, activities, work packages, assignments to be executed more or less independently. The construction project is seen as a sequential, assembly-like, linear process, which can be planned and executed in accordance with the drawings and specification. Consequently, construction project management operates top down, particularly management-as-planning (Ahern et al., 2014). All supplies are believed to be made in accordance with the project programme/schedule, which is often changed weekly, and all resources such as equipment and crew are supposed to stand by, and be ready for the project with availability based upon the linear thinking mind.

However, this is not reality: the construction process should reflect this situation. Small uncertainties can add up to a significant uncertainty on the project's workflow.

New materials, new methods of procurement with the overlapping of design and production, and new types of production systems with off-site manufacturing, make the management of construction projects more complex, they cannot be controlled effectively with linear thinking. The construction industry is fragmented: construction firms cooperate in ever changing patterns. Construction projects are divided into subordinate parts that are subcontracted to individual enterprises. Construction firms perform more than one project at the same time and must optimise the resources. The construction site is a working place for humans and equipment, a place for cooperative and systematic interactions responding to continuously changing and unexpected events.

A change of thinking from linear to system thinking is needed to understand the complexity and interactions of the various parts of a whole framework. The transactional-based linear thinking mechanism is unsuited for projects where there is a lot of dynamic complexity. Construction projects involve a large number of activities that create different interfaces. The interfaces that arise can be classified into categories, for example, materials interface, organisational interface, professional interface, stage interface, as well as work package interface. Each interface is interconnected between two or more entities each work unit or activity within a construction project comprising several of these entities. The interactions between these entities across work units, project phases, work packages, and throughout the project presents a myriad of interfaces that can at best be considered as a systematic thinking approach.

The unpredictability and complexity of unforeseen consequences of actions need new methods of managing, planning and executing strategy can be recognized from initial project stage. Under a system thinking approach, all production phases naturally self-organize to accomplish pre-determined goals based on the feedback they have received in the past, the current emerging circumstances and their expectations of the future.

4.2.2 Complex systems

The aim of research within complexity theory is to understand and predict complex systems. Complexity theory seeks complex survival strategies macroscopically within the changeable modern system (Holland, 1995; Chiva et al., 2014). Complex systems are inaccurate and self-executing systems (~~Byrne, 2003~~ Chiva, 2014). However, components of society and nature can learn to respond proactively. Through self-learning, they acquire knowledge of the environment as well as how to adapt to a changing environment. Various abilities, communication, learning, reaction, and adaptation are considered adaptive characteristics in the system. For example, in a mammal such as a human being, the immune system is a kind of complex adaptive system in itself responding to external stimulus (Alberto and Marco, 2002; Robertson and Combs, 2014). Its operation is something like that of biological evolution, but on a much faster time scale.

Complex adaptive systems are an expanded form of these adaptive characteristics of individual entities. In social or economic systems such as the human nervous system, business processes, and urban or local communities, large components generate their own distinct structures and rules using autonomous learning and interaction. Although these processes are to some extent predictable, using observation or comparison to other complex systems, it can be identified as a complex adaptive system because it still cannot be measured accurately. Complex adaptive systems consist of meta-components, which are combinations of individual components, and these individual components act in accordance with mutual stimulation and reaction rules. In consideration of the above features, the majority of complexity theory research in the social field is based upon complex adaptive systems. Most social systems, such as business processes and management tools can develop themselves by responding actively to internal or external stimuli in the system.

4.2.2.1 Scientific approach

Researchers utilize computer-based methods to analyse complex adaptive systems. With the breakthrough in computational technology as a tool to analyse the complex phenomena and systems, interdisciplinary research is accelerated (Frenken, 2006). Different computational methodologies have developed in complexity theory fields such as neural nets, genetic algorithms, and system dynamics. Computer modelling is essential in scientific research methodologies for complexity systems. Well-structured modelling can analyse critical features of real-world phenomena as well as complex systems. Complex system modelling is simpler than real complexity adaptive systems and can explain the system structure accurately.

Most modelling is based on statistical analysis that has revealed unexpected problems including external stimulations and reactions to them. The reason for this is that when presenting the accuracy of the model, complex interrelationships between components are often overlooked. In complex systems accurate modelling is better, however it is important that the complexity of the modelling should always be maintained at a certain level at which the system should be able to develop itself and to respond to unexpected stimulation at any time. To maintain an appropriate level of complexity, various layers of interactive components should be included in the framework of the modelling.

Most types of computational modelling complex systems is classified as macro or micro modelling. Micro models concentrate on the operating mechanisms of the model, while macro models more on key components associated with entire system.

4.3 System dynamics

The investigation of complexity theory is used to explain the phenomena of contemporary construction projects, research models are divided into four main categorises as seen in Figure ***4.3.***

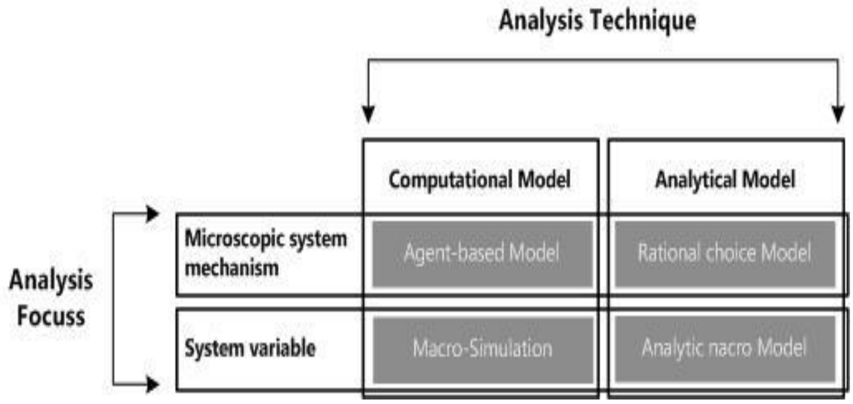

Figure 4.3 Detailed methodology of complex adaptive system

System dynamics belong in the category of Macro-Simulation because it focuses on individual variables and relationships within systems simulated by computational models. Because system dynamics focuses on simulation, the computational models based on variables allow a diverse range of complex phenomena to be explained and presented. After the modelling and simulation of the dynamic changes of different feedback structures, systems dynamics seeks to change the way predictions are made on the developing or changing patterns over time (Yim *et al.*, 2004). Through the simplification of complex phenomena and repeated experimentation, verification of the hypothesis and efficient decision-making can be determined.

System dynamics can satisfy both quantitative and qualitative analysis. It has the distinct characteristic of overall context and partial situations being analysed simultaneously. In addition, numerical and non-numerical data can be analysed in system dynamics (Lyneis *et al.*, 2001). Therefore, with the utilization of system dynamics, multi-layered and complex variables interconnected with each other can be experimented on in the virtual space that will have implications in the real world.

4.3.1 Application of system dynamics

Jay Wright Forrester (1961), a MIT professor proposed the application of system dynamics in his book, *The Industry dynamic*. System dynamics is a practical method used to predict the patterns of growth and change by describing the correlations that cause changes of systems in reality (Forrester, 1961). System dynamics was developed by engineers who focused on problems of economics and industrial management. Initially, system dynamics was utilized mainly as both a design tool for business strategy and governmental policy, later it was used in decision-making processes across industries including manufacturing, distribution business, and the construction industry (Rodrigues and Bowers, 1996b; Feng *et al*., 2013).

System dynamics has been applied in management strategy, demand forecasting, energy and environmental issues, and decision-making. The utilization of system dynamics, enables subjective and abstract research, which is difficult to present as an explicit form or in figures, to be conducted more practically. System dynamics is focused on dynamic changes and in particular, how components change according to the progress of time.

A fundamental characteristic of complex systems is that a certain result is not directly linked with one dominant cause. System dynamics explains all the phenomena in terms of a feedback structure. In other words, dynamic changes of components are recognized as a result of active interactions between components.

The emphasis on the interaction means that the critical change of the system occurs by changing the overall feedback loop rather than changing several components that are recognized as critical within the system (White and Fortune, 2012). System behaviour patterns can be recognized within the structural aspects of the system through investigation of the result of the dominant feedback loops.

4.3.2 Research procedures in system dynamics

A core principle of system dynamics is feedback thinking. System dynamics research generally focuses on the feedback loop which is established using computational modelling. System dynamics modelling consists of six steps as seen in Figure 4.4.

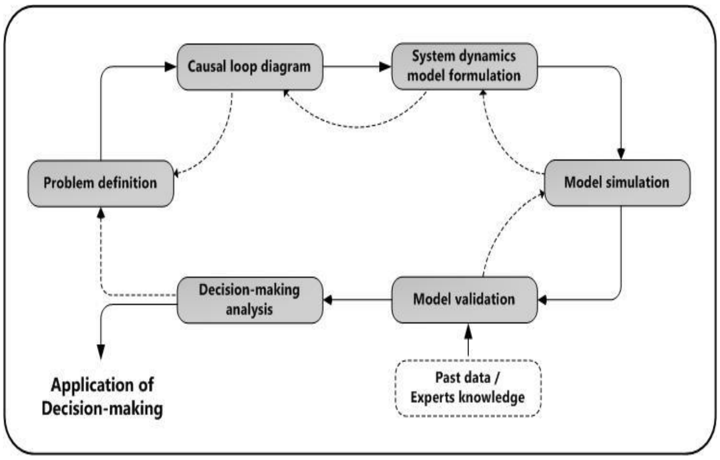

Figure 4.4 Modelling procedure of System dynamics

(Richardson and Pugh, 1981)

The six steps are not always straightforward. Often modelling needs to be revised when there are certain systematic problems caused by previous steps.

First, the problem is identified and defined to ensure the appropriate system dynamics model is used in analysis. During the establishment of causalities, problems can sometimes seem as ambiguous or unclear. If a problem is relatively clear or the cause of the problem exists within a system, the system boundary would be formed from an endogenous component. There can be direct and indirect reasons causing project failure which means that problem definitions should be flexible depending on the problem, either inside or outside of the system (Richardson and Pugh, 1981; Chiva *et al*., 2014). If the system boundary is limited to the inside system, problems can be defined as a lack of coordination or internal conflicts between components. If the system boundary is expanded to outside of the system, problems can be defined as the changes in the market or external environment.

Secondly a causal loop diagram is established based on feedback thinking. Causal loops are used to describe the reasons and effects of component behaviours and how the components are connected to each other. This allows the cause of the problem within the system to be identified (Cavana and Mares, 2004). Causal loop diagrams consist of arrows, signs, and feedback loops. Arrows express relationships between selected components. In a system dynamics model, causality is not statistical but practical and intuitive, because it often arises from specific experiences.

Thirdly, based on the causal loop diagram in the previous step, a stock and flow diagram is created to simulate the mutual influences between feedback loops. Numerical information of each component is expressed in a stock and flow diagram. According to the characteristics of each component, stock, flows, and the auxiliary variables and constant are used respectively.

Fourthly, the system dynamics model using the integration of stock and flow diagram is simulated. Simulation results are used for analysis of the real case decision-making.

Fifthly, validation of the model is undertaken as a comparison between the simulated data of past real case data (Lynesis and Ford, 2007). However, if the model is unique and there is no previous data, validation can be replaced by a comparison between predictive values from experts and simulated data.

Finally, unforeseen system factors can be revealed to see if they will have a significant effect on the entire process or system. From this, the strategy and decision-making can be adjusted before applying it to the real process or system.

4.3.3 Causal loop diagram

Understanding of the feedback structure is essential. In feedback structures, all system components are connected via a circular causal chain to overcome the limitations of linear thinking mechanisms (White and Fortune, 2012). It is called the causal loop diagram. The entire process or feedback structure of the system can be generalized and understood by making elaborate causal loop diagrams.

A causal loop diagram consists of arrows, "+ or −" signs, and feedback loops. The direction of causality between components is indicated by the arrow having "+" or "–" signs. The "+" sign indicates a positive impact on the feedback result, while the "–" sign indicates a negative impact (Yearworth and White, 2013). When different causalities make a certain closed-circle, the circle is called a feedback loop. Relationships can be expressed by using a feedback loop as seen in Figure

4.5. For example, if many new babies are born, the total population will increase: the increased population will have even more babies (birth rate). Conversely, when the total population increases, the number of people who pass away (death rate) will also increase resulting of the population being reduced once more.

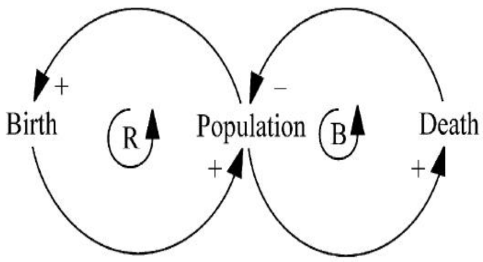

Figure 3.5 Diagram of causal relationship

(Yim *et al.*, 2004)

In the causal loop diagram, feedback loops have positive or negative codes in centre of the loop. A positive feedback code means a unilateral development or decline, by which the result of the previous behaviour would be the dominant cause and affect the following behaviour or phenomenon. Conversely, with a negative feedback code, the system is gradually stabilizing as time progresses (Lynesis *et al.*, 2001; Bendoly, 2014; Chiva *et al*., 2014). Complex systems consist of various feedback structures. According to the dominant loop structure i.e. positive or negative, the whole system can be developed, or will decline in one direction continuously or stabilize at a certain point of in time.

A critical feature in a causal loop diagram (except for a feedback structure) is time delay. Time delay means that the effect of decision-making or a new policy does not occur immediately (Motawa *et al.*, 2007). Time delay is a unique feature to system dynamics; this analysis function is applied amongst different social analysis tools. Using the analysis of the time delay function, the complex social systems or phenomena can be established and simulated in detail. Simulated results are analysed differently according to the various conditions of delayed time. This means that the performance of a system model can be simulated according to how quickly the decision-making or policy can be implemented. For example, a shower tap is a suitable sample to explain the time delay effect as seen in Figure 4.6.

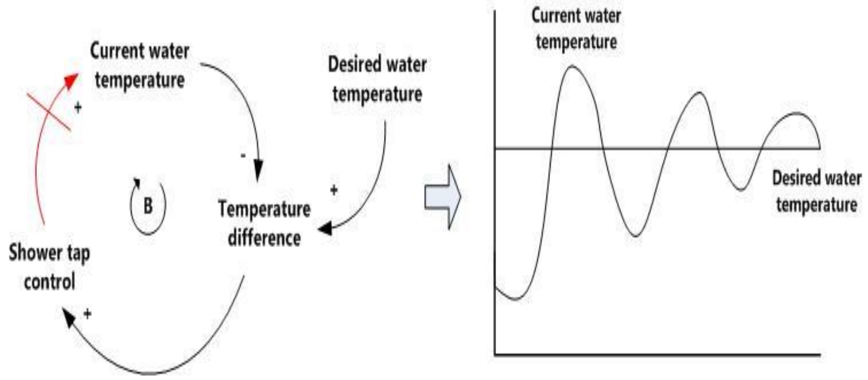

Figure 4.6 Sample diagram of time delay

When hot water is turned on, it comes out after a certain period. However, if the water is too hot, cool water should be turned on again. This process will be repeated until the temperature of the water becomes suitable for a shower. This situation is a kind of self-balancing positive feedback loop involving time delay. If the time delay is ignored in a feedback loop structure, all component behaviours are not controlled so the system cannot reach a stable state and fluctuations are occur around the target object. Based on the integration of different feedback loops, causal loop diagrams of whole systems can be established. When a certain decision-making is determined in complex systems, through causal loop diagrams, correlations and the flow of variables can be understood comprehensively.

4.3.4 System dynamics modelling

Different phenomena and behaviours that occur within a system can be understood more easily when computational analysis is supported. Although the ability of the human brain can understand a few feedback loops or overall system structures, it is impossible to infer the dynamic changes in the complex system when there are many feedback loops (Rodrigues and Bowers, 1996a; Aslania *et al*., 2014). Thus, causal loop diagrams involving the integration of different feedback loops should be formulated systematically using computational support such as a system dynamics program. In system dynamics, causal loop diagrams can be turned into stock and flow diagrams to be modelled and simulated. Basically causal loop diagrams are generated with only several simple rules, while system dynamics modelling is formulated under complicated rules including various functions and mathematical operations. Following this, intuitive and conceptual interrelationships between system components, which are presented in causal loop diagrams, turn into more explicit numerical equations in system dynamics modelling. All equations defined are expressed on stock or level variables and use rate or flow variables (Sterman, 2001; Jones, 2014). The relationship between these variables is defined using the following equation ①:

$$\frac{dL}{dt} = \mathrm{R} \text{ -- ①}$$

From the equation ① "*L*" means one of the stock or level variables and "*t*" indicates time. Changing the rate of the stock or level variable changes the rate or flow variable, which means the stored variables change because of the stock or level variable according to time progress. For example, the stock or level variable represents the state of the system such as population, product inventory, debt, cash reserves, etc. Conversely, the rate or flow variables indicate the flow of changing stock such as production and shipments, births and deaths, loans and repayments, investment and depreciation, and income and expenses. Below Figure 4.7 is an example of a stock and flow diagram expressed using a causal loop diagram.

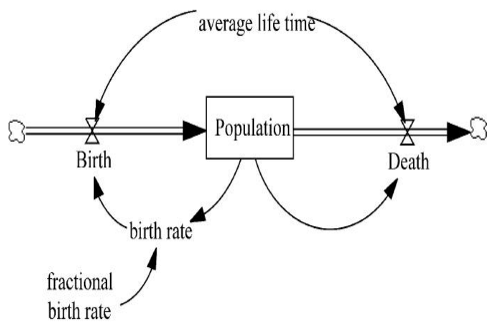

Figure 4.7 Stock and flow diagram (Yim *et al.*, 2004)

Each stock and flow diagram is integrated and extended to formulate of the whole causal loop diagram, and then becomes the essential data input for system dynamics modelling as seen in Figure 4.8.

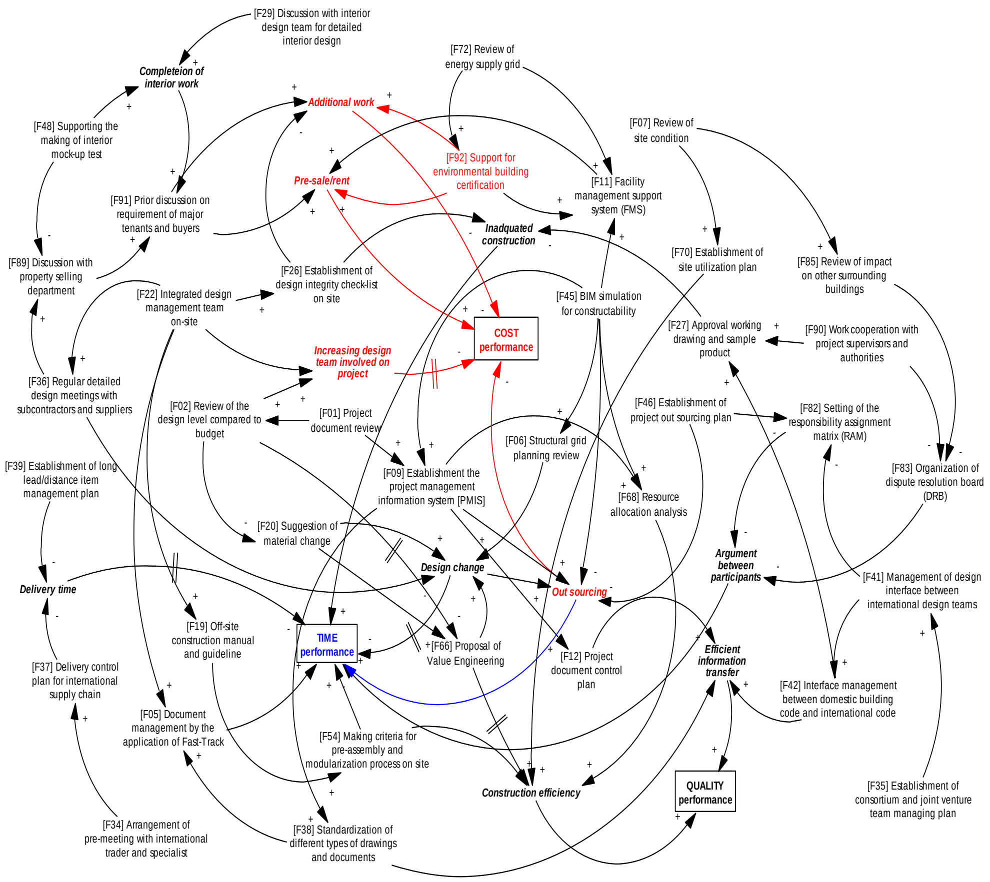

Figure 4.8 Sample of causal loop diagram

Figure 4.8 is used as a sample image of a causal loop diagram, which is described and explained in detail in Chapter 7. Thus, a brief explanation is given here to help understand the structure of the causal loop diagram. This diagram consists of different feedback structures and each feedback structure consists of various stock, flow, auxiliary variables, and constants. According to the feedback loop structure, some design-production management (DM) factors which begin with [F00] and "*Italic*" are used as stock or flow variables and other DM factors and are used as auxiliary variables and constants. Later on all the values of DM factors are unified and quantification is converted into a formulation within system dynamics modelling. In this diagram, cost, time, and quality of performance are the main stock variables. Different feedback structures and stock and flow diagrams are formulated and integrated based on these three main stock variables. During the formulation process, design-production management factors are implemented for a variety reasons; constants, auxiliary variables, and stock or flow variables.

For example, in terms of the cost performance feedback structure, *Additional work, Pre-sale/rent, Increasing design team involvement on project*, and *Out sourcing* are used as flow variables which directly determine the cost performance variable (main stock variable). In this process, the "Support for environmental building certification [F92]" factor plays a role as a flow variable, which increases the "*Additional work*" and "*Pre-sale/rent*" rate. This means that a DM factor can give both a positive and a negative impact on cost performance at the same time. The degree of practical influence can change depending on the application duration and the amount of input resources. Detailed cost performance should be calculated and analysed using system dynamics simulation as discussed in a later chapter.

On the other hand, including "*Out sourcing*" as a stock variable causes the opposite effect on cost performance and time performance simultaneously. In general, increasing the out-sourcing rate will have a negative impact on cost performance and a positive impact on time performance. However, as time progresses, excessive outsourcing can have a small effect on time performance, conversely, the appropriate outsourcing plan may lead to a more effective cost performance. As in the case above, all DM factors as variables and constants are very complicated and influence the project performances.

4.3.5 Simulation and evaluation of modelling

System dynamics is a useful tool for finding optimal solutions using trial and error, whilst considering feedback. It is a scenario approach that uses an incomplete system at the simple simulation level. It develops gradually by tracking the cause of the results of simulation (White and Fortune, 2012). After the assumption of diverse scenarios, probable errors are reflected in the system model through the simulation considering below Table 4.1.

Consideration factor	Description
Result estimation	Prediction the final and mid-course result before model simulation
Implementation of simulation	Comparison between simulation result and predicted result
Adjustment	Adjusting the value of the parameter so as to approximate as much as possible to the real value
Result comparison	Comparing the simulation result and the actual data with the passage of time
Variable values	Adjusted parameters should have relationship with meaningful values in the real case
Extreme condition test	By changing the conditions of the model unrealistic situation, looking at the reaction of the main variables

Table 4.1 Consideration factors for system dynamics simulation

The result of the simulation of system dynamics is expressed in graph form as shown in Figure 4.9 according to the time progression.

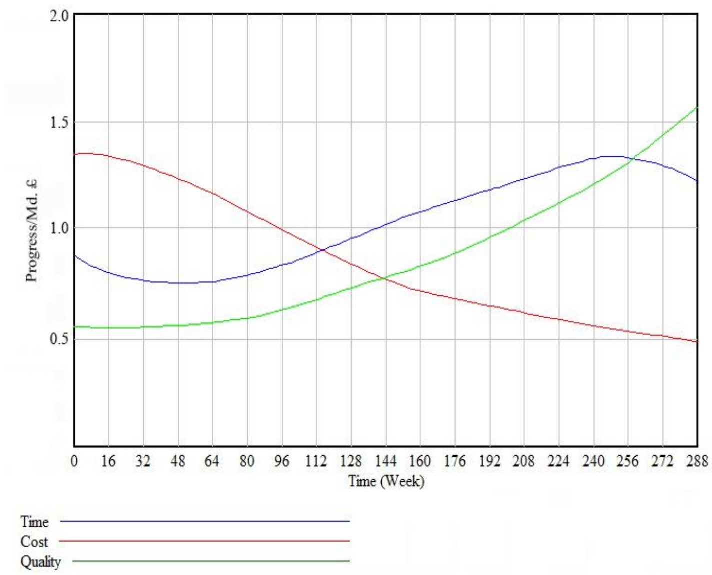

Figure 4.9 Sample of a system dynamics simulation graph

Different behaviour patterns are analysed and interpreted by the fluctuations of the graph. Through the observation of changing behaviour patterns (y-axis) the time progression (x-axis), the state of each variable (three main project performances) as well as the structure of entire system is included. Figure 4.9 is a sample graph to explain the simulation result of system dynamics model. Even if the time, cost and quality graphs are used to show overall project performance, the performance result of all variables (DM factors) can be presented in graph form. This means that in the real project performance analysis, the performance result of not only the main project implementation strategy, but also subordinate decision-making can be simulated and analysed in advance using system dynamics. Moreover, even unforeseen factors and effect of these factors on the entire system or project can be recognized. Through the diverse simulations reflecting different scenarios, decision-making can be altered to respond to specific unexpected situations, which are always present within real systems.

Figure 4.9 is used as a sample graph and is the simulation graph of the "Reference model" in Chapter 7 (Figure 7.5). Time, cost and quality performance, which are used as variables respectively are simulated according to the time progress. If at any point in time (x-axis), there are problems in performance (y-axis), these can be improved using the formulas and constants changes (here the change of amount or duration of input resources). Through this, with limited resources, the most effective and optimal behaviour patterns (performance) can be simulated before the actual commencement of the project.

4.4 Complexity in the construction industry

The built environment has diverse social meanings such as value, ideas, and knowledge. With the advent of a technology-driven society, these social meanings are more complicated and diversified in the built environment with the integration with technology. The influences between the human realm and nature cause diversification of the system component, and interconnections among diverse social systems (Vidal and F. Marle, 2008; Nian et al., 2013). The construction industry reflects the diverse social meanings, which have become complex. A number of organizational, institutional, historical, and cultural values are intertwined throughout the construction industry, from architectural or urban planning to site production.

4.4.1 Complex systems in the construction industry

In the architecture, engineering, and construction industry, the application of complexity theory is in its infancy. In construction industry, social affairs such as mutual respect, dispute or collaboration have been recognized as minor aspects comparing with top down processed technological aspect. Thus, complexity theory that investigates the mutual and complicated relationships and feed-backs between project participants or elements has not paid attention from construction industry. As a result, an attempt of application of complexity theory has been made by the metaphorical method in the industry (Sha'ar *et al*., 2016).

Initially, complexity theory was applied in architectural and urban planning fields. They were applied to architectural designs such as façade designs, and not to scientific and substantive issues (Well, 1999). For example, fractal architecture proposed by Peter Eisenman, is the concept of scaling using fractal structure[9] as a design principle (Yun and Che, 2005). Metaphysical approaches of system such as flow of traffic or cost estimation were applied to the AEC industry. For example, Batty (2005) defined a city as a self-organizing complexity system and simulated the growth of the city through several models based on complex systems. Batty developed different innovative models for the direct approach of complex system

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[9] A fractal structure is a natural phenomenon or a mathematical set that exhibits a repeating pattern displayed at every scale. It is also known as expanding symmetry or evolving symmetry. If the replication is exactly the same at every scale, it is called a self-similar pattern. Fractals are different from other geometric figures because of the way in which they scale. Doubling the edge lengths of a polygon multiplies its area by four, which is two (the ratio of the new to the old side length) rose to the power of two (the dimension of the space the polygon resides in). As mathematical equations, fractals cannot usually be differentiated. An infinite fractal curve can be conceived of as winding through space differently from an ordinary line, still being a 1-dimensional line yet having a fractal dimension still indicating its resemblance as a surface.

in city development. The definition of project complexity involves a number of factors beyond simply having a large number of interacting parts. This complex aspect can be seen from three perspectives.

1) The constructions project is an assembly-like process often complicated, parallel and dynamic: thus more complex than the traditional production process. An ordered view in which all project elements are ready to be implemented by pre-determined plan and schedule is reality because of the dynamic nature of construction. Project resources, including equipment, building materials and components and workers are supposed to be available without any unexpected external or internal interruption. And changes caused by incompatibility among project elements can occur at any time (Thomas and Mengel, 2008; Stephen and Maylor, 2009; Nian *et al*., 2013; Naderpajouh and Hastak, 2014).

2) All construction projects are divided into parts that are subcontracted to individual enterprises. The construction industry is highly fragmented and implemented in ever changing condition. They are also interwoven: every individual participates in more than one project, utilizing the same production capacity. Mapping the supply chain in any project is very difficult given the uncertainty (Yearworth and White, 2013; Zavadskas *et al*., 2014; Parraguez *et al*., 2015; Qazi *et al*., 2016).

3) The construction site is a complicated place for different production activities and a place for a transient social system. This aspect is often hidden by the fact that each participant and organization that work together in a construction site is not necessarily hired and reimbursed by the location where they work. They all

have their own internal problems and unrevealed situation. According to their own condition, all participants' behaviours have no choice but to be changeable (Lucas, 2000; Vidal *et al*., 2007***;*** Ozorhon *et al*., 2010; White and Fortune, 2012).

Many researchers have focused on uncertainty as being the dominant issue (De Meyer et al., 2002; Williams, 2005); however, difficulty with technical or management challenges and organisational challenges are equally important (Baccarini, 1996; Williams, 2002; Chiva et al., 2014). Complexity theory help to understand how these aspects affect the project as a system (Remington & Pollack, 2007; Whitty and Maylor, 2007). Complexity theory has been gaining in popularity with the research community as the basis for better understanding how complexity and chaos can be managed in construction (Austin et al, 2002; Jafari, 2008; Ivory and Alderman, 2005; Hass, 2007; Geraldi and Adlbrecht, 2007; Jafari, 2008; Richardson, 2008; Thomas and Mengel, 2008; Vidal and Marle, 2008; Stephen and Maylor, 2009).

A challenge is to understand the complexity caused by the interface between the design and production process where international joint venture teams are involved. Complexity theory has embraced different kinds of subordinate theories which have evolved independently in their own areas. Using computer-aided modelling, complexity theory can understand and explain different unexpected and complicated issues that were recognized as system errors or unrecoverable problems in different construction industry from construction to management. The increasing scale and scope of project mean that contemporary construction projects are becoming ever more similar to complex systems. Dynamic activities and system components that are involved in construction projects are all intertwined.

4.4.2 High complexity in the management of construction projects

The conventional project management approach assumes a world of order and a predictable environment in which one can set and deliver a clear set of goals in a defined manner. Project management understands the project as an ordered and simple, and thus predictable phenomenon, which can be divided into contracts, phases, activities, work packages, assignments etc. to be executed more or less independently (Zavadskas *et al*., 2014). The project is also seen as a mainly sequential, assembly-like, linear process which can be planned in any degree of detail through an adequate effort, and the dynamics of the surrounding world is not taken into account. Different project participants and components are interwoven having different targets and objectives, but have to collaborate in order to complete the project successfully.

In contemporary construction projects, particularly international large-scale construction projects (LSPs), enormous numbers of activities and project components interact throughout the project. Based on the fundamental uncertainty and dynamics of construction projects, different layers of complexity are added, caused by size, multi functionality, globalization, or joint venture design teams (JVDTs). They have totally different working processes, system, criteria, and even culture, their decisions and approaches are inevitably complex at every construction stage.

In the management of large-scale projects, numerous problems and pitfalls must be recognized and overcome before commencing construction. From a contractor's perspective, LSPs call for extraordinary patience, capital resources, risk control, and high front-end costs. Like other complicated decision-making processes, project management of LSPs, which entails a collaborative process in response to the project's changed design, critical construction method, site condition, and different external influences, is a highly complex process. According to Maylor (2003), complex construction process comprises three factors:

Organizational complexity (the number of people, departments, organizations, locations, nationalities, languages, and time zones involved, level of organizational buy-in, authority structure).

Resource complexity (the scale of the project, often indicated by the size of the budget).

Technical complexity (the level of novelty of any technology, system, or interface, and uncertainty about the process or the requirements).

It necessitates different contradictory or relevant project components to be controlled (Gray and Hughes, 2001). In particular, due to the application of advanced technologies and innovative designs in LSPs, managing interfaces between design and construction technologies increases project complexity. Thus, construction project managers must begin to pay greater attention to the non-linear and subtle influences in their planning and management, and shift away from the primal importance they grant to quantitative analysis and project controls. Due to the application of advanced technologies, more detailed management in implementation plans and coordination is required well organized and flexible management processes are needed to respond to highly dynamic and complex projects.

4.5 Summary

In rapidly changing and highly complex industrial societies, essential choices lead to changes or the need for adaptation to fit in with the complexity. To understand these changes, the complexity theory is proposed in this chapter as an underpinning theory. A description of the general aspects and an explanation of how complexity theory is suitable to deal with the different complex changes in industrial societies and social phenomena were introduced. In particular, this was to show the suitability of the complexity theory to the built environment. For the effective application of complexity systems in the built environment, appropriate processes should be provided at a management level, because many components are involved in construction projects.

System dynamics, which is one of the subsidiary research methods of complexity theory, is proposed as an explicit research method to analyse the dynamic changes and complexities in construction project. Especially in large-scale projects implemented by joint venture design teams, system dynamics can analyse the complex integration and dynamics changes between various components constituting the system. Through the system dynamics modelling and simulation, unexpected risks can be recognized and appropriate decisions can be made before the actual commencement of the project.

CHAPTER 5 RESEARCH METHODOLOGY

5.1 Introduction

Deciding on the appropriate research methodology involves four key issues; what research questions to study; what data is relevant; what data to collect; and how to analyse the results (Yin, 1994). Whilst Yin's list is correct, it is incomplete; the important issues of framing the research, development of the output, and validating the output are not discussed. This chapter focuses on the design, development, and execution of the research methods, describing research philosophy, strategies, techniques, and the validation of research methods.

