To my mother and father
ACKNOWLEDGMENTS

What I would like to say is only one: this work has not been done by me. My parents, their constant encouragement was a source of inspiration and their unconditional love and endless support have driven me to never give up. This work is the result of their smiles, tears, caring, patience, belief, and sacrifice. Words cannot express my appreciation. What I can say is only that I love them. I love my mother and father.

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<td>Constraint</td>
<td>Anything that limits a system from achieving higher performance versus its goals</td>
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<td>Constraint thoroughness</td>
<td>The process to identify constraints derived under schedule compression and to analyze their impacts on project</td>
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<td>Constraint management</td>
<td>The process to stabilize work environment by managing constraints and increase the accuracy of prediction and decrease uncertainties to create the best performance</td>
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<tr>
<td>Evolution</td>
<td>The rate at which design information is generated from the start of an activity through the completion of the activity</td>
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<td>Latency</td>
<td>The possibility of any failure- errors, changes, and side effects under schedule compression</td>
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<tr>
<td>LLT</td>
<td>Latent Lazy Time. The possibility of time reduction by applying schedule compression</td>
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<td>Latency thoroughness</td>
<td>The process to detect latency generated under schedule pressure and manages to solve or reduce the problems</td>
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<td>Parkinson’s Law</td>
<td>Work expands so as to fill the time available for its completion</td>
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<td>QM</td>
<td>Quality Management. Any actions to ensure all activities’ requirement and to improve their work performance</td>
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<td>Reliability</td>
<td>The degree to which LLT could be detected through SCT</td>
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<tr>
<td>Schedule compression</td>
<td>A reduction of time available to complete the work compared to the normal experienced time or optimal time for the type and size project being planned within a given set of circumstances</td>
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<td>SCM</td>
<td>Schedule Compression Management. The process that validates the possibility of time reduction by managing LLT in accordance with schedule compression</td>
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<tr>
<td>SCT</td>
<td>Schedule Compression Thoroughness. The process to monitor and discover LLT including all unintended LLT</td>
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<tr>
<td>Sensitivity</td>
<td>The amount of work required of upstream information change</td>
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<td>Stability</td>
<td>The degree to which the schedule compression within the detected LLT scope would be performed successfully</td>
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<td>Term</td>
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<td>Yerkes-Dodson Law</td>
<td>An empirical relationship between arousal and individual performance, which dictates that performance increase with cognitive arousal but only to a certain point</td>
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<td>90% syndrome</td>
<td>A project reaches about 90% completion according to the original project schedule but then stall; finally finishing after about twice the original project duration has elapsed</td>
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Abstract of Dissertation Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

DYNAMIC PROJECT MANAGEMENT METHODOLOGY: MANAGING SCHEDULE COMPRESSION

By

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Chair: Ralph D. Ellis
Major: Civil Engineering

Despite aggressive efforts of project managers to maintain a project schedule or to recover from a lapsed schedule, delays and cost overruns have become routine phenomenon at many construction projects. This research proposes a proactive schedule compression method to reduce the expected project completion time by removing latent lazy time caused by fallible scheduling and constraints that impose non-value-added effects on project. An additional objective of this research is to develop a systematic environmental model, the Dynamic Project Management Model under Schedule Compression (DPM), to improve performance against latency and complexities of design and construction projects in schedule compression. Developing and implementing the DPM model will result in the following research outcomes: the association of schedule compression and project components with the construction process and their effects on construction performance; detecting and eliminating latent lazy time that project has potentially; managing latency caused by schedule compression; understanding of schedule compression frameworks; and developing system dynamics-based schedule compression model to improve performance under the condition of latency and complexities of design and construction project.
The project management team is responsible for finding methods of meeting the control budget and schedule rather than justifications for not meeting them. – in E/C contractor’s project management policy

Delays and cost overruns are the rule rather than the exception in construction (Sterman 1992). Working under schedule pressure and in a stressful environment has become a routine phenomenon at many construction sites (CII 1989; Nepal et al. 2006). Despite the aggressive efforts to maintain the project on schedule or to recover from a lapsed schedule, project managers walk the “via Dolorosa.”

Time conservation is a prime concern for the both of owners and contractors on construction projects due to the fact that time inevitably equals money; consequently time savings greatly improve profits, while a loss of time can lead to financial distress (Chang et al. 2005). There have been many researches devoted to avoiding the losses of time and money by delay and developing models to control operations and resolve the problems. The efforts, however, have had limited success in terms of dealing with delay prevention or keeping the schedule on time. Studies have also been conducted to determine how to pressure schedule effectively by means of increasing work hours and adding resources and how to manage labor productivity or disputes on the schedule pressure. These studies suggested the alternative and passive solutions because the solutions are acted after delay already takes place and demand to accelerate a project by aggressively pushing the schedule and to cost owner and contractor is necessary.

Although accelerating a project can be rewarding, the consequences can be troublesome (Thomas 2000; Pena-Mora and Park 2001; Nepal et al. 2006): productivity and quality are often sacrificed for the sake of remaining ahead of schedule (Ballard and Howell 1998b), and the
negative effects of schedule pressure arise mainly from working out of sequence, generating work defects, cutting corners, and losing the motivation to work (Nepal et al. 2006). This implies, therefore, that the strategies devised so far cannot be the optimal solutions for time conservation.

Another important factor to be considered is the fact that cost and time are commonly estimated based on historical data and past experiences of contractors and project managers in the planning and designing phases. However, because many projects have been struggling with delays and cost overruns, it is true that the historical data include the projects that did not finish on time and on budget. Furthermore, project performance prediction relies on project manager’s judgments. These judgments are subjective and ambiguous decisions that will be made to control an urgent situation on the job site. For this reason, there is a need for a better proactive and objective system into project control.

The term schedule compression is defined as a reduction of time available to complete the work compared to the normal experienced time or optimal time for the type and size project being planned within a given set of circumstances (CII 1994). In spite of its important role in construction scheduling, only a small amount of research has been conducted on the effects of schedule compression and, more importantly, there are the limited understanding on pressing schedule after delay and disruption, as mentioned above. In an effort to address this issue, researchers must recognize a timely and proactive manner which to mitigate any negative impacts on both schedule and cost is required. In addition, rather than historical data and subjective judgment, which causes unpredictable results, more systematic and objective efforts to estimate cost and time in the condition of schedule compression must be analyzed.
This research is based on the assumptions that there is an optimal pressed schedule at which performance is maximized. A project contains either potentially reducible duration that it originally consists of or preventable delays created by constraints that possibly can be mitigated or removed. As illustrated at (a) in Fig.1-1, a project may have reducible duration at the planning phase. By the normal execution of construction, the duration can be removed at the end of construction phases, (b) in Fig.1-1. Otherwise, the projected schedule is accelerated ahead; such as (c) early schedule compression, (d) late schedule compression, and (e) split schedule compression in Fig.1-1. As a result, the executed duration can be shortened as much as reducible duration and thus, the need of proactive mannered scheduling is explained.
Relying on the theories supporting these assumptions, this research intends to propose a dynamic project management model (DPM) to understand how schedule compression and constraints that impose non-value-adding effects on project are associated with the construction process and how they affect construction performance. Also, this research will develop the systematic environmental model in order to improve performance under the condition of latency and complexities of design and construction project. Thus, the proposed model is expected to benefit the entire life cycle of design and construction projects by reducing costs and duration, avoiding delays, increasing quality, and improving project management by eliminating counterproductive activities.

The objective of this study is as follows:

- **Objective 1:** to identify latent lazy time and latency on construction process and their effects;
- **Objective 2:** to understand the association of project components with construction process under schedule compression;
- **Objective 3:** to develop systematic environmental dynamic model to manage construction project under schedule compression;
- **Objective 4:** to improve performance under high pressured schedule by managing latency; and
- **Objective 5:** to validate the results by conducting case studies.
CHAPTER 2
RESEARCH APPROACH

2.1 Research Assumptions

The application of theory in psychology can elucidate how individual performance is related to stimulation, time, stress, and motivation. An individual’s performance influences the entire process of a project and its results. That the time allotted for a task and an individual’s performance of which tasks are interrelated is supported by two main psychological theories: the Yerkes-Dodson Law and Parkinson’s Law.

2.1.1 The Yerkes-Dodson Law

The relationship between arousal and work performance is curvilinear in which the optimum level of performance is obtained at an intermediate level of arousal (Wickens and Hollands 2000). The Yerkes-Dodson Law (Fig.2-1) explains an empirical relationship between arousal and individual performance modeled as the converted U-shaped curve. It dictates that performance increases with cognitive arousal, but only to a certain point. Performance, however,
decreases when levels of arousal become too high. An inference is that there is an optimal level of arousal at which performance is at a maximum. The upward portion of the converted U can be thought of as the energizing effect of arousal. Negative effects of arousal on cognitive processes on the other hand cause the downward portion.

According to the Yerkes-Dodson Law and in relation to project management, we assume that there exists an optimum level of schedule pressure at which performance is at a maximum. When schedule pressure is too low, the performance is affected because of a lack of urgency or awareness or through boredom, for example. On the other hand, when there is too much pressure, the expected performance may be difficult to achieve as a result of phenomena such as information filtration and omission, adaptation, frustration, and decreased human judgment, and coping strategies tend to be active (Nepal et al. 2006). In this reason, the Yerkes-Dodson Law indicates the importance of finding the optimal schedule pressure to maximize the product performance and explains that appropriate and well managed schedule pressure can increase their productivity up to a particular level (Lee et al. 2006a).

2.1.2 Parkinson’s Law

Parkinson’s Law states that work expands so as to fill the time available for its completion. It can be explained as follows: the demand upon a resource always expands to match the supply of that resource. Put another way, it is if you give someone 8 hours to do a 2-hour project, it will take the full 8 hours to get done, not 2 hours. In Fig.2-2, the planned work, the area of $p_1 \times t_1$, is equal to the complete work, $p_2 \times t_2$.

Parkinson’s Law supports the assumption that there exists the latent lazy time which creates rubber band duration. Time added to the original duration may not effectively protect the planned schedule because when people realize that they have more time to complete a task than the time actually specified, their work productivity usually goes down, often with the task being
deferred to the last minute. This phenomenon is explained in 90% syndrome as well. 90% syndrome defines a project that reaches about 90% completion according to the original project schedule but then stalls; finally finishing after about twice the original project duration has elapsed. Ford and Sterman (1999) found out that the average time to develop a product was 225% of the projected time, with a standard deviation of 85%. The study, furthermore, insists that the management of the final 10% during the last half of the project is typically of the most concern to managers because this portion of the project obviously and significantly deviates from planned progress, focusing attention on the failure of the project to meet its targets, and that eliminating the 90% syndrome could potentially reduce cycle time roughly 50% (Ford and Sterman 1999).

2.2 Research Applications

Based on the Yerkes-Dodson Law, the optimal schedule pressure exists at a maximum of performance. When schedule pressure is higher or lower than the optimal schedule pressure, it induces lower performance and the lower performance results longer duration than expected. The
optimal schedule pressure supported by the Yerkes-Dodson Law will improve the performance. And this affects the relationship between the project duration and the schedule compression.

Putting more pressure on the schedule can result in the time reduction for a project. When the time reduction can be detected by schedule pressure and the performance remains the same amount as it was ($t_2 \rightarrow t_1$), the time difference ($\Delta t = t_2 - t_1$) between the expected duration ($t_2$) and the pressed duration ($t_1$) indicates latent lazy time (Fig.2-3). This statement is supported by Parkinson’s Law, which assumes there may be more time allocated to complete a project than is actually needed. If this latent lazy time can be detected and eliminated or reduced by the imposition of schedule pressure, the reduction of total project duration will result.

The Yerkes-Dodson Law proposed that different tasks might require different levels of arousal. Difficult or intellectually demanding tasks may require a lower level of arousal for optimal performance to facilitate concentration, whereas tasks demanding stamina or persistence may be performed better with higher levels of arousal to increase motivation.

![Figure 2-3. Time reduction by eliminating latent lazy time (Lee et al. 2007)](image)
Figure 2-4. Worse performance by schedule pressure (Lee et al. 2007)

When there is no latent lazy time or schedule pressure is higher or lower the optimal schedule pressure, schedule pressure causes worse performance ($p_1 \rightarrow p_2$) and it affects the project duration ($t_1 \rightarrow t_2$); $A \rightarrow B$ (Fig.2-4). This is the last objective of this project. If, under schedule pressure, we can determine the reason causing worse performance, called latency, we can institute strategies to improve work performance under high schedule pressure without delay. Further, we should consider the preparation about unexpected results on the high schedule pressure.

2.3 Methodology Overview

To accomplish the objectives described in the introduction, this research was conducted based on three major steps: analysis, development, and validation. In the analysis step, research objectives were established and research components to be studied were determined through diverse methods. Based on this analysis, the components were evaluated and applicably developed to the research objectives by systematic concepts and models: constraints management and system dynamics. Then, the models and all components developed in the
Figure 2-5. Concept of dynamic project management model (Lee et al. 2007)

previous stage were validated through a couple of real-world case projects. It is important to note that these steps are not sequential, but spiral and parallel at some parts.

To satisfy the research objectives, first two main studies, project management under schedule compression and the improvement of reliability and stability of projects, were conducted simultaneously. As mentioned before, although accelerating a project can reduce project duration and satisfy owners’ requirements, productivity and quality are often sacrificed and the actual benefits may not be worth the time saved. By these reasons, the reliability and stability of projects are prerequisites to the implementation of schedule compression. For reliability and stability to be improved, it is necessary to identify and manage the constraints creating non-value adding activities. Constraints management and lean construction play the critical role in the improvement of reliability, rather than the reduction of project duration. Consequently, the proactive mannered strategies controlling the constraints should be set up simultaneously with the schedule compression (Fig.2-5).

2.3.1 Analysis

In this analysis step, diverse research methods - literature review, practitioner interview and questionnaire survey - were conducted to identify what to solve and how to solve in detail.
According to the data relied on the diverse methods, the identification and the influence of latent lazy time and latency, and their association with construction process were analyzed, and the constraints deteriorating reliability and stability were identified. Based on the analysis, major issues for the development were determined.

2.3.2 Development

There are three major development phases: development of systematic frameworks for schedule compression, constraints management framework, and the combined management mechanism based on system dynamics approach. Through the phase of development of the schedule compression framework, more practical and realistic concepts and methods were
determined based on the results of the analysis step. At the same time, a constraints management model was established to improve reliability and stability of projects. The analyzed frameworks aim to understand how the influence of schedule compression is associated with constrains, and how they affect construction performance. Finally, based on the frameworks, management mechanism was created to manage the detrimental impact of these components and simulated via system dynamics-based model.

2.3.3 Validation

As the last step, all developed dynamic project management models are applied to schedule compressed activities of real-world case projects to be verified. Through this process, the result of validation shows how close this model presents to the actual performance. The validation phase is conducted through three steps: input elicitation, application to DPM, and comparison of model value with actual value.
CHAPTER 3
SCHEDULE COMPRESSION MANAGEMENT FRAMEWORK

According to the Construction Industry Institute (CII 1990), schedule compression is referred to as the shortening of the required time for accomplishing one or more engineering, procurement, construction or startup tasks (or a total project) to serve one of the three purposes: (1) reducing total design-construction time from that considered normal; (2) accelerating a schedule for owner convenience; and (3) resolving lost time after falling behind schedule. Also, CII states that the primary reasons for compressing or accelerating the schedule of a construction project can be attributed to the following: (1) monetary considerations such as project financing, lost producing during construction, or stockholder pressure; (2) the development of a new product or service by the owners’ organization that needs to get to market as soon as possible due to rising loss-of-opportunity costs; and (3) the planning and design phases of the project delivery cycle have fallen behind the required schedule, forcing the construction phase to make up the lost time (CII 1990; Noyce and Hanna 1998).

In this phase, the association of construction process, latent lazy time, and latency under schedule compression and how they dynamically affect construction performance are discussed. The frameworks for this purpose consist of two main frameworks, the internal management framework and the external management framework, which are combined for the entire project management. These frameworks are the bases for the next step, the management mechanism, in order to develop system dynamics-based project management model under schedule compression model.

3.1 Literature Review

Schedule compression is commonly regarded as a time-cost trade-off problem between the amount of compression and the consequent increase in direct costs due to schedule compression
(Yae et al. 1990; Noyce and Hanna 1997). Many heuristic methods and models have been developed as means of mathematically compressing individual activities of a project schedule (Perera 1980; Perera 1982; Coskunoglu 1984; Ritchie 1985; Vrat et al. 1986; Ritchie 1990; Yae et al. 1990; Moselhi 1993; Senouci et al. 1995; Noyce et al. 1997). Despite the attribution of the schedule compression to the project duration, very little has been published in regard to office and field techniques used to compress a schedule originally developed using normally expected durations. Only a few studies attempted the discrete ways such as work force, financial incentives, overtime, and work scheduling.

The notable studies for schedule compression applicable to office and field have been conducted by Construction Industry Institute, in University of Texas Austin. Based on the expert survey and interview, CII defined the 94 concepts and methods for schedule compression through Delphi methods. The study identified schedule compression techniques that can be used in one or more of the engineering, procurement, and construction phases of the project, and evaluate each technique’s impact on the cost and duration of the project when applied at the three phases of the project.

Moreover, CII gives the definition on each techniques based on the expert survey and literature review. For example, the definition of ‘Just-in-Time Material Deliveries’ in ‘Material Management’ is;

5.03 Just-in-Time Material Deliveries

Deliver materials to the work place as they are needed without intermediate on-site storage. This technique eliminates the time normally allowed for on-site storage. However, successful execution of just-in-time deliveries requires extreme planning, coordinating and expediting action since any failure in the process can produce delays throughout the system. A fringe benefit of this technique is the elimination of double handling of materials on site with consequent reduction of work-hour requirements and potential for loss or damage in handling or storage (CII 1990).
Based on the CII’s schedule compression concepts, Noyce and Hanna delineated planned and unplanned schedule compression to increase productive time and reduce the project schedule. This model contains 34 concepts and methods that are determined to most directly apply to the construction phase. Planned schedule compression is defined as schedule compression that was anticipated and planned for before the start of the construction phase of the project, whereas Unplanned schedule compression is defined as schedule compression that was not anticipated and planned for before the start of construction. Unplanned schedule compression is commonly a result of some form of unanticipated change to the originally planned scope of the work and/or construction schedule (Noyce and Hanna 1998).