Cooper (1998) and Pickering and Byrne (2013) suggest research is a five-stage process: problem formulation, data collection and literature review, data evaluation, analysis and interpretation, and the presentation of results. This chapter uses Cooper's structure with five method stages including the identification stage of the contractor's design risk in Korean LSPs, the literature review, practical data collection from the construction sector, data standardization, and simulation by computational support.

5.2 Research philosophy

The two kinds of research are pure and applied research (Fellows and Liu, 2003; Creswell, 2013). Pure research, sometimes called blue-sky research, develops a fundamental understanding and knowledge, and contributes to the body of theory. Applied research seeks to address issues of applications and to help solve practical problems. In order to choose a suitable research method, the research design and purpose should be taken into consideration, as well as the questions being investigated, and the resources available (Tzortzopoulos, 2004).

According to Kagioglou *et al.* (2008), research can be categorized into holistic and integrated methods where the research philosophy, approach, and technique are interrelated as shown in Figure 5.1. A recognition of the elements that constitute the methodology provides an appropriate alignment between the research method and the study area. The research philosophy has an impact on the research approach, which embodies qualitative and quantitative methods. The research technique is incorporated into the literature review, interviews, questionnaire surveys, experiments, observation and workshops.

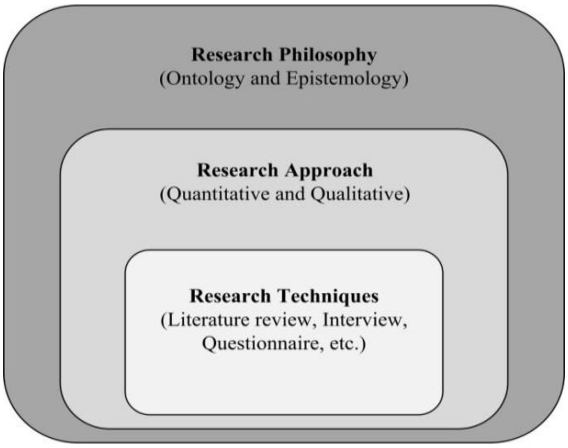

Figure 5.1 Nested research methodology (Kagioglou *et al.*, 2008)

The research methodology relates to the epistemological and ontological methods. The epistemological approach deals with questions of knowledge acceptability in disciplines and methods (Bryman, 2012). The epistemological method is about debate and how to best conduct research, describing different, and competing inquiry paradigms. The ontological method involves the logical investigation of the different ways in which things are thought to exist, and the nature of various kinds of existences (Silverman, 1998; Yearworth and White, 2013). The ontological method refers to all approaches to science that consider scientific knowledge to be from empirical sources and only those that can be directly experienced and verified between different observers to generate scientific knowledge. It mainly uses quantitative and experimental methods to test hypothetical-deductive generalisations (Blaikie, 1993; Treiman, 2014).

The aim of this research is the development of a design-production management process map, reflecting the management of design for international large-scale projects in Korea. Explicit experiments using computational modelling and simulation are conducted, based on the knowledge and opinion of professionals (epistemological method). This research is rooted in interpretive epistemology. All research components used for the development of the process map are evaluated by professionals who have the advantage of knowledge, insight, and experience.

5.3 Research approach

The research approach is a way of describing how a research is conducted. It is a strategy of inquiries, which is suitable to carry out research, choosing a specific style of research and the application of suitable research methods such as the design of research procedure or data collection. The most common research approaches are quantitative, qualitative and combined methods - which is known as triangulation or the mixed research method (Love *et al.*, 2002a; Creswell, 2013).

Diverse research techniques are utilized according to the research purpose or type and the availability of the research data (Naoum, 2007).

For this research, a mixed approach is utilized, where both quantitative and qualitative data are used, integrating two data forms and using distinct research designs. The mixed approach is occasionally used to refer to a broad approach which combines multiple observers, theoretical perspectives, and methodologies and is frequently used interchangeably to describe research strategies that incorporate a combination of quantitative and qualitative research methods (Creswell, 2013). The combination of qualitative and quantitative approaches provides a more comprehensive understanding of a research problem than either approach does alone. Qualitative data tends to be open-ended without predetermined responses, while quantitative data usually includes closed responses such as on questionnaires or when using psychological instruments.

The purpose of the qualitative approach is to understand a particular social situation, event, role, group, or interaction. It is largely used as an investigative process where the researcher gradually makes sense of social phenomenon by contrasting, comparing, replicating, cataloguing, and classifying the object of study (Amaratunga *et al.*, 2002). Using a qualitative approach, this research can have the comprehensive perception and understanding of the current problems in the complex construction sector. Through careful observation of contemporary international large-scale projects, different contractor's design risks are understood, and through semi-structured interviews, diverse design-production management (DM) ways are recognised as the initial research data are collected. In addition, complexity theory is applied as the underpinning theory of this research by the use of the qualitative approach explaining the complex and unexpected construction industry and LSPs.

Based on this perception of complexity and contractor's design risks in international large-scale projects and the initial criterion of appropriate design-production management for contractors, practical research data are collected by quantitative method including a questionnaire and computational modelling. Later, after analysis of the quantitative data, the qualitative approach is used again to validate analysed data using simulation and reinterpret the data by the development of a new management process map.

Whilst, in this research, a qualitative approach is used to understand the comprehensive research situation and perceive the potential design-production management ways, which can be used as the research data later, a quantitative approach is used more substantially to collect practical data using questionnaire and computational modelling. The quantitative approach is a scientific method in which the initial study of theory and literature yields precise aims and objectives within the hypotheses to be tested (Fellow and Liu, 2003). Quantitative research is for testing objective theories by examining the relationship among variables. These variables can be measured typically on instruments, so that numbered data can be analysed using statistical procedures. Thus, this research uses empirical quantitative approaches including survey methods and numerical methods such as questionnaires and computational modelling.

The main strengths of the quantitative approaches lie in its precision and control

(Myers, 1997; Merriam and Tisdell, 2015). The data collected for research are often large and representative, hence using a quantitative method, a larger population is able to be generalised within acceptable error limits (Bryman, 2012). No matter what the nature and amount of data collected, a quantitative approach is appropriate to measure raw data to search for patterns. Therefore, in this research, quantitative methods are used in order to supplement the qualitative data. Raw research data yielded using the qualitative method are processed through quantitative approaches (questionnaire survey) to analyse and ascertain any distinct patterns or classification using a statistical program such as SPSS. After defining and analysing the collected data by a quantitative method, later qualitative methods (modelling and simulation) are used again to satisfy research purpose. Quantitative data can help with the qualitative side of a study by finding a representative sample and locating deviant samples, while qualitative data can help the quantitative side of the study by aiding conceptual development and instrumentation (Creswell, 2013). Therefore, by the application of mixed methods, the research process can be conducted effectively and appropriately.

5.4 Research strategy

The research strategy should be established according to the research situation. Each research strategy has its own specific function in collecting and analysing empirical data, and therefore each strategy has both advantages and disadvantages (Yin, 1994). Yin (2003) suggested five different research strategies: surveys, experiments, archival analysis, histories and case studies as seen in Table 5.1. This research used three of these research strategies; archival analysis, survey, and experiment.

Strategy	Form of Research Question	Requires control of behavioural event	Focuses on Contemporary Event?
Experiment	How, why?	Yes	Yes
Survey	Who, what, where, how many, how much?	No	Yes
Archival Analysis	Who, what, where, how many, how much?	No	Yes/No
History	How, why?	No	No
Case Study	How, why?	No	Yes

Table 5.1 Requirements and focus of different research strategies (Yin, 2003)

This research tries to prove the research hypothesis that design-production management is critical at the initial stages of large-scale projects and seeks to establish a management process map. For this, using archival analysis (literature and industrial data review), the current problems in the design management of international large-scale project is understood and potential design management ways are recognized. After that, more practical research data are collected using survey such as questionnaires. These collected data are validated and reinterpreted by experimental methods (computational modelling and simulation).

5.5 Research techniques

Different subordinate research techniques are used to collect data: literature review, semi-structured interview (pilot survey), and a questionnaire survey, described as seen in Figure 5.2.

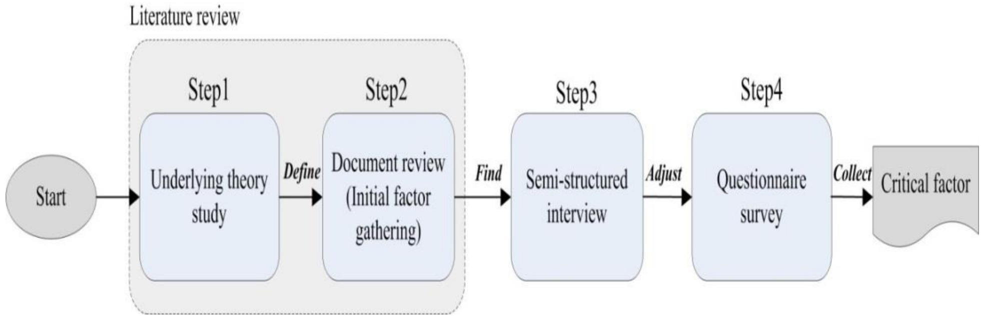

Figure 5.2 Procedure of design-production management factor

Qualitative data as perceived through the literature review (steps 1 and 2) are formulated and quantified using the quantitative approach (steps 3 and 4). The research data is analysed and simulated in the next step.

5.5.1 Literature review (Steps 1 and 2)

The literature review provides a description and critical analysis of the current state of the knowledge in the subject area (Bordens and Abbott, 2005). A literature review provides an in-depth understanding of international LSPs and design management. It also provides an up-to-date assessment of the current maturity and direction of design management research and identifies a framework of research for the formulation and execution in the next research step (i.e. the semi-structured interviews). During the literature review, current problems of design management in large-scale projects are reviewed. Then, based on the understanding of underpinning theory (i.e. complexity theory), diverse design management factors are identified from diverse literature and practical project data.

5.5.1.1 *Underpinning theory*

In order to understand such complex phenomena and provide an appropriate research direction, the application of the appropriate underpinning theory covering the research topic and hypothesis is required. After an in-depth literature review on the current situation and the problems of design management in international large-scale projects, complexity theory is adopted as the underpinning theory of this research to develop the appropriate design-production management process map (DMPM).

5.5.1.2 *Document review (Initial data collection)*

Document review is a tactic which includes documentary evidence, physical evidence, and archival analysis. The archive can exist in a variety of formats such as files, maps, drawings, films, sound recordings and photographs (Naoum, 2007). Recently, the internet has replaced other sources as a provider to access archival and published materials. In this research, apart from the academic literature review, empirical industrial data and reports involving features of the Korean construction sector are investigated. Using different documents and practical project data reviews, initial research data (design management factors) are identified and collected.

Through the initial data collection procedure, 93 potential design-production management (DM) factors were obtained which came from different academic researches and previous project data. The project manager handles design and production issues and the project management team covers all post-tender construction phases from design and production on site, several DM factors can have similar features with project management factor. Initial DM factors were obtained from the literature review; “Body of Knowledge” (APM, 2012), “A Guide to the Project Management Body of Knowledge” (PMI, 2013) and “Factors in project success" (BGM, 2014)”. The literature deals with project managing factor or success factors (RIBA, 2002; Fewings, 2005; Baars, 2006; Emmitt, 2010; Kerner, 2013). This was supplemented and combined with real project data (See Chapter 7.4.1) collected by the author for a large mixed-use redevelopment complex project in Korea, including 3 high-rise (over 50 storeys) offices, commercial, and residential buildings. It is a Korean complex and international LSP. In Chapter 7, this project data are used as basic data for system dynamics simulation (reference model).

A large number of project management and design-production management factors were collected from the Korean LSP. The factors were analysed to remove duplication and ambiguity, and combined to reflect a list representative of the design management factors. 46 factors were obtained from the literature review and real project data (78 factors). Finally 93 initial DM factors were identified as being appropriate for the research. Hence, the initial data (design management factors) are adjusted using semi-structured interviews to be used as the meaningful research data.

5.5.2 Pilot survey (Semi-structured interview, step 3)

This research adopted semi-structured interviews as a pilot survey. Semi-structured interviews are a very useful technique, potentially providing a rich account of the interviewee's experiences, knowledge, ideas and impressions (Merriam and Tisdell, 2015). Through a pilot survey, which consists of face-to-face semi-structured interviews and simple pre-determined questions, collected data are determined and adjusted to ensure the clarity of obtained factors and sufficient research questionnaires. All participants who have been involved in international large-scale construction projects (LSPs) or international joint venture design teams (JVDTs) project were asked to identify initial design management factors, which were then used for the research questionnaire. Based on their comments and suggestions on question items, item wording, item sequence, and the directions in completing the construct were also solicited (Robson, 2002).

5.5.3 Questionnaire survey (step 4)

A questionnaire survey is an important data-gathering method for many researchers. A questionnaire is a structured series of questions, which are asked directly to the respondents to investigate their attitudes, opinions, and knowledge (Tornatzky and Klein, 1982; Bryman, 2012). It allows for an analytical approach towards exploring relationships between variables. Thus, it is an appropriate method to discover the current international large-scale project practices and to gather their opinions regarding design-production management from the contractor's perspective. This method has been widely adopted from previous studies for deriving critical success factors in different contexts (e.g. Li *et al.*, 2005; Lu *et al.*, 2008) as it can reach a broader group of respondents (Ng *et al.*, 2009).

This research uses closed questions, which offer respondents a set of predesigned replies. Unlike open questions which have no definitive response and normally begin with words such as 'how', 'why', or 'what', closed questions can achieve enough data samples and are easier to respond to and analyse. A Likert scale was used in the closed questions. It allows the respondents to decide on the strength of their agreement or disagreement with a series of statements (Amaratunga *et al.,* 2002). The Likert scale is the most common scale for obtaining respondent's opinions. It is possible to achieve the various construction experts' views using such approaches. Their responses are given a numerical value and/or a sign, which reflects the strength and direction of the respondent's attitude to each of the statements.

The questionnaire is in two parts, each with a different purpose. Part 1 includes six questions and is designed to obtain personal and general information. In part 2, the respondents were asked to evaluate the degree of importance and preference of each design-production management (DM) factor and the interrelationships between DM factors according to the participant's previous experiences and grounded knowledge.

The final research out-put is to be expressed as a process mapping, thus, in the next stage, the research data collected from the questionnaire survey will be used as basic data for computational modelling and simulation in order to develop a design-production management process map.

5.6 Statistical data analysis

Collected research data was analysed using statistical methods. According to the results of the questionnaire survey, only 43 DM factors were recognized as worthy of being analysed in-depth. Among 93 initial factors (See Appendix A), 43 DM factors receive importance greater than overall (2.752) by questionnaire of experts. In this research, only DM factors with an above-average importance were used as basic data for the system dynamics modelling and simulation. Using SPSS 22.0, factor analysis was conducted on the 43 DM factors. Factor analysis is a research method used to identify groups, which consist of related factors into a more easily, understood framework (Norusis, 2012). It is adapted to group the factors that have similar features, using the distinctiveness of each factor and the relationship with other factors.

Categorized MD factors by factor analysis were analysed again using an importance-priority matrix (IPM) which is transformed from importance-performance analysis (IPA). Originally, IPA was developed as a marketing research technique that involves the analysis of customer attitudes towards the main product or service (Matzler *et al.*, 2003; Wong *et al.*, 2011) and nowadays, it is widely used in various research areas. In IPM, all critical DM factors are plotted on the matrix according to their own importance or priority value. Based on the horizontal and vertical axis, analysis results were graphically displayed on an easy to interpret, two-dimensional grid (Wong *et al.*, 2011).

5.7 Modelling and simulation (System dynamics)

Based on the result of the statistical analysis in which numerical importance value and degree of the interrelationship of design-production management (DM) factors are recognized, computational modelling and simulation are conducted using system dynamics. System dynamics is an approach to understanding the non-linear behaviour of a complex system and behaviour pattern of all project components (Richardson and Pugh, 1981; Jones, 2014). It is modelled using combination and integration of causal loop diagrams, which are also established based on interrelationships between project components (i.e. DM factors). Because system dynamics can be used for complex and long-term projects (Yearworth and White, 2013), it is suitable for research of LSPs. It enhances the comprehensive recognition of the entire project system and provides an evaluation of major parameters identifying distinct behaviour patterns between system components (Whang and Flanagan, 2015).

The main purpose of this research is to develop a design-production management process map (DMPM), thus collected data are processed and validated using system dynamics modelling and simulation. In the system dynamics modelling procedure, the entire system structure (i.e. the large-scale project) and interrelationship between variables (i.e. the DM factors) are recognized and formulations are established by the integration of variables within system. Then, all functional values of variables and formulations are quantified to be programmed for simulation. Through the computational simulations, system dynamics shows a reliable performance result according to the application of different DM factors in graph form.

5.8 Validation

Even if system dynamics can provide objective major parameters according to the simulation results, in the modelling procedure of system dynamics, the researcher's personal knowledge and experiences may influence modelling formulation. In order to prevent systematic mistakes and researcher bias, detailed validation on system dynamics modelling are carried out. With the utilization of the Vensim (Vensim DSS Version 4.0), system dynamics, modelling can be formulated and validated accurately. The Vensim program is a kind of computer simulation language for system dynamics. It provides flexible formulating simulation forms constituting stock and flow diagrams (as shown in Figure 5.3), which convert complex variables of system dynamics into computational formulations (Lyneis *et al.*, 2001).

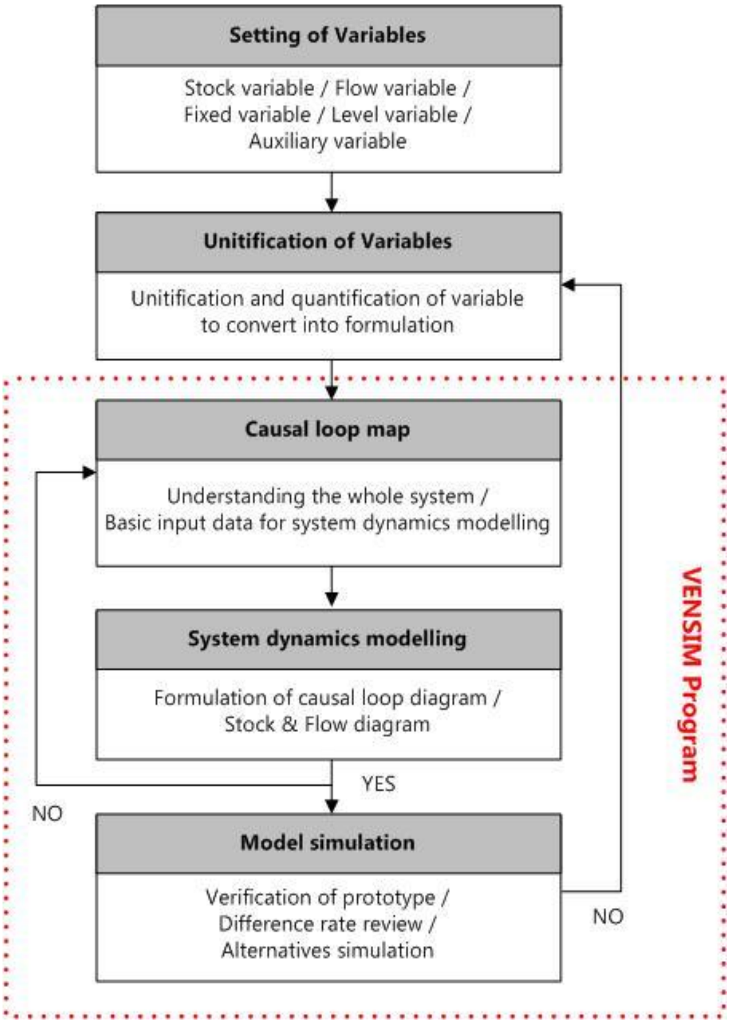

Figure 5.3 Procedure of system dynamics model

Vensim is useful for validating the system dynamics modelling as it uses different internal verification functions including model structure verification and formulation verification. In addition to these technical validation methods, scenario-based approaches such as time, cost, and quality-based, system dynamics modelling is validated providing practical reliability and compatibility.

5.9 Summary

This chapter explains the research methods and procedures adopted in this research. The methodology has been linked to research objectives to clarify the whole research. The chapter begins by describing the need for a research philosophy and approach for the research methodology. The practical research strategy is described with the semi-structured interview and questionnaire survey methods are research techniques used for the main data collection. All research data collected using the above methods are analysed using different statistical analysis tools such as factor analysis and an importance-priority matrix. Finally, based on collected and analysed research data, system dynamics modelling is formulated and simulated using the Vensim program. The next chapter will present and discuss the practical and detailed procedures of the research data collection and analysis.

CHAPTER 6 RESEARCH DATA AND ANALYSIS

6.1 Introduction

This chapter presents the collection and analysis procedure of the research data. According to the questionnaire survey, 43 higher important DM factors that have greater than average importance (2.752) were used for research data. They were recognized as being the critical design-production management (DM) factors from the questionnaire of construction experts. The selected 43 DM factors were analysed by factor analysis and an importance-priority analysis. Through the analyses, a more in-depth analysis was conducted of the individual DM factors and interrelationships between critical DM factors. In the factor analysis, all DM factors were categorized according to their characteristics and their impact on the entire project. In addition to this, the importance value and preference of each DM factor and interrelationships between them were put through importance-priority analysis.

6.2 Research data

6.2.1 Questionnaire distribution

The questionnaires were distributed via e-mail and in person to increase the response rate. All respondents were selected from Grade 1 contracting and engineering firms registered with the Construction Association of Korea or International Contractors Association of Korea. The main purpose of the questionnaire survey was to obtain the practical knowledge and experience of the application and interrelationships of design-production management (DM) factor from construction experts. Based on the results of these responses, different analyses were conducted and a system dynamics model was formulated and simulated. Thus, in order to obtain more accurate and reliable responses, the questionnaire asked about different issues such as importance, preference, and interrelationships of DM factors. Because the questionnaire had many questions, the response rate was expected to be very low. In order to increase the response rate, experts who have a direct or indirect relationship with author such as alumni, previous colleagues, or colleagues of author's previous colleagues or alumni were considered as respondents of this survey. A total of 328 questionnaires were distributed and 127 valid responses were returned, a response rate of 44%.

Table 6.1 shows that among the 127 returned responses, 21 respondents (16.5%) are project managers, 51 (40.1%) are site managers, 22 (17.3%) are project engineers, and 33 (26.1%) are design managers.

Group	Project Manager	Site Manager	Project Engineer	Design Manager	Total Responses
LSP	10	22	7	7	46
PDA	7	13	5	11	36
IBP	4	16	10	15	45
Total	21	51	22	33	127

*Note. LSP: Large-scale project, PDA: Project designed by foreign architect, IBP: International-based project

Table 6.1 Project types and positions held by respondents

The majority of the respondents (86%) have more than five years' working experience in their organization. They are professionally positioned at the middle or higher management level, which improves the credibility and reliability of the collected data. Table 6.2 shows that 36.21% had under 10 years' experience, 48.82% 11-20 years, 9.46% 21-30 years, and 5.51% more than 30 years, respectively. Remarkably, almost half (48.82%) of respondents have 11 to 20 years' working experience.

Experience (Years)	Project Managing	Site Managing	Project Engineering	Design Managing	Total Responses
Under 5	-	4	6	7	17 (13.38%)
5-10	2	12	6	9	29 (22.83%)
11-15	6	17	5	6	34 (26.77%)
16-20	8	11	4	5	28 (22.05%)
21-30	3	6	-	3	12 (9.46%)
Over 30	2	1	1	3	7 (5.51%)
Total	21	51	22	33	127(100%)

Table 6.2 Working period of respondents

6.2.2 Critical factors

Among the 93 initial factors (see Appendix A), a limited number of factors were determined as critical design-production management (DM) factors from the results of questionnaire survey. The critical DM factors were ranked in order of importance and the mean value and standard deviation of each factor were derived from the total sample to determine their level of importance. If two or more factors had the same mean value, the factor with the lower standard deviation was considered more important. Factors that had greater mean values than the average value of all factors (2.752) were classified as critical DM factors that affect a contractor's performance at the early stages of projects. Finally, the identified 43

DM factors were labelled as critical and their rankings are shown in Table 6.3.

No.	Design-production management factors	Rank	Importance	Standard deviation
F02	Review of the design level compared to budget	1	3.984	0.514
F01	Project documents (cost statement, B.O.Q, drawing, specification) review	2	3.955	0.629
F41	Management of design interface between international design and engineering firms	3	3.888	0.802
F22	Integrated design management team on-site	4	3.862	0.673
F09	Establishment the project management information system (PMIS)	5	3.739	0.663
F18	Pre-tender meeting with bidding and construction team	6	3.737	0.520
F35	Establishment of consortium and joint venture team managing plan	7	3.720	0.716
F37	Delivery control plan for international supply chain	8	3.638	0.554
F46	Establishment of project out sourcing plan	9	3.626	0.738
F05	Documents management by the application of Fast-Track (drawing distribution/instruction)	10	3.573	0.738
F38	Standardization of different types of drawings and documents	11	3.545	0.608
F42	Interface management between domestic building code and international code	12	3.531	0.590
F45	BIM simulation for constructability	13	3.508	0.722
F36	Regular detailed design meetings with subcontractors and suppliers	14	3.494	0.535
F34	Arrangement of pre-meeting with international trader and specialist	15	3.470	0.576
F54	Making criteria for pre-assembly and modularization process on site	16	3.447	0.635
F66	Proposal of value engineering	17	3.226	0.798
F03	Terms and conditions review	18	3.208	0.624
F56	Establishment of project implementation plan (PIP)	19	3.207	0.686
F19	Off-site construction manual and guideline	20	3.192	0.518
F70	Establishment of site utilization plan (access, stock yard, work shop, site office)	21	3.174	0.567
F12	Project document control plan	22	3.170	0.649
F07	Review of site conditions (site topography/ground facilities)	23	3.145	0.598

F92	Support for environmental building certification (LEED/BREEAM)	24	3.109	0.599
F68	Resource allocation analysis (labour/material/equipment)	25	3.082	0.517
F74	Simulation of life-cycle cost (maintenance cost)	26	3.076	0.762
F39	Establishment of long lead/distance item management plan	27	3.044	0.729
F90	Work cooperation with project supervisors and authorities	28	3.018	0.654
F26	Establishment of design integrity checklist on site	29	3.013	0.615
F06	Structural grid planning review (over design, omission)	30	3.007	0.740
F78	Similar projects case study (design, construction method and cost, duration, advanced technologies)	31	2.993	0.687
F72	Review of energy supply grid	32	2.961	0.718
F85	Review of impact on other surrounding buildings (view, insolation, privacy, vibration, dust, smell)	33	2.959	0.681
F83	Organization of dispute resolution board (DRB)	34	2.917	0.518
F20	Suggestion of material change (constructability, low price, local production)	35	2.904	0.699
F82	Setting of the responsibility assignment matrix (RAM)	36	2.890	0.693
F91	Prior discussion on requirement of major tenants and buyers	37	2.867	0.701
F29	Discussion with interior design team for detailed interior design	38	2.830	0.647
F27	Approval working drawing and sample product	39	2.812	0.709
F13	Simulation for interior finishing/schedule	40	2.801	0.595
F89	Discussion with property selling department (concept of interior design, computer graphics, interior finishing simulation)	41	2.788	0.776
F11	Facility management support system (FMS)	42	2.782	0.780
F48	Supporting the making of interior mock-up test	43	2.759	0589

Table 6.3 Critical design-production management factors

Individual critically ranked DM factors are very distinct, but they also have common features, this allowed them to be categorised into three groups; high, middle, and low-ranked groups. In accordance with Table 6.3, relatively high-ranked critical DM factors tend to play a role in managing the interfaces between factors that have different tendencies and characteristics respectively. Particularly, six factors amongst the high-ranked factors (1st to 14th) are closely related with either interface management or the integration aspects. For example, “Integrated design management team on-site [F22]” is a useful factor when managing the interface between the contractor and the different architects, designers, engineers, and consultants. “Establishment of the project management information system (PMIS) [F09]” is related to the integration of the enormous amount of data and information throughout the project. “Standardization of different types of drawings and documents [F38]” also deals with various design criteria. On the other hand, the rest of the three high-ranked factors are all about the management of multinational aspects; “Management of design interface between international design and engineering firms [F41]”, “Establishment of consortium and joint venture team managing plan [F35]”, “Interface management between domestic building code and international code [F42]”. These findings indicate that Korean LSPs are becoming more globalized as different international players work together throughout each project stage.

Middle-ranked DM factors (15th to 29th) are about conventional or dominant management factors in the current AEC industry. Amongst them, seven factors [F03, F56, F70, F12, F07, F68, F74] have been recognized as essential managing factors in the AEC industry for a long time. Thus, they can be applied in not only Korean LSPs, but also almost all construction projects for any purpose and in any place. In particular, the following three factors; “Off-site construction manual and guideline [F19]”, “Support for environmental building certification (LEED/BREEAM) [F92]”, and “Establishment of long lead/distance item management plan [F39]” are predominantly management factors in current large-scale construction projects. Overall, this category tends to focus more on the entire and comprehensive project management than in-depth design or production aspects on site.

Generally, low-ranked factor groups have more specific and regional features. In comparison with the above two factor categories, this category is composed of more explicit management factors, which support the above two categorised factors. Amongst them, six factors [F06, F78, F72, F85, F27, F13] deal with specific tasks, which should be managed during the production stage. In particular, factors F06, F27 and F13, “Structural grid planning review (over design or omission)”, “Approval working drawing and sample product”, and “Simulation for interior finishing/schedule” respectively are not predominant, but explicit and essential for sufficient management of design-production issues. Other factors such as “Prior discussion on requirement of major tenants and buyers [F91]”, “Discussion with interior design team for detailed interior design [F29]”, and “Discussion with property selling department (concept of interior design, computer graphics, interior finishing simulation) [F89]” are unique factors reflecting features of the Korean construction sector.

6.3 Data analysis

In order to identify the critical design-production management factors that affect the construction performance of large-scale projects, all collected data were analysed using factor analysis, importance-priority analysis, and interrelationship analysis. Statistical analysis of this research was facilitated using the Statistical Package for the Social Sciences (SPSS). For this, the Cronbach alpha coefficient test is used to evaluate the reliability of the questionnaire by measuring the internal consistency among the factors (Norusis, 2012). The result of the test was 0.852, which is greater than the 0.5 significant level indicating that the five-point scale measurement is reliable for this research analysis.

6.3.1 Factor analysis

Factor analysis is an advanced statistical technique that is used to examine the underlying patterns or relationships of a large number of variables and to determine whether the exhaustive list of variables can be condensed or summarized into a smaller set of explainable components (Norusis, 2012). This statistical technique identifies a relatively small number of factors that can be used to represent relationships among sets of multiple interrelated variables. Although factor analysis is a conventional mathematical model typically used for condensation of large number of variables into fewer groupings, it is still being extensively employed in research for its benefits (Toor and Ogunlana, 2008). Factor analysis focuses on a data matrix produced by collecting data from numerous individual cases or respondents (Bartholomew and Knott, 1999; Kline, 2014). It is used in this research to explore the groupings that might exist among the critical design-production management (DM) factors. The research data that was obtained from the 43 critical DM factors was incorporated into SPSS 22.0 for principal component analysis, which is a reliable technique for analysing factors (Brown, 2014). The result of the analysis showed that the value of the Bartlett test of sphericity is 618.137 and the associated significance is 0.000 - see Table 6.4.

Kaiser-Meyer-Olkin measure of sampling adequacy		.742
Bartlett test of sphericity	Approx. x^2	618.137
	df	124
	Sig.	.000

Table 6.4 KMO and Bartlett test

It implies that there is no need to remove any other variables from the analysis. The value of the KMO is 0.742 and so larger than 0.5, which indicates that the sample is acceptable for factor analysis. The lower limit of eigenvalues is taken as 0.60 as suggested by the scree plot obtained during analysis (Brown, 2014).

Comp -onent	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	Varian ce (%)	Cumul -ative (%)	Total	Varian ce (%)	Cumul ative (%)	Total	Varian ce (%)	Cumul -ative (%)
01	5.782	15.571	15.571	5.782	15.571	15.571	4.776	12.862	12.862
02	3.636	9.792	26.362	3.636	9.792	26.362	3.524	9.490	22.351
03	2.218	5.973	31.335	2.218	5.973	31.335	3.165	8.523	30.875
04	1.863	5.017	36.352	1.863	5.017	36.352	2.243	6.040	36.915
05	1.748	4.707	41.059	1.748	4.707	41.059	1.732	4.664	41.579
06	1.606	4.325	45.384	1.606	4.325	45.384	1.413	3.805	45.384
07	.982	2.644	48.029	-	-	-	-	-	-
08	.960	2.585	50.614	-	-	-	-	-	-
09	.937	2.523	53.137	-	-	-	-	-	-
10	.892	2.402	55.539	-	-	-	-	-	-
11	.854	2.300	57.839	-	-	-	-	-	-
12	.831	2.238	60.077	-	-	-	-	-	-

13	.811	2.184	62.261	-	-	-	-	-	-
14	.803	2.162	64.423	-	-	-	-	-	-
15	.788	2.122	66.545	-	-	-	-	-	-
16	.767	2.065	68.611	-	-	-	-	-	-
17	.767	2.065	70.676	-	-	-	-	-	-
18	.739	1.990	72.667	-	-	-	-	-	-
19	.688	1.853	74.519	-	-	-	-	-	-
20	.661	1.780	76.299	-	-	-	-	-	-
21	.647	1.742	78.042	-	-	-	-	-	-
22	.625	1.683	79.725	-	-	-	-	-	-
23	.576	1.551	81.276	-	-	-	-	-	-
24	.573	1.543	82.819	-	-	-	-	-	-
25	.551	1.484	84.303	-	-	-	-	-	-
26	.532	1.433	85.735	-	-	-	-	-	-
27	.506	1.363	87.098	-	-	-	-	-	-
28	.490	1.320	88.418	-	-	-	-	-	-
29	.490	1.320	89.737	-	-	-	-	-	-
30	.461	1.241	90.979	-	-	-	-	-	-
31	.433	1.166	92.145	-	-	-	-	-	-
32	.387	1.042	93.187	-	-	-	-	-	-
33	.375	1.010	94.197	-	-	-	-	-	-
34	.336	.905	95.102	-	-	-	-	-	-
35	.305	.821	95.923	-	-	-	-	-	-
36	.251	.676	96.599	-	-	-	-	-	-
37	.238	.641	97.240	-	-	-	-	-	-
38	.221	.595	97.835	-	-	-	-	-	-
39	.196	.528	98.363	-	-	-	-	-	-
40	.172	.463	98.826	-	-	-	-	-	-
41	.160	.431	99.257	-	-	-	-	-	-
42	.140	.377	99.634	-	-	-	-	-	-
43	.136	.366	100.00	-	-	-	-	-	-

*Extraction method: Principal component analysis.