With a different approach, Nepal et al. (2006) analyzed the effects that schedule pressure has on construction performance, and focuses on tradeoffs in scheduling and developed scheduling strategies resolving the negative ripple effects. A research framework has been developed using a causal diagram to illustrate the cause-and-effect analysis of schedule pressure. This study indicates that the advantages of increasing the pace of work—by working under schedule pressure—can be offset by losses in productivity and quality.

The negative effects of schedule pressure arise mainly by working out of sequence, generating work defects, cutting corners, and losing the motivation to work. The adverse effects of schedule pressure can be minimized by scheduling construction activities realistically and planning them proactively, motivating workers, and by establishing an effective project coordination and communication mechanism (Nepal et al. 2006). Despite their tremendous works, the researches all failed to show how the effects of schedule compression work systemically to construction process. Accordingly, the systemic understanding and analysis about schedule compression are required.
3.2 Feedback Process of Schedule Compression

Construction is inherently dynamic and involves multiple feedback processes that produce self-correcting or self-reinforcing side effects of decisions (Sterman 1992; Pena-Mora and Park 2001). These feedback processes contribute to generating indirect and/or unanticipated events during the project execution and make the construction process dynamic and unstable, which cannot be captured in the traditional planning tools (Park 2001).

Dynamics in a system arise from the interaction of two types of feedback processes, reinforcing and balancing, among the components of the system, not from the complexity of the components themselves (Sterman 2000). Fig.3-1 shows the conceptual reinforcing and balancing feedback process of latent lazy time and latency by schedule compression. Reinforcing loops tend to reinforce or amplify whatever is happening in system. Those are all processes that generate their own growth. Balancing loops counteract and oppose change, which describes all processes that tend to be self-limiting and that seek balance and equilibrium (Sterman 2000).

Under schedule compression, projects can generate two effects; time reduction or side effects. Time reduction can be achieved by removing latent lazy time. And, ill-managed schedule compression can cause side effects such as errors and changes creating delays or reworks. The balancing loop shows that the management to rectify latency and reduce latent lazy time can have the intended effect of resolving the issues if the decision is correct and well implemented. At the same time, the reinforcing loop illustrates that it can produce side effects that may augment some unintended problems, such as if the decision is incorrect, not well implemented, exceeds the time frame of its effectiveness or if a project manager does not realize the impact of the control actions on other related activities.
3.3 Latent Lazy Time and Latency

Before project launch, anticipating the exact process of it is truly hard. Contractors and project managers commonly estimate costs and time based on the historical data from past projects that they have done. Many projects, however, have been struggling in delays and cost overruns. Hence, it is true that the historical data includes the projects that did not finish on time and within budget. In other words, there could be a time that can be reduced on execution as seen in Fig.1-1.

Latent lazy time is defined as the possibility of time reduction by applying schedule compression. If optimal duration is shorter than planned duration, the difference between the former and the latter is latent lazy time. The reducible duration in Fig.1-1 and the 6 hours in the example of Parkinson’s Law, which is that it will take the full 8 hours to get done not 2 hours if you give someone 8 hours to do a 2-hour project, all can be latent lazy time.
According to the Yerkeys-Dodson Law, there exists an optimum duration on the level of schedule pressure at maximum performance. When schedule pressure is too low or too high, however, the expected performance may be difficult to achieve as mentioned before. That could result phenomena such as failure, errors, changes, or delays. These sort of side effects are called latency (Fig.3-2). Latency is defined as the possibility of any failure- errors, change, and side effects with or without schedule compression.

Latent lazy time can be explained by the results-oriented control method. The result-oriented control is intended to reveal problems so they can be solved. Suppose a compression concept, Just-in-Time (JIT) material deliveries, is applied to an activity. As described in literature review, JIT concept can eliminates double handling of materials on site, so that the technique has the benefit of consequent reduction of time allowed for on-site storage and work-hour requirements, and potential for loss or damage in handling or storage (CII 1994). The time reduction after accelerating schedule, JIT in this example, can be defined as latent lazy time. We can detect the latent lazy time and reduce time and cost by this method, which is also assumed and depicted in Fig.2-3.

Figure 3-2. Effect of latent lazy time and latency (Lee et al. 2007)
On the other hand, schedule compression may result site effects (Fig.3-2). Back to the JIT example, if any failure in the JIT process followed by mal-coordination of implementation of ill-implementation of the action occurs, unexpected delay is produced through the system. In this context, the side effects after applying the compression concept are latency. Latency is divided into two components: existing latency and non-existing latency. Existing latency is any possibility of failure such as unforeseen errors and changes that projects inherently have. Non-existing latency is the site effects after applying schedule compression such as time delay after JIT in the previous example.

3.4 Relationship of Activities

Traditional project management methodologies based on the Critical Path Method (CPM) and the Project Evaluation and Review Technique (PERT) describe the relationship of construction processes and activities as static and linear. However, the actual relationship of real world is more dynamic and complicated. For closer to the real model, the concepts of evolution and sensitivity are applied to this project.

3.4.1 Evolution and Sensitivity

Krishnan et al. (1997) insisted that the information from the upstream to the downstream and the dependency of the downstream to the information from the upstream are the important components of product development to product faster, especially in the overlapping process. Evolution is referred to as the refinement of the upstream information generated from its preliminary form to a final value in their project (Krishnan et al. 1997). Also, Bogus et al. (2005) define evolution as the rate at which design information is generated from the start of an activity through the completion of the activity.
Therefore, project launch highly relies on the completeness of the information of planning and design phases according to the dependency of them. In the foundation activity, pouring concrete cannot be started before form work has been done fully or partially. Such a relationship connecting activities is information dependency. The downstream activity is affected by the information from the upstream activity. So, evolution entails how fast to release the information from the upstream to downstream.

Evolution is identified by design optimization, constraint satisfaction, internal and external information exchange, and standardization (Fig.3-4). A faster evolution does not have to mean a shorter duration for an activity. Evolution is defined in terms of the rate at which information is generated, which does not necessarily relate to the overall duration of an activity. However, activities with fast evolution are more amenable to overlapping than activities with slow evolution. Removing information dependencies allows sequential activities to reduce the project schedule (Bogus et al. 2005).
Sensitivity is the amount of rework required of upstream information change (Bogus et al. 2005), and it is determined by constraint sensitivity, input sensitivity, and integration sensitivity (Fig.3-4). For example, installing pipeline is highly sensitive to pouring concrete. If the pipelines are not properly installed, the concrete foundation has to be removed and the work of pouring concrete has to be redone. Moreover, this relationship will affect the entire project duration. Identifying the sensitivity toward downstream activities is important in planning decision. Starting a highly sensitive activity before all upstream information is complete entails an increased risk that significant rework will be required.

The faster the evolution of information in an activity, the less risky it is to begin a downstream activity before the upstream activity is finalized. Also, the lower the sensitivity to changes in upstream information, the less risky it is to overlap activity (Bogus et al. 2005).

3.4.2 Dependency

Ford and Sterman (1998a) researched how dynamically the role of these relationships plays in the construction progress. Fig.3-5 depicts the internal dependency in situations with constraints affecting work progress (A) and without constraints (B). It can explain that in the situation on B the reliability of latency is 0%. So, the possibility of success of schedule compression would be 100% and time reduction will be expected as much as latent lazy time.
Constraints, however, exist in most construction processes and can affect the development progress and time of the construction.

Graph A in Fig.3-6, which is about the external dependency, explains the relationship that the downstream activity is scheduled to start at 50% completion of the upstream activity, and then finishes with the upstream. It means that the downstream work is dependent on the upstream activity partially. Graph B represents that the downstream activity can start and finish.
regardless of the process of the upstream activity. In this case, two processes are not related to each other. In this context, applying these concepts, the internal and external relationships allow anticipating and managing work process more practically and efficiently.

3.5 Schedule Compression Management Framework

At the project design and planning phases, project duration and cost are estimated based on the historical data from the completed project to achieve the accuracy of prediction. The characteristics of construction project, however, illustrate its large size, uniqueness, uncertainty, on-site production, and highly dynamic complexity, and these characteristics abate certainty of prediction, and the worse prediction is not able to manage construction process effectively.

Latent lazy time and latency are hard-predicted and hard-managed variables by their characteristics of unfamiliar identification and complex process. Maybe, they could be detected and analyzed even after completion of projects. For this reason, the systematic identification and understanding of the construction process with respect to latent lazy time and latency under schedule compression in terms of project and activity level is mostly required to manage the variables successfully.

The multiple feedback processes in construction project necessitate that LLT and latency must be considered and managed as continuous and constant factors. One response to the variables could generate other responses in iterative cycle. The scheduled compression management framework helps to identify the generation and management of iterative relationship focused on LLT and latency under schedule compression. The frameworks are supposed to be proposed in the way of internal management and external management framework. The holistic view of frameworks facilitates to draw the big picture of project and identify the inter-connection of its components.
3.5.1 Internal Project Management Framework

As defined before, LLT is the possibility of time reduction by managing project schedule systematically. When planned project duration is larger than the optimal duration and does not have any intention such as time buffering at the start stage, the project originally involves LLT. It just comes from the nature of project derived from the historical data during the estimation of project duration. The internal project management framework scrutinizes the relationship and effects of LLT and latency with other components under schedule compression within a single activity.