Table 6.5 Total rotated factor variance explained for critical factors

The principal component analysis generates six factor clusters with eigenvalues greater than 1.0, explaining 45.384% of the variance as shown in Table 6.5. The remaining factors account for 54.616% of the variance.

	Critical DM factors	Component (Factor Cluster)					
		1	2	3	4	5	6
Information management							
F02	Review of the design level compared to budget	0.833	-	-	-	-	-
F01	Project documents (cost statement, B.O.Q, drawing, specification) review	0.815	-	-	-	-	-
F03	Terms and conditions review	0.770	-	-	-	-	-
F09	Establishment the project management information system (PMIS)	0.749	-	-	-	-	-
F05	Documents management by the application of Fast-Track (drawing distribution/instruction)	0.731	-	-	-	-	-
F07	Review of site conditions (site topography/ground facilities)	0.705	-	-	-	-	-
F12	Project document control plan	0.685	-	-	-	-	-
F06	Structural grid planning review (over design, omission)	0.662	-	-	-	-	-
F13	Simulation for interior finishing/schedule	0.630	-	-	-	-	-
F11	Facility management support system (FMS)	0.614	-	-	-	-	-
F78	Similar projects case study (design, construction method and cost, duration, advanced technologies)	0.608	-	-	-	-	-
Design coordination							
F18	Pre-tender meeting with bidding and construction team	-	0.796	-	-	-	-
F22	Integrated design management team on-site	-	0.774	-	-	-	-
F19	Off-site construction manual and guideline	-	0.742	-	-	-	-
F26	Establishment of design integrity checklist on site	-	0.715	-	-	-	-
F20	Suggestion of material change	-	0.676	-	-	-	-

	(constructability, low price, local production)						
F29	Discussion with interior design team for detailed interior design	-	0.635	-	-	-	-
F27	Approval working drawing and sample product	-	0.623	-	-	-	-
International JVDT							
F41	Management of design interface between international design and engineering firms	-	-	0.881	-	-	-
F35	Establishment of consortium and joint venture team managing plan	-	-	0.826	-	-	-
F38	Standardization of different types of drawings and documents	-	-	0.793	-	-	-
F42	Interface management between domestic building code and international code	-	-	0.750	-	-	-
F36	Regular detailed design meetings with subcontractors and suppliers	-	-	0.738	-	-	-
F34	Arrangement of pre-meeting with international trader and specialist	-	-	0.694	-	-	-
F37	Delivery control plan for international supply chain	-	-	0.669	-	-	-
F39	Establishment of long lead/distance item management plan	-	-	0.627	-	-	-
F83	Organization of dispute resolution board (DRB)	-	-	0.613	-	-	-
Support production stage							
F56	Establishment of project implementation plan (PIP)	-	-	-	0.882	-	-
F46	Establishment of project out sourcing plan	-	-	-	0.876	-	-
F45	BIM simulation for constructability	-	-	-	0.752	-	-
F54	Making criteria for pre-assembly and modularization process on site	-	-	-	0.737	-	-
F48	Supporting the making of interior mock-up test	-	-	-	0.683	-	-
F82	Setting of the responsibility assignment matrix (RAM)	-	-	-	0.624	-	-

Large-scale project							
F66	Proposal of value engineering	-	-	-	-	0.775	-
F68	Resource allocation analysis (labour/material/equipment)	-	-	-	-	0.766	-
F72	Review of energy supply grid	-	-	-	-	0.743	-
F74	Simulation of life-cycle cost (maintenance cost)	-	-	-	-	0.682	-
F70	Establishment of site utilization plan (access, stock yard, work shop, site office)	-	-	-	-	0.649	-
F85	Review of impact on other surrounding buildings (view, insolation, privacy, vibration, dust, smell)	-	-	-	-	0.614	-
Korean feature							
F90	Work cooperation with project supervisors and authorities	-	-	-	-	-	0.742
F92	Support for environmental building certification (LEED/BREEAM)	-	-	-	-	-	0.713
F91	Prior discussion on requirement of major tenants and buyers	-	-	-	-	-	0.680
F89	Discussion with property selling department (concept of interior design, computer graphics, interior finishing simulation)	-	-	-	-	-	0.659

*Extraction method: Principal component analysis; Rotation method: Varimax with Kaiser normalization.

*Rotation converged in seven iterations.

Table 6.6 Component matrix after varimax rotation

All DM factors belong to one of the six factor clusters generated by the factor analysis, with the loading on each factor exceeding 0.60. The factor clusters, based on a varimax rotation (See Table 6.6), are:

Factor cluster 1: Information management

Factor cluster 2: Design coordination

Factor cluster 3: International joint venture design team

Factor cluster 4: Support production stage

Factor cluster 5: Large-scale project

Factor cluster 6: Korean feature

6.3.2 Result of factor analysis (Six factor clusters)

6.3.2.1 Factor cluster 1- Information management

According to factor analysis, 11 design-production management (DM) factors were included in the factor cluster 1 - Information management. Most of the factors were related to project data or information, thus this factor cluster is labelled as Information management. Traditionally, the initial project information such as drawings, bill of quantity (BOQ), or specification is quite important in estimating the project cost and duration and to prepare suitable construction execution (Braglia and Frosolini, 2014). Because the project information can have a huge impact on the fundamental project condition and execution, all project information should be properly analysed and reviewed on time.

Six out of the 11 cluster 1 factors [F01, F02, F03, F06, F07, F78] were related to the initial stage information. “Project documents (cost statement, BOQ, drawing, specification) review [F01]”, “Review of the design level compared to budget [F02]”, and “Terms and conditions review [F03]” are very fundamental factors affecting the project condition or phases. Another three factors; “Structural grid planning review (over design, omission) [F06]”, “Review of site conditions (site topography/ground facilities) [F07]”, and “Similar projects case study (design, construction method and cost, duration, advanced technologies) [F78]”, affect project execution particularly at an early stage. With a detailed review of these factors completed before construction, the contractor can predict unexpected design-related risks and prepare suitable solutions in advance. In contemporary construction projects, the importance of information management has increased. Particularly in large-scale and international projects, integrated information and data process management is one of the most critical factors for successful design-production management (Pen˜a-Mora *et al.*, 1999; Li *et al.*, 2015). Appropriate information management enables a coherent flow of information between project team members, which significantly helps them to keep people on task and up-to-date (Raymond and Bergeron, 2008). In factor cluster-1, four factors [F05, F09, F11, F12] are related to systematic information management, and another factor (Simulation for interior finishing/schedule [F13]) has indirect relevance to information management. The lack of sharing or distribution of information between project team members generally determines the additional expenditures for reworking and re-design. It is due to either inconsistent information, or information that is not received in time or from the right individual or team (Braglia and Frosolini, 2014). Well-managed information allows a number of productive outcomes, such as the reduction of errors and reworks, by assuring that the current drawings or documents are generated by sufficient integration of information. Thus, information management is extracted as one of the factor clusters necessary for efficient project execution.

6.3.2.2 Factor cluster 2 - Design coordination

Factor cluster 2, which is about design coordination, consists of seven critical design-production management (DM) factors. In this research, it is hypothesized that design-production management is closely related with all production activities on site. Advanced and integrated design management has become a critical factor for the contractor. As the project scale and complexity increases, larger design elements and design technologies are applied.

From the contractor's perspective, design management can usually be divided into two stages; the pre-production and the production stage. In the pre-production stage, design management focuses on reducing the project risks connected with the design elements. Design management aims for an effective construction process by preparing for on time design information delivery, or managing long-lead material deliveries. In the pre-production stages, design documents account for a large number of the total project documents (Emmitt, 2010; Walker, 2015). Therefore, effective design coordination between different disciplines can reduce design-related risks caused by incomplete design. For example, in this cluster, two factors [F18, F26] are applied only at the pre-production stage. The effectiveness of the application of the F18 (Pre-tender meeting with bidding and construction team) should be shown during the pre-production stage before estimating suitable bid amounts and preparing the appropriate construction execution plan. However, the effectiveness of the "Establishment of design integrity checklist on site [F26]" factor has an influence throughout production.

In the production stage, the contractor's design coordination focuses on how different production activities can be carried out efficiently within a limited project period and resources. The contractor's experiences from the coordination experience of incomplete designs in previous projects are useful to manage and predict unexpected design changes and design errors during the production stage, which may reduce the unnecessary rework and construction delay. In addition to this, experienced contractors can coordinate the different interfaces between off-site and in-situ product during assembly on site. In particular, because of diversification and complexity of project delivery, the contractor has more responsibilities. Thus, the contractor should manage the whole project process very carefully and effectively from design to the construction phases (Koskela, 2004; Walker, 2015). Design-production management from the contractor's perspective involves a much more practical set of relationships between the contractor and other project participants including the client, architect, design consultancies, vendors, manufacturers, and specialists (Andersen *et al.*, 2005).

Within cluster 2, four factors [F19, F22, F27, F29] are very practical and are applied during the production stage in order to increase construction performance. In particular, the "Integrated design management team on-site [F22]" factor is essential to coordinate different design-caused problems on site. In international large-scale projects, contractors often operate an on-site design management team, which coordinates all design-related issues including different design documents, foreign architects, international sub-contractors, and suppliers. In international design-based projects, when a certain design error occurs during the production stage, the contractor does not have enough time to wait for design changes from the joint venture design team (JVDT) and also the JVDT cannot afford to change the incomplete design immediately or actively. Thus, the main role of the on-site design management team is to actively solve all design-related problems through design review, the proposal of alternative solutions, organizing the process of the design change, and managing the subsequent delayed production activities. Sometimes they discuss with the issues with original international JVDT or local design partners, otherwise they find their own solutions from a contractor's perspective. F19, the "Off-site construction manual and guideline" factor indicates the changing role of design coordination in construction projects. Due to the rapid development of building materials and the increasing complex of building, numerous building products are being produced in off-site factories and assembled on site (Blismas *et al.*, 2006). Because these off-site products are produced based on different building codes and standards, interface management between off-site and in situ production is recognized as a significant role in the contractor's design coordination (Eastman and Sack, 2008),

6.3.2.3 *Factor cluster 3 - International joint venture design team*

Factor cluster 3 consists of 9 factors within the international joint venture design team. International/Multinational LSPs are expected to meet additional demands to present top architectural quality that is internationally-recognised in a regional landmark project. To create designs that fulfil those purposes, highly qualified international architects are invited to work collaboratively in a multi-disciplinary design team. In terms of management of the joint venture design teams (JVDTs) between various international architects and engineers from different disciplines, attention is drawn to the effective coordination based on the understanding that well organized JVDTs have a positive influence on production outcomes (Demirbag and Mirza, 2000).

Of the 9 international JVDT factors, 5 focus on managing factors [F34, F35, F36, F41, F83] for joint venture team members. International JVDTs are difficult to manage because of the various differences between team members such as different managerial systems, values, attitudes, and working processes. Thus, centralized managing factors, which have strong leadership, are required to reduce design risks occurring on site (Girmscheid and Brockmann, 2010). In cluster 3, some factors dealt with managing interfaces between foreign and local designers [F41] and contractors and suppliers [F34, F36]. Others are about establishing a management plan between joint venture team members [F35, F83]. In particular, the "Organization of dispute resolution board (DRB)" [F83] factor is essential in international LSPs, because they comprise multi-stakeholder problems where negotiation, goal definition, and decision-making processes are the main considerations.

The remaining four factors [F37, F38, F39, F42] are about the coordination of interfaces between international standards. Recently, international joint venture projects have become an essential part of the global construction business between developing and industrialized countries. Most international LSPs have to deal with the escalating complexity in different areas such as building codes, construction standards, and specialized building materials during production stage (Sillars and Kangari, 2004; Ozorhon *et al.*, 2010). Thus, not only the management of JVDT members, but also the coordination of interfaces between international standards should be considered as critical factors. "Standardization of different types of drawings and documents" [F38] and "Interface management between domestic building code and international code" [F42] indicate practical ways to coordinate the criteria gap between different construction industries. Distinct from the previous two factors, "Delivery control plan for international supply chain" [F37] and "Establishment of long lead/distance item management plan" [F39] are relatively production-oriented, however they are more likely to be considered as crucial managing factor in international JVDT projects.

6.3.2.4 Factor cluster 4- Support production stage

Factor cluster 4 consists of six DM factors, which apply to support to a contractor in the production stage. It involves a relatively wide range of sub-construction processes from the initial project execution plan to the practical building erection. According to the application of state-of-the-art building technologies in contemporary LSPs, production stages need more practical design management support when integrating design and production aspects (Tzortzopoulos and Cooper, 2007). Thus, the role of design management has shifted to support the production process from the design process.

Among the six factors, "Establishment of project out sourcing plan" [F46], "Establishment of project implementation plan (PIP)" [F56], and "Setting of the responsibility assignment matrix (RAM)" [F82] were considered as being applied before the start of the production stage, which deals with general aspects such as project implementation, out sourcing, and responsibility assignment. Performance at the production stage may depend on the effectiveness of managing these general aspects at the pre-production stage. Particularly, because outsourcing plans involves different levels of detailed designs and production activities, and interface management is needed amongst architects, the site engineering team, and out sourcing suppliers. According to the contractor's schedule and the site conditions, various detailed design information can be altered and revised during the production stage, thus contractors should prepare various countermeasures in advance to support the site engineering team a using practical managing plan and detailed criteria.

The other two factors, "BIM simulation for constructability" [F45] and "Making criteria for pre-assembly and modularization process on site" [F54] are more practical factors which have been developed recently according to the needs of large and complex project (Prins and Owen, 2010). Large-scale projects are inherently complex and dynamic involving multiple interconnected project activities. Successor activities often have to start without complete information or work from predecessor activities (Lee *et al.*, 2005). By applying "BIM simulation for constructability" [F45] all production processes are linked as one flow, and the whole production stage is practically monitored and controlled. In addition to this, according to BIM simulation, the changed cost and schedule, which is associated with production activities and processes, is re-simulated automatically to predict the entire project performance before the input of practical resources.

Nowadays, modular construction is gaining popularity in the AEC industry due to the increased demand for faster and simple construction processes. For the effective execution of construction activities, the contractor establishes and applies a detailed pre-assembly plan (Meiling *et al.*, 2012). Particularly in international

LSPs because the rate of modular construction has increased rapidly, the “Making criteria for pre-assembly and modularization process on site” [F54] factor is also an essential support in the production stages.

6.3.2.5 Factor cluster 5 - Large-scale project

Factor cluster 5, which deals with aspects of large-scale construction project (LSP), consists of six design-production management (DM) factors. Given that LSPs utilize enormous amounts of project resources (including capital, energy, manpower, facilities, time, and materials) and need to coordinate different project constraints (such as incomplete designs, limited site conditions, and non-favourable environments), this factor cluster 5 can be divided mainly two groups: how to use the project resources, and; how to manage the project constraints.

In terms of project resources, “Resource allocation analysis (labour/material/equipment)” [F68], “Review of energy supply grid” [F72], and “Simulation of life-cycle cost (maintenance cost)” [F74] are related the efficient utilization of project resources. The utilization of the project resources, particularly in Korean LSPs, has been poor. Compared to medium-sized projects, the average cost at the completion stage has increased by 122.4% of the original budget and the average duration has been extended by about 3.6 years (Han *et al.*, 2009). In LSPs in which large amounts and a wide range of resources are needed, the aspect of how contractors can build and maintain facilities with limited resources is crucial. Particularly because most LSPs require tremendous energy resources and advanced maintenance technologies both in production and in the maintenance stage, “Review of energy supply grid” [F72] and “Simulation of life-cycle cost (maintenance cost)” [F74] have become more critical DM factors in LSPs.

Another three factors [F66, F70, F85] are related with the practical project condition or site constraints. Unfortunately, due to many reasons, high performance or success of projects is not often found in international LSPs, thus under fixed and limited project environments contractors have to have quality assurance or systematic managing tools in order to overcome project constraints. With the same context as above, the "Proposal of value engineering" [F66] factor is recognized particularly by Korean contactors as the last opportunity to change incomplete designs and construction methods in a way that could reduce project costs and duration (Cheah and Ting, 2005). Using value engineering, contractors can try to improve project constraints such as fixed original designs or unverified construction methods if contractors have alternatives that are more effective. In addition to this, "Establishment of site utilization plan (access, stock yard, work shop, site office)" [F70] and "Review of impact on other surrounding buildings (view, insolation, privacy, vibration, dust, smell)" [F85] factors are also critical when managing the project's physical environment, because unforeseen site conditions, confined sites, and problems with neighbours can serious influence the entire project's cost and duration (Al-Momani, 2000; Assaf and Al-Hejji, 2006).

6.3.2.6 *Factor cluster 6 - Korean features*

Factor cluster 6 which represents features of the Korean construction industry, consists of 4 design-production management (DM) factors [F89, F90, F91, F92]. Compared to other factor clusters, the number of factors is low. However, these 4 factors cannot be overlooked or ignored by the contractor, because they are all derived from Korean regulations, existing market trends, the political situation, and the social structure. Depending on the compliance with government guidelines or policy, clients or contractors can receive incentives such as tax cuts or raised floor area ratios from the government (Acharya and Lee, 2006).

Due to increasing environmental crises, the Korean government has enforced sustainable construction methods. Most large-scale projects must be developed based on the government's sustainable guidelines. To receive incentives, clients and contractors aim to achieve environmental certification such as the Green Building Certification Criteria (GBCC) (Whang and Kim, 2014). In addition to this, to increase the commercial value of building, they also aim to achieve international environmental building certification such as LEED (Leadership in Energy and Environmental Design) or BREEAM (Building Research Establishment Environmental Assessment Methodology). However, it is quite complicated and difficult to maintain a sustainable level throughout the stages of a project to satisfy the standards of GBCC, LEED, or BREEAM. Without the appropriate management, it may have a serious impact on project performance as well as the life-cycle cost. Thus, the "Support for environmental building certification (LEED/BREEAM)" [F92] factor is critical for the contractor's design management team.

Another feature of the Korean construction industry is that there are very favourable policies for contractors. In order to foster a strong construction industry over a short period, the government has provided various contractor-friendly policies. For example, contractors can sell or lease the facility before the start of the project on behalf of a client. It has been a great advantage to the stability of project cash flow. Thus, to increase pre-sales or the lease ratio "Discussion with property selling department (concept of interior design, computer graphics, and interior finishing simulation)" [F89] and "Prior discussion on requirement of major tenants and buyers" [F91] factors are essential for contractors. During production stages, according to the requests of major buyers, some parts of the design can be changed (Bea *et al.*, 2006). In this case, to minimize the project delay for changed building permission from government, contractors have to maintain a close and cooperative relationship with the project supervisors and the authorities [F90].

6.3.3 Importance-priority analysis

Importance-performance analysis (IPA) is a graphical tool to develop effective management strategy based on the importance and performance of each attribute. Martilla and James introduced IPA matrix as a management strategy in 1977 (Martilla and James, 1977). This tool was originally used as a mean for the assessment standard in order to measure people's satisfaction with regard to a competency, service, and product (Matzler *et al.*, 2003; Cvelbar and Dwyer, 2013). In this regard, many researchers have studied IPA and its relevant interpretation. As a result, the IPA matrix has proven to be a reliable assessment tool that is not only a convenient criterion in order to interpret outcomes, but it also can be applied to establish management strategies (Kitcharoen, 2004; Wong *et al.*, 2011). In IPA matrix, data is normally collected from questionnaire surveys to construct a two-dimensional matrix in which importance is indicated by the x-axis and performance by the y-axis.

However, in this research, the y-axis has been replaced with priority instead of performance. This is because the performance of overall and individual factors will be evaluated and analysed later in the system dynamics simulation section, this analysis stage just focuses on recognizing the importance and priority aspects between factors. By the analysis of the factor priority, contractors can recognize which factors are actually preferred by different construction experts regardless of the importance. Due to distinct project conditions or constraints, sometimes a factor, which is convenient and low-cost to apply, is preferred, even if it has relatively low importance value. Thus, the comparison between the importance value and the priority of the design-production management factor is essential.

6.3.3.1 *Importance-priority matrix (IPM)*

An importance-priority matrix (IPM) revised from the IPA can evaluate the features of each component and analyse the results without using complex statistical methods. An attractive feature of IPM is that the results are graphically displayed on an easily interpreted, two-dimensional grid. In accordance with the Likert-scales based on questionnaire, the priority of factors is plotted on the horizontal axis and the importance of factors is plotted on the vertical axis. In IPM, there are two reference lines; importance baseline, priority baseline, to divide areas of quadrants. All design-production management factors are classified into four categories on quadrants. It is easy to determine the positions of each factor once it is evaluated, and then to establish the resource input planning in accordance with factor positions (Kim and Kim, 2013). In this research, quadrants are divided by average values (importance of x-axis and priority of y-axis) of questionnaires. A definition and explanation of each quadrant is indicated in Figure 6.1.

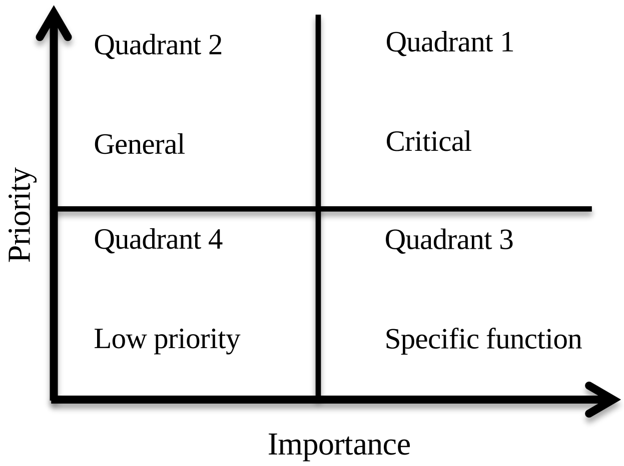

Figure 6.1 IPM and attributes at each quadrant

- ***Quadrant 1***: In this data analysis approach, known as the data-centred quadrant approach, design-production management factors that belong to the quadrant 1 (Critical) refer to the aspects or attributes that have both highly importance and priority. Attributes are recognized as quadrant-1 factors are essential for efficient design management. Factors which have both a high importance and priority value are not only advantageous to give immediate and direct influences on the entire project performance, but also as having high compatibility with other critical DM factors, which can make design management more balanced and complementary during production stage. Thus, these factors are worth applying preferentially in the pre-production stage.
- ***Quadrant 2***: Factors that belong to quadrant-2 have a low important value, but Korean construction experts prefer them because such factors have general and cooperative features. They can also interact with other factors

to improve the efficiency or performance through interactions. These kinds of factors sometimes can be abused by contractors who are not convinced of whether the factor has the ability to solve the urgent problems during production stage. Thus, contractors tend to apply these factors in the relatively early stages before the occurrence of specific problems. However, because the low importance value of these factors means less practical efficiency on performance, the combined application with other factors or timely application should be considered instead of the sole application in order to increase practical efficiency.

- ***Quadrant 3***: Attributes are recognized as having a high importance value, but a relatively low level of priority. It can be shown that even if the quadrant-3 factors are effective in managing and resolving the specifically targeted problems, contractors need to put in excessive efforts to operate and control it. The effectiveness of these factors can be direct and immediate, but are not preferred by construction experts in the early stages. When they establish the construction implementation plan in the pre-production stage, they are not facing any urgent or serious design-related problems, which need to be resolved immediately.
- ***Quadrant 4***: These factors are placed in the less important and preferred area. In other words, they are recognized as not only difficult to help achieve immediate solutions when design-related problems occur, but they are also not dominant design-production management factors. Except for in specific circumstances, contractors do not need to be overly concerned about these factors.

6.3.3.2 *Analysis result of IPM*

In LSPs designed by international joint venture design teams, the differences of design-production management (DM) factors between the importance and priority values are presented in Table 6.7. For reliable analysis, a paired sample T-test was conducted and the significance level (*p*-value) was verified using SPSS 22.0. The result of the analysis showed that the *p*-value of all DM factors was in the $p < 0.05$ level, thus the importance and priority values can be recognized as having a significance level (Kent, 2001; Miles et al., 2013).

The average importance and priority values were 3.24 and 3.23 respectively, so almost the same. This shows that the high importance and priority values of DM factors are perceived and utilized evenly without bias. In other words, in accordance with practical project conditions or development purposes, both importance and priority factors, which have immediate or stable effectiveness, can be applied evenly. The top five factors which have largest gap between importance and priority values were “Approval working drawing and sample product [F27]”, “Setting of the responsibility assignment matrix (RAM) [F82]”, “Resource allocation analysis (labour/material/equipment) [F68]”, “Pre-tender meeting with bidding and construction team [F18]”, and “Arrangement of pre-meeting with international trader and specialist [F34]” in this order as shown in Table 6.7.

No.	Design-production management factors	Impor -tance	Priority	Gap	T-value	P-value
F02	Review of the design level compared to budget	3.984	3.352	0.632	5.771	.000
F01	Project documents (cost statement, B.O.Q, drawing, specification) review	3.955	3.870	0.085	3.018	.001
F41	Management of design interface between international design and engineering fir ms	3.888	3.479	0.409	2.624	.000
F22	Integrated design management team on-site	3.862	4.023	0.161	6.440	.015
F09	Establishment the project management information system (PMIS)	3.739	3.781	0.042	3.647	.003
F18	Pre-tender meeting with bidding and construction team	3.737	2.964	0.773	7.254	.000
F35	Establishment of consortium and joint venture team managing plan	3.720	3.136	0.584	3.558	.031
F37	Delivery control plan for international supply chain	3.638	3.128	0.510	3.695	.001
F46	Establishment of project out sourcing plan	3.626	3.712	0.086	4.015	.006
F05	Documents management by the application of Fast-Track (drawing distribution/i nstruction)	3.573	3.086	0.487	3.665	.000
F38	Standardization of different types of drawings and documents	3.545	3.518	0.027	5.969	.000
F42	Interface management between domestic building code and international code	3.531	3.271	0.260	3.847	.024
F45	BIM simulation for constructability	3.508	3.915	0.407	2.153	.007
F36	Regular detailed design meetings with subcontractors and suppliers	3.494	2.779	0.715	2.622	.000
F34	Arrangement of pre-meeting with international trader and specialist	3.470	2.724	0.746	6.529	.000
F54	Making criteria for pre-assembly and modularization process on site	3.447	3.651	0.204	4.401	.001
F66	Proposal of value engineering	3.226	3.536	0.310	3.165	.000
F03	Terms and conditions review	3.208	3.365	0.157	5.754	.002
F56	Establishment of project implementation plan (PIP)	3.207	2.967	0.240	2.624	.032
F19	Off-site construction manual and guideline	3.192	3.768	0.576	3.014	.007
F70	Establishment of site utilization plan (access, stock yard, work shop, site office)	3.174	3.286	0.112	5.583	.002

F12	Project document control plan	3.170	3.075	0.095	2.294	.000
F07	Review of site conditions (site topography/ground facilities)	3.145	3.018	0.127	2.640	.000
F92	Support for environmental building certification (LEED/BREEAM)	3.109	3.156	0.047	5.185	.010
F68	Resource allocation analysis (labour/material/equipment)	3.082	3.883	0.801	1.652	.000
F74	Simulation of life-cycle cost (maintenance cost)	3.076	2.849	0.227	3.957	.005
F39	Establishment of long lead/distance item management plan	3.044	2.721	0.323	2.746	.001
F90	Work cooperation with project supervisors and authorities	3.018	2.794	0.224	4.253	.014
F26	Establishment of design integrity checklist on site	3.013	3.441	0.428	4.446	.000
F06	Structural grid planning review (over design, omission)	3.007	2.559	0.448	3.620	.022
F78	Similar projects case study (design, construction method and cost, duration, adva nced technologies)	2.993	2.952	0.041	1.157	.002
F72	Review of energy supply grid	2.961	2.873	0.088	6.874	.000
F85	Review of impact on other surrounding buildings (view, insolation, privacy, vibra tion, dust, smell)	2.959	2.829	0.130	4.018	.001
F83	Organization of dispute resolution board (DRB)	2.917	3.066	0.149	3.527	.005
F20	Suggestion of material change (constructability, low price, local production)	2.904	3.568	0.664	2.625	.029
F82	Setting of the responsibility assignment matrix (RAM)	2.890	3.783	0.893	2.159	.010
F91	Prior discussion on requirement of major tenants and buyers	2.867	3.243	0.376	2.322	.008
F29	Discussion with interior design team for detailed interior design	2.830	2.941	0.111	4.995	.000
F27	Approval working drawing and sample product	2.812	3.787	0.975	3.657	.000
F13	Simulation for interior finishing/schedule	2.801	2.659	0.142	2.618	.019
F89	Discussion with property selling department (concept of interior design, compute r graphics, interior finishing simulation)	2.788	2.823	0.035	2.015	.001
F11	Facility management support system (FMS)	2.782	3.320	0.538	2.664	.000
F48	Supporting the making of interior mock-up test	2.759	2.598	0.161	2.848	.000

Table 6.7 Results of paired sample T-test

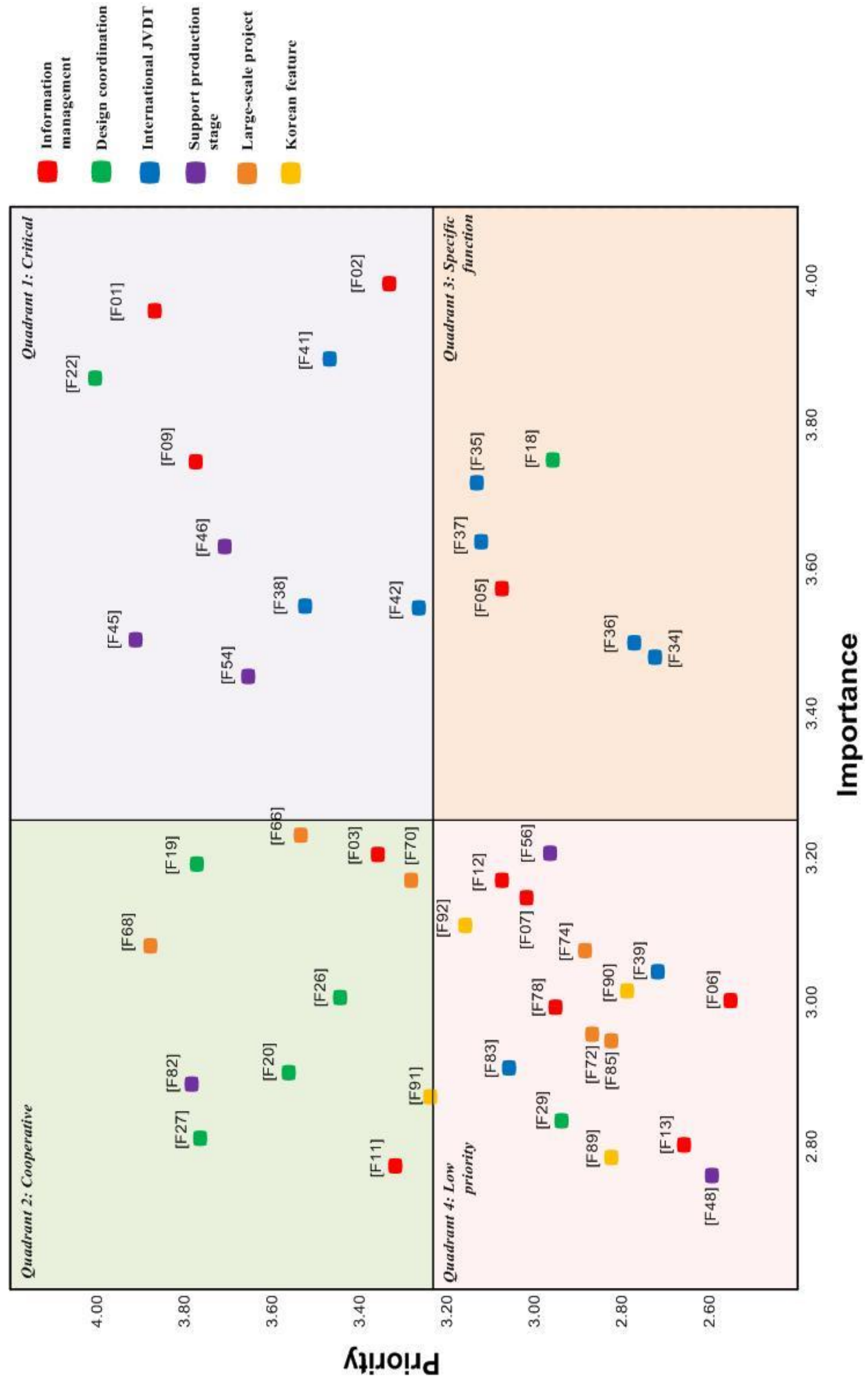

Figure 6.2 Importance-Priority Matrix

As a result of the analysis of importance-priority matrix (IPM), Figure 6.2 presents the proposed importance-priority grid. The four quadrants are based on the importance weights and priority ratings. Using the factor analysis, which was conducted in previous chapters, all 43 critical design-production management factors were categorised into six factor clusters and each cluster was presented respectively according to their own colours on IPM. This means that factors that have same colours are relevant to each other as well as having similar function. Features of the critical factors, which belong to one of the four quadrants, are depicted below.