All tasks and activities should be monitored and addressed to detect LLT before the judgment of the possibility of schedule acceleration. In order to depict this process, Schedule Compression Thoroughness (SCT) is introduced. SCT is the process to monitor and discover LLT including unintended LLT and the unintended LLT is generated from upstream activities or LLT reevaluation after the failure of SCT. The term, reliability is used in this step to indicate the degree to which LLT could be detected through SCT.

For example, if the estimated duration of an activity is 100 days, the predicted LLT of the activity is 10%, and the activity has 80% reliability on SCT, then the total reducible time by LLT is 10 days, and 8 days out of 10 days are detected through SCT. It is considered the actual time that can be reduced by schedule compression within the total work scope of the activity. These relationships are formulated as follows;

\[ D_L = D_p \times L \]

Eq. 3-1

\[ D_A = D_L \times R \]

Eq. 3-2

So,

\[ D_A = D_p \times (L \times R) \]

Eq. 3-3
Figure 3-7. Internal management framework
where, $D_p$ is the planned duration, $D_l$ is the total reducible duration by LLT. $D_a$ is the actual reducible duration through SCT, $L$ is LLT, and $R$ is reliability.

However, it is impossible to identify all of LLT through SCT. Therefore, the unidentified LLT should go back to the monitoring step again, and this step is iterative until LLT is completely removed. By this means, $L$ and $R$ are reformulated.

$$L = L_1 + \prod_{k=2}^{n} L_k$$  \hspace{1cm} \text{Eq. 3-4}$$

$$R = R_1 + \prod_{k=2}^{n} R_k$$  \hspace{1cm} \text{Eq. 3-5}$$

Detected LLT at the first attempt is determined by $L_1$ and $R_1$. Others are detected by $\prod_{k=2}^{n} L_k$ and $\prod_{k=2}^{n} R_k$. However, the completed detection of LLT is impossible in real world, and the LLT and reliability on SCT can vary due to the impact of a diverse set of variables during the work process. So, an alternative step is needed to supplement these deficits. This will be explained in the step of Quality Management process.

The identified LLT steps forward Schedule Compression Management (SCM) to be managed and removed. But, unidentified LLT is remonitored with unintended LLT before the work scope is adjusted. SCM is the process that validates the possibility of time reduction by removing LLT in accordance with scheduled compression.

With the known characteristics of schedule pressure, it is very difficult to execute time reduction without any loss of performance from side effects, such as out-of-sequence work, cutting corners, losing motivation, fatigue, and errors and changes. So, the role of SCM reducing project duration by eliminating LLT in stable work environment is the most important, along with consideration of proper techniques for schedule compression.
To satisfy this condition, the concept of stability is brought in with the SCM process. Stability designates the degree to which the execution of schedule compression within the detected LLT scope would be performed successfully. High stability of schedule compression increases the success of execution, and it results in more time reduction. In the application of schedule compression in SCM, for instance, an activity has 50% stability on schedule compression means 50% possibility of time reduction from the detected LLT in the previous example for SCT. Hence, the 50% stability of schedule compression process creates time reduction by as much as half of detected LLT from SCT, 4 days in the example, and that would be the final actual reduced duration through SCM process.

Then, the executed project duration would be 96 days by 4 days, shortened from the planned duration. In the formulation,

\[ D_{F} = D_{A} \times S \]  \hspace{1cm} \text{Eq. 3-6}

then,

\[ D_{T} = D_{F} - D_{p} \]  \hspace{1cm} \text{Eq. 3-7}

where, \( D_{F} \) is the final actual reducible duration through SCM, \( S \) is the stability for schedule compression on an activity, and \( D_{T} \) is the total executed duration of project.

Evolution is the dependency of information for work process before the execution as described fully in Chapter 3.4. The information of identified LLT by the reliability through SCT and the stability for schedule compression application decided in the SCM process influence the decision of implementation and its management during project process in accordance with the information of upstream work process, downstream activity readiness, constraints, design completion, and so forth. Only high evolution enables works stability.
Then, all of these factors decide how single activity is dependent on each other. For example, in the foundation activity, pouring concrete work totally relies on the completion of formwork as seen earlier. If reducible time (LLT) is detected in formwork, project managers have to prepare and execute schedule acceleration. But, the stability of removing LLT on the formwork significantly makes the influence on the time and the process of the concrete pouring work. Like this, the upstream information release and the downstream readiness and steadiness in an activity are the internal evolution and sensitivity, and they are thoroughly managed through the SCM process. These tasks are all involved in SCM process and increase the creation and the completion of schedule compression in the model.

If the schedule compression is well-managed and LLT is successfully removed from the first work scope, the result will generate the time reduction and the work scope will be adjusted according to schedule change, and then the activity is released to the downstream activities or the next phase of project.

However, if the situation under schedule compression is not managed effectively or other unforeseen problems hinder the work process during the implementation of an activity, some

![Evolution Loop](image)

Figure 3-8. Evolution loop
portion of errors or delays, such as unintended side effects, can be created. These side effects are not predicted under the normal project process, which is the planned work process. For instance, the failure of schedule compression, which would be out-of-sequence work by workers fatigue or misunderstanding of LLT by project managers, generates derivative errors and reworks. But, it will not happen if the schedule is not accelerated. In terms of this, these side effects are called latency as described before.

Latency thoroughness is the process to detect latency generated under schedule pressure and manages to solve or reduce it and its problems the way the function of the processes of SCT and SCM works. Quality Management (QM) is defined as any actions to ensure all activities’ requirement and to improve their work performance. For this, all tasks about the management of latency belong to the QM process. Then, the managed side effects that may include other LLT should be monitored again and take the iterative steps to manage LLT and latency. Additionally, the information from the internal evolution to QM, the shadowed area, affects decisions and influence for SCM to manage LLT under schedule compression.

Consequently, the development of information on upstream activity increase the evolution, evolution increases the predictability about the situation of works, and then the predictability finally stabilizes the execution of the downstream or the activity under schedule compression. In addition, high stability ameliorates the correctness of information to downstream (Fig.3-8). Adjusting scope is used to address the total impacts on projects by the processes of internal project management framework and introduce new scope of work to be controlled at the next steps. If the scope of work or project is not adjusted according to the management of schedule and works, it causes an overflow of work and consequently, could cause a project to suffer from slow progress at the later steps (Lee, 2006).
Figure 3-9. External management framework
3.5.2 External Project Management Framework

The external project management framework in Fig.3-9 explains the impacts of schedule compression managing LLT and latency on activities to other related activities of construction processes.

The relationship between the upstream activity and the downstream activity is connected by the concepts of sensitivity and evolution of each activity. The SCM and QM processes of upstream activity influencing its own SCM process, the shadowed area, provide information to downstream as well. This helps manage LLT on the downstream activity, and this process is defined as the external evolution.

Figure 3-10. Extended project management framework
LLT existing in the downstream activity is sensible to external relationship of activities. Unintended LLT, for example, is originally generated from external environment. And, unmanaged latency from upstream also may create unpredicted LLT to downstream. On this account, the LLT of downstream is influenced by the total impact of the upstream activity.

Even though the external management framework starts from the simple interrelationship by sensitivity and evolution between upstream and downstream, the real work process is extended and much more complicated and dynamic (Fig.3-10).
CHAPTER 4
CONSTRAINTS MANAGEMENT FRAMEWORK

Goldratt (1988) defined a constraint as anything that limits a system from achieving higher performance versus its goals and insisted that every system must have at least one constraint. Whether it is originated from in a project or is derived from factors of project processes, constraint is the target that must be identified and managed to improve performance and productivity of a project.

As mentioned before, although accelerating a project can reduce project duration and satisfy owners’ requirements, productivity and quality are often sacrificed and the actual benefits may not be worth the saved time. Hence, for the success of the schedule management, reliability and stability of projects are prerequisite, constraints creating non-value adding activities should be managed, and the proactive manner strategies controlling the constraints should be set up simultaneously with the schedule compression.

As seen in Fig. 3-2, accelerating schedule could either reduce project duration or generate side effects. The objectives to be obtained in this phase are to improve reliability and stability by reducing uncertainty and variation, thereby providing a better environment, enhancing the effects of applied schedule compression and reducing completion time in a project. The ways to improve stability include increasing predictability of downstream activities, removing insecure variables and wastes, decreasing sensitivity by less dependency, reducing uncertainties, and managing constraints. For this constraints management framework, the theory of constraints, key constraints management, and shielding production system based on lean construction were applied to create constraints management framework and satisfy the prerequisites.
4.1 Applied Concepts

4.1.2 Theory of Constraints

Based on the Goldratte’s concept (1988), Rahman (1998) summarized the Theory of Constraints (TOC) as: Every system must have at least one constraint; and the existence of constraints represents opportunities for improvement. Constraint is the weakest link among activities or bottleneck in a process. Any improvement in the constraints’ performance translates directly into improved overall system performance. By strengthening this weakest link, the whole process is stronger; by increasing the flow through the bottleneck, overall system output is increased (Womack and Flowers 1999). Due to the limitation of resources and time, however, it is impossible to explore every single constraint in the system for the best result. For practical resolution, it is necessary to locate the most crucial constraints and resolve them with the highest priority, according to which resolving the constraints at the bottleneck production processes leads to enhanced overall system performance. By these reasons, Goldratt (1990 and 1992) proposed a five-step generic procedure for ongoing improvement in the TOC (Fig.4-1):

(1) *Identify the system’s constraint(s).* Identify these constraints and also necessary to prioritize them according to their impact on the goal(s) of the organization.