Quadrant 1 (Critical):

This quadrant comprises three main factor clusters; Information management (red), International JVDT (blue), and Support production stage (purple). All factors of this quadrant received both high importance and priority rates from experts. This means that they can be applied to any condition of LSPs such as large-scale or multi-functional. In quadrant-1, the Support production stage (purple) factors have relatively high priority rate compared to blue factors (i.e. International JVDT) as seen in Figure 6.3. Purple factors; "Establishment of project out sourcing plan [F46]", "BIM simulation for constructability [F45]", and "Making criteria for pre-assembly and modularization process on site [F54]" are all closely related with the production stage supporting construction activities. Blue factors; "Management of design interface between international design and engineering firms [F41]", "Standardization of different types of drawings and documents [F38]", and "Interface management between domestic building code and international code [F42]" are related more closely with design aspects. Even if both side factors have similar importance rates, experts give the Support production stage (purple) factors a higher preference. From the contractor's perspective, which is a focus of the main hypotheses of this research, it is reasonable to imply that construction experts prefer more production-friendly factors than design-related factors.

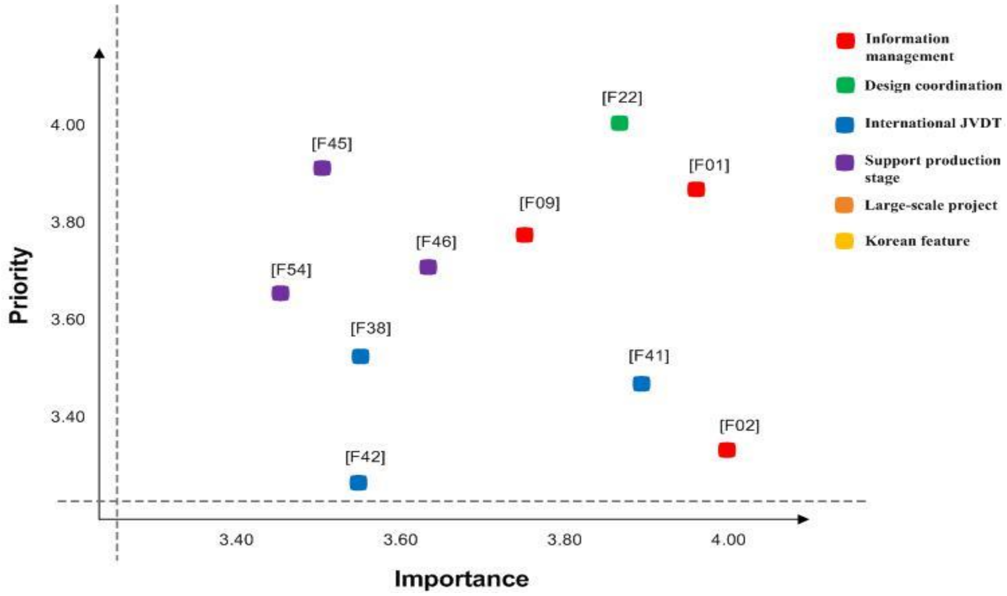

Figure 6.3 Quadrant 1 (Critical)

All top five importance factors; "Review of the design level compared to budget [F02]", "Project documents review [F01]", "Management of design interface between international design and engineering firms [F41]", "Integrated design management team on-site [F22]", and "Establishment the project management information system (PMIS) [F09]" are placed higher than the average line of priority (3.20) - see Figure 6.2. It means that top five important factors are also compatible enough to be applied at any project condition and with any other critical design-production management (DM) factors. In particular, [F22] and [F01] are ranked as both top five important and prior factors. In contemporary large-scale projects, exhaustive document review [F01] and placement of on-site design management team [F22] are aware of most critical and preferable DM strategies.

Quadrant 2 (Cooperative):

Quadrant 2 is composed of two main factor clusters; Design coordination (green) and Large-scale project (brown). Design coordination factors account for 36% of this quadrant. More than half of the total Design coordination factors (four out of seven) are located in this quadrant as seen in Figure 6.4. More interestingly, according to Figure 6.2, 71% (five out of seven) Design coordination factors (green) are located under the average line of importance, whereas the same rates of green factors are placed over the average line of priority. This strongly indicates that even if most of the Design coordination factors are perceived as relatively less important by Korean construction experts, they are preferentially applied into the real projects. This is due to their general and cooperative characteristics by which green factors have various interrelationships with other critical design-production management factors.

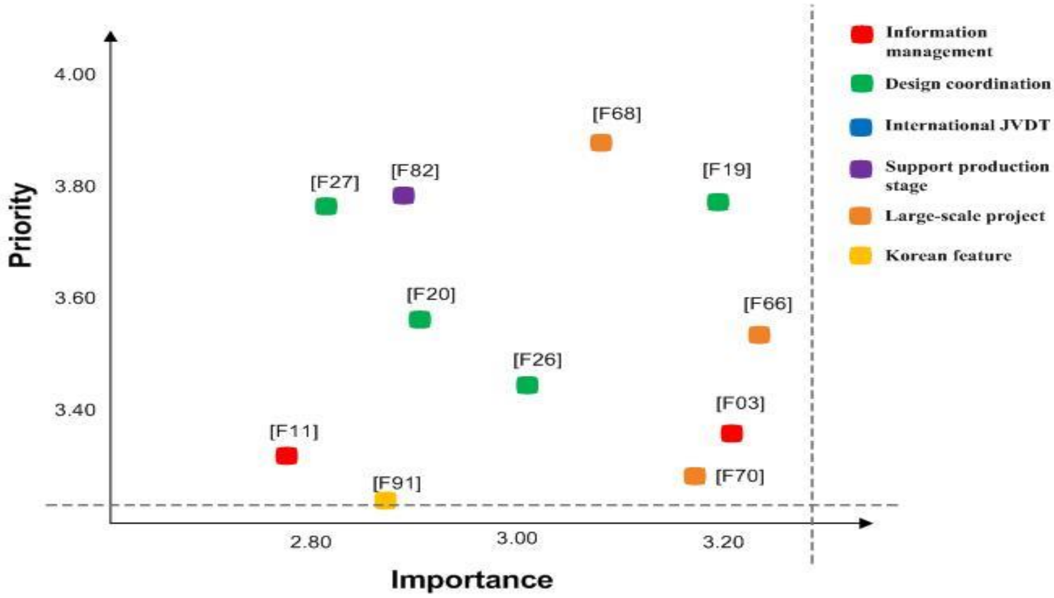

Figure 6.4 Quadrant 2 (Cooperative)

Indeed, “Approval working drawing and sample product [F27]” and “Off-site construction manual and guideline [F19]” factors cooperate with specific production activities, while “Suggestion of material change [F20]” and “Establishment of design integrity checklist on site [F26]” factors are more related to design aspects during the production stage.

Except for Design cooperation factors, two high priority factors; “Resource allocation analysis (labour/material/equipment) [F68]” and “Setting of the responsibility assignment matrix (RAM) [F82]” (ranked as the top five priority factors), are located in this quadrant. Interestingly, two high priority factors which are under the average line of importance value means that not all preferred factors are always highly important. According to the project situation or condition, less important factors can be applied preferentially, if they have compatible advantages matching the circumstances. These two high priority factors are very general and interact well with all project participants from designers to subcontractors or suppliers.

Quadrant 3 (Specific function):

This quadrant is composed of only six factors out of a total of 43 critical DM factors. Compared to the other quadrants, which have 10 to 16 factors respectively, this quadrant has a small number of factors (see Figure 6.5). Because these factors show a relatively low priority rate compared to their high importance rate, It is recognized that, in spite of the significant and direct effectiveness of these factors, their actual application is limited due to their fragmentary or incompatible features. Most factors have quite explicit functions to resolve design-related production problems, thus if there are no urgent or specific problems in during the production stage, contractors will probably choose other more balanced DM factors over general and specific features. “Pre-tender meeting with bidding and construction team [F18]” and “Documents management by the application of Fast-Track [F05]” factors can have a direct and immediate influence on specific production activities. However, their scope of influence are somewhat isolated or fragmentary limiting them to the bidding stage or to fast-track projects.

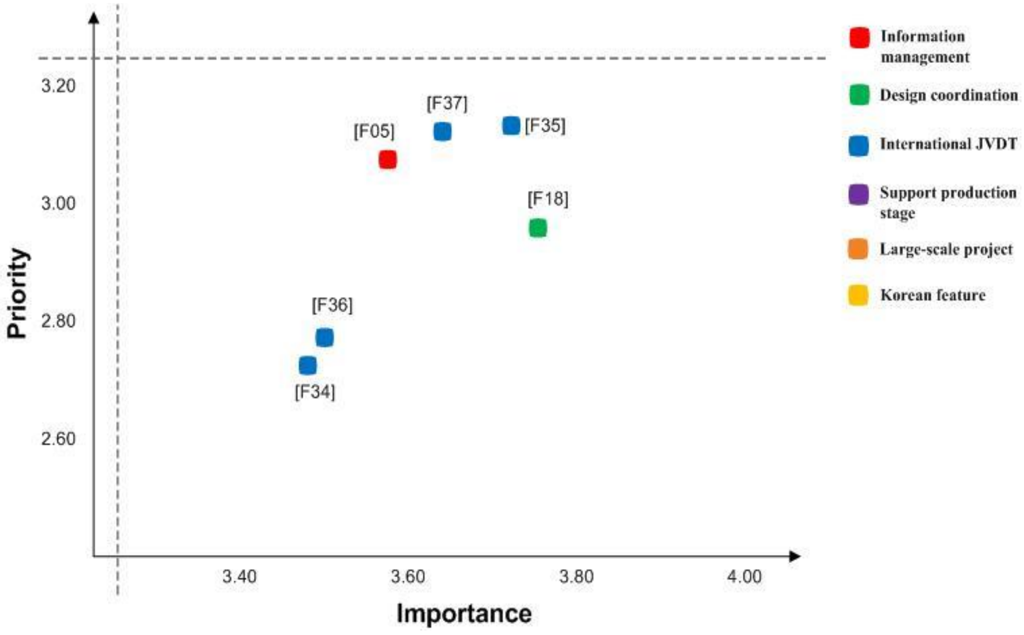

Figure 6.5 The Quadrant 3 (Specific function)

Factors of international JVDT (blue) account for the two-thirds (66%) of quadrant 3 factors. According to Figure 6.2, blue factors show both a relatively high importance rate and low priority rate. Seven out of the nine factors are ranked over the average line of importance, but only three are ranked over the average line of priority. International JVDT factors deal with limited issues (multinational aspect), thus preference of these factors is relatively low. Only when a project suffers from multinational issues, which are difficult to manage using normal management methods, do International JVDT factors tend to be applied. However, because most factors deal with design-related issues such as design interfaces or criteria and design team members from the contractor’s perspective, these International JVDT (blue) factors can be recognized as crucial.

Quadrant 4 (Low priority):

Quadrant 4 is composed of low importance and priority factors. These factors are analysed as having a somewhat specific but limited features to respond problematic project situations, thus their preference is not high and the influences on project performance is limited. Remarkably, most Korean feature (yellow) factors and half of Large-scale project (brown) factors are placed in this quadrant as seen in Figure 6.6. This means that, in spite of the research focus by which research survey was conducted for international LSPs in Korea, the regional (Korean) factors are recognized as less important and less preferable by construction experts.

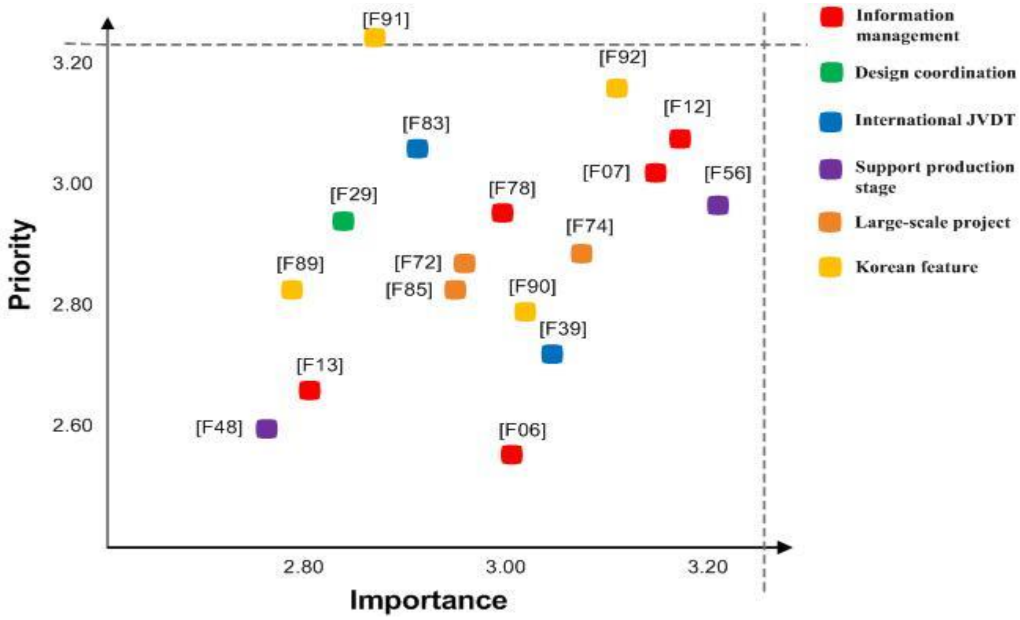

Figure 6.6 The Quadrant 4 (Low priority)

Moreover, even if they do not belong to Korean feature factors, the three lowest-importance factors; “Supporting the making of interior mock-up test [F48]”, “Simulation for interior finishing/schedule [F13]”, and “Discussion with interior design team for detailed interior design [F29]”, are somewhat related to Korean features. In Korea, because Korean contractors can sell the whole or part of building before starting construction, even interior-related factors are recognized as being within the contractor’s management role.

Overall, quadrant 4 factors have various interrelationships with other high importance and priority factors throughout the production stage, even if they are not high importance or priority factors by themselves. For example, “Project document control plan [F12]”, “Establishment of project implementation plan (PIP) [F56]”, and “Work cooperation with project supervisors and authorities [F90]” affect the overall production stages within a wide context.

6.3.4 Analysis of factor interrelationship

In this research, interrelationships between critical design-production management (DM) factors also have significant meaning as much as their importance or priority value. Due to the increasing complexity and a growing number of multinational projects, all project components have to be interconnected and given mutual influence over each other during production stages. Fragmentary application of only a couple of critical DM factors is meaningless, even if they have very highly importance and priority value. All critical DM factors have somewhat advantageous and disadvantageous impacts simultaneously on performance of other factors and entire project.

Thus, this section focuses on the analysis of all interrelationships between critical DM factors. In the previous section (6.3.3 Importance-priority analysis) by importance-priority matrix (IPM), each DM factor was analysed as to what factors have effective interactions with other factors and how much they have importance and priority value. Based on the result of IPM, the matrix of interrelationships between critical DM factors (Figure 6.7) is established according to the frequency of questionnaire response from Korean construction experts.

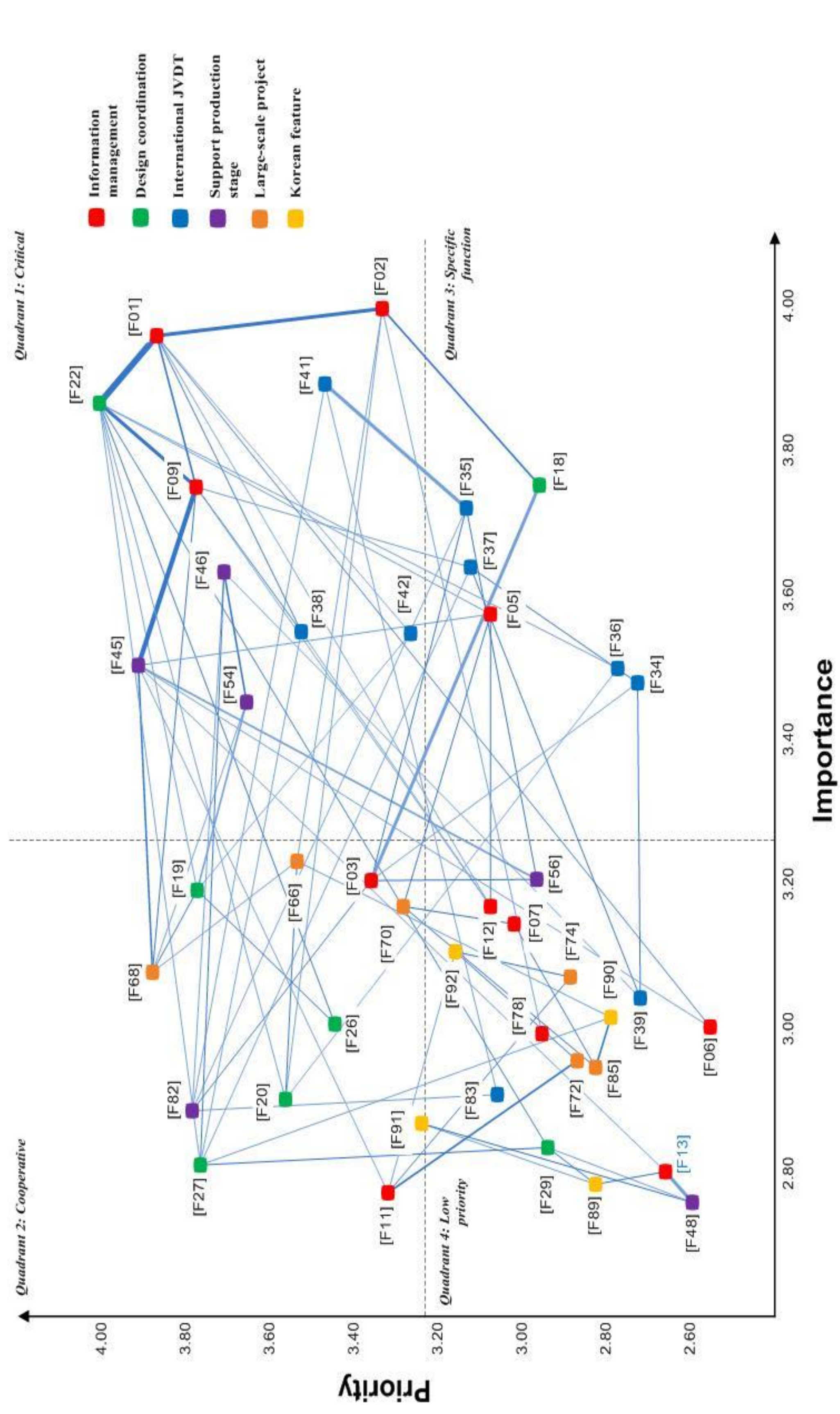

Figure 6.7 Interrelationships matrix between DMFs

In Figure 6.7, interrelationships of all the design-production management factors that are placed on the importance-priority matrix (IPM), based on importance and priority weight, are presented. The degree of the interrelationship is evaluated by questionnaire survey. When questionnaire surveys were distributed to evaluate importance and priority, it was requested that Korean experts chose other interrelated design-production management (DM) factors for each individual factor. In the surveys, multiple choices was possible: however, only factors that receive over 20% of the total choice rate, including multiple choices, were recognized as having meaningful interrelationships and so presented as blue lines on the matrix. Strong and closed relationships are expressed as a bold and thick line on the matrix according to the questionnaire responses. Each DM factor has 3.65 average interrelationships with other factors. Overall, high priority factors indicate diverse relationships with other critical DM factors, while high importance factors have comparatively stronger relationships.

Quadrant 1 (Critical):

No	Design management factor	Factor cluster
F01	Project documents (cost statement, B.O.Q, drawing, specification) review	Information management
F02	Review of the design level compared to budget	Information management
F41	Management of design interface between international firms	International JVDT
F22	Integrated design management team on-site	Design coordination
F09	Project management information system (PMIS)	Information management
F46	Establishment of project out sourcing plan	Support production stage
F38	Standardization of different drawings and documents	International JVDT
F42	Interface management between international building codes	International JVDT
F45	BIM simulation for constructability	Support production stage

F54	Making criteria for modularization	Support production stage

Table 6.8 Quadrant 1 (Critical)

The quadrant -1 factors are interconnected in all directions. Normally, they have strong interrelationships with the same quadrant factors and diverse relationships with other quadrant factors at the same time. Particularly, [F01], [F09], [F22], and [F45] indicate various interrelationships, which all are linked to 7 or 8 other DM factors, respectively. Compared with the average interrelation (3.65), it is almost twice the number. In addition to this, there are strong relationships between [F01] and [F22], and [F09] and [F45], which have 73.43% and 68.07% of selection frequency, respectively from questionnaire surveys. In other words, given the multiple choices, about 73% and 68% of Korean construction experts responded in survey that there are meaningful interrelationships between them. For example, when investigating the relationship between [F01] and [F22], which have the strongest and closest relationship, it can be seen that to achieve optimal project performance in the production stage, all project documents [F01] should be reviewed and managed by on-site design management teams [F22] (Tzortzopoulos and Cooper, 2007).

Quadrant 2 (Cooperative):

No	Design management factor	Factor cluster
F66	Proposal of value engineering	Large-scale project
F03	Terms and conditions review	Information management
F19	Off-site construction manual and guideline	Design coordination

F70	Establishment of site utilization plan	Large-scale project
F68	Resource allocation analysis	Large-scale project
F26	Establishment of design integrity checklist on site	Design coordination
F20	Suggestion of material change	Design coordination
F82	Setting of the responsibility assignment matrix	Support production stage
F91	Prior discussion on requirement of major buyers	Korean feature
F27	Approval working drawing and sample product	Design coordination
F11	Facility management support system	Information management

Table 6.9 Quadrant 2 (Cooperative)

Even if the importance weights of factors in quadrant 2 are low compared to quadrants 1 or 3, they have diverse interrelationships with other critical DM factors. The average interrelationship of these factors is 4.09, which is higher than the total average score of 3.65. This score is second highest among the 4 quadrants, after quadrant 1 (5.33). It means that even if the importance value is relatively low, factors that have diverse interrelationships with other critical DM factor are preferred in the real project. For example, the importance value of "Setting of the responsibility assignment matrix (RAM) [F82]" and "Approval working drawing and sample product [F27]" are ranked 36th and 39th out of 43 (see Table 6.7), which are almost the lowest.

However, as shown in Figure 6.7, they have 5 and 6 interrelationships with other critical DM factors. In other words, they are selected by the 5th and 6th highest priority from Korean construction experts. In the same way as above, factors which do not have high importance values such as [F19], [F27], [F68], and [F82], can play a role as hub factors having diverse interrelationships with other DM factors (Whang and Flanagan, 2015).

Quadrant 3 (Specific function):

No	Design management factor	Factor cluster
F18	Pre-tender meeting with bidding and construction team	Design coordination
F35	Establishment of consortium and joint venture team managing plan	International JVDT
F37	Delivery control plan for international supply chain	International JVDT
F05	Documents management by the application of Fast-Track	Information management
F36	Regular detailed design meetings with subcontractors and suppliers	International JVDT
F34	Arrangement of pre-meeting with international trader and specialist	International JVDT

Table 6.10 Quadrant 3 (Specific function)

Factors that belong to quadrant 3 have relatively low relationships with other factors because they have specific functions with immediate and narrow range influence on production activities. Average relationships of these factors are 3.16, which is 0.45 lower than average relationship (3.65) of total DM factors. Even if the importance value of the quadrant 3 factors is relatively higher when compared to quadrant 2, the interrelationships between factors are much lower (0.93) than quadrant 2 factors. It indicates that factor preference is more closely related with interrelationships than importance value in the actual project. In spite of the high importance weights in IPM, “Pre-tender meeting with bidding and construction team [F18]”, “Delivery control plan for international supply chain [F37]”, and “Documents management by the application of Fast-Track (drawing distribution/instruction) [F05]” factors which are ranked 6th, 8th, and 10th on the highest importance list respectively (see Table 6.3) are less preferred by Korean construction experts.

Interestingly, quadrant 3 factors have a somewhat strong relationship with quadrant 1 factors. Interrelationship degrees between [F35] and [F41], and [F18] and [F02] are 54.68% and 42.01% respectively, which are much higher than average interrelationship degree (35.83%). With specific and limited function, quadrant 3 factors play a role in supporting the high important and preferred critical factors that belong to quadrant 1. For example, the Establishment of consortium and joint venture team managing plan [F35] that belongs to quadrant 3 can have a positive effect on the management performance of the design interfaces between international firms [F41] in quadrant 1.

Quadrant 4 (Low priority):

No	Design management factor	Factor cluster
F56	Establishment of project implementation plan (PIP)	Support production stage
F12	Project document control plan	Information management
F07	Review of site conditions (site topography/ground facilities)	Information management
F92	Support for environmental building certification (LEED/BREEAM)	Korean feature
F74	Simulation of life-cycle cost (maintenance cost)	Large-scale project
F39	Establishment of long lead/distance item management plan	International JVDT
F90	Work cooperation with project supervisors and authorities	Korean feature
F06	Structural grid planning review (over design, omission)	Information management
F78	Similar projects case study	Information management
F72	Review of energy supply grid	Large-scale project
F85	Review of impact on other surrounding buildings	Large-scale project

F83	Organization of dispute resolution board (DRB)	International JVDT
F29	Discussion with interior design team for detailed interior design	Design coordination
F13	Simulation for interior finishing/schedule	Information management
F89	Discussion with property selling department	Korean feature
F48	Supporting the making of interior mock-up test	Support production stage

Table 6.11 Quadrant 4 (Low priority)

Quadrant 4 factors have the lowest interrelationship score (average 2.50) between design-production management factors. In addition, they have the lowest weight in both importance and priority. They tend to be connected to each other within the same quadrant, otherwise they are connected with factors, which are placed outside the quadrant no matter how high their importance, and preferred values are. It can be interpreted that low priority factors can increase their managing competence by collaborating with similar less preferred factors.

On the other hand, some quadrant 4 factors are interconnected with quadrant 1 factors. Using this finding, it can be recognized that the quadrant 4 factors have unexpected close relationships with the quadrant 1 factors, even if there are opposite properties, concept, and features between the two quadrants. Many of the quadrant 4 factors can be analysed to show that they play a subordinate role in promoting the performance of dependent design-production management factors of quadrant 1. Indeed, "Structural grid planning review [F06]" factor (quadrant 4) plays a supportive role to review different project documents [F01] more accurately and in detail. "Project document control plan" [F12] (quadrant 4) also supports "Project management information system (PMIS) [F09]" to be operated efficiently throughout the production stage.

6.4 Summary

The procedure of data collection and analysis has been presented. Research data collected from the questionnaire survey was analysed using different statistical analysis. Amongst the 93 initial factors surveyed, only 43 factors that received a high importance weighting from respondents were analysed in the next stage. Given the 43 design-production management (DM) factors, the data analysis consists of three analysis stages; factor analysis, importance-priority analysis, and factor interrelationship analysis.

Using factor analysis, the 43 design-production management factors were categorised into 6 main factor clusters according to their functions and characteristics: Information management; Design coordination; International joint venture design teams; Support production stage; Large-scale project, and; Korean feature. Then these 6 categorised factors were analysed again using importance-priority analysis. All critical design-production management factors were ranked in an important-priority matrix (IPM). Matrix analysis was performed to divide all DM factors into four quadrants according to their importance and priority values: Critical quadrant; Cooperative quadrant; Specific quadrant and; Low priority quadrant. Finally, based on the result of the IPM, the interrelationships of each DM factor were analysed. The analysis result was presented by various linking lines between interconnected factors on IPM in accordance with the degree of interrelationship.

Through different data analyses, not only the importance value and preference in actual project of DM factors, but also the interrelationships between critical factors were analysed. In the next chapter, more explicit analysis will be conducted using system dynamics modelling and simulation to find out how these complex interconnected DM factors influence the entire project performance and when or how much they should be installed in each project stage.

CHAPTER 7 THE INTERRELATIONSHIP AND SIMULATION OF FACTORS

7.1 Introduction

In international-based large-scale projects, understanding the complicated integration between interrelated factors is more essential than just focussing on several predominant critical factors. Interconnected DM factors give different effects on project performance according to factor application timings and the duration or amount of project resources input.

Based on the matrix of factor interrelationship established in the previous chapter, causalities of all critical DM factors are expressed in a causal loop diagram. This causal loop diagram will be used as basic input data to increase the comprehensive understanding of the whole system structure and factor interrelationships. Using system dynamics simulation, complex interconnected factors can be monitored and analysed in detail. After a simulation of dynamic changes of diverse causalities between DM factors including the simulation of reference modes and scenario approaches, system dynamics predicts and finds the optimal behaviour patterns of interrelated factors as time progresses. Established behaviour patterns are expressed in graphic form to make it easier to understand and compare the simulation results.

7.2 Causal loop diagram

A causal loop diagram is an analysis method for system dynamics, which is used in this case for the development of complex and long-term projects. Thus, it has been used for different LSPs to analyse project structure and entire project systems. Causal loop diagrams consider interrelationships and sequences between parameters rather than the importance of parameters.

All design-production management (DM) factors have an advantageous or disadvantageous impact on project performance simultaneously. Each DM factor has its own optimal application timing and duration for best project performance. Some of the DM factors which have the greatest effect on project performance, if applied at an early stage, can also have a serious influence on performance due to belated application. Most critical DM factors cannot perform well if they are applied or implemented at the wrong time or during the wrong process, because they need many project resources such as labour, equipment, or money to be installed and implemented successfully. According to the features and functions of DM factors, each of them has an optimal application time and duration.

For example, "Review of the design level compared to budget" [F02], "Pre-tender meeting with bidding and construction team" [F18] factors are needed at the very early project stage, whilst "Discussion with interior design team for detailed interior design" [F29], "Facility management support system (FMS)" [F11] factors may be able to perform best when they are installed at a later production stage. The other factors such as "Management of design interface between international design and engineering firms" [F41], "Integrated design management team on-site" [F22], "Establishment the project management information system (PMIS)" [F09] are preferably implemented throughout the project stages. However, because these DM factors are interconnected with each other, contractors do not know exactly when they should be installed and how much project resources should be inputted during the implementation of factors. Thus, the most important thing is to understand how DM factors are interconnected and perform cooperatively. In a more practical example, the application of BIM [F45] is essential to improve productivity. However, at the same time, it also can cause the increase of construction cost and duration if it is applied in the wrong way or situation due to increasing out-sourcing costs for BIM modelling and training costs for BIM operators.

A causal loop diagram is generated to recognize the structure of the whole system and causalities by the formulation of all interrelated system parameters. The structure of a causal loop diagram consists of arrows, "+ or −" signs, and feedback loops. The direction of causality is expressed using arrows. The "+" sign indicates a positive impact on the result, whereas the "–" sign means a negative impact. According to the dominant loop structure, the whole system can be increased or reduced in one direction continuously or stabilized at a certain point in time. Causal loop diagrams are established using different feedback loops of causalities among system parameters. When different parameters are determined to be applied into the system, through the formulation of the causal loop diagram, the entire implementation strategy or mutual influences between systems factors can be understood comprehensively.

In this research, causal loop diagram used different DM factors to analyse not only the structural features of the entire project, but also mutual influences between factors. Even if the causal loop diagram is not able to provide a detailed solution or accurate cost prediction, it can improve the comprehensive understanding of whole system structure and behaviour pattern of individual subordinates, which directly influence project performances. The traditional factors of time, cost, and quality represent project performance (El-Rayes and Kandil, 2005; Mir and Pinnington, 2014). Although, due to the increasing social impact on the construction industry, different factors such as health & safety or environmental effect are included as additional criteria for the evaluation of project performance (Chan and Chan, 2004; Zavadskas et al., 2014), this research focuses on only traditional criteria (time, cost, and quality) are used as performance criteria. Since this research was undertaken from the contractor's perspective not project itself. Figure 7.1 shows the causal loop diagram using design-production management (DM) factors for international large-scale construction projects in Korea. It was established based on the results of the factor interrelationship analysis in the previous chapter. In factor interrelationship analysis, only interrelationships between two counterpart factors are measured without consideration of the other successive factor flows or the direction of the effect. However, a causal loop diagram not only shows the relationships between factors, but also supports more detailed information what kind of impact is taken from other factors and how much impact is given to others.

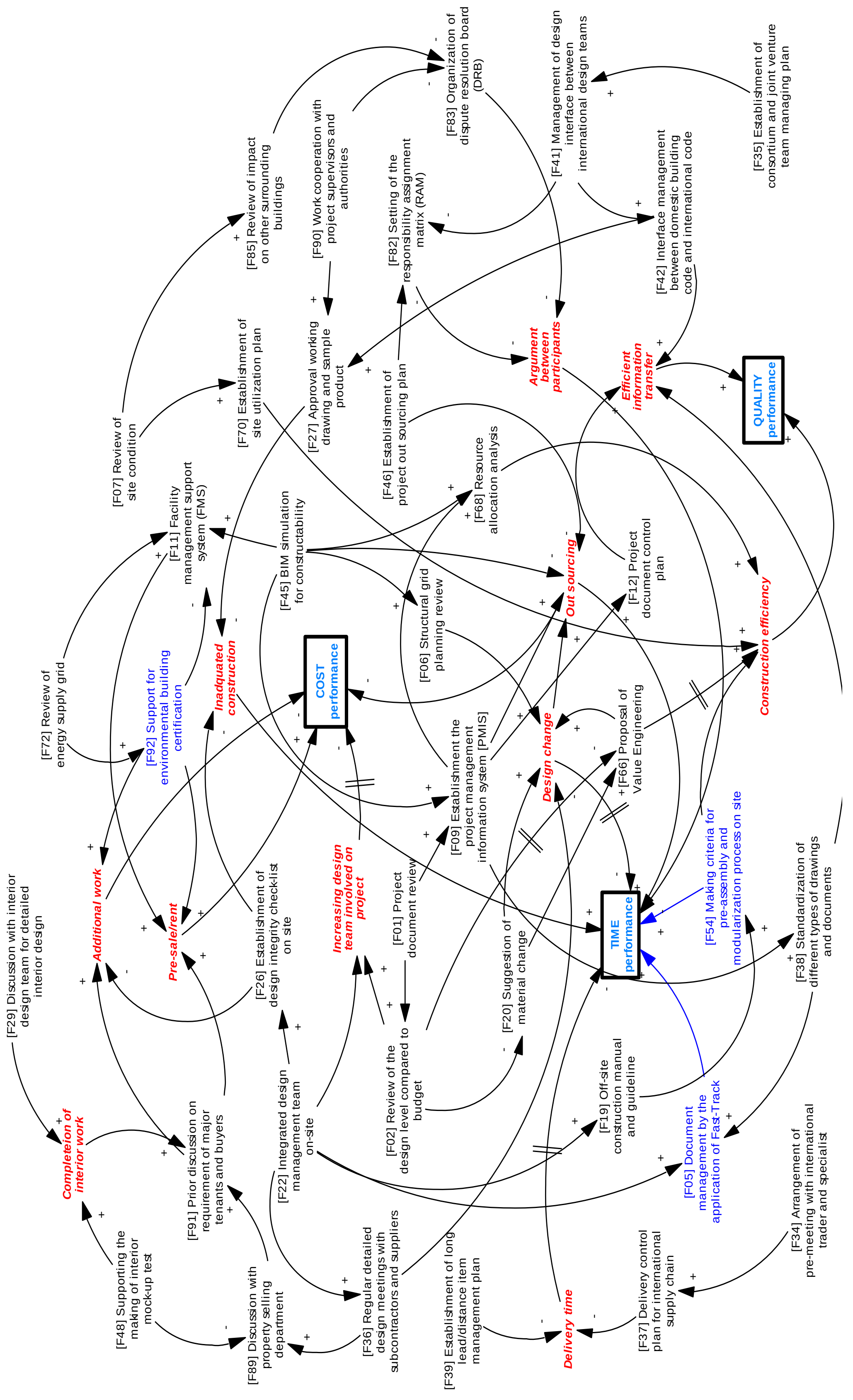

Figure 7.1 Causal loop diagram of design-production management (DM) factor

Causal loop diagram presents positive or negative effects and the direction of the effects using "+" or "-" marks and arrows, respectively. In addition, to make a more flexible and reasonable diagram structure, different auxiliary variables were used between flows of DM factors. All connections of the DM factors were converged into three main project performance criteria: time, cost, and quality. However, in the process, among the 43 design-production management (DM) factors only 37 factors were utilized to formulate the causal loop diagram. Six factors were excluded: they have the same causality structure or feedback loop with other DM factors. This overlapped causality structure can cause a serious system error in the system dynamics simulation process later, thus the 6 DM factors were excluded in causal loop diagram and system dynamics modelling. They were merged with other DM factors that have similar function and same causality structure. Finally, the 37 DM factors used in this research modelling are shown in Table 7.2 in a later section.

In this diagram, some DM factors such as [F05] and [F54] are shown as directly influencing project performance, while other factors' influence on project performances are indirect via other auxiliary variables. Indeed, in this diagram, DM factors pass through an average of 3.12 variable or auxiliary variable steps to effect project performances. However, interestingly, time-related DM factors pass through an average of 2.72 variable steps. It can be explained that, compared to the other two performance criteria (cost and quality), time-related factors have a more direct influence on time performance. In problematic situations during the construction stage, time-related factors such as "Documents management by the application of Fast-Track" [F05] and "Making criteria for pre-assembly and modularization process on site" [F54], which directly affect time performance, can be selected preferentially by a contractor to improve time-delay problems. However, in terms of a substantial degree of influence, they will be analysed in the next chapter using system dynamics. Using this DM factors are substantially simulated and this shows how many project resources are needed and when they should be applied.

In causal loop diagrams, stock variables (shown in red) play a sub-role in explaining project situations caused by the integrated application of different DM factors. All DM factors influence project performance using their own managing feature (dependent variable) and sometimes using a changed project situation (stock variable) as a result of the integration of different DM factors. Three project performances criteria are linked by different stock and auxiliary variables. As in the explanation in chapter 3, cost performance is influenced by four stock variables (*Additional work, Pre-sale/rent, Increasing design team involvement on project*, and *Out sourcing).* In this process, the "Support for environmental building certification [F92]" factor has a negative impact on additional work performance and positive impact to pre-sale/rent performance at the same time. Substantial degrees of influence are different according to the application timing and amount of input resources. Detailed results of cost performance will be monitored and analysed later using a system dynamics simulation.

Furthermore, causal loop diagrams involve integrations of different auxiliary variables and dependent variables (DM factors). For example, the *Design change* auxiliary variable, which is affected by four different DM factors ("Structural grid planning review" [F06], "Suggestion of material change" [F20], "Regular detailed design meetings with subcontractors and suppliers" [F36], and "Proposal of value engineering" [F66]), influences time and cost performance via the *Out sourcing* stock variable. In other words, these four different DM factors, which have different functions and features, can have a positive impact on time performance directly through the design change stock variable. At the same time, they also can have a negative impact on cost performance indirectly by increasing the out sourcing cost.

Causal loop diagrams are useful as a management method in themselves. Through the establishment of a causal loop diagram, contractors can not only establish their design-production management strategies at the early pre-production stages, but also select suitable DM factors according to project features and purposes (Cavana and Mares, 2004; Schaffernicht, 2010). Moreover, it is used as basic input data for system dynamics to investigate the changing effect and behaviour patterns of the DM factor according to the flow of time (Ananda *et al.*, 2006; Bendoly, 2014). In the next section, based on the results of the causal loop diagram, system dynamics modelling will be carried out to investigate explicit effects of individual DM factors.

7.3 Factor simulation

Factor simulation is a mean of understanding both interrelationships between factors and their effect using computer programs. In this research, system dynamics is used as a practical simulation of design-production management (DM) factors. A model of factor simulation is established based on the result of the causal loop diagram generated in the previous section. Using computational simulation, it can be predicted when latent problematic issues occur and how the contractor can manage these issues before direct input of project resources (Sterman, 2000; Jones, 2014). The substantial effect of each DM factor is dependent on the application timing and duration. This is because by only using a causal loop diagram, explicit changing effects and performances of DM factors cannot be monitored and simulated. Thus, system dynamics is used to achieve practical quantitative simulation data. Based on different factor relationships established in the causal loop diagram, all equations and functions of the DM factors are formulated as stock and flow diagram for system dynamics simulation.

7.3.1 System dynamics

System dynamics looks at dynamic changes and how particular parameters change over time rather than the accurate measurement of model parameters at a certain point in time. In system dynamics, all derived DM factors are divided as stock, flow, auxiliary variables, and constants to formulate stock and flow diagrams. All DM factors are then evaluated by numerical values to be converted into formulation form for the modelling of the system dynamics program (Rodrigues and Bowers, 1996a; Lyneisa and Ford, 2007). Various and powerful functions of system dynamics such as loop tracking tools, visual comparison tools, and powerful optimizing tools enable an in-depth understanding of the complex system and appropriate solutions.

In a stock and flow diagram (or level & rate diagram), the stocks (level) variable serves to change the project performance by storing or integrating the changed value of factors. The stock variable has an accumulated value and the amount of inflow and outflow of stock variable depends upon the flow variable over time. System dynamics modelling is established using the integration of various stock and flow diagrams, which are constituted by different stock, flow, and auxiliary variables. Moreover, simulation of system dynamics modelling is determined by various formulae which define the relationship between different variables (i.e. DM factors). Finally, simulation results are used for analysis to establish the appropriate design-production management strategy and to apply suitable DM factors in the right time and place according to the project purpose and situation.

With the utilization of the Vensim program, system dynamics modelling can be formulated and simulated more easily and accurately. The Vensim program is a computer simulation languages program for system dynamics, which converts complex variables of causal loop diagrams into formulations for computational modelling. Thus, in this research, the Vensim program (DSS Version 4.0) is used for modelling and simulation of system dynamics using different DM factors. It is also useful for development of the optimization model, model analysis, and validation of model (Lyneis *et al.*, 2001).

7.3.2 Modelling for system dynamics simulation

System dynamics simulation uses a scenario approach for a system that is not completed at a specific time, but develops gradually over time (White and Fortune, 2012). For simulation modelling, all feedback loops determined in the causal loop diagram are interconnected and converged into stock and flow diagrams

(Rodrigues and Bowers, 1996b; Feng *et al*., 2013). Following this, the integration of different stock and flow diagrams are utilized as essential input data for system dynamics modelling.

7.3.2.1 Setting of modelling demarcation

System dynamics configures the modelling with various feedback causalities and monitors this configuration in the modelling over time. In this system dynamics modelling, the configuration of the time setting is shown in Table 7.1. Time range of the modelling is set at 6 years (288 weeks) referring to the duration of international LSPs. Here, project duration means that throughout the project the stages from project bidding to closing are considered from the contractor's perspective.

	Time variables	Unit
Time	Simulation period	6 Years (288 Weeks)
Initial time	Simulation start time	Time=0
Final time	Simulation end time	Time=288
Time step	Simulating unit	1 (Week)
Unit for time	Week	-

Table 7.1 Simulation time variables

The conceptual diagram to establish system dynamics modelling is shown in Figure 7.2 below. All variables of system dynamics modelling have close and dynamic interrelationships, which have complex mutual influences on each other. Modelling is set to determine project performance that is composed of time, cost, and quality performances. Here, three main performance criteria (time, cost, and quality) are constituted using different subordinate criteria (stock variables) respectively. The structure of system dynamics modelling is different from the structure of causal loop diagrams. In system dynamics modelling, only the stock variable can have an influence on the project performance and this variable depends on various auxiliary variables and constants (i.e. DM factors).

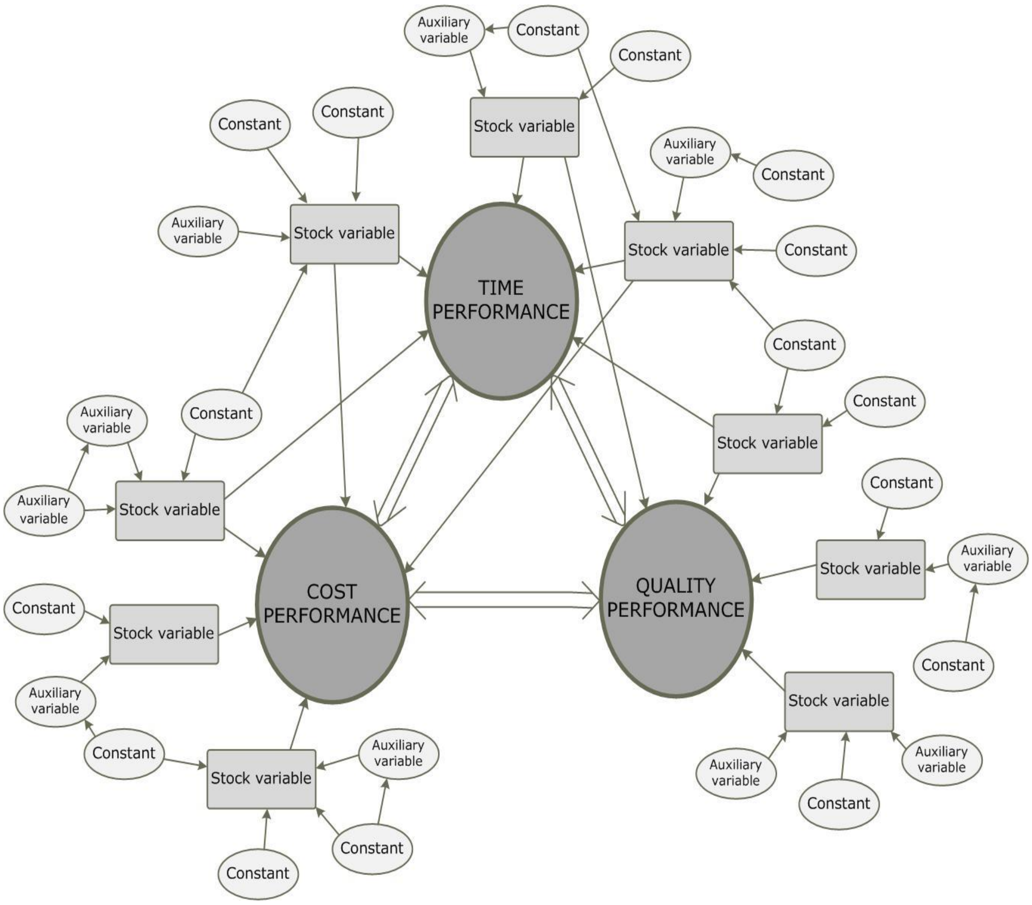

Figure 7.2 Conceptual diagram of simulation modelling

7.3.2.2 Review of key variables in modelling

As described in the previous section, variables used in system dynamics modelling are divided into stock and flow rates according to their functions. The stock rate indicates critical production issues such as Delivery control and Design change, which are related to design-production management and influence project performance. Thus, contractors monitor and referring to this make decisions affecting the entire system or project. The flow rate determines the inflow and outflow of stock rates in the system. In other words, flow rates can be viewed as changing the project situation. These are also influenced by auxiliary variables and constants (design-production management factors) and influence stock rates (construction issue) at the same time. Auxiliary variables and constants mean that integrated or individual DM factors directly or indirectly influence stock and flow rates. In this form of modelling, stock and flow variables are selected on the basis of construction activities that directly affect the project performances (time, cost, and quality). By shifting constants (i.e. input project resources for application of DM factor) stock, flow, and auxiliary variables are calculated and determined. Dozens of stock, flow, and auxiliary variables and constants are interconnected within modelling. Moreover, because of the amount and timing of the input project resources are very different, it is also impossible to conduct simulation without the aid of a computational program.

7.3.2.3 *Formulation of causality*

As described above, the first step in the modelling of system dynamics is to identify the boundaries of the system model. The next step is to understand all causality structures; this can be the most critical stage of system dynamics. Formulations of modelling are established using a realistic mind-set, empirical data, and comprehensive knowledge of the project and system itself. Once the formulation of causalities is completed, the overall modelling repeats the process of verifying and resetting for simulation. Through this process, technical errors in formulation can be amended and unexpected errors and functions can be found before simulation.

Even if design-production management (DM) factors sometimes include immeasurable concepts, system dynamics modelling should be intuitive. Thus, in order to make a causality structure and formulate the causalities between MD factors and project performance, modelling is established in a more objective and specific setting. In this modelling, based on the 37 MD factors which were used as auxiliary variables and constant values, 18 stock and flow variables and 30 flow variables were formulated. Eventually, all stock and flow variables converged into 3 main project performance criteria (time, cost, and quality) as shown in Figure 7.3.

7.3.2.4 *Stock and Flow diagram modelling*

Modelling of system dynamics is a series of converting processes in which interconnected causal loop diagram is converted into a specific stock and flow diagram. This is very advantageous if accurately calculated and simulated modelling having various formulas and functions. Thus, stock and flow diagrams include various variables and formulas to accurately infer the dynamic changes within modelling. System dynamics modelling integrates different stock and flow diagrams. Interrelationships between variables (i.e. DM factors) are expressed as different formulations using not only simple arithmetic, but also complex calculations and the function formulae. In this research, using the Vensim program, dynamic model structures and elaborate formulas were established, modified, and simulated.

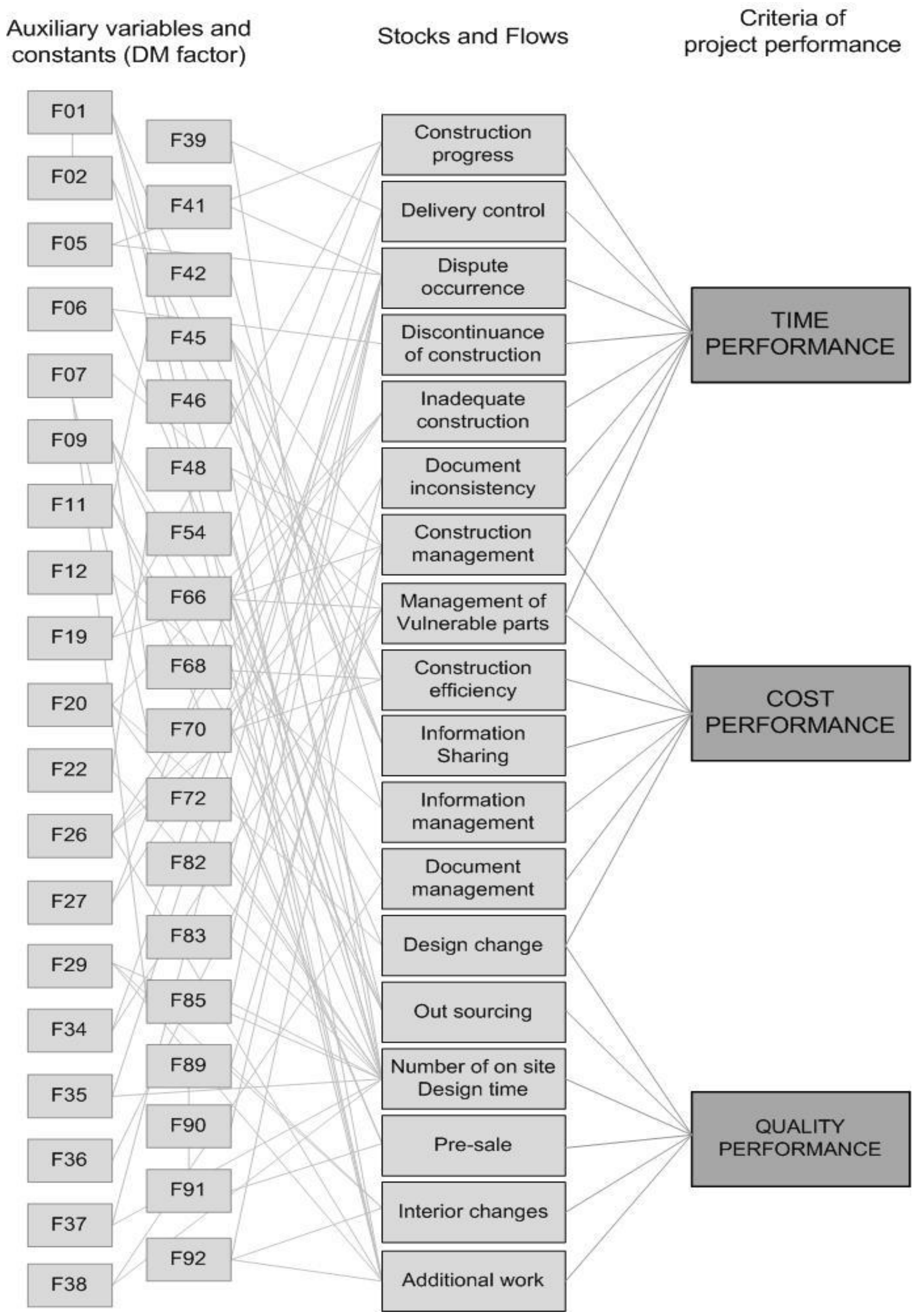

Figure 7.3 Analysis of causality structure

As shown in Figure 7.3, 18 stock and flow variables are collected from data of real case project. The author was involved in this project as a design manager hence has detailed understanding of the project. Stock and flow variables are all the significant project phases or managing activities, which gave most direct and significant impact on the project's performance (time, cost, quality). All relationships between variables including auxiliary, stock and flow variable become different groupings according to response from the questionnaire (See Table 6.3) and DM factor interrelationship matrix (See Figure 6.7). Groupings of all DM factors into three-project performance (time, cost, quality) will be used later for establishment of reference model in system dynamics (See Figure 7.4).

To calculate accurately the formulas in modelling, various function expressions such as Smooth, Integration, Delay, and Look up, in the Vensim program are used. Through the integration of different stock and flow diagrams, reference models of system dynamics were generated as shown in Figure 7.4. Overall, the structure of modelling is established with reference to the causal loop diagram made in the previous section (see Figure 7.1) and detailed interrelationships between variables (DM factors) are referred to from the questionnaire responses. In modelling, constants and auxiliary variables, which are presented as factor numbers [F01-F92], mean DM factors. Values of constants and auxiliary variables depend on the input project resources when a DM factor is applied. As a reference model (Base Run in the Vensim program), it is established based on the causal loop diagram and questionnaire results described previously without any modification to improve the performance.

7.4 Evaluation and analysis of system dynamics model

7.4.1 Reference model

Reference models are fundamental in monitoring and predicting the long-term behaviour patterns of system. Based on this reference model, decision-making alternatives can be determined using analysis of the change of system parameters. After setting different subordinate stock and flow diagrams, which constitute the whole model, the reference model allows monitoring which behaviour patterns have changed and predicting how behaviour patterns will change over time.

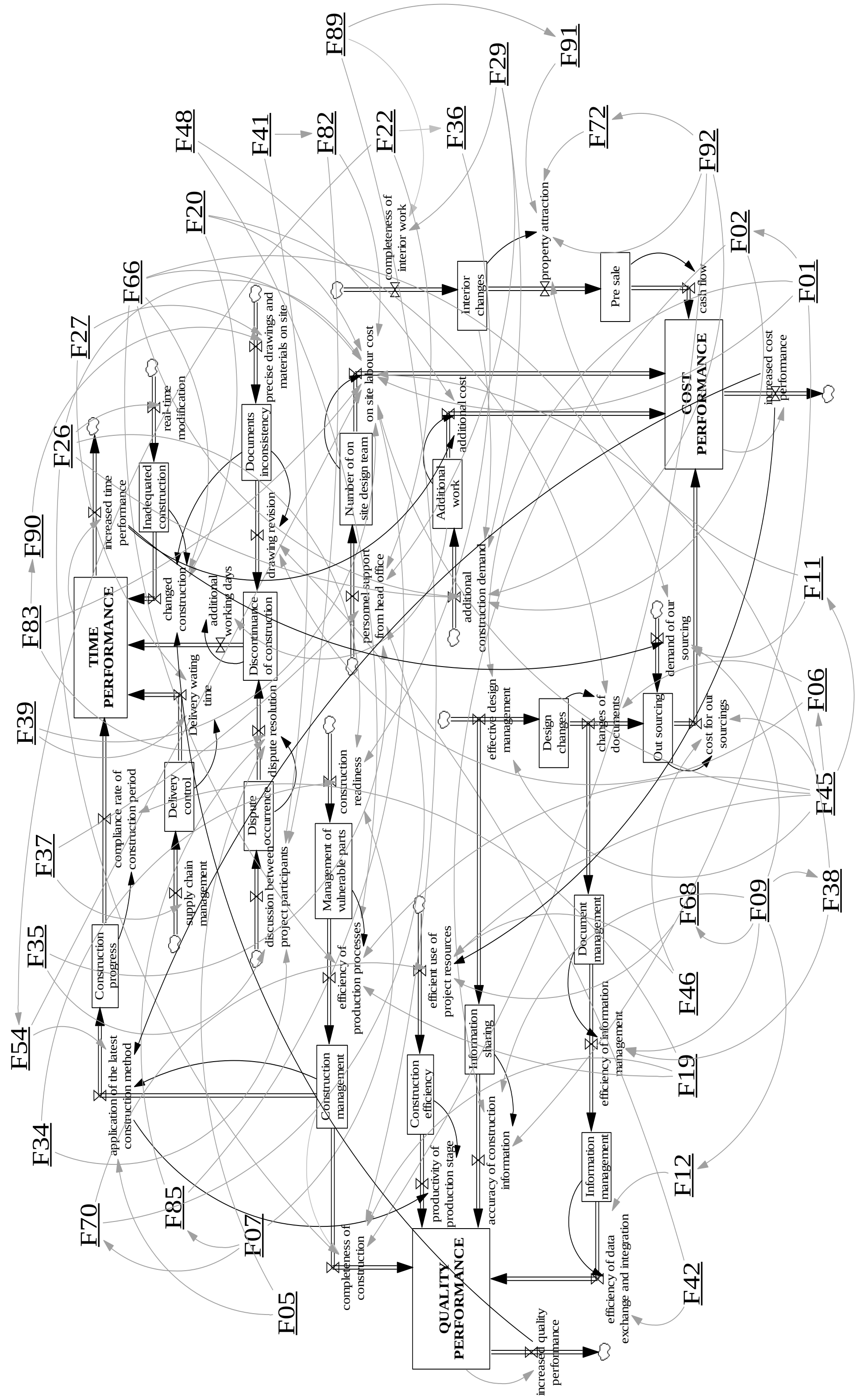

Figure 7.4 United system dynamics modelling

In this research, as seen in Figure 7.4, a reference model is generated, not only to evaluate performance patterns based on research data such as causal loop diagrams or survey responses, but also to compare with scenario-based models that are modified based on the reference model to achieve optimal performance pattern. Moreover, through analysis of the comparisons between reference and scenario-based models, which are time, cost, and quality-oriented models, different solutions and decision-making can be determined.

For reliable modelling, the relationship between each DM factor and 18 stock variables (See Figure 7.3) are validated by pre-simulation in system dynamics. Under reference model condition, each DM factor's performance is simulated in order to find causality between each DM factor, one of the 18 stock variables shows highest performance. With the same simulation process, these 18 stock variables are simulated again with Time, Cost and Quality performances in order to find optimal factor grouping. For example, F37 (Delivery control plan for international supply chain) shows the highest performance when it links to Delivery Control (one of the Stock variables), Delivery Control also indicates optimal performance when it belongs to Time performance grouping. Fortunately, in pre-simulation, most grouping of DM factors and causality structure are the same as the result of the reference model. Only the simulations of 6 DM factors show slightly different results, with reference model. Since the differences are not significant, causality structures of these 6 DM factors were modified: differences are difficult to distinguish visually in graphical form. The pre-simulation is used as a subsidiary function in order to validate the whole modelling structure and groupings of DM factors into three main performance criteria (time, cost and quality).

For accurate simulation of system dynamics modelling, substantial numerical data (practical project input resources) also is used from the real project data as shown in Table 7.2. Amount of input resource (See Table 7.2) for each DM factor is applied to simulate the modelling. This real case project is very similar to research model in the sense that international experts and a joint venture design teams are involved in Korean large-scale project. Duration of construction was 5 years 8 months, which is similar to the set period of simulation in this research. These similarities will give more objective and reliability of the system dynamics modelling which is established using real project data that the author conducted. All numerical input values of auxiliary variables and constants are presented as Md or Md/£ as seen in Table 7.2.

Auxiliary variable and constant (DM factors)	Criteria	Input project resources	Importance weight
[F01] Project documents review	Completeness of document review	298.20 Md	1.21
[F02] Review of the design level compared to budget	Budget error rate	239.89 Md	1.22
[F05] Documents management by the application of Fast-Track	Construction period by Fast-Track	186.34 Md	1.10
[F06] Structural grid planning review	Over or omitted structural design	177.62 Md/£	0.92
[F07] Review of site conditions	Expected site problems	143.72 Md	0.96
[F09] Establishment the project management information system (PMIS)	Information sharing efficiency	3,126.02 Md/£	1.15
[F11] Facility management support system (FMS)	Maintenance cost saving	155.52 Md/£	0.85
[F12] Project document control plan	Document control efficiency	115.20 Md/£	0.97
[F19] Off-site construction manual and guideline	Reduced construction cost or duration	357.98 Md/£	0.98
[F20] Suggestion of material change	Changed material items	378.80 Md	0.89

[F22] Integrated design management team on-site	Design management staffs on site	7,776.00 Md	1.18
[F26] Establishment of design integrity checklist on site	The number of checked items	182.40 Md	0.92
[F27] Approval working drawing and sample product	Approval rate of drawing and sample	384.81 Md	0.86
[F29] Discussion with interior design team for detailed interior design	Discussed items of detailed interior design	228.72 Md	0.87
[F34] Arrangement of pre-meeting with international trader and specialist	The number of discussed agenda	187.23 Md	1.06
[F35] Establishment of consortium and joint venture team managing plan	Disputes occurred on site	244.49 Md	1.14
[F36] Regular detailed design meetings with subcontractors and suppliers	Disputes on reviewed detail design	302.41 Md	1.07
[F37] Delivery control plan for international supply chain	Average delivery time	630.08 Md/£	1.12
[F38] Standardization of different types of drawings and documents	Drawing standardization ratio	882.68 Md	1.09
[F39] Establishment of long lead/distance item management plan	Reduced delivery time	483.22 Md	0.93
[F41] Management of design interface between international design and engineering firms	Consistency ration between basic and detailed design	569.81 Md	1.19
[F42] Interface management between domestic building code and international code	Integration of building codes	418.73 Md	1.08
[F45] BIM simulation for constructability	Construction productivity	4,773.60 Md/£	1.08
[F46] Establishment of project out sourcing plan	The number of out sourcing items	384.27 Md	1.11
[F48] Supporting the making of interior mock-up test	Tested interior design items	511.94 Md/£	0.85
[F54] Making criteria for pre-assembly and modularization process on site	Assembly error rate on site	206.76 Md	1.06
[F66] Proposal of value engineering	Reduced construction duration	672.18 Md/£	0.99
[F68] Resource allocation analysis	Amount of additionally used resources	984.18 Md	0.95
[F70] Establishment of site utilization plan	Site use efficiency	445.61 Md	0.97
[F72] Review of energy supply grid	Expected energy consumption	202.38 Md/£	0.91
[F82] Setting of the responsibility assignment matrix (RAM)	Clarity of responsibility between stakeholders	578.26 Md	0.89

[F83] Organization of dispute resolution board (DRB)	Dispute resolution ratio	762.08 Md/£	0.89
[F85] Review of impact on other surrounding buildings	Claims occurring from surrounding buildings	384.83 Md	0.91
[F89] Discussion with property selling department	Pre-sale or rental rate	307.84 Md	0.86
[F90] Work cooperation with project supervisors and authorities	Permit processing time	508.61 Md	0.93
[F91] Prior discussion on requirement of major tenants and buyers	Acceptance rate of customer demands	835.72 Md	0.88
[F92] Support for environmental building certification (LEED/BREEAM)	Achieved certification points	1,738.92 Md/£	0.95

*Md = Man-days *Md/£ = Man-days+£

Table 7.2 Reference model input data

In order to apply a design-production management (DM) factor to the project, a period of time is necessary to prepare and adapt to the project system as well as manpower (Md) and cost (£). Here, Md means man-days i.e. the level of manpower included in the entire project. Based on an 8-hour working day, Md indicates how much workforce is needed to apply a certain DM factor in the project. For example, 1Md means a workforce conducted by one expert for one day (8 hours). And Md/£ shows that based on Md, the application or operation cost of the DM factor is included. It indicates the extra budget needed according to application of the DM factor, except for the original project budget, which may be outsourcing or overhead costs. In addition to this, the importance value of each DM factor, which is determined from the expert surveys (see Table 6.3), is reflected in the input data. On the basis of the average importance value of the 37 design-production management factors (3.260) which are finally used for research modelling, each importance weight is determined.

Reference models are validated through the verification of defined formulae and functions, and the feasibility validation processes that are labelled as "Check Model" in the Vensim program. Through the Check Model process, all formula or function errors are chased and monitored in advance. As a result, the entire structure of reference models can be completely built through the setting of relevant causalities and self-reviews of internal formula. In addition, through the "Sensitivity Test" of 18 stock variables and 30 flow variables, the reference model is verified to ensure it is appropriate for simulation. Detailed results of tests are described in the next chapter. As a result of these tests, the reference model is shown to have strong feasibility within the error range of 95% and the simulation result which is presented in graph form on three main project performances (time, cost, and quality) is seen in Figure 7.5.

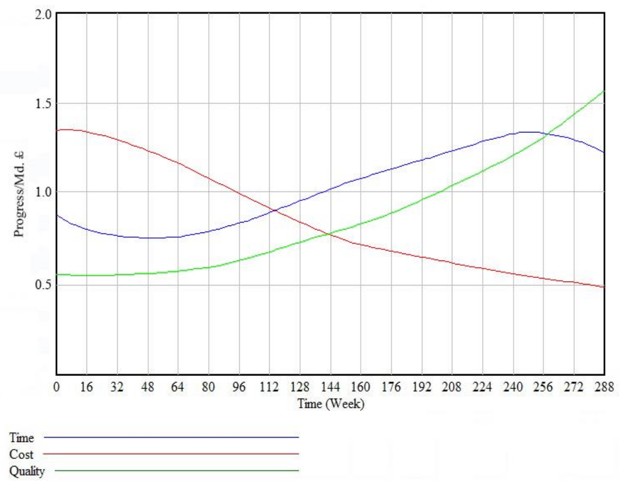

Figure 7.5 Project performance of reference model

In this graph, each result of the performance value is not important. Instead, the graph shows the fluctuations of performance in accordance over time, not the specific performance value during project duration (288 weeks). Because three project performances are interconnected with each other throughout the construction period, the comparison of individual performance between them is meaningless. It is just used to monitor the flows of the three main project performances at a glance. Later, this graph of the reference model will be compared with the graph of the optimal model simulated using a scenario approach.

According to the result of this graph, cost performance is highest in the early project stages and the project progress performance is continuously lowered. In particular, the graph falls relatively steeply in the first half of the project. In the second half, the descent is somewhat gradual. The reasons for this could be that at the beginning, various project preparation activities, outsourcings, and contracts with subcontractors or suppliers can create high expenditure in the construction budget. Thus, compared to expenditure, cost performance cannot decrease at the early project stage. From the contractor's perspective, it is at the critical managing point at which contractors try to keep the high cost performance value; this is as late into the project stages as possible.

The time performance graph shows a more dynamic fluctuation when compared to other graph forms. From the starting point of the project, the performance value had been reduced, which is somewhat similar to the cost performance graph. However, after the early stage, the graph shows quite a different shape to cost performance. In the early construction stage on site, basement excavation works, for example, can be delayed because of different ground issues. Due to the nature of large-scale construction project, massive and deep underground work is necessary, thus disputes with neighbours, the blasting of underground rock, and unexpected underground utilities can temporarily interfere with the pre-set critical path during the basement work stage. After the mid-construction stage, the time performance value increases gradually. Normally, this period involves full-scale reinforced concrete or steel frame work. As described in the previous chapter, due to the development of building technologies, construction productivity is increasing particularly in concrete or steel frame work, thus during this period, the construction speed is very fast compared to other construction stages. Lastly, at the end of the project stage, the time performance falls again, because of additional re-works, trial runs of the facilities, site clean-up, etc.