(2) *Decide how to exploit the system’s constraint(s).* A managerial constraint should be eliminated and replaced with a policy, which will support increased throughput.

(3) *Subordinate everything else to the above decision.* Every other component of the system (nonconstraints) must be adjusted to support the maximum effectiveness of the constraint. Because constraints dictate a firm’s throughput, resource synchronization with the constraint provides the most effective manner of resource utilization. If nonconstraint resources are used beyond their productive capacity to support the constraint, they do not improve throughput, but increase unnecessary inventory.
Figure 4-1. Process of on-going improvement (Rahman 1998)

(4) *Elevate the system’s constraint(s).* If existing constraints are still the most critical in the system, rigorous improvement efforts on these constraints will improve their performance. As the performance of the constraints improves, the potential of nonconstraint resources can be better realized, leading to improvements in overall system performance.

(5) *If in any of the previous steps a constraint is broken, go back to step 1.*

4.1.2 Key Constraints Analysis

With possibly hundreds of constraints in existence at a time in the course of a project, it is not realistic to consider all constraints equally important given the fact that both time and resources are limited. Therefore, Goldratt suggest that it is more efficient to improve the overall system performance through controlling constraints at the bottlenecks and iterating the procedure for incremental improvement.
A bottleneck is formed when the rate of releasing job orders exceeds the capacity of a machine. In most cases, bottlenecks occur only at a few places while the production system, in general, may still have extra capacity. Bottlenecks exist when there are impediments in the flow caused by unresolved constraints so that work is not released fast enough for downstream activities. It makes sense that constraints at the bottleneck should be highlighted and tackled with priority, especially those resulting in delays (Chua el al. 2005). Such constraints are denoted as key constraints.

4.1.3 Shielding Production

Ballard and Howell (1998b) maintained that the construction production control system should be erected in terms of production planning, material coordination, and work management, and the system should be considered in four different project levels, initial planning, lookahead planning, commitment planning, and methods planning. Initial planning produces the project budget and schedule, and provides a coordinating map that pushes completions and deliveries onto the project. Lookahead planning details and adjusts budgets and schedules and pulls resources into play, thereby focusing supervisors’ attentions toward what is supposed to be done in the near future as well as directing their present actions in a way ensuring that the desired future actions occur. Commitment planning is a commitment to what will be done, after evaluating “should” against “can” based on actual receipt of resources and completion of prerequisites. And planning methods decide how work is actually going to be done with more detailed specification of methods from top to bottom (Ballard and Howell 1998b). Among these planning levels, lookahead and commitment planning enable the system to specify desired input and process so possibly anticipate output and decrease uncertainties within projects.
Figure 4-2. Shielding production (Ballard and Howell 1998b)

Shielding production (Fig.4-2) is an alternative strategy, which shields the direct work force from upstream variation and uncertainty. Shielding occurs from selecting only assignments that can be successfully completed, assignments for which all materials are on hand and all prerequisite work is complete. In order to avoid a mismatch between labor force and workflow, shielding is required to match labor and labor-related resources (tools, construction equipment, temporary facilities, etc) to the workflow into backlog. Lastly, in order to perfect the shield, the degree of fit between the works that have been done and that will be done must be measured, the root causes of failures to complete planned work identified, and those causes to prevent repetitions eliminated (Ballard and Howell 1994a). Shielding is accomplished by making quality assignments, thereby increasing the reliability of commitment plans (Ballard and Howell 1998b).

4.2 Constraints Management Framework

The purpose of the constraint management framework is to create the management structure with which to understand the association of construction process and constraints generated by side effects under schedule pressure and to with which to manage the constraints (Fig.4-3).
Constraints thoroughness is the first step in identifying constraints derived under schedule compression and in analyzing their impacts on the project. This step requires the iterative cycle to detect all possible constraints. Identified constraints are evaluated and prioritized according to their criticalities to the project.

The criticality of constraint is determined by its impact on project performance. Top ranked constraints through evaluation and prioritization process cause larger defects to the
project rather than the others and make it more critical. By this mean, reducing and eliminating critical constraints are more practical and effective to achieve the required performance.

After evaluation and prioritization of constraints, the reasons for delays or any other deficiencies caused by constraints should be explicitly determined based on the consideration of information, resources, and processes involved in activities. This process leads to the necessity of adjusting dynamically work process, scope, and schedule in accordance with the changes of constraints.

A stabilized environment is a prerequisite for a successful completion of a project. Only the stability of work environment produces the rigid information flows from upstream to downstream and provides the improvement of downstream performance, so that the right sequence of work can move best toward project objectives (Fig.4-4). In order to achieve this objective, it is important to protect the direct work from upstream variation and uncertainty. A prediction system estimating the level of stability is introduced and facilitates the understanding of: (1) what characteristics of an activity or the project lead to defects or delay, (2) what the causes are, and (3) the understanding of to understand how these causes are related to effects (Motawa et al. 2007). Through these steps, only stabilized work is released for next processes.

Figure 4-4. Generation from stabilized environment
CHAPTER 5
SYSTEM DYNAMICS-BASED PROJECT MANAGEMENT MODEL

The dynamic and iterative processes of construction increase its complexity and this may balance the systematic structure of construction process by itself or reinforce side effects of decisions. Network-based tools, such as Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT), do not explicitly consider the feedback relationships of activities and other soft variables affecting a project. A system dynamics approach provides an alternative view considering these major relationships and influences on a project and suggesting much of the detail to increase project performance with different ways that traditional project management tools do not employ.

In the previous chapters, the frameworks were developed to analyze the association of construction process, latent lazy time, latency, and constraints under schedule compression and how they dynamically influence one another and affect construction performance are discussed. Based on these progressions, this chapter develops a system dynamics-based project management model to simulate how schedule compression is managed, how this engenders malfunction, how they are combined with constraint management, and how they work in real environment.

5.1 System Dynamics

System dynamics was developed in the late 1950s to apply control theory to the analysis of industrial systems (Richardson 1985). Since then, system dynamics has been used to analyze industrial, economic, social, and environmental systems of all kinds (Turek 1995). System dynamics is a method for studying the world around us. Unlike the traditional study by breaking object up into smaller and smaller pieces, system dynamics looks at things as a whole. The central concept of system dynamics explains how all the objects in a system interact with one
another. The objects and people in a system interrelate through feedback loops, where a change in one variable affects other variables over time, which in turn affects the original variable, and so on. What system dynamics attempts to do is to understand the feedback of system and thus propose the behavior it can produce.

The traditional project management tools experiment with the data from a projected work before it is executed. From the data, the work is decomposed into elements that can be individually related to previous experience. It is then possible to produce reasonable estimates for each element’s duration, cost, and resource requirements (Rodriques and Bowers 1996a). By this imposed discrete view, it is impossible to analyze and revise problems at the point where those happened. The system dynamics approach, however, can capture the major feedback processes to solve defected components of a project where detected until they have completely subsided.

The other major roll of system dynamics model is the way to approach a project based on a holistic view. The strictly discrete view of the traditional tools may not be appropriate to the continuous nature of construction projects. Traditional tools can provide a detailed description of the process including specific estimates of costs and duration and detecting the direct causes of the impacts of project is possible. But, these methods are limited by their use of an indirect project measure and by bundling the characteristics of and relationships among scope, resources, and processes in each activity into a single duration estimate. They also tend to ignore iteration or require that iteration be implicitly incorporated into duration estimates and precedence relationships (Ford and Sterman 1998a). On the other hand, the system dynamics approach considers highly aggregated views of project structure and the focus on the understanding at the project level instead activity level.
Table 5-1. Comparison of the traditional approach and system dynamics approach

<table>
<thead>
<tr>
<th>Nature</th>
<th>Traditional Approach</th>
<th>System Dynamics Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point of View</td>
<td>Discrete and particular</td>
<td>Continuous and holistic</td>
</tr>
<tr>
<td>Approach</td>
<td>Focus on problem</td>
<td>Feedback</td>
</tr>
<tr>
<td>Dependency</td>
<td>Precedence</td>
<td>Internal and external dependencies in the entire project duration</td>
</tr>
<tr>
<td>Input</td>
<td>Resources</td>
<td>Resources and soft variables</td>
</tr>
<tr>
<td>Analysis</td>
<td>What-if analysis</td>
<td>Policy analysis and guidelines</td>
</tr>
<tr>
<td>Linear</td>
<td>Linear</td>
<td>Linear and Non-linear</td>
</tr>
<tr>
<td>Progress</td>
<td>Fixed</td>
<td>Varied</td>
</tr>
</tbody>
</table>

The traditional models view the relationship among activities of project work as the linear dependency, start to start, start to finish, finish to start, and finish to finish. With this approach, perceiving the impacts and the variation of resources and the change of processes is hardly possible. The system dynamics model is used to detail the continuous flow analysis of work process from initial state to the final. This, in turns, predicts the effects of performance, scope, and human factors, including resources and processes with project sequence.