Unlike the above two graphs, quality performance shows a gradual rise in performance value according to project progress, but the increasing slope becomes steeper over time. There is no construction project, which starts with full preparation because of the limited construction cost and period. In addition, because the contractor's profit will increase if the project is completed on time and on budget, most contractors want to start construction as soon as possible even in an unprepared situation. Thus, the initial quality performance relatively low when compared to later stages. However, after the project environment has stabilized and all construction support systems are set, the quality of the performance increases relatively steeply and continuously.

In real projects, it is difficult to be sure that quality performance will rise constantly, because unexpected project risks and problems such as supply chain problems, design changes, or re-work always occur during the construction stages. However, because this graph is simulated as a mode of reference, minor problems are already reflected in the modelling and more extreme problems that can influence total quality performance are excluded.

7.4.2 Sub-ordinate model

Originally, the reference model is formulated based on the integration of three project performances. Each project performance can be individually simulated and analysed in more detail. Through the simulation of individual project performances, sub-ordinate managing elements can be monitored and analysed in detail under specific project conditions. For example, if a shortened construction duration is the highest priority in a certain project, sub-ordinate models which are composed of only time performance-oriented variables such as Delivery control or Construction progress variables can be independently simulated and analysed in more detail.

7.4.2.1 Time performance-oriented model

The time performance-oriented model is composed of 8 stock variables, 14 flow variables, and 20 auxiliary variables and constants as shown in Figure 7.6. Auxiliary variables and constants (design-production management factors) affect the stock and flow rate, and the converged rate of the stock and flow variables finally becomes a time performance value. The entire time performance value and 8 sub-ordinate (stock variable) values are presented in a graph in Figure 7.7. In the reference model, these 8 stock variables are determined to mostly influence time performance value. Delivery control and Inadequate construction variables are analysed as having a relatively direct and linear impact on the entire time performance. In particular, the “Inadequate construction” variable has a negative impact.

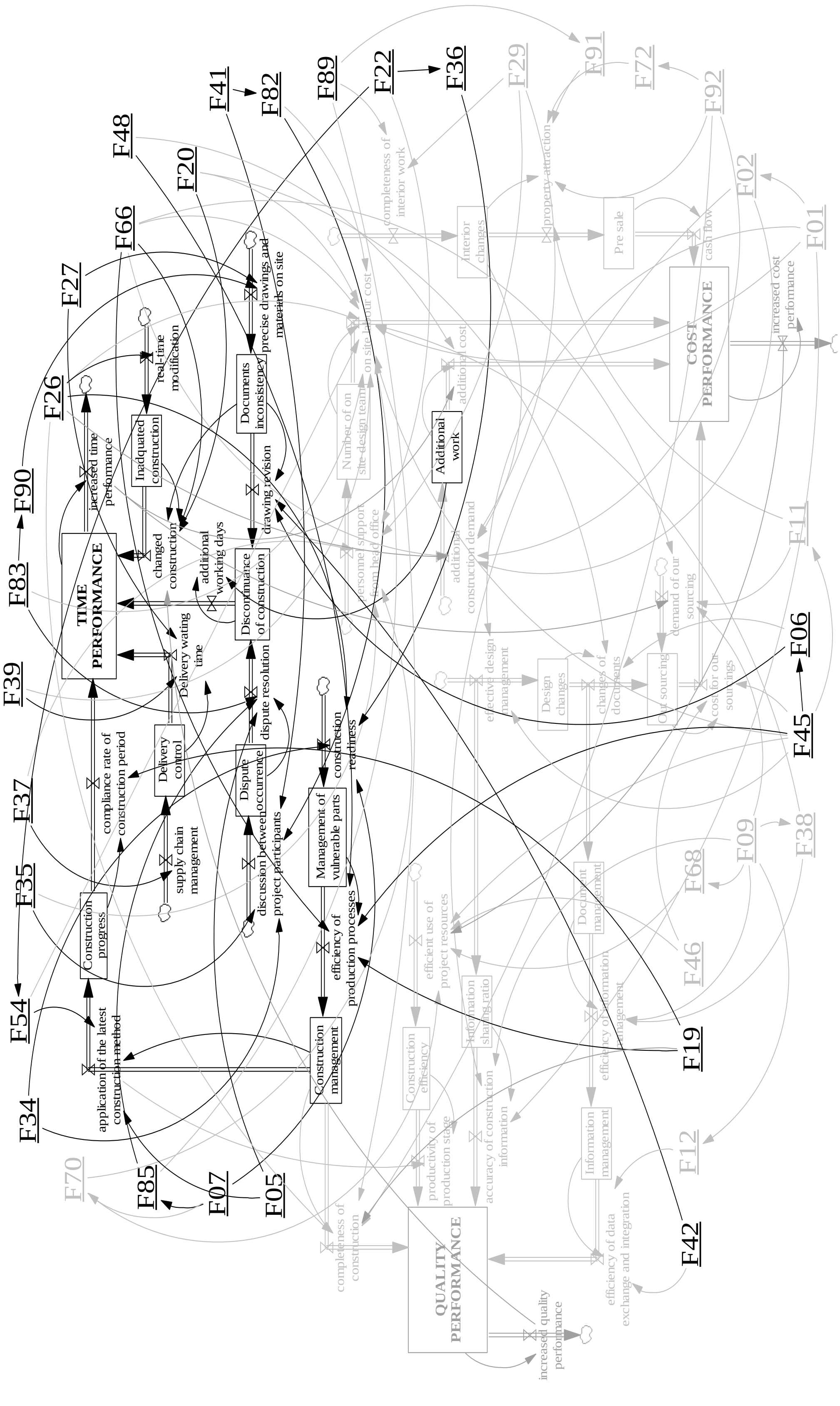

Figure 7.6 Time performance-oriented modelling

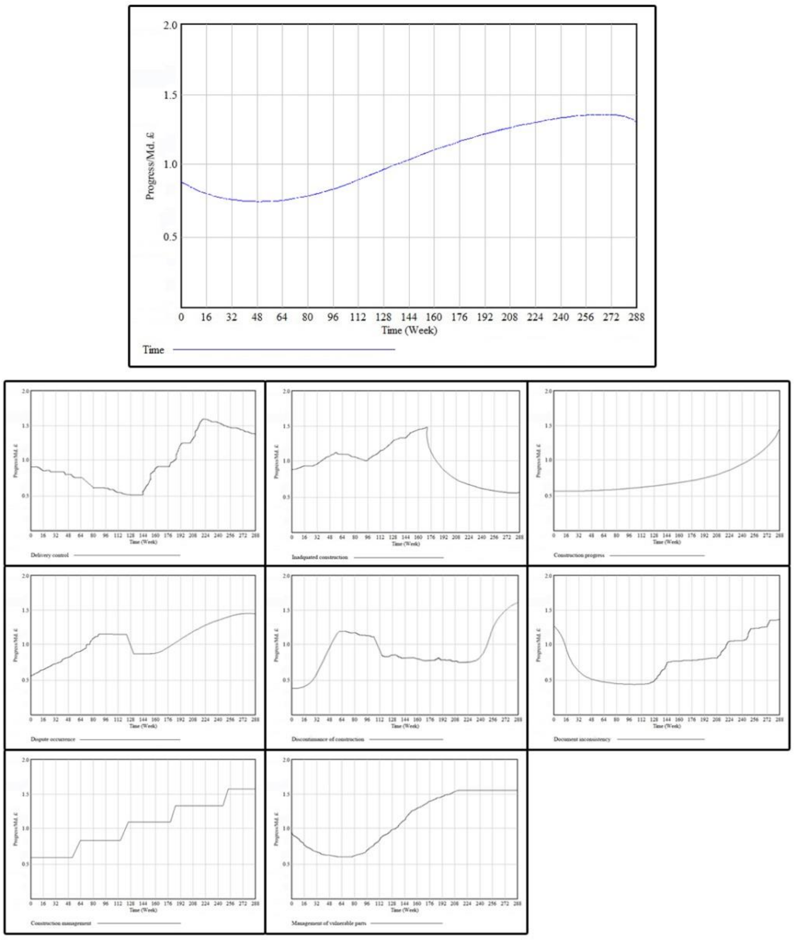

Figure 7.7 Time performance and sub-ordinated variable graphs

Other stock variables (sub-ordinate performance criteria) which are influenced by different auxiliary variables and their constants have a non-linear and relatively dependent impact on time performance. For example, the “Discontinuance of construction” variable is formulated by the convergence of the “Dispute occurrence” and “Documents inconsistency” variable values. When analysing the performance of the “Discontinuance of construction” variable in detail, the sub-ordinate graph shows very irregular and unpredictable behaviour patterns. The reason for this is that this variable is influenced by 2 stock variables, 4 flow variables, 4 auxiliary variables, and 10 constants at the same time, which all have their own rate. Graph simulations show very complicated and fluctuating behaviour patterns as shown in Figure 7.7.

7.4.2.2 Cost performance-oriented model

The cost performance-oriented model comprises 6 stock variables, 12 flow variables, 28 auxiliary variables and constants as shown in Figure 7.8. A large number of DM factors (28 auxiliary variables and constants) affect the total cost performance and its sub-ordinate performance values. Among the 37 total design-production management (DM) factors, 75% of DM factors are related to cost performance. DM factors, which are applied to increase the duration or quality of performance, require equivalent costs which would be labour costs, outsourcing, equipment etc. This means that all DM factors that have a positive impact on time or quality performance can also have a negative impact on cost performance at the same time. Thus, contrary to the other two project performances (time and quality), the cost performance graph shows continuous decline. There are only differences in the degree of decline according to the project period. Particularly, even if all sub-ordinate graphs of cost performance show greatly changed behaviour patterns as shown in Figure 7.9, the cost performance graph which is a result of the convergence of different sub-ordinate graphs shows a gradual and modest decline as the project progresses.

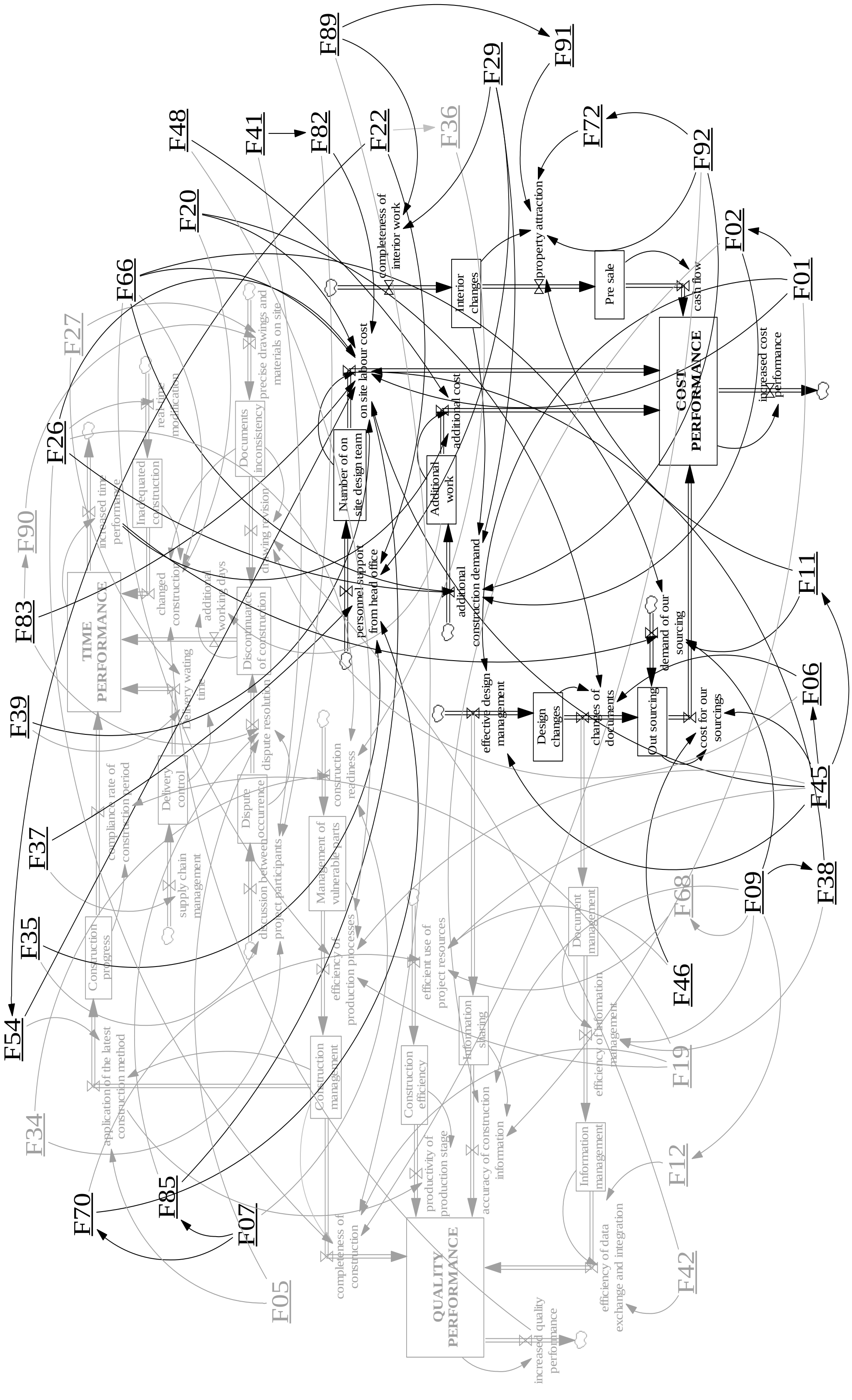

Figure 7.8 Cost performance-oriented modelling

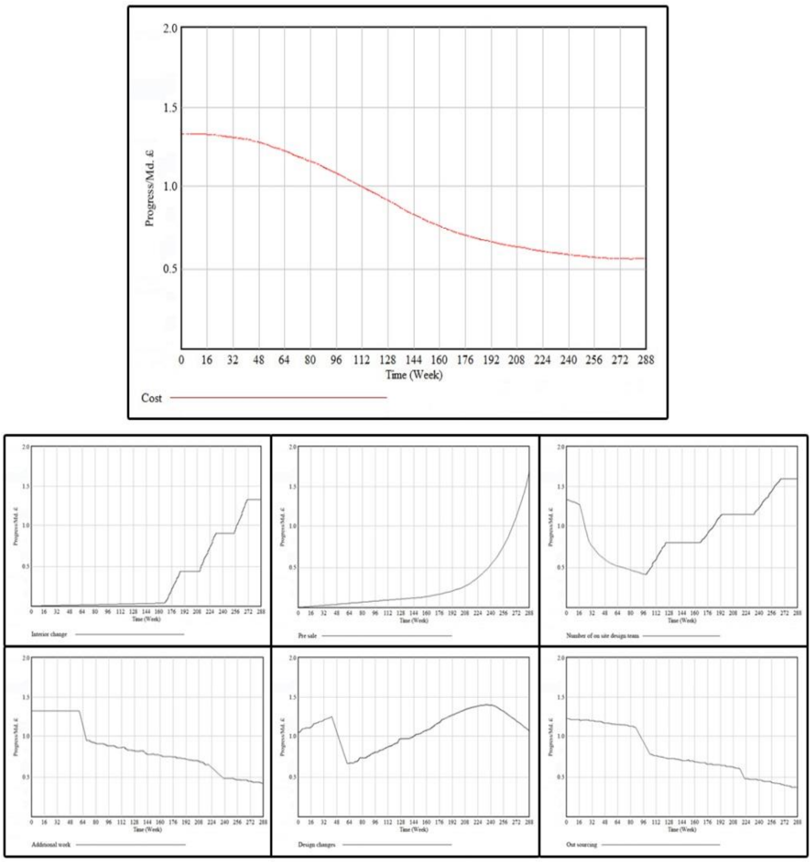

Figure 7.9 Cost performance and sub-ordinated variable graphs

Remarkably, the cost performance is structurally close, but contrary, to the time performance. 17 of the 28 auxiliary variables and constants (DM factors) have a contrary impact on both cost and time performance. For example, even if F22 (Integrated design management team on-site) and F66 (Proposal of value engineering) are critical DM factors to increase the time performance, at the same time there are many cost necessities to maintain such as experts on site throughout the construction stages and when making extra contracts with external experts for value engineering consulting.

7.4.2.3 Quality performance-oriented model

The quality performance-oriented model is composed of 7 stock, 12 flow variables, and 24 auxiliary variables and constants as shown in Figure 7.10. Quality performance tends to be influenced by management-related variables such as Construction management, Information management, and Document management variables. Because the majority of stock and flow variables have management-oriented aspects, which are not expected to have immediate effect on performance after the application of specific design-production management factors, the quality performance graph shows a gradual increase without rapid and dynamic changes - see Figure 7.11.

Among the three project performance criteria, only the quality performances' model structure is directly connected to the two other performances. "Construction management" and "Management of vulnerable parts" variables affect both quality and time performance at the same time. Moreover, the "Design changes" variable affects cost and quality performances (see Figure 7.10). For example, well performed the "Construction management" variable affects both time and quality performance by "Application of the latest construction method" and "Completeness of construction" variables, respectively. Particularly, the "Application of the latest construction method" variable, which affects the time performance, also affects another quality performance-related variable (Productivity of production stage) simultaneously.

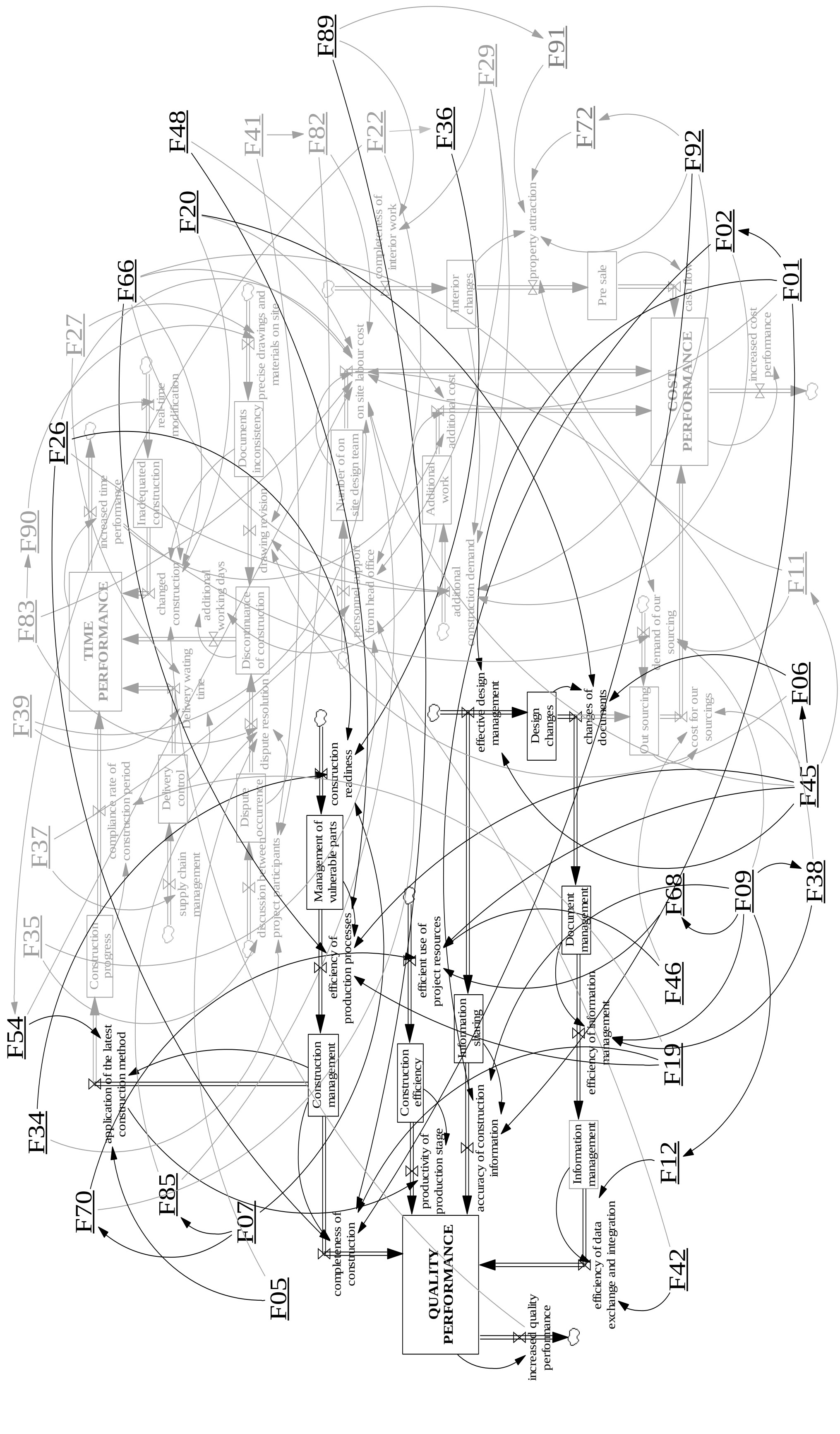

Figure 7.10 Quality performance-oriented modelling

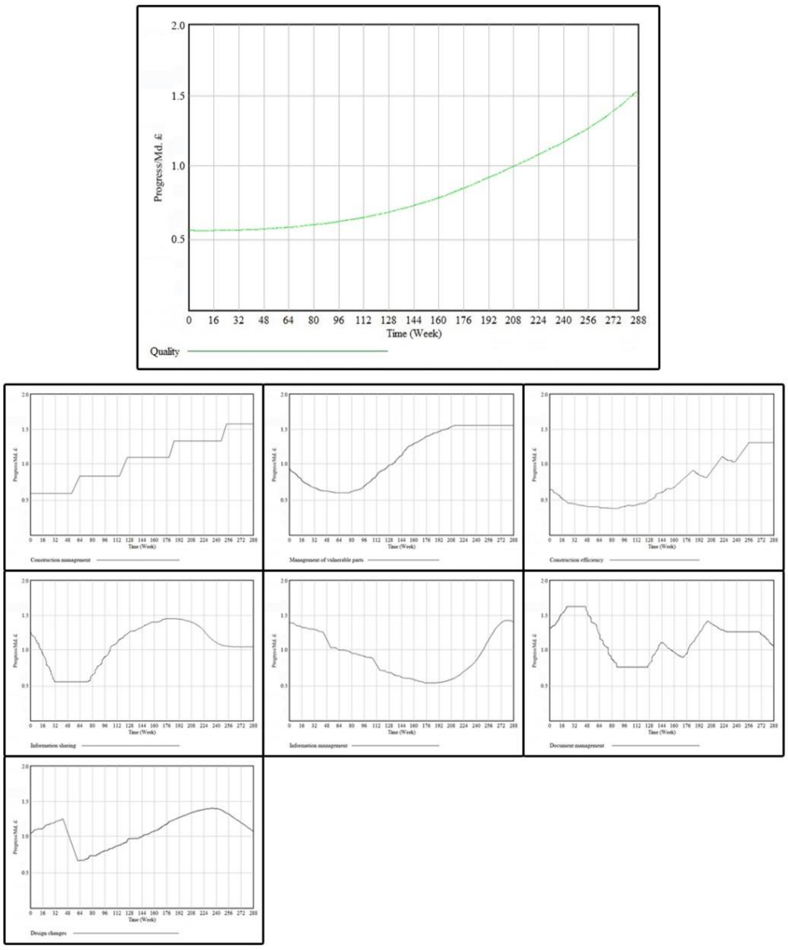

Figure 7.11 Quality performance and sub-ordinated variable graphs

As above, compared to the time or cost performance model in which performance is affected more immediately and directly by the application of specific DM factors, the quality performance model has a more complicated and interconnected structure. This means that, even if time or cost performance can be increased within a short period of time using intensive input of project resources, the quality performance model needs careful and elaborate managing skill to increase performance.

7.5 Research findings of the system dynamics simulation

Through the integration of stock and flow diagrams of different variables and constants, a system dynamic model for design-production management was developed. After different simulations, it was recognized that the variables and constants (DM factors) in the model have complex relationships with each other, and these relationships are dynamically changed to make a single system. Due to the development of dynamics modelling which integrates different sub-ordinate variables into a single system, simulation became available to monitor and analyse the behaviour patterns of the entire system or diverse subordinate systems.

Through the adjustment of even one variable or constant value, all related stock and flow variables, which are connected by the feedback structures, can be changed in response to a chain reaction. Because various variables and constants (DM factors) are interconnected, thousands of different performance result cases can be obtained through simulation of modelling. These results are automatically calculated and analysed by a computer program. Through the simulation result, the system dynamics output can provide major parameters on which design-production management (DM) factors should be used for interface management between design-production activities. It shows when each DM factor should be applied to achieve optimal performance, and how many project resources such as labour, materials, and budget should be used according to the simulation result. By this, the entire workflow can be understood and future managing tasks can be predicted in advance. This information is critical for contractors to minimize the unexpected design-production risks in real large-scale projects particularly when implemented by international joint venture design teams.

7.6 Summary

The interrelationships between all DM factors were analysed and simulated. Using of a causal loop diagram and system dynamics simulation, the interrelationships of DM factors were established and understood. Their suitability and usefulness is used in the design-production management process of a real large-scale project. First of all, the causal loop diagram is established using various feedback loops and variables interconnected with each other. Primarily, it is used to understand the structural features or the entire project system. The diagram is also used as basic input data for system dynamics. Based on the causal loop diagram, reference models of system dynamics are established using the integration of different stock and flow diagrams. For a more reliable and realistic simulation, a reference model is formulated using the results of the survey of experts and real project data. In addition, for a more detailed analysis of the reference model, sub-ordinate models (time, cost, and quality-oriented) are established and simulated respectively.

System dynamics simulation is monitored and has shown the behaviour pattern of different project performances. Through this, complicatedly interconnected DM factors are expressed and simulated in detail. In the next chapter, using the simulation results of the reference model of design-production management, a process map will be generated. For this, the reference model will be verified in terms of reliability and suitability through comparisons with the optimal model and different scenario-based models. Then a DM process map will be generated based on the analysis of the results of the reference and optimal model simulations.

CHAPTER 8 DEVELOPMENT OF A DESIGN-PRODUCTION MANAGEMENT PROCESS MAP

8.1 Introduction

In this chapter, system dynamics modelling is validated through different scenario-based simulations. Time, cost, and quality-oriented simulations validate the stability and reliability of modelling created by the Vensim program. Following compliance verification on the modelling of system dynamics, a design-production management process map (DMPM) is developed based on the simulation results. Considering the features of simulation results and the effects of each design-production management factor on an international large-scale project, DMPM will reduce design-related construction risks from the contractor's perspective. It will support the production implementation plan, taking into account all design-production aspects at the early project stages.

8.2 Validation of system dynamics modelling

System dynamics is as way of establishing how a series of processes (including conceptualization, deployment, simulation, verification, and elaboration of modelling) are repeatedly conducted (Rodrigues and Bowers, 1996b). System dynamics involves modelling that describes a cause and effect relationships within a system. However, the real world is so complex that all behavioural patterns of social variables and mechanism of changing environment are difficult to be predicted. Hence, all system dynamics modelling should try to describe these reactive and changing real social phenomena perfectly as much as possible (Bendoly, 2014). Modelling is verified by different simulations. In this research, because a design-production management process map is developed based on the results of system dynamics modelling and simulation, a precise verification of modelling is critical whether the formulas and functions of modelling are logically completed. The purpose of model validation is to confirm that system dynamics modelling is formulated and calculated properly to perform this research and that it simulates different scenario-based conditions.

In this research, system dynamics modelling is formulated using the Vensim[10] program. It is one of the computational simulation programs for system dynamics; the verification process is also conducted using Vensim as seen in Figure 8.1. System dynamics modelling is so complex (see Figure 7.4 and Table 7.2), containing enormous equations and variables each interconnected to each other. Without computational support, accurate calculations and simulation of modelling is impossible. Vensim provides not only a convenient user interface and easy operating environment, but it also has sufficient verification tools within the program. Indeed, the Reality check and Sensitivity tests by which technical

[10] Vensim is a simulation program. It primarily supports continuous simulation (System dynamics), with some discrete event and agent-based modelling capabilities. Vensim provides a graphical modelling interface with stock and flow and causal loop diagrams, on top of a text-based system of equations in a declarative programming language. It includes a patented method for interactive tracing of behaviour through causal links in model structure.

verification of this research modelling was conducted are representative of the verification tools in Vensim. After the technical verification, including structure and equations, modelling is validated once again for its suitability for large-scale construction projects (LSPs) using comparative analysis. For this, a reference model that is basic model of system dynamics formulated on the basis of the survey results, is compared to the optimal model and scenario-based models (time, cost, and quality-oriented model).

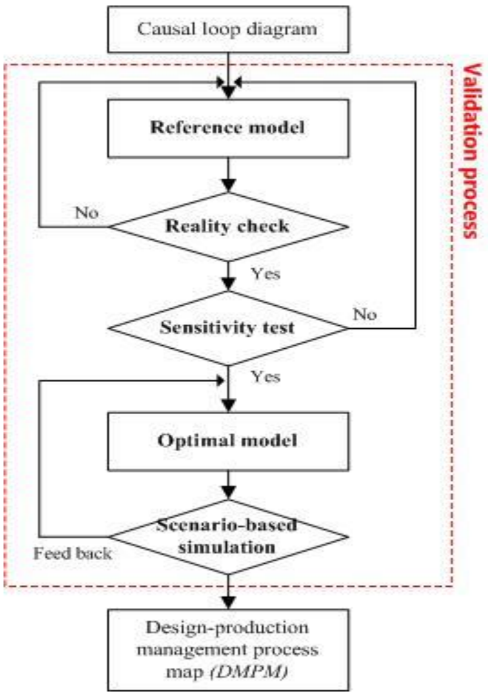

Figure 8.1 Validation process of system dynamics model

Here, the optimal model means the best performance model that is generated by adjustment of the reference model. Through continuous simulations applying different constant values (input resource of design-production management factors), the modelling structure and appropriate design-production management

(DM) factors for the optimal model are fixed. If the variation between the reference and optimal models is at an acceptable level, system dynamics modelling can be recognized as suitable for application to real large-scale construction projects.

8.2.1 Technical verification

8.2.1.1 *Reality check of model equations*

System dynamics has a basic verification function within it to confirm that modelling is formulated by a logical process. In this research, Vensim verified the whole formulation of the modelling using its own computational verification tools. The verification is conducted to find any structural and equational errors within the modelling. In other words, it is a checking process that all equations and calculations used in modelling are following the system dynamics principle.

There are two main tools in Vensim to verify the stock and flow formula in modelling. After completion of modelling, Vensim carries out an Equation check tool. The primary modelling is confirmed to ensure there is no structural error between equations and units. After setting all variables and constant values, Vensim carries out another verification tool, Check model, where errors of modelling structure are discovered and modified if necessary. Using the verification tools of Vensim, including Equation check and Check model, structural and equational aspects of system dynamics modelling can be validated. This means that modelling is formulated without any significant technical errors.

8.2.1.2 *Sensitivity Test*

The sensitivity test is one of the methods used to validate system dynamics modelling. Unlike the technical verification described above, which verifies the structure and equation of modelling, the Sensitivity test is a way of examining the validity of the modelling through the application of the wide range of constant values. These values are modelled and analysed for any change in behaviour patterns with respect of the constant values. Here, a constant value means an amount of input project resources in accordance with the application of each design-production management factor. The test using Vensim is performed by the application of different constant values from maximum to minimum ranges of project resources such as Man Hours or project budget (see Table 7.2). The sensitivity test is an essential process in order to demonstrate the completeness of modelling.

In system dynamics modelling, each DM factor has its own amount of input resources. For example, as shown in Table 7.2, F45 (BIM simulation for constructability) needs 4,773.60 Md/£ of project resources, not only to install the BIM system on projects and the whole company, but also to educate operators and project teams. In the same context, the sensitivity test monitors the changing results of the system dynamics simulation according to the variation of input of project resources of the design-production management factors. In this research, system dynamics modelling is supposed to be modified and simulated many times in order to find the optimal performance model. Thus, great differences (i.e. high sensitivity) in accordance with wide range of application of constant value shows that formulated model cannot be applied to a real large-scale construction project.

The sensitivity test is a kind of simulation, which is taken when the parameters in a model are uncertain. Normally, system dynamics models tend to be less sensitive to changes in the variables (Love et el., 2002b; Robinson, 2014). Thus, if the result of the sensitivity test is highly sensitive to changes in the variables, the model should be checked to ensure whether it properly reflects the real phenomena, otherwise the model is wrongly formulated. Through this, the system dynamics modelling can be re-analysed and reconstructed to provide a more reliable and compatible form. Vensim provides a Monte Carlo mode as a simulation principle (Eberlein and Peterson, 1992; Jones, 2014). This sensitivity test shows the result of simulations performed by the application of random numbers for constant values. The results of the sensitivity test are presented in a graph form. The wide graph shape means that the sensitivity of the model is high. The graph colour indicates how many simulations are carried out using random numbers for constant values (amount of input resource) with a percentage of sensitive responses (i.e. 50%, 75%, 95%, and 100%) as seen in Figure 8.2.