The system dynamics modeling technique can incorporate the causality links between the variables in a construction system and the activity production process. The model explicitly delineates and simulates the relationships between each variable mathematically. Furthermore, the system dynamics modeling technique allows the construction crew to test the different strategies in a controlled environment. One of the most powerful features of system dynamics lies in its analytic capability, which can provide analytic solutions for complex and nonlinear systems. Table 5-1 shows the notable differences between the traditional approach and the system dynamics approach.

**Why System Dynamics**

Sterman (1992) and Lee (2006) detailed the analytic strength of system dynamics in construction projects with respect to understanding to understand multiple feedback processes in
a project, dealing with soft data, developing computer-based model, and managing the complexity and dynamics of large-scale projects.

**Feedback Process:** Feedback processes usually drive the uncertainty and complexity of construction projects. Understanding the feedback process is particularly important in the strategic decision-making process, because good policy decisions come from exhaustive understanding the system. The main idea behind system dynamics is that dynamic and complex behaviors are derived from system structure. System dynamics enables good policy-making and eventually, facilitates the strategic decision making process in project management.

**Aggregation:** One of the features of system dynamics is the ability of the aggregate representation of a project. For example, the stock and flow structure, which is a core model structure in system dynamics, can represent the aggregate behavior. This aggregate representation can contribute to the understanding of the overall system, which in turns enables effective strategies. Once an overall understanding is developed, a detailed decision can be supported by adjusting the level of aggregation in system dynamics.

**Soft Variables:** In most construction simulation, the majority of variables are hard variables that are available as quantitative metrics and numerical data. However, most of what we know about the world is descriptive, impressionistic, and has never been recorded. Thus, soft variables, such as goals, perceptions, and expectations, are significant in representing the world. Particularly, in strategic construction simulation, soft variables become more important because some policies are derived from these soft variables. That is why system dynamics encourages the use of soft variables in modeling of the strategic decision making process. The wide use of soft variables in system dynamics allows us understand how a policy can be implemented and further, how it can affect construction performance, which in turn, contributes to determining a good policy.
Computer Modeling: Computer models help overcome many of the limitations of mental models because they are explicit, and their assumptions are open to all for review. The system dynamics model has naturally has many variables based on the modelers’ assumptions. Computer models are able to interrelate these many factors simultaneously and infallibly compute the logical consequences of the assumptions. The model explicitly delineates and simulates the relationships between each variable mathematically. Moreover, the computer modeling can be simulated under controlled conditions, allowing analysts to conduct and experiments that are not feasible or ethical in the real system.

Large-Scale Projects such as Construction: Large-scale projects such as construction belong to the class of complex dynamics systems. Such systems are extremely complex, consisting of multiple interdependent components, and highly dynamic. Also, these projects involve multiple feedback processes, nonlinear relationships, and both “hard” and “soft” data. The analytic capability of system dynamics facilitates to represent systems with these characteristics and manage the complexity and dynamics of large-scale projects properly.

5.2 Modeling Process

System dynamics modeling normally follows the five steps; system understanding, conceptualization, formulation of a simulation model, validation, and policy design and analysis. Activities of articulating problems to be addressed are conducted in the system understanding step. In this step, key variables to be considered for a project are introduced, and reference modes are developed. The reference mode explains the background of the project and gives the answers to the questions: what is the historical behavior of the key concepts and variables and what might their behavior be in the future?
Table 5-2. Modeling process

<table>
<thead>
<tr>
<th>System Understanding</th>
<th>Formulation of a Simulation Model</th>
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<tbody>
<tr>
<td>Problem articulation: What is the problem? What is the purpose of the model?</td>
<td>Causal loop diagrams: The feedback structure of systems in the relation of variables</td>
</tr>
<tr>
<td>Key variables</td>
<td>Stock and flow maps: The underlying physical structure of variables accumulating material, money, and information</td>
</tr>
<tr>
<td>Reference modes: Specifying the study focus. A set of graphs and other descriptive data showing the development of the problem over time</td>
<td>Policy structure diagrams: Causal diagrams showing the information inputs to a particular decision rule</td>
</tr>
</tbody>
</table>

Conceptualization

Dynamic hypothesis: Working theory of explanation of the dynamics characterizing the problem in terms of the underlying feedback and stock and flow structure of the system

Model boundary diagrams: The scope of key variables which are endogenous, exogenous, and excluded

Validation

Comparison to reference modes

Sensitivity Analysis

Policy Design and Analysis

The creation of entirely new strategies, structures, and decision rules

‘What-if’ analysis

Taking into account the purpose of the project and the reference modes, the explanation for model boundary development to scope the variables to the project, the model for simulation is formulated based on the causal loop diagram and stock and flow maps. That characterizes the state of the system and generates the information upon which decisions and actions are based by giving the system inertia and memory (Sterman 2000). Once the model is completed, validation and analysis steps are needed in accordance with the purpose of the project. As one of the strengths of system dynamics approach, the model generates several levels of scenarios to particularly simulate difference decision models. The policy analysis helps to create new strategies, structures, and decision rules for the improvement of project performance.
5.3 Model Boundary

A model boundary chart characterizes key variables in accordance with the scope of the model focused on the modeling purpose. The model boundary divides key variables into considerations: which one is included (endogenous), which one is assumed (exogenous), and which one is ignored (excluded). Such a characterization is important because the clearer the divisions of variable are, the more successful model is built. Endogenous variables are the primary factors of the model to be considered all the time of simulation and they can be modified in conformity with the simulation environments. For example, the project duration is one of the considerable key factors for this research model. Throughout the accelerating schedule in proportion to reducible duration, the duration of the activity with the reducible duration will be changed. Finally, depending on the variations of other factors influenced by reduced time, the

<table>
<thead>
<tr>
<th>Table 5-3. Model boundary chart</th>
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<tbody>
<tr>
<td><strong>Endogenous</strong></td>
</tr>
<tr>
<td>Latent lazy time</td>
</tr>
<tr>
<td>Latency generation and iteration</td>
</tr>
<tr>
<td>Constraints</td>
</tr>
<tr>
<td>Activity and project progress</td>
</tr>
<tr>
<td>Project Duration</td>
</tr>
<tr>
<td>Activity duration</td>
</tr>
<tr>
<td>Productivity</td>
</tr>
<tr>
<td>Schedule compression (pressure)</td>
</tr>
<tr>
<td>Reliability and stability</td>
</tr>
<tr>
<td>Evolution</td>
</tr>
<tr>
<td>External and internal sensitivity</td>
</tr>
<tr>
<td>Workforce allocation and utilization</td>
</tr>
<tr>
<td>Work quality</td>
</tr>
<tr>
<td>Adjusted activity duration</td>
</tr>
<tr>
<td>Adjusted work scope</td>
</tr>
<tr>
<td>SC Thoroughness</td>
</tr>
<tr>
<td>Delay</td>
</tr>
</tbody>
</table>
total duration that estimated at the planning phase will be changed at the final phase.

Exogenous variables are defined and set by users and do not change during the simulation. The variables have their important roles for a project such as the planned duration of project, but the values do not change for the analysis of endogenous variables’ impacts during the simulation. However, if they need to be changed and involved in the major impacts on the simulation, the value can be changed for the purpose of simulation.

The excluded variables are cautiously not included in the simulation model because they are beyond the focus of the scope and purpose of simulation model. The factors such as weather and other environmental impacts are hardly anticipated and do not have crucial influence of the project management under schedule compression.

5.4 Feedback Processes of Construction under Schedule Compression

As introduced in Chapter 3, a construction project consists of multiple feedback processes, and causal loop diagram is an important tool for representing the feedback structure of systems and showing the dynamics of variables involved in the system. A causal loop diagram comprises variables connected by arrows that denote the causal influences among the variables, and the important feedback loops are also identified in the diagram (Sterman 2000). A positive (+) sign indicates that an increase (decrease) in one variable causes a corresponding increase (decrease) in the dependent variable above what it would otherwise have been. On the other hand, a negative (-) sign indicates that an increase (decrease)

![Causal Loop Diagram](image)

Figure 5-1. Concise causal loop diagram of schedule compression and LLT (Lee et al. 2007)
in the independent variable causes a corresponding decrease (increase) in the dependent variable (Sterman 2000). Fig.5-1 illustrates the relationship between schedule compression and LLT. When delay happens and schedule needs to be accelerated and LLT is detected through SCT, the removal of LLT is required. Finally, LLT is reduced by schedule compression. So, this process is represented as the negative relationship.

Fig.5-2 delineates the causal loop diagram describing the feedback process possibly existing in general construction. B1, the loop consisting of delay, schedule pressure, workforce, and production, explains the self-balance loop about the positive impacts of schedule pressure. When delay is detected, schedule should be accelerated. Appropriate schedule pressure can increase production of project, which is generated by increased workforce. And the increased

![Causal Loop Diagram](image)

Figure 5-2. Feedback process of general construction
production can be the important role to catch up the delayed schedule.

At the same time, R1, the loop of the replacement of production to productivity in B1, indicates the self-reinforcing loop to deteriorate performance under schedule acceleration by changes and errors. As in B1 loop, the right amount of schedule pressure can satisfy its purpose to reduce delayed project duration. However, too much high schedule pressure can create too much pressure on workforce, and it results in the decline of productivity. For clarity, the concepts of production and productivity are introduced like this way. Consequently, this cycle can generate another delay, and it requires another acceleration on schedule.

B2 (schedule pressure – workforce – production – delay – duration) and R2 (schedule pressure – workforce – productivity – construction process – duration) are the feedback processes about the relationship between schedule pressure and project duration. B2 is the loop to reduce the project duration by compressing schedule process through increasing production. R2 is the negative loop of the extension of duration creating additional work caused by decreased productivity. Over-accelerated scheduling and the inappropriate execution of schedule compression can generate side effects. One of the side effects from schedule pressure is working out-of-sequence. This can create another error and change on plan and reworks are necessary. This delays construction process, and the delay leads alternative actions to meet schedule, the loop R3 of schedule pressure, work out-of-sequence, changes and errors, rework, and delay.

Depending on the characteristics of project and the purpose of simulation, causal loop diagram for feedback process can vary. Schedule pressure could increase production through more completed work if workers are not fatigued and do not make mistakes under the situation as in the loop B1. However, schedule pressure may ruin the sequence of work as described in R1. Both two loops increase workforce, but drive opposite results. The structure of causal loop can
be changed depending on the requirement of model and the intention of users. For this, the dynamic state of construction caused by feedback processes makes it difficult to create a dynamic model for simulation and to anticipate or measure the construction performance.

Nevertheless, understanding the construction process with the point of dynamic view based on feedback process enables us to create a unique model for every required situation. The model satisfies the purpose of the project and its model, as traditional network-based tools cannot support and the dynamic model makes it convenient to comprehend project with a holistic view.

**Feedback Process of Construction under Schedule Compression**

The project management framework analyzed in Chapter 3 is the base of the causal loop diagram of construction process under schedule compression. In this project model, LLT has become one of the most important factors that construction projects inherently have. With the consideration of the delay in the historical data, LLT originates depending on the accuracy of estimation from the design and planning phase.

LLT needs to be detected and managed, which leads to the necessity of schedule compression thoroughness (SCT) (Fig.5-3). SCT, the process to detect LLT in a project, is highly governed by the reliability to identify LLT and the information from upstream activity. High reliability increases the correctness of SCT, and the correctness identifies more LLT. However, unidentified LLT augments the total LLT of project.

Fig.5-4 illustrates the cause-effect relationship of evolution and sensitivity in schedule compression management at the activity level. The information flowing from activities based on LLT and latency makes influence on decisions as to whether or not the schedule compression on the activity would be possible and could be executed successfully. If the activity has more tasks that include LLT and require accelerating schedule, the tasks are more sensible to other activities...
Figure 5-3. LLT generation loop
Figure 5-4. Internal evolution and sensitivity loop
Figure 5-5. Schedule compression management loop
Figure 5-6. Quality management loop
Figure 5-7. Causal loop diagram of construction process under schedule compression
by variation of schedule change. This high sensitivity in activity results in the decrease of
construction productivity. In the example of the foundation activity, the task of pouring concrete
task highly relies on formwork and pouring concrete task can begin after a portion of completion
of formwork. In addition, fractions of the duration of formwork are discovered as LLT. Then,
some actions for schedule compression are taken to remove LLT, and the change of the upstream
task duration, the form work in the example, engenders the following reprocess of downstream
task, the pouring concrete in the example. Otherwise, the change of the upstream task could
generate another error or change of the downstream task.

Schedule compression management (SCM) is the process to manage the detected LLT
through SCT described in the Chapter 3 and stability decides the possibility of success of SCM.
Stability increases the task completeness under schedule compression. And, the more tasks are
completed in schedule compression, the fewer tasks need schedule compression (Fig.5-5).
Meanwhile, schedule pressure is required by the increase of tasks with LLT, which is able to
apply schedule compression. However, schedule pressure generates either positive or negative
effects. The positive effect results in more tasks completed in schedule compression commonly.
But, the negative effect delays projects by the decrease of productivity from too much pressure
on workforce. Furthermore, completed tasks potentially have the information for the downstream
task, which gives the answer to the question how much work can now be completed based upon
how much the work has progressed thus far. The increase in the number of tasks makes the
completion rate of the downstream tasks increase.

Schedule pressure can create not only delays, but also other side effects including latency.
Latency is the other important concept together with LLT of this model; so, it must be
considered separately from other side effects, and it is highly related to LLT. More LLT
produces more latency in project (Fig.5-6). These side effects require more management through the latency thoroughness process. The credibility of the latency thoroughness process reduces the problem of side effects and this, in turn, generates more managed side effects and less unmanaged side effects. These processes recursively influence LLT. Latency thoroughness increases the project quality although side effects decrease it. The project quality heavily influences the degree of stability-controlling schedule compression process. Finally, through schedule compression management and quality management processes, LLT can be removed and the removed LLT reduces the project duration as a result. Fig.5-7 shows all feedback process of construction process under schedule compression.

5.5 System Dynamics-Based Project Management Model

The generic construction process structure is suited to represent the generic process of construction projects under schedule compression and depicts the dynamic interactions among variables of activities. In particular, the process structure provides a model to manage schedule compression in a stabilized work environment and to analyze its impacts on the construction performance through three development processes: constraints management process, schedule compression management process, and quality management process (Fig.5-8).

The causal loop diagrams developed at the previous step explain the interdependences and feedback processes of construction project. Based on the diagrams, generic construction process structure is modeled to express quantitative work process consisting of stock and flow structure, which represent stored quantities and control quantities flowing into and out of stocks, or accumulations, respectively. These stocks characterize the state of the system and generate the information upon which decisions and actions are based, and stocks are altered by the rates of inflow and outflow (Sterman 2000).
Figure 5-8. Development processes in the model structure

The model structure provides the methodological approach to control construction project under schedule compression through three development processes at work, activity, and project levels, and the processes are described with the stock and flow structures (Fig. 5-13). In the model structure, development works flow into and through six stocks: Work to Do, Work to be Stabilized, Work Awaiting Redesign, Work to be Checked, Work Done not Checked, and Work Completed. Available works from project start-up or the upstream activities are introduced into Work to Do stock through Initial Work Rate for the first time. Before work execution, the introduced works are monitored and checked for the existence of constraints and LLT. The discovered constrained works through Constraint Thoroughness activity are carried into the stock of Work to be Stabilized by the number of Constraint Identification Rate and waiting for constraints management process. Constraints management is the process to remove the discovered constraints in works and to stabilize the work environment. Work Stabilization Rate defined by the constraints management process moves the works in Work to be Stabilized stock
into *Work to Do* stock for execution. The series of this development is constraints management process (Fig.5-10).

Stabilized works are scrutinized to detect LLT after constraints management process, and if the works in *Work to Do* stock do not include LLT, the works are finished through the performance of the work activity, work rate, and then the finished works accumulated in the stock of *Work Done not Checked*. These works are not inspected as to whether or not they are defective or have not passed through quality management process. Depending on work quality, fractions of finished works are returned to *Work to Do* stock through *Iterate Work Rate* to be corrected, or released to the downstream activities through *Work Completion Rate*. This is quality management process.

If stabilized works, however, potentially have LLT, the works are managed and redesigned to remove LLT and accelerated project schedule. Works with LLT flow into *Work Awaiting Redesign* stock through *Perceived LLT Rate*, and schedule compression management redesigns work process and work rate, *Reintroduced Work Rate*. During schedule compression management, if latency is considered at the works in the stock of *Work Awaiting Redesign*, and then the works are reintroduced to deal with latency through *Request to Check Rate* and *Latency Modified Work Rate*. Schedule compression management process includes all of these activities (Fig.5-12).

These stock and flow relationships can be described with the differential equations listed below and equations define how variables of construction project work and influence each other. For the complexity and dynamics of construction projects, equations for the simulation of the generic construction process model are represented using three dimensional levels, activity, preceding, and succeeding, which are respectively denoted with subscripts $j$, $i$, and $k$, where $i,j,$
and \( k \in \{1, 2, \ldots, n\} \). These indicate activity itself and the relationships of activities with upstream and downstream activities. For clarity, the subscripts \( j \) is omitted in the absence of subscripts \( i \) and \( k \).

\[
\frac{d}{dt}(\text{Work to Do}) = \text{Initial Work Rate} + \text{Work Stabilization Rate} + \text{Latency} + \text{Modified Work Rate} + \text{SCT Reprocess Rate} + \text{Iterate Work Rate} - \text{Work Rate} - \text{Constraint Identification Rate} - \text{Perceived LLT Rate} \quad \text{Eq. 5-1}
\]

\[
\frac{d}{dt}(\text{Work to be Stabilized}) = \text{Constraint Identification–Work Stabilization Rate} \quad \text{Eq. 5-2}
\]

\[
\frac{d}{dt}(\text{Work Awaiting Redesign}) = \text{Perceived LLT Rate} - \text{Reintroduced Work Rate} - \text{SCT Reprocess Rate} - \text{Request to Check Rate} \quad \text{Eq. 5-3}
\]

\[
\frac{d}{dt}(\text{Work to be Checked}) = \text{Request to Check Rate} - \text{Latency Modification Work Rate} \quad \text{Eq. 5-4}
\]

\[
\frac{d}{dt}(\text{Work Done not Checked}) = \text{Work Rate} + \text{Reintroduced Work Rate} - \text{Work Completion Rate} - \text{Iterate Work Rate} \quad \text{Eq. 5-5}
\]

\[
\frac{d}{dt}(\text{Work Completed}) = \text{Work Completion Rate} \quad \text{Eq. 5-6}
\]

### 5.5.1 Basic Work Rate

The feedback process in the causal loop diagram of construction process, as seen in Fig.5-7, depicts the negative loop consisted of work available, work rate, and work completed (described as \textit{Task Available}, \textit{Work Force}, and \textit{Task Completed} respectively in Fig.5-7), and the cause-effect relationships among these three variables decide the work rate. Work rate is based on work available, average work time, and resource constrain.