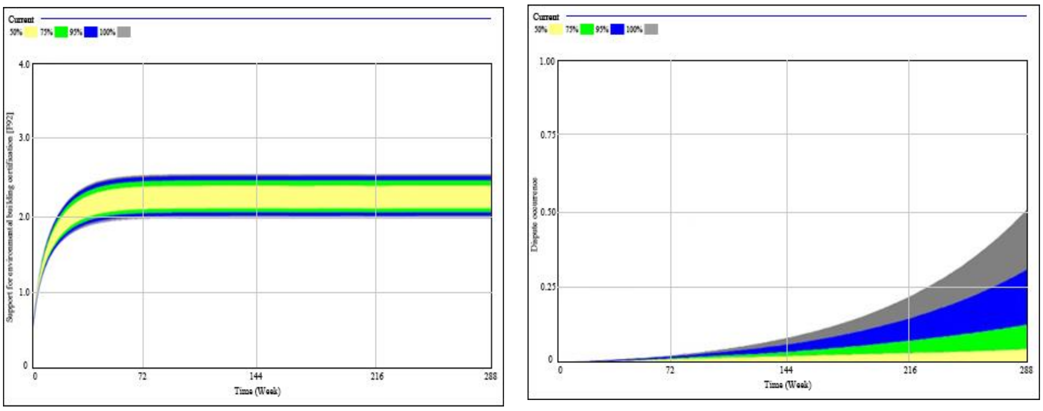

Figure 8.2 Dominant patterns of sensitivity test

In most sensitivity tests, a range of constant values are normally set from ±10% to

20%, based on default value. However, in this test, the range of constant value is set around ±100%. This is because, in real large-scale projects, deviation of input project resources are greater in accordance with the project's characteristics, and the discretion of the project manager. All simulations are carried out for 18 stock variables, 29 flow variables and 37 constants values, including auxiliary variables. The simulation results are divided into two main graph patterns as seen in Figure 8.2. The first pattern shows that, after a sharp rise in the sensitivity graph it plateaus. In the second pattern, the sensitivity is constantly increasing.

Sensitivity test of Stock variables - As a sample of a sensitivity test on stock variables, the test results of "Construction Management" variables which have four constant values (four relevant DM factors - Off-site construction manual and guideline [F19], BIM simulation for constructability [F45], Supporting the making of interior mock-up test [F48], and Proposal of value engineering [F66]) are used and presented in Figure 8.3. Among the different stock variable simulations, the Construction Management variable shows the most typical graph pattern. A total of 43% stock variable graphs show a similar pattern to that in Figure 8.3, which is increasing rapidly in the early stages and then stabilising.

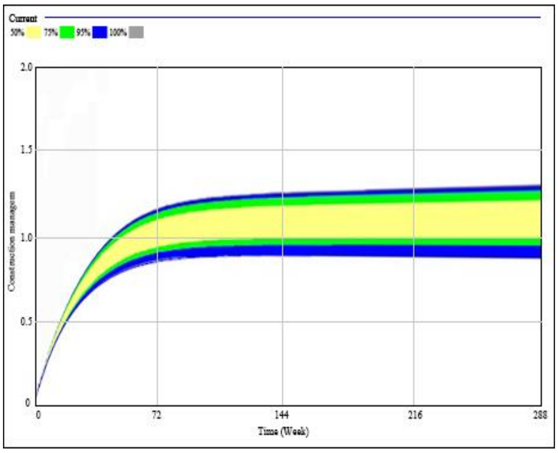

Figure 8.3 Stock variable sensitivity graph (Construction management)

Like the pattern in the graph above, sensitivity tests of major stock variables are presented as becoming stable without continuous change despite the application of a wide range of random numbers as constant values.

Sensitivity test of Flow variables - Among the various flow variables, test results of the "Additional construction demand" variable connecting with six constants, is presented. Among the six constants, two sensitivity test results of constants, which show the most representative patterns, are presented in Figure 8.4.

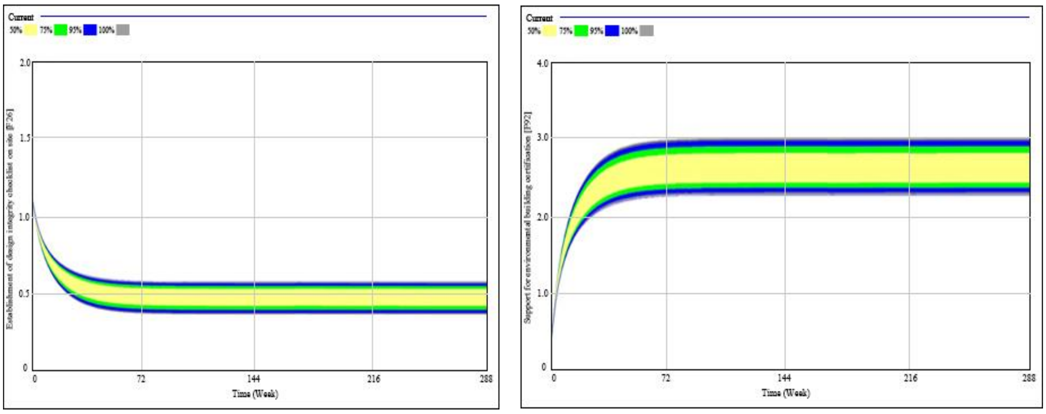

Figure 8.4 Flow variable sensitivity graphs

Increasing value [F92] and Decreasing value [F26] - F92 increases the flow rate, whilst F26 plays a role in decreasing the flow rate of the "Additional construction demand" variable. When comparing two constants, there is no great difference in sensitivity. Because several constants simultaneously affect flow rate, a great sensitivity gap between constants can create an unexpected error during simulation of the entire model. Thus, the range of the random number, which makes the sensitivity gap between constants, should be adjusted to have similar sensitivity. Using the sensitivity test, system dynamics modelling is validated so that there is no significant formulation error when the simulations apply different constant values to find out optimal performance of modelling.

8.2.2 Suitability test for actual project

After technical verification including the Equation check and Sensitivity test, suitability tests of models on actual construction projects are conducted. The suitability test is a method for determining the configuration of models and whether or not they are established compatibly to reflect various situations of real projects. Normally, the validation of compatibility and suitability of the system dynamics model is carried out through the exchange of opinions of expert groups and comparisons of the existing data or previous project. If the suitability test of a model (reference model), established by research data, shows similar result patterns when it is tested using previous real project data, it can be verified to ensure its suitability to be applied into real large-scale construction project (LSP). However, given the one-off feature of construction projects, there is no similar/same previous model, which can be compared to the reference model. Thus, in this case, the system dynamics model is verified by using a comparison with results of scenario-based models which are formulated under specific project conditions.

8.2.2.1 Optimal performance simulation

Based on the reference model (formulated in the previous chapter), the optimal performance model is formulated by not only the adjustment of variables and constant values of the reference model, but also by the applied timing and duration of variables and constants (DM factors). To describe this more simply, the reference model is simulated based on the system dynamics modelling of Figure 7.4 applying the data of design-production management (DM) factor in Table 7.2 to the constant value. An optimal model is formulated by changing equations and the constant value based on reference model (See Figure 7.4). In order to find the combination of equations and constant values to perform optimal project outcomes, an optimal model is simulated, continuously applying different equations, functions, and constant values. In this research, the results of model simulation (project performance) are presented by time, cost, and quality graphs - the basic standards for measuring the performance of the project. In recent years, based on these three, new standards such as Sustainability or Health & safety are added. Because this research focuses on the success of the production stage from the perspective of the contractor, not the success of the project itself economically and socially, in this research only time, cost, and quality are determined as main standards of project performance. As seen in Figure 8.5, the X axis presents a six-year project duration (288 weeks) and the Y axis represents the performance efficiency in contrast to input project resources (manpower and project budget).

The reference model is generated using survey results from construction experts, whereas the optimal model is formulated through repeated computer simulations with applications of a wide range of constant values until the optimal result is derived. However, when the optimal model is simulated, there is no difference in the total amount of constant values (amount of project resources) between the reference and optimal models for a more fair and substantial comparison. The optimal model is formulated by finding the most efficient combinations of resource input, but not using unlimited resources. Like real construction projects where project resources such as manpower and budget are determined in advance and spent within a pre-set range, all project resources of optimal model are also adjusted and applied within a limited amount.

Through the comparison of the simulation results of project performance between the two models, the suitability of the model can be validated. Generally, in terms of the overall shape of patterns, performances graphs of time, cost, and quality show similar patterns in similar size or function of projects. Thus, the performance result of the optimal model shows similar patterns with the reference model as shown in Figure 8.5. Because the optimal model is formulated based on the reference model, and if in this research system dynamics modelling is formulated appropriately, the simulation result of the optimal model should show an improved graph pattern compared to the reference model.

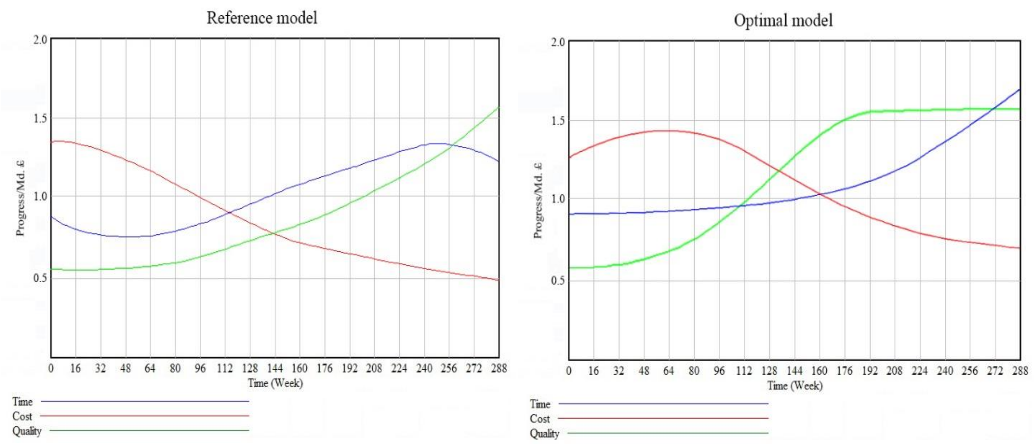

Figure 8.5 Comparison between reference and optimal model

The optimal performance model is established in three stages. In the first stage, all functions, variables, and constants that make up the whole model are changed and adjusted. Then, through repeated simulation, the most suitable timing and input amounts of project resources for the application of each variable (i.e. the DM factor) is determined. Finally, the third stage is the adjustment of the application duration, resulting in the optimal performance modelling being formulated. In other words, in order to reach the optimal result, the input amount of project resources, application timing, and the application duration of each design-production management (DM) factor are changed and adjusted. However, the formulation process of the optimal model does not always follow this order. During repeated simulation, the process order is inevitably changed, because model structures are interconnected, making them complex.

When comparing the simulation result of these two models, the optimal model shows more active graph forms, but with somewhat less fluctuation than the reference model. Project performance (time, cost, quality) is increased overall in the optimal model simulation. In terms of time performance, compared to the reference model, there is a relatively distinct change in the optimal model. In the reference model, the graph falls, rises, and falls again according to the project process, which is somewhat difficult for contractors to respond appropriately to the project dynamic. However, in the optimal model as shown in Figure 8.5, the time performance graph shows gradual and continuously increasing patterns. This represents a decrease of rework that has a negative effect on the construction duration normally in the final stage. Quality performance is changed from a gradually increasing graph pattern in the reference model to a sharply increasing then flat pattern in the optimal model which is a relatively sharp increase from the mid-stage of the project (around the 64th week) and is maintained (around 176 weeks) until project completion. The cost performance graph does not show a distinct difference. Unlike the reference model in which the cost performance graph went down from the early stage and continued until project completion, the cost performance graph of the optimal model has been maintained and even enhanced in its performance level for a while after the project beginning and then gradually falls in the mid-to-late period.

As shown in Figure 8.5, the graph pattern of the optimal model fluctuates within a similar range to the reference model without any mutated behaviour. Even if different equations and functions are adjusted and a wide range of constant values is applied to formulate the optimal model, it has the same model structure as the reference model. Through comparison of both graph patterns, the suitability and compatibility of both models can be validated. The simulated performance graph of both models is formed within the same zone and the simulated graph pattern of both models do not differ significantly. During the simulation, despite outstanding performance outcome, the simulations which have abnormal graph patterns or mutant amplitudes were excluded from the simulation sample.

For contractors who have to predict the construction costs and make an appropriate execution plan from the early pre-production stage, a less fluctuated project is favourable in order to distribute the project resources effectively and respond for unexpected resource input situations. In international LSPs, where the contractor has to deal with a long duration, complex processes, and numerous experts at once, reducing the project fluctuation is one of the most critical management tasks during the production stage. Thus, pre-performance simulation throughout the project stage including time, cost, and quality can be a great help in reducing the project risk of the contractor.

8.2.2.2 *Scenario-based simulation*

Unlike the sensitivity test, which just monitors the graph changes made by the application of various constants, a scenario-based simulation observes the behaviour pattern of models through changed structures including the equation and function of the optimal model. Because design-production management process maps (DMPM) are developed based on the simulation result of the optimal model (except for the verification of the model structure such as the Sensitivity test and Equations check), the optimal model should be validated to check whether they can be adapted into different project conditions or purposes. Thus, in this section, the optimal model is validated in whether it can be simulated properly under various time, cost, and quality-oriented project conditions.

Scenario 1: Time-oriented simulation. Time-oriented modelling is simulated by assuming that because of specific project purposes or unexpected project situations, time performance could be improved or projects could be finished within a limited period of time. Like the comparison between the reference and optimal models, the total amount of input resources of a time-oriented model is the same as an optimal model. Through the intensive input of project resources on only time-related design-production management (DM) factors and the application of DM factors taking account of construction duration, the time-oriented performance model is formulated and simulated.

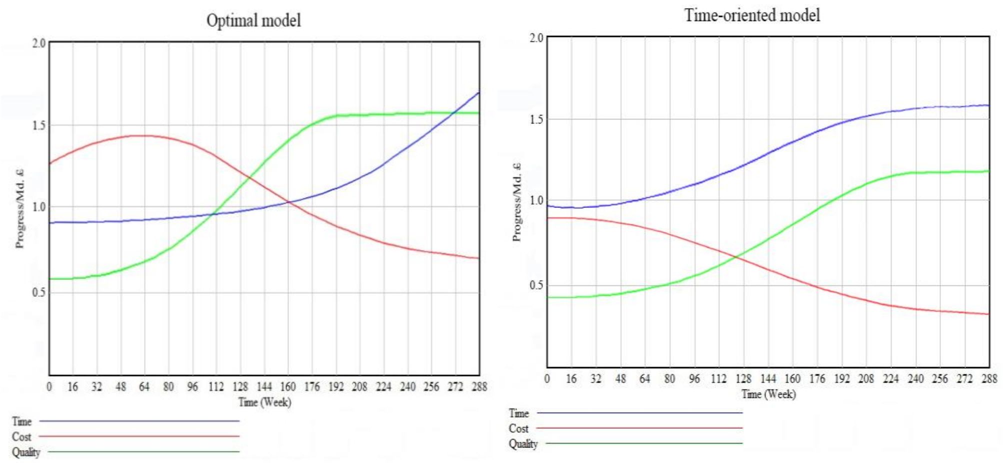

Figure 8.6 Comparison between time-oriented scenario and optimal model

Figure 8.6 shows a comparison of the simulated result on three performance criteria between optimal and time-oriented scenario models. Compared to the optimal model, the time performance graph of the scenario model shows a quietly improved graph form, even if the rest of the cost and quality performance graphs show similar or even lower performance levels than the optimal model.

Particularly, cost performance is reduced remarkably, which allows contractors to see that time performance has opposite managing features of cost performance.

Scenario 2: Cost-oriented simulation. The cost-oriented scenario model is simulated by assuming that, as in the above time-oriented model, only cost performance should be improved or projects should be carried out within a tight budget. The cost-oriented scenario model is also formulated and simulated by the adjustment of the existing variable cost-related DM factors in favour of cost performance without any change to the total amount of input i.e. project resources.

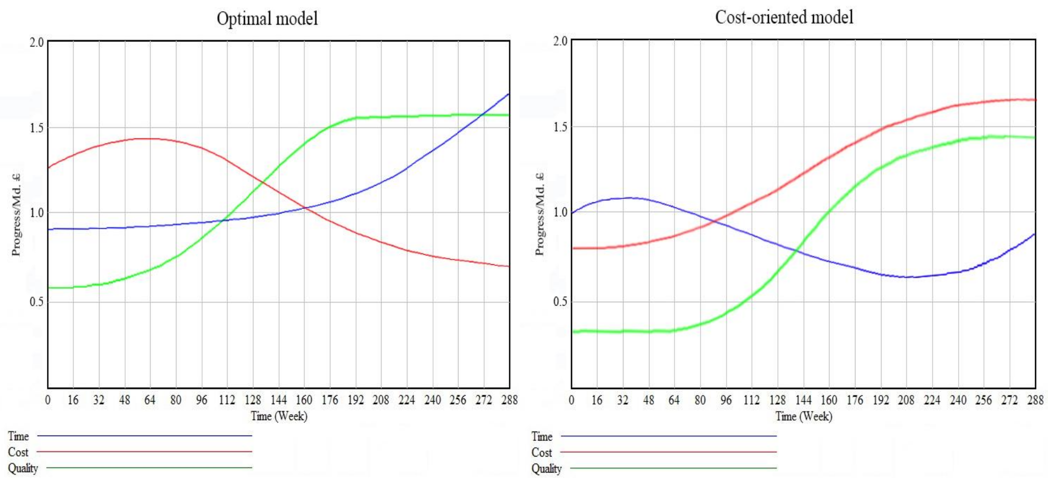

Figure 8.7 Comparison between cost-oriented scenario and optimal model

The difference in cost performance graphs between the optimal and cost-oriented model is presented in Figure 8.7. Unlike time-oriented simulation results, in which cost performance is reduced as much as increasing time performance, in this simulation, time performance is not noticeably decreased in spite of the enhancement of cost performance. Interestingly, in terms of quality performance, there is no significant difference between the optimal and cost-oriented models, which shows that scenario-based models generated based on optimal model, have structural consistency with the optimal model and do not have significant structural differences in graph pattern.

Scenario 3: Quality-oriented simulation. The quality-oriented scenario model is simulated by assuming that in some cases, like public projects, quality performance is recognized as the most important condition. According to a simulation result of the quality-oriented model as shown in Figure 8.8, quality performance is improved compared to optimal model, however the degree of improvement is not outstanding.

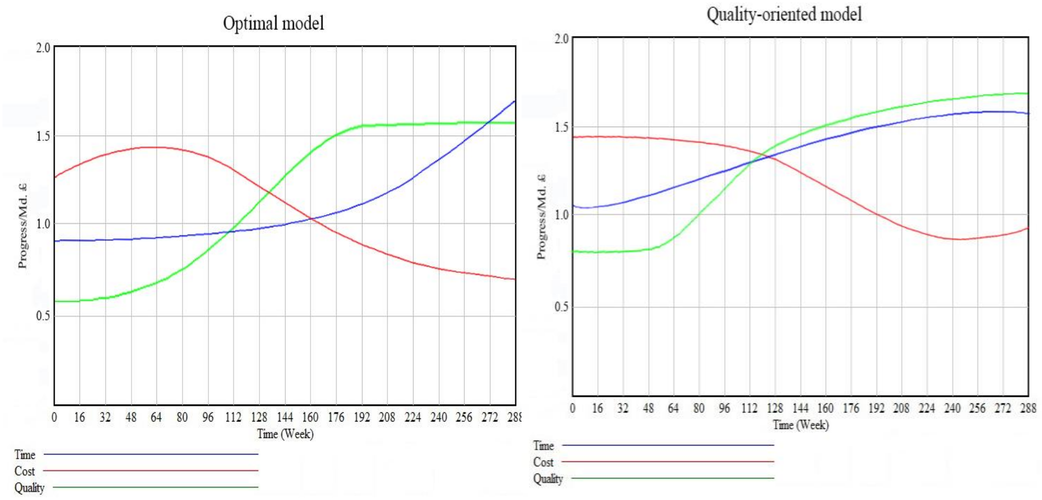

Figure 8.8 Quality-oriented scenario modelling

Unlike other scenario models, in which only the target performance tends to be improved dramatically, quality performance is not improved as expected in the quality-oriented simulation. More remarkably, quality performance is improved compared to the other two performance criteria simultaneously, although it is not outstanding progress. This simulation result shows that even if project quality cannot be improved dramatically by intensive input of project resources in the short term, improved project quality can have an overall positive effect on other cost and time performances.

8.2.3 Result of the verification

In the section above, through a Check model and Sensitivity test, structural and equational problems of the reference model (system dynamics modelling) are resolved and the technical validity of the model and simulations have been found. Check model is the computational program function (Vensim) used to verify the structure of the equations and systema and the sensitivity test is a validation process to verifiy the whole model structure using pre-defined constants and a wide range of random numbers. As a result, it has been verified that the structure and equation of the whole reference model has been suitably formulated by setting the causality principle of system dynamics model. Through the different technical verification it has been confirmed that all constants, functions, and variables are suitable for use in modelling and simulation of the reference model. Moreover, the reference model shows a consistent pattern of behaviour in accordance with the change of the constants with a validity in the 95% margin of error. Due to these different technical verifications of the reference model, the optimal model and scenario-based models, which are formulated based on structure of reference model, are simulated without significant structural errors for diverse and specific real case project. Because the simulation result of the optimal model will be used for the design-production management process map (MDPM), different technical verifications and suitability tests are very basic and critical for this research. Through this, system dynamics modelling using Vensim is validated demonstrating its reliability and completeness.

After the verification of the model formulation using a comparison between the reference and optimal models, the suitability and compatibility of the optimal model for actual project is verified using a comparison with the scenario-based models. Through comparisons with more detailed time, cost, and quality performance simulations, subordinate structures and formulae of the optimal model are verified by seeing whether their behaviour patterns of graph changed consistently within an acceptable range. Using these three scenario-based simulations, it can be proven that the optimal model has enough consistency both in modelling and simulation to be used in the actual project. Thus, all simulation results, model structures and equations, variable interrelationships, and constants can be used as basic data to develop the design-production management process map without the need for serious modification of the model structure or formula.

8.3 Development of design-production management process map

8.3.1 Process map from the contractor's perspective

In the construction and production industries, process models or maps are recognized as an important managerial tool (Clark and Fujimoto, 1991; Winch and Carr, 2001; Tyagi et al., 2015). Smith and Morrow (1999) and Wang *et al*. (2014) point out that development of process maps is useful for understanding the whole system and for improvement and control. Process mapping is one of the visual and logical presentations that can help process improvement, making clear individual and collective activities on site. A design-production management process map (DMPM) was developed as a managerial tool used from the contractor's perspective for research. The DMPM provides an overview of the whole project structure, describing the critical stages and/or activities. It focuses upon flow and the cooperation of design and production information within the project team from the contractor's perspective.

The construction industry has used process mapping in, for example, the generic process models and mappings developed by the RIBA and other organisations (Gray and Hughes, 2001; RIBA, 2007). Due to application of diverse project delivery system, contemporary large and international project needs to consider various project situations and stakeholders. In order to control them throughout production stages, it is very essential that contractors possess their own managing process model considering their ability and project environment (Tunstall, 2000; Wang *et al*, 2014). From the contractor's perspective, the main purpose of the development and implementation of process maps is to provide suitable decision-making and management solutions whilst considering design aspects which can affect the entire production. Using such maps, contractors can establish detailed implementation plans using limited project resources and deal with unexpected design-related problems such as rework or design changes in advance.

A management process map is quite difficult to develop and is operated by construction engineers. This process map is sometimes too detailed to be used by the principal contractors who are non-specialist in individual engineering or technology sectors, thus contractors may overlook or mishandle the detailed interfaces between parts of the process map, such as the architectural design, supply chain, pre-assembly, etc. Moreover, such as in the Korean case, the modelling of system dynamics may be difficult for contractors who are not used to using system dynamics to establish, simulate, and understand process map. Thus, complex and difficult process models are shifted into management process maps that are easy to understand and modify by construction engineers and are compatible with other construction management tools including PMIS, Primavera, or BIM (Nitithamyong and Skibniewski, 2006). As the purpose of this research is to develop a design-production management process map (DMPM) from the contractor's perspective, in order to reduce design-related production risks. The DMPM is implemented at the pre-production stage. This allows the prediction of future production problems and the ability to apply suitable management solutions in advance by understanding the entire project structure and interrelationships between project elements. For this, all diagrams, modelling, and simulations, which are analysed and verified, are carried out to develop an appropriate DMPM from the contractor's perspective.

8.3.2 Process map description

This section describes the DMPM developed based on different research data and the results of simulated system dynamics modelling. As the DMPM is developed to be implemented and operated more easily by contractors (not system engineers or program developers), this section includes a generic explanation of how to read the DMPM using a key or legend. It also gives explicit descriptions of how effective decision-making and management factors are applied to construction activities. The DMPM is designed to encourage both a holistic approach and the detailed management of each design-production management factor at the same time. Thus, the structure of the process map is divided into two layers as shown in Figure 8.9.

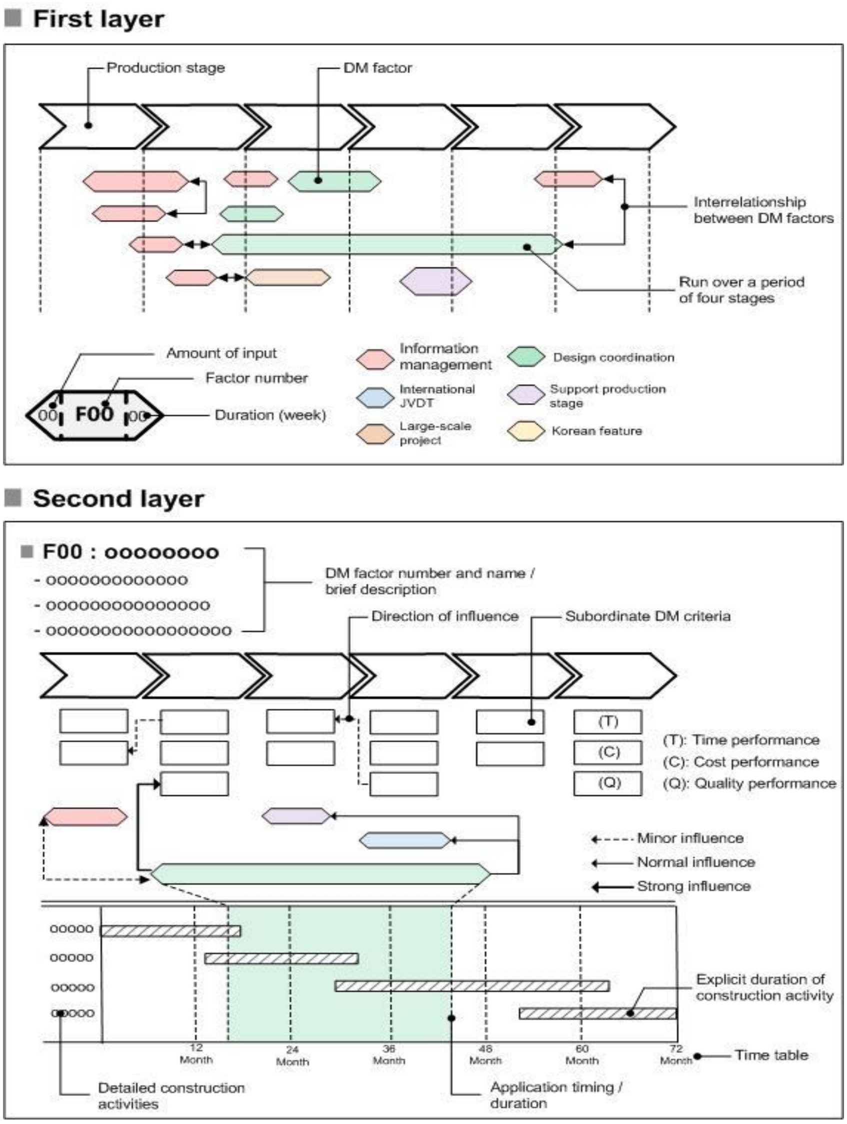

Figure 8.9 Key for DMPM

In the first layer, the construction process is conceptually expressed in 6 explicit production phases. All 37 DM factors are located on the process map according to the applied production stage and applicable period. As shown in the legend in Figure 8.9, the amount of input project resources and the duration of design-production management (DM) factor application are presented on the both side of the legends. Simulated data of individual DM factors, which are applied to the optimal model, such as the amount of input resource, application timing, and application duration, are presented in an easy to understand legend in the DMPM. The second layer consists of more detailed information about each DM factor, thus this DMPM has 37 individual second layers the same as the number of DM factors. In the second layer arrows, link all interrelationships between DM factors and subordinate performance criteria. Here, subordinate criteria means project situation or management solutions, which have a direct influence on three main project performances whether negative or positive. The direct effect is presented as a solid line, the indirect effect is presented as a dotted line, and the critical interrelationship is expressed as a thick and solid line as shown in legend.

The design-production management process map (DMPM) is structured in a matrix form, based on the formulated and simulated system dynamics modelling from the previous chapter. Because system dynamics modelling and simulation results are difficult to read and operate directly on an individual management level, the DMPM in which the detailed information of each DM factor is presented can be complementary to the modelling and simulation of system dynamics as shown in Figure 8.10 and 8.11. It is convenient for various project participants to interpret and can be operated by contractors and engineers.

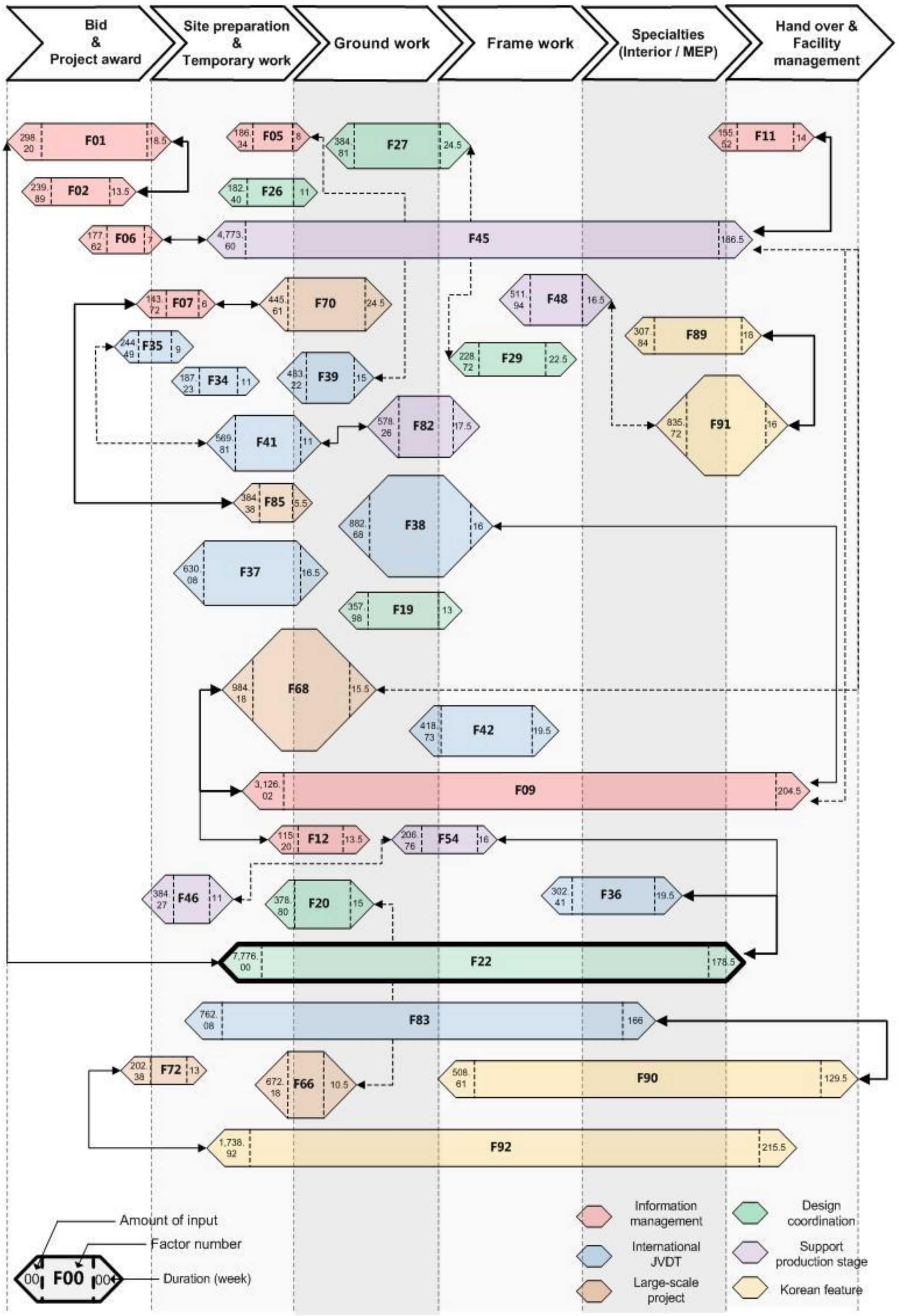

Figure 8.10 Design-production management process map (1st Layer)

Figure 8.10 shows the 1st layer of DMPM that is created based on the results of system dynamics modelling and simulation (Optimal model) for large-scale projects. The process map is the hierarchical structure, which presents the two different levels of detail i.e. the entire production phases and descriptions of individual DM factors. The main purpose of the 1st layer is to represent all DM factors on the process map enabling them to be seen at a glance. The map divides the entire construction process conceptually into six production stages and the 37 DM factors are categorized into six clusters (see Chapter 6.3.2) using their own identification colours. Contractors can recognize in advance which DM factor is applied and when. Albeit roughly, they can understand which factors should be considered to be applied and how long, and to what extent, they should be applied before the start of each production stage.

For example, in the very early production stages such as the bid and project award stage, most DM factors are related to Information management factors (red). Red DM factors such as F01 (Project documents review) or F02 (Review of the design level compared to budget) do not need many project resources or long periods of application. Information management factors should be reviewed and considered to be applied in this stage. In the early stages of international large-scale projects, the management, contribution, and interpretation of initial project information is critical, if the contractor wants to avoid design-related risks.

In Figure 8.10, the legend of each DM factor has different thickness and length according to amount of input resources needed and the application duration except. These are expressed as a constant thickness, regardless of the amount of resources. Accurate numeric information about the actual amount of input and application duration are expressed at both ends, thus users can recognize the detailed information of each DM factor easily. Moreover, all relevant DM factors are interconnected with each other using arrows. Indirect interrelationships are presented as a dotted line and direct interrelationships are presented as a solid line. Strong and close interrelationships are presented as a thick solid line. As this DPMP is developed based on the system dynamics simulation of complex intertwined DM factors, all mutual influences are already reflected in the process map. Thus, contractors (users) can predict before each production stage which production issue has high possibility of causing a design-related problem, and which DM factor should be applied to resolve this problem.