Average work time is the average time required to complete a development work on an activity if all required information, materials, and resources are available and no defects are generated (Ford and Sterman 1998a). Therefore, the work rate mostly relies on work available in average work time, which indicates work productivity. Also, work process highly depends on the amount of materials, equipment, and labors. Hence, each activity requires sufficient resources and enough of information. Accordingly, the work rate of activity is determined as the minimum
of resource constraint and work productivity that is the value of work available divided by average work time.

In this manner, work to do is introduced by Initial Work Rate, and Initial Work Rate is obtained from Initial Work Available, Initial Work Time, and Initial Resource Constraint.

\[
\text{Initial Work Rate} = \min (\frac{\text{Initial Work Available}}{\text{Initial Work Time}}, \text{Initial Resource Constraint})
\]

Eq. 5-7

5.5.2 Constraints Management Process

Before work execution, the works in the stock of Work to Do are considered whether work process is stable or constrained by inappropriate resources or irregular process through constraint thoroughness. In the similar manner with the basic work rate, Constraint Thoroughness is the lesser of Constraint Thoroughness Restriction and the number of work waiting for constraint thoroughness divided by the average time, which the process requires to constraint thoroughness.

\[
\text{Constraint Thoroughness} = \min (\frac{\text{Work to Do}}{\text{Avg. Constraint Thoroughness Time}}, \text{Constraint Thoroughness Restriction})
\]

Eq. 5-8

Once constraints are under consideration, the works accumulate in Work to be Stabilized stock to remove constraints and stabilize work environment through Constraint Identification Rate. Meantime, constraint thoroughness is not perfect and all constraints cannot be discovered.
So, Constraint Identification Rate is determined by Discovery Rate of assumed constraints with the fraction of constraints in total work based on Constraint Thoroughness. Therefore, Work Rate of Unconstrained Work is the outflow from Work to Do stock and includes both of stabilized work after constraints management and work with undiscovered constraints.

\[
\text{Constraint Identification Rate} = \text{Constraint Thoroughness} \times \text{Discovery Rate} \times \left( \frac{\text{Total Constraints in Work}}{\text{Work Scope}} \right) \quad \text{Eq. 5-9}
\]

\[
\text{Work Rate of Unconstrained Work} = \text{Constraint Thoroughness} - \text{Constraint Identification Rate} \quad \text{Eq. 5-10}
\]

The discovered constraints in works are managed through the constraints management process. The constraints management process was explained in the Chapter 4, and Fig.4-3 shows the framework of constraints management. Through the process, Work Stabilization Rate is
defined by constraints management rate and *Constraint Subordination*. Then, the works are released through *Stabilized Work Release Rate* relied on *Managed Constraint Rate*.

\[
\text{Work Stabilization Rate} = \text{Stabilized Work Release Rate} \times \text{Managed Constraint Rate} \times \min \left( \frac{\text{Work to be Stabilized}}{\text{Avg. Constraints Management Time, Constraint Subordination}} \right)
\]  
*Eq. 5-11*

### 5.5.3 Schedule Compression Management Process

The stabilized works released from constraints management process accumulate into the stock of *Work to Do* for Schedule Compression Management (SCM) process. If project managers or workers find any reducible duration in a work or neglected work force (work rate) through Schedule Compression Thoroughness (SCT) process and designate the need of schedule acceleration, the assumed works are carried into the stock of *Work Awaiting Redesign* through *Perceived Latent Lazy Time Rate* for rescheduling. Otherwise, works in *Work to Do* stock proceed with the initially scheduled work process according to *Work Rate*. This process is determined by the value of *LLT Potential*. Finally, *Perceived LLT Rate* is lesser of the SCT process rate and *LLT Potential* in *Work Rate of Unconstrained Work*.

\[
\text{Perceived LLT Rate} = \min \left( \frac{\text{Work to Do}}{\text{Avg. SCT Time}}, (\frac{\text{Constraint Thoroughness} - \text{Constraint Identification Rate}}{\text{Constraint Thoroughness}}) \right) \times \text{LLT Potential} 
\]  
*Eq. 5-12*

\[
\text{Work Rate} = \min \left( \frac{\text{Work to Do}}{\text{Min. Work Time}}, (\frac{\text{Constraint Thoroughness} - \text{Constraint Identification Rate}}{\text{Constraint Thoroughness}}) \times (1 - \text{LLT Potential}), \text{Resource Constraint} \right) 
\]  
*Eq. 5-13*

Works in the stock of *Work Awaiting Redesign* are waiting for rescheduling by removed LLT and following schedule compression. The outflow from the stock extremely depends on *Schedule Compression Thoroughness*, which is the process to monitor and discover LLT. However, SCT cannot detect all of LLT from perceived LLT. So, the work that possibly does not include LLT returns to *Work to Do* stock for the reconsideration of SCT or the planned process of work execution. As a result, *Schedule Compression Thoroughness Reprocess Rate* is determined by incorrectness of SCT upon reprocess time.
SCT Reprocess Rate = (1 – SCT) * (Work Awaiting Redesign / Min. Reprocess Time) 
Eq. 5-14

‘Reintroduce Work Rate’ is the work rate based on productivity newly generated by schedule compression. This is concerned with the possibility of LLT detection and the stability of rescheduled construction process on schedule compression applications.

Reintroduced Work Rate = SCT * Stability * min ((Work Awaiting Redesign / Avg. Reschedule Time), Schedule Pressure Resource Constraint) 
Eq. 5-15

However, the adjusted work rate after schedule compression should always be larger than the initial work rate. For further information, let’s assume there was a project of which the planned duration was 100 days and the total work amount was 100,000 W. (W is used as a hypothetic work unit.) And, 10 days LLT existed in the planned duration. Then, the project should have finished in 90 days. The work environment including work force, material resources, and information of this project had ability to finish the project in 90 days. But, the schedule planned to be done in 100 days. In terms of productivity, 1,000/9 (productivity_{should} – productivity_{planned}) is wasted as LLT.

So, the project should be rescheduled by increasing throughput (a – b) in a day work amount based on the productivity_{should}. The work environment decides arousal, which is interpreted as schedule pressure that determines corresponding productivity. Details of this are shown in the description of the Yerkes-Dodson Law. To remove LLT, the arousal that decides schedule compression should be the optimum level of productivity, productivity_{should} in this case. However, if there is too much schedule pressure on project, the productivity in the execution of the project is getting lesser than productivity_{should} in accordance that the executed arousal is lesser than A_O or more. Finally, the productivity is lesser than productivity_{planned} that concludes project delay.
For this, *Reintroduced Work Rate* must be larger than *Work Rate*. If *Reintroduced Work Rate* is smaller than *Work Rate*, the *Reintroduced Work Rate* would contrarily delay project, which means the uselessness of schedule compression and the need of the reconsideration of SCT. By this reason, the equation 5-15 should be reformulated as:

\[
\text{Reintroduced Work Rate} = \begin{cases} 
\text{IF THEN ELSE (SCT} \times \text{Stability} \times \min (\text{Work Awaiting Redesign} / \text{Avg. Reschedule Time}, \text{Schedule Pressure Resource Constraint}) > \text{Work Rate, (SCT} \times \text{Stability} \times \min (\text{Work Awaiting Redesign} / \text{Avg. Reschedule Time}, \text{Schedule Pressure Resource Constraint}), 0) 
\end{cases}
\]  

Eq. 5-16
Through *Reintroduced Work Rate* of schedule compression management process, works with reducible duration or neglected work rate are carried into the stock of *Work Done not Checked* and waits for quality management process before the works are released to downstream activities.

Under the consideration of schedule compression with respect to detecting and removing LLT, once the possible failure of schedule compression is identified, the schedule compressed processes should be reconsidered and the possibility of latency should be eliminated. This step is influenced by *Schedule Compression Thoroughness* and in-*Stability* of the schedule compression execution to detect LLT.

\[
\text{Request to Check Rate} = \text{SCT} \times (1 - \text{Stability}) \times \left( \frac{\text{Work Awaiting Redesign}}{\text{Min. Reprocess Time}} \right) 
\]

Eq. 5-17

The identified latency is managed and the works after latency modification move back to *Work to Do* stock for work execution. This step is similar to the step of constraints management.
Latency Modified Work Rate = \min \left( \frac{\text{Work to be Checked}}{\text{Avg. Latency Modify Time}}, \right. \left. \text{Latency Modification Constraint} \right) \quad \text{Eq. 5-18}

5.5.4 Quality Management and Work Completed

Executed construction works through \textit{Work Rate} and \textit{Reintroduced Work Rate} accumulate in the stock of \textit{Work Done not Checked} to be monitored and inspected. According to the results of quality management, the works in \textit{Work Done not Checked} stock are either released to the downstream activity or iterated for rework. \textit{Quality Assurance} (QA) activity is the process to discover defective works. If works are not defective, the works leave \textit{Work Done not Checked} stock and pass through \textit{Work Completion Rate} into