As all DM factors applied and amount of project resources required are presented at a glance in accordance with progress of production stages, a contactor can use this map to establish an efficient distribution plan for the design-related experts and the design management budget. Moreover, all DM factors are expressed with six categorized colours (Information management, Design coordination, International joint venture design team (JVDT), Large-scale construction project (LSP), Support production stage, and Korean feature). When a problem occurs during the production stage, contractors (users) can use quick decision-making on whether project resources are concentrated in which coloured (categorized) DM factors.

Considering the generic features of all DM factors, the critical findings are revealed in this DMPM. In the DMPM, the majority of DM factors are involved in the Site preparation & Temporary work stages which can be represented as pre-production stages. 23 of the total 37 DM factors (over 62%) are applied and managed during the work stage, which reiterates how important appropriate design-production management is at this stage. Particularly, on international large-scale projects, lots of design-production activities need to be reviewed and dealt with at the pre-production stage. Because these design-production activities are about production issues, they cannot be managed at the design stage. However, because they are also design-related issues, they should be resolved before the start of the production stage. Thus, in order to avoid unexpected design-related production risks, most DM factors should be reviewed and managed at the pre-production stage. In addition to this, some DM factors (F45, F09, F22, F83, F90, and F92) are applied and maintained throughout the production stages. Thus, it is also critical to use the limited project resources effectively and in a stable manner throughout the production stages. Using the DMPM, long-duration DM factors or production issues can be reviewed and managed. This is consistent with another view of this thesis, which is that in LSPs involving international joint venture design teams, where design-production management continues throughout the production stages, it should be implemented from the contractor's perspective and not the designer's.

In the 1st layer of DMPM, the entire project processes and application of DM factors are dealt with in terms of design management, production activities, and project resources. Based on the comprehensive and integrated approach of the 1st layer of DMPM, the 2nd layer information describes individual DM factors. Explicit influences on the three project performance criteria (time, cost, and quality) and practical relationships with actual construction process are presented in the 2nd layer using detailed and accurate factor data, not conceptual information. The 2nd layer comprises 37 individual DM factor descriptions with each layer linked to the 1st layer. For example, as in Figure 8.10 and 8.11, if users double click F22 on the 1st layer process map, they can access detailed data of F22 in the 2nd layer of the process map.

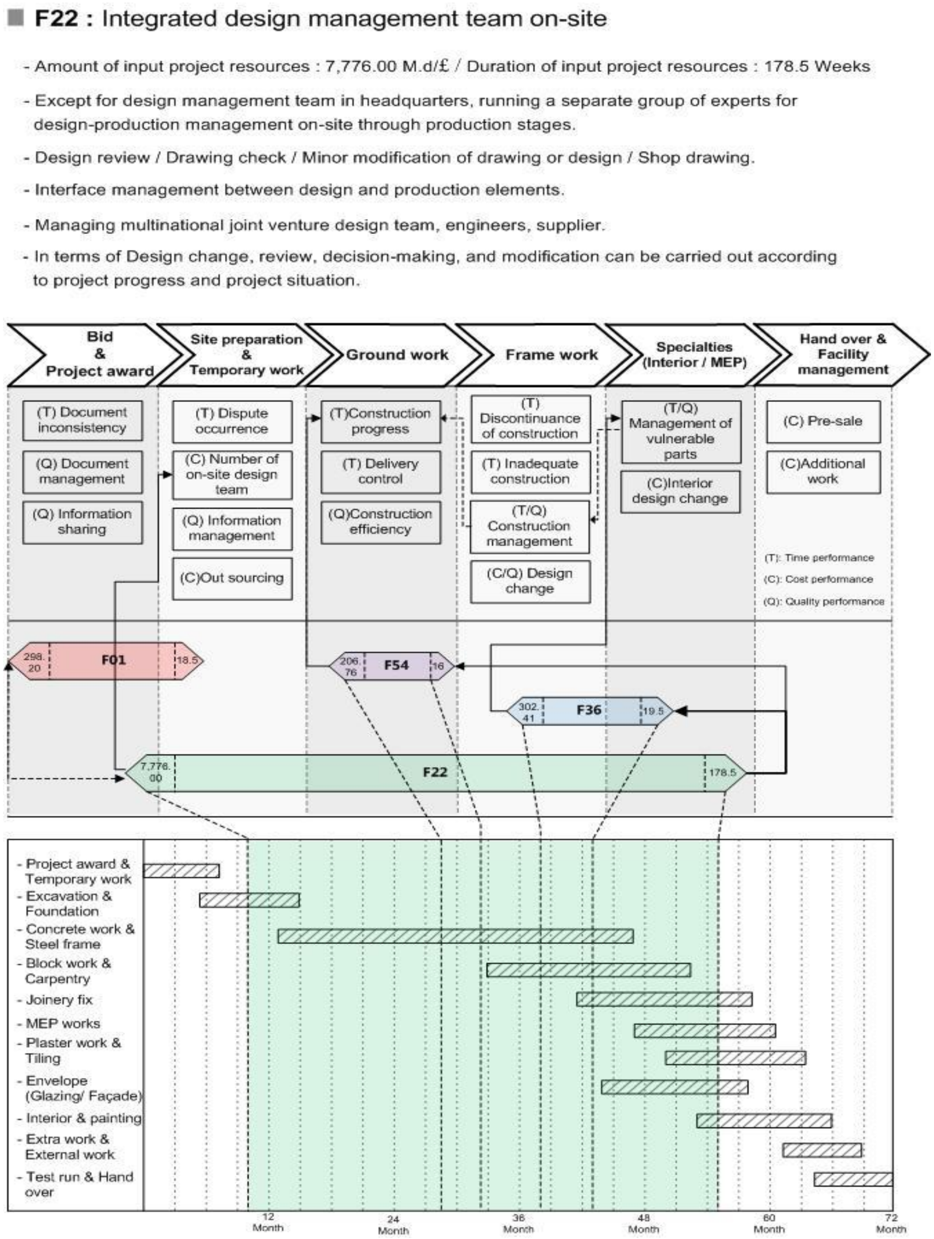

Figure 8.11 Design-production management process map (2nd Layer-F22)

Figure 8.11 is an example of a 2nd layer of F22. For the actual operation, the DMPM is developed as a computational approach, so that users may be able to conveniently access both the 1st and 2nd layers interconnecting each other on a computer by just a double click. The 2nd layer contains more detailed and practical data including relationships between not only other related DM factors, but also subordinate production issues. This layer can be divided into three main parts. The first part describes general information of F22 (Integrated design management team on site), which includes an explanation of the management guide and role, the expected effects, other relevant production activities, the amount of input resources, and the application duration. In the second part, interrelationships are shown, not only between F22 and other related DM factors, but also between DM factors and subordinate production issues. For example, "Number of on-site design team" issues are influenced directly by F22. "Construction progress" issue and "Management of vulnerable parts" issues are indirectly related by F22 through F54 and F36. Moreover, in the 2nd layer, the performance graph of all factors (i.e. F22 and relevant DM factors) and subordinate production issues can be monitored throughout the project processes

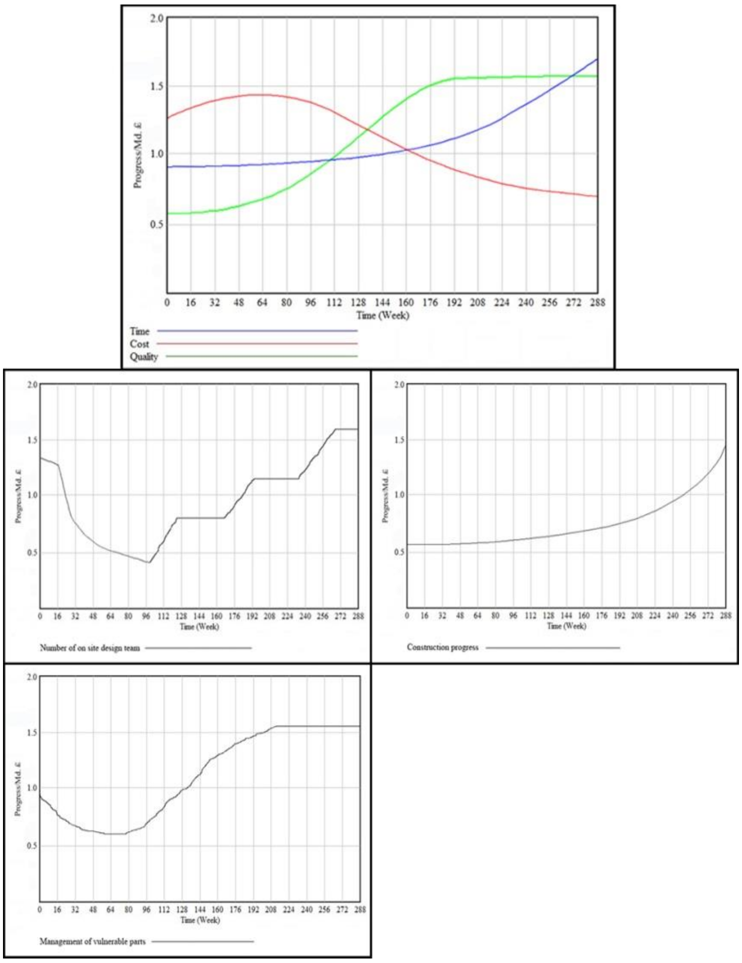

Figure 8.12 System dynamics simulation linked with 2nd Layer (F22)

As shown in Figure 8.12, the simulated performance graphs of DM factors and subordinate production issues can be expressed easily by clicking. As the 2nd layer of the DMPM is about F22 and where it, and relevant DM factors (F01, F36, and F54), influence three subordinate production issues (Number of on-site design team, Construction progress, and Management of vulnerable parts), the linked simulation graph section shows a performance graph of F22 (see Figure 8.12). In the last part of the 2nd layer, the accurate application timing and duration of F22 and relevant DM factors are indicated on the actual LSP progress schedule (bar chart). Using this, the contractor can predict when DM factors (i.e. F22 and relevant DM factors) influence detailed production activities throughout the production stages. The production schedule can be changed or substituted by different forms such as critical path or BIM-simulated schedule in accordance with project feature and situation.

8.3.3 Implementation of process map

The main purpose of development of a DMPM is to achieve consistency in project performance through a comprehensive understanding of design-production management and to gain control of the production stages in order to reduce unexpected design-related risks for the contractor. Contractors or project team members who have no special training in system dynamics can use this process map, as it is relatively simple and convenient. DMPM should be implemented in the very initial stage before the bidding stage and is operated throughout the project unless there are significant structural changes. This is true even if the total amount of input resources, project duration, and number of DM factors are changed. At the bidding stage, contractors have to review incomplete designs, estimate the amount of tender, and make different critical decision-making within a short period of time. Moreover, particularly in contemporary large-scale projects designed by multinational joint venture design teams, initial project information is likely to be incomplete with many assumptions made by the contractor. By implementing DMPM in the initial stages, contractors can recognize in advance when the critical production stage will occur.

Design-production management process map (DMPM) can corporately implemented within the production process along with other managing tools or systems. Originally the fundamental structure of the DMPM is consistent with the construction process, thus application timing and the duration of DM factors is set at each production stage. Even if this DMPM uses a typical time table, aligned to the project progress schedule, construction processes can be viewed as a timetable of this process map. In particular, the performance result of each DM factor and main project performances are presented in graph form across time. Thus, users of this process map (contractors) can estimate project progress and predict the design-related production issues in advance. Based on this data, contractors can decide upon the tender price and establish a comprehensive construction execution plan.

8.4 Summary

This chapter consists of two parts. The first focused on the validation of the structure, equations, and constants of system dynamics model. For this, different validation methods such as reality checks and sensitivity tests were used to verify the technical perfection of the modelling, followed by a simulation of the optimal model. As a result of the comparison between the reference and optimal models and different scenario-based models, the system dynamics modelling is validated as a stable model structure with reliable equations and constants that could be applied in the real large-scale project.

In the second part, after the practical model verification of system dynamics, a DMPM is developed using the optimal model structure and detailed simulation data. In order to be operated and monitored easily by contractors, the DMPM is designed to illustrate the comprehensive project stages in the 1st layer and detailed data of DM factors, including interrelationships with other design-production management factors and subordinate production issues, in the 2nd layer.

Considering the features and the effects of each DM factor and the interrelationships between them, the DMPM provides major parameters within which the DM factors could be used for interface management between design-production activities. This would include when each DM factor should be applied to achieve optimal performance, and how many project resources such as manpower, materials, and budget should be inputted according to the simulation results. Using this process map, contractors can manage unexpected design-related risks from their own perspective before the start of the production stages.

CHAPTER 9 CONCLUSIONS

9.1 Conclusions

There were three statements used at the outset of the thesis.

Statement 1 suggested that complexity and interdependence were an integral part of the management of design information for large-scale projects in Korea. The research concluded that this was an important aspect of the management of information where complexity plays an important part. The requirement for systems tool was justified by use of system dynamics and process mapping.

Statement 2 discussed how design management has evolved as a systems approach. This is an important point for the mapping of information and the development of the process map.

Statement 3 considered the importance of bid, post-contract award and pre-production stages from the contractor's perspective. The research showed the importance of this stage and the interfaces between design and production. This research has fully considered these aspects.

The research problems in sections 1.1 and 1.3, stated that, due to increasing project scale and complexity, the contractors' project management at the pre-production and production process is becoming increasingly complex and difficult. This is exacerbated on large-scale construction projects (LSPs) in Korea, where international joint venture design teams (JVDTs) are commissioned. It introduces another layer of project complexity with the difficulty of dealing with different interfaces between design and production aspects on projects. LSPs incorporate enormous design and production issues that require unique and innovative structural, mechanical, electrical, and environmental system solutions, which must be integrated. The different cultural and language barriers, time zones, work processes, interpretation of technical standards, and building codes, resulting in collaboration issues between the design team and the production team, influence a project involving international JVDTs. Such complexity involves the contractor having to pay more attention at the bid, post-contract planning and pre-production stages in order to manage the interfaces between design and production.

The contribution to knowledge of this research is in the development of a systematic approach using a design-production management process map (DMPM) from the contractor's perspective. It can be useful at the pre-production stage of the project, by modelling the complexity and interdependence of the data and information embodied in the initial project documents using a systematic approach. Based on complexity theory that considers a dynamic and unpredictable project environment, the DMPM from the contractor's perspective helps to resolve the contractor's design-related risk. Using analysed research data, including importance and priority value and interrelationships of individual DM factors, the DMPM was formulated. Thereby, a contractor can better understand the whole structure of a complex project, and establish an appropriate execution plan corresponding to each production stage. By using this DMPM at the early pre-production stage, a contractor can develop a suitable bidding plan and mitigate design-related production risks.

9.2 Research findings

The research had five objectives:

Objective 1 was to understand complexity theory and the interdependences of complex systems. This research showed the importance of understanding how complexity theory influences the management of information and the management of design.

Objective 2 considered the special characteristics of the Korean construction sector, which has a special system whereby the contractor takes responsibility for both design and production. In common with Japan, this is special characteristic and has significant implications for the contractor. Hence, this research addresses the important issue of the interface between design and production, particularly at the bid, post-contract award and pre-production stages.

Objective 3 looked at the organizational and managerial characteristics of international joint venture design teams. The research found many complex interfaces, particularly where a local Korean design team implements the subordinate design concept at the production stage. International joint venture design teams have language, cultural, and technical issues to manage. This adds significantly to the complexity of a large-scale construction project.

Objective 4 considered how a process map could be developed using a system dynamic approach. This was an important facet of the research and showed how it can be used by the contractor at the bid, post-contract award, and pre-production stages. This research makes a valuable contribution to knowledge by exploring this aspect in detail.

Objective five considered how the process map can be evaluated and this was proven in chapter 8.

The author explained why complexity theory is an important underpinning theory behind the thesis. The work also draws upon the theory relating to system dynamics which is a systems approach. Both these theoretical aspects are considered in detail in the research.

The research has five major outputs, each corresponding to specific research objectives as follows:

1. **Complexity in large-scale construction project (LSP) involving joint venture design teams (JVDTs).** Given the highly dynamic and complex components of projects, management has become more difficult. In particular, large-scale or international joint venture projects have another layer of complexity to project performance or construction duration. In order to respond to this problem the research understands the project and interactions between production activities from the complex systems perspective. The research found that the integrated management between design and production aspects or interface management between different management approaches can mitigate design-production risks caused by complexity of LSP involving JVDTs.
2. **Unique Korean construction environment and contractor's risk for project delivery**. In Korea, contractors have a strong authority and responsibility throughout the project stages from design to maintenance. Thus, contractor should consider a wide range of production issues to

mitigate different risk factors in the early stages. In particular design-related risk is very critical, because contractors cannot influence the design stage. In order to reduce this design-related risk in the production stage, this research found that design-production management should be implemented from the early post-contract award and pre-production stages. Thereby, the contractor can estimate appropriate bid amounts by a detailed review of design information and predict what latent design-related risks can influence the production stage before the bid stage.

3. **Critical design-production management (DM) factors from the contractors' perspective.** By different reviews of industrial documents and data analysis, 43 DM factors were determined as critical, which have high importance and preference value. The 43 DM factors were categorised into 6 factor clusters according to their distinct characteristics (see sector 6.3.1 and 6.3.2). Then, based on this classification, an analysis of factor relationship was undertaken. As a result, the research found that high important factors have strong and close relationships with similar high important factors. On the other hand, high preference factors have various relationships with both high important and relative low preference factors simultaneously (see section 6.3.3). All DM factors, whether they have high importance or preference value or not, have a significant impact on whole project performance using their own management features and interaction with others.

4. **Integrative approach using system dynamics at pre-production**

stages. Based on the concept of complexity theory, this research found that an integrative approach using system dynamics can show the whole structure of a project or system, also the detailed behaviour pattern of individual subordinate components over time. Using system dynamics, the whole structure of international LSPs was recognized, complex interactions between design and production factors due to the involvement of JVDTs were monitored and simulated throughout the project stage.

5. **Design-production management process map (DMPM).** The research found that the most efficient management way for complex intertwined design-production management (DM) factors is a process map. Even if the analysed research data and system dynamics simulations are very significant and useful, it is difficult to read and interpret. Thus, based on the results of the system dynamics modelling and simulation, this research developed a DMPM in which the interrelationship between DM factors and individual effect of DM factors on project performance are easily interpreted. By using the design-production management process map, all participants can easily understand all design- related risks and prepare the suitable project implementation plan reflecting these risks in advance.

9.3 Contribution to knowledge

The research has both a theoretical and practical contribution to knowledge. It proposes a paradigm shift in the requirements for design management that has been isolated and separated between design and production aspects. Based on the use of complexity theory, the research challenges the fundamental assumption that integrated interface management can fill the gap in project management between design and production for large-scale projects involving joint venture design teams. The research has made an original contribution to the field of design management by the application of complexity theory, and in-depth interviews with Korean construction experts. It extends the debate around the importance of design management from the design stage to the production stage and continues the research focus on contractor's design management.

Design and production processes have developed independently. As a result, this isolated development in each section leads to increased separation between design and production, without any significant attempts to integrate them. There has been a gap in the body of knowledge between the design and construction stages. Research that attempts to interlink them or fill the gap between design and production has not fully addressed the bid stage and the pre-production stage. This research is about how to manage efficiently interfaces between design and production, in particular for large-scale projects. With a comprehensive understanding and knowledge on both design and production aspects, the most efficient and timely design-production management method was postulated. After in-depth analysis that how much design-production management (DM) factors interacts each other and influences the whole project performance, this research has promoted the need for integrative research between design and production on body of knowledge of management fields.

For more reliable results and accurate data samples, this research narrowed down the research focus to Korean large-scale construction projects involving international joint venture design teams. The results of this research can be helpful for developing countries' AEC industries where management competence is less mature.

9.4 Contribution to practice

This research makes a contribution to practice by allowing the contractor to achieve the benefits of using a design-production management process map (DMPM) on international large-scale construction project involving joint venture design teams. An integrated interface management tool between design and production aspects has been developed. The DMPM provides an understanding of the whole project structure and detailed information on individual subordinate design-production management (DM) factors. The DMPM can be implemented at the early post-contract award and pre-production stages from the contractors' perspective. Using DMPM, contractors can recognize in advance the suitable DM factors that will allow them to manage specific problems as well as when and how much project resources should be allocated to implement a particular DM factor. Thus, contractors can procure critical resources in advance and prepare relevant production activities in accordance with production stages, These are very significant and essential managing factors to carry out international large-scale construction project successfully.

The DMPM can help contractors improve their support for individual project and substantial competitiveness. Management attention is shifted from the project level to the company level, involving the effective sharing of design and production information between project team members on site and the corporate support team. Contractors could accumulate and create a set of new and improved practices, which may contribute to their competitiveness. Implementation of DMPM also implies the development of design-related abilities within the company such as the development of an improved managing model, training to increase the capabilities of design managers and coordinators, or the collaboration with other management systems.

9.5 Limitation

This research addressed the mitigation of contractors' design-related risks from early post-contract award and pre-production stages using the design-production management process map (DMPM). In order to enhance reliable and accurate outcomes, this research narrowed down the research subject to international LSP involving JVDTs in Korea. A limitation is that not all relevant issues and data could be dealt with in the course of this research. There are two main research limitations:

The process of the DMPM production comprises different research steps from data collection through statistical analyses to modelling and simulations. During this process, research data obtained from archival document or industrial data can be selected by subjective opinions and experiences of the author. In particular, due to the nature of causal loop diagrams and system dynamics, the author's personal opinions and experience are reflected in the modelling. In this research, the initial research data was determined through interviews with experts and the model was produced based on survey responses, not the author's opinion or judgement. This helped to maintain objectivity. However, because this research has different research steps including surveys, modelling and simulation, other ways that enhance the objectivity of the research should be applied.

In this research, it was argued that time, cost, and quality performances were used as criteria for judging the contractors' design-production management using the DMPM. Even if conventionally these criteria have been used as the criteria for project performance or success, in accordance with cultural features, project purpose and location, various criteria can be added to evaluate factors. Recently, for example, environmental and health & safety factors are newly recognized as important criteria. In this research, other criteria tend to be overlooked, because this research was conducted from the contractor's perspective. Instead of seeking success throughout the project, the focus was on the contractor's profit in the construction stage. Factors that evaluate entire project performance or success were excluded from the research criteria. However, with the rapid changes in the AEC, other subsidiary criteria could be evaluated for further reliable research.

9.6 Future research

Through the review of the research findings and limitations, this subject can be developed by further research, for example:

- A practical benefit of project performance after application of the design-production management process map (DMPM) should be investigated. In this research, it was suggested that the DMPM may improve project performance from the contractors' perspective. Thus, there would be a benefit if performance was measured after application of DMPM using the actual data from LSPs. Thus, practical effectiveness of the DMPM application and individual DM factors could be measured.

- Design-production management was carried out focussing on traditional procurement, and design-bid-build. However, new/different procurement types by which the contractor can influence design solutiosn at an early stage such as design-build and public private partnership (PPP), have being adapted in the AEC industry. Further research should address DMPM application in other procurement types, to investigate how the DMPM should be modified and to identify the shifting role of the contractor for DM in various large-scale construction projects.
- The DMPM was developed to be compatible with other project management or implementation processes. However, it can use limited project information such as critical path or project resources allocation. As integrated management is so important in contemporary complex international LSPs, further research needs a more integrative approach with other computational managing processes such as BIM, PMIS, or Primavera.

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Appendix A. Survey questionnaire

Survey questionnaire

University of Reading

Development of contractor-led design-production management process map in large-scale project involved international joint venture design team.

Most of all I would like to appreciate for your participate in this questionnaire survey.

This survey will be utilized as a part of PhD research and aim of this research is developing a design-production management process map from the contractor's perspective at pre-production stage for the large-scale construction project involving international joint venture design teams in Korea. Here design-production management means that design management carried out by contractor to increase the construction efficiency. With close and interconnected interrelationships with construction stage not design stage, design-production management is applied at pre-production stage to deal with all design-related risk factor during construction stage. Particularly, this research focuses on only large-scale project implemented by multi-national joint venture design team and other foreign experts.

Therefore, all factors used in this survey are:

1. To represent contractors' perspective not the architect or client
2. To focus on complex large-scale construction project in Korea
3. To be applied in multi-national project designed by joint venture design team
4. To manage the interface between design management and production stages
5. To be applied at pre-production stage for effective construction
6. To be used for development of design-production management process map

As a professional working in international large-scale construction project, you are invited to participate in this research survey. Participation is voluntary; you do not have to complete all of the questions and you can stop at any time. If you participate in this research survey, please give your answers considering above information. Your effort will contribute in the achievement of a better recognition for the contractors' decision making regarding design-production management issues. Responses will be anonymous and confidential. The only persons to see your response are only I and my supervisors. All detailed information of respondents will be kept confidential. Your identity and place of employment will not be mentioned within any publications/presentations resulting from this survey.

If you have any questions about the questionnaire or the research do not hesitate to contact either myself

Seoung-wook Whang, PhD research student.

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Question Part 1

Respondents' general particulars

Name:

Company/Organisation:

Email:

Q1. What is your responsibility and position within your company/organisation?

Department:
Responsibility or role:
Position:

Q2. How long have you been working in the construction industry?

1. Under 5 year
2. 5 to 10 year
3. 11 to 15 year
4. 16 to 20 year
5. 21 to 30 year
6. Over 30 year

Q3. How long have you worked in multi-national based project?

1. Under 5 year
2. 5 to 10 year
3. 11 to 15 year
4. 16 to 20 year
5. 21 to 30 year
6. Over 30 year

Q4. What was your main role when you worked in international high-rise building project?

1. Project manager
2. Site manager
3. Project engineer
4. Design manager
5. Etc ( )

Q5. What of the following back grounds have you experienced before existing role?

1. Developer
2. Architect
3. General contractor
4. Construction manager (PM/CM)
5. Construction engineer
6. Consultant
7. Etc ( )

Q6. How long have you been working in your existing position?

1. Under 5 year
2. 5 to 10 year
3. 11 to 15 year
4. 16 to 20 year
5. 21 to 30 year
6. Over 30 year

Question Part 2

In the Question part 2, all design-production management factors are identified to investigate that what factor belongs to the any management categories and what relationships exist between factors. And also, importance and priority value of each factor are evaluated, respectively.

Below each question item (design-production management factor) includes several subordinate questions. Thus, please choose the number to express your opinion for importance and priority evaluation of each factor and decide a single category this factor can belong to. Lastly, please choose other factors at least 5 and maximum 10, which are considered to have close relationship during production stages.

Design-production management factors

No.	Design-production management factors
F01	Project documents (cost statement, B.O.Q, drawing, specification) review
F02	Review of the design level compared to budget
F03	Terms and conditions review
F04	Preliminary simulation of energy performance
F05	Documents management by the application of Fast-Track (drawing distribution/instruction)

F06	Structural grid planning review (over design, omission)
F07	Review of site conditions (site topography/ground facilities)
F08	Feedback of site situation to PMIS system
F09	Establishment the project management information system (PMIS)
F10	Review of special measurement report (verticality, twist, tilting, column shortening)
F11	Facility management support system (FMS)
F12	Project document control plan
F13	BIM simulation for interior finishing/schedule
F14	Application of web-based individual IT device (for two-way communication)
F15	Check of general tendering policy
F16	Making of colour schedule s for internal decoration
F17	Establishment of project life cycle plan
F18	Pre-tender meeting with bidding and construction team
F19	Off-site construction manual and guideline
F20	Suggestion of material change (constructability, low price, local production)
F21	Interface management between owner furnished items and purchased materials
F22	Integrated design management team on-site
F23	Design risk control and management plan
F24	Review of detailed drawings
F25	Establishment of shop drawing master schedule
F26	Establishment of design integrity checklist on site
F27	Approval working drawing and sample product
F28	Changing design coordination (material change, changed items, constructability, delivery schedule)
F29	Discussion with interior design team for detailed interior design
F30	Design interface management between concrete part and steel part
F31	Overlapping of work packages between design and construction
F32	Detailed design interface management between in suit and Off-site concrete material
F33	Reinforcement of building structure re according to changed construction method or design
F34	Arrangement of pre-meeting with international trader and specialist
F35	Establishment of consortium and joint venture team managing plan
F36	Regular detailed design meetings with subcontractors and suppliers
F37	Delivery control plan for international supply chain
F38	Standardization of different types of drawings and documents
F39	Establishment of long lead/distance item management plan
F40	Cooperation of technical design and material information with international sub-contractor and specialist
F41	Management of design interface between international design and engineering firms
F42	Interface management between domestic building code and international code

F43	Interface management between Korean standard and international standard
F44	Establishment enquiry system between subcontractor and suppliers
F45	Preliminary simulation for constructability
F46	Establishment of project out sourcing plan
F47	Discussion of earthwork method (lump / division construction)
F48	Supporting the making of interior mock-up test
F49	Permanent drainage system (Under slab drainage system)
F50	Review of soil parameters (bearing capacity/density/shear modulus)
F51	Analysis of different concrete form systems (selection of form methods)
F52	Precast frame work package control
F53	Set the work breakdown structure (WBS)
F54	Making criteria for pre-assembly and modularization process on site
F55	Review of concrete quality report (Slump test, air content test, strength test)
F56	Establishment of project implementation plan (PIP)
F57	Development of stock system on site (associated with PMIS system)
F58	Review of performance test report of building materials
F59	Regular monitoring of concrete admixtures
F60	Making performance criteria of building envelope
F61	Review of curtain wall and window performance test report
F62	Review of opening system according to wind tunnel test
F63	Monitoring of sound insulation performance
F64	Establishment of mechanical and electrical facilities up-grade plan
F65	Discussion of extra requirements from client and authorities
F66	Proposal of value engineering
F67	Building frame work master schedule (milestone schedule management and control)
F68	Resource allocation analysis (labour/material/equipment)
F69	Analysis of cost and duration increasing factors according to sustainable design
F70	Establishment of site utilization plan (access, stock yard, work shop, site office)
F71	Interface management between structural and finishing work packages
F72	Review of energy supply grid
F73	Establishment of renewable energy plan
F74	Simulation of life-cycle cost (maintenance cost)
F75	Impact review of large equipment against building structure
F76	Establishment of cooperation plan between structural and earthwork engineer by Top-Down method
F77	Special contract condition review
F78	Similar projects case study (design, construction method and cost, duration, advanced technologies)
F79	Project side effect study

F80	Owner's project requirement review
F81	Fire and smoke simulation according to fire resistance required for each zone
F82	Setting of the responsibility assignment matrix (RAM)
F83	Organization of dispute resolution board (DRB)
F84	Analysis of geographical features
F85	Review of impact on other surrounding buildings (view, insolation, privacy, vibration, dust, smell)
F86	Adjustment of cadastral errors and changes
F87	Claim analysis of similar project
F88	Investment of intelligent building system (IBS)
F89	Discussion with property selling department (concept of interior design, computer graphics, interior finishing simulation)
F90	Work cooperation with project supervisors and authorities
F91	Prior discussion on requirement of major tenants and buyers
F92	Support for environmental building certification (LEED/BREEAM)
F93	Establishment of separated construction plan by pre-utilization of partial building

Example.

Q1. (F01) Project documents (cost statement, B.O.Q, drawing, specification) review.

Q1-1. Factor importance					*Q1-2. Factor priority*				
Not Significant	Slightly significant	Moderately significant	Very significant	Extremely significant	Not preferred	Slightly preferred	Moderately preferred	Very preferred	Extremely preferred
①	②	③	④	⑤	①	②	③	④	⑤

Q1-3. Choose other factors which have interrelationships (at least 5) (ex. F00, F0, Etc.)
( )

- Q1 Means the name of design-production management Factor and (F01) indicates fact or number.
- Q1-1 request to choose the number according to your experience and opinion that ho w much this factor is important.
- Q1-2 request to choose the number according to your experience and opinion that ho w much you prefer this factor to apply in your project, when consider limited time a nd budget.
- Q1-3 means to choose other factors which have close or strong interrelationship with F01. By this, factor relationship between design-production management factors will be investigated.

Q1. [F01] Project documents (cost statement, B.O.Q, drawing, specification) review

Q1-1. Factor importance					*Q1-2. Factor priority*				
Not significant	Slightly Significant	Moderately significant	Very significant	Extremely significant	Not preferred	Slightly preferred	Moderately preferred	Very preferred	Extremely preferred
①	②	③	④	⑤	①	②	③	④	⑤
Q1-3 Choose other factors which have interrelationships (at least 5) (ex. F00, F00, Etc.)									
(									)

Q2. [F02] Review of the design level compared to budget

Q2-1. Factor importance					*Q2-2. Factor priority*				
Not significant	Slightly Significant	Moderately significant	Very significant	Extremely significant	Not preferred	Slightly preferred	Moderately preferred	Very preferred	Extremely preferred
①	②	③	④	⑤	①	②	③	④	⑤
Q2-3. Choose other factors which have interrelationships (at least 5) (ex. F00, F00, Etc.)									
(									)

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Q92. [F92] Support for environmental building certification (LEED/BREEAM)

Q92-1. Factor importance					*Q92-2. Factor priority*				
Not significant	Slightly Significant	Moderately significant	Very significant	Extremely significant	Not preferred	Slightly preferred	Moderately preferred	Very preferred	Extremely preferred
①	②	③	④	⑤	①	②	③	④	⑤
Q92-3. Choose other factors which have interrelationships (at least 5) (ex. F00, F00, Etc.)									
(									)

Q93. [F93] Establishment of separated construction plan by pre-utilization of partial building

Q93-1. Factor importance					*Q93-2. Factor priority*				
Not significant	Slightly Significant	Moderately significant	Very significant	Extremely significant	Not preferred	Slightly preferred	Moderately preferred	Very preferred	Extremely preferred
①	②	③	④	⑤	①	②	③	④	⑤
Q93-3. Choose other factors which have interrelationships (at least 5) (ex. F00, F00, Etc.)									
(									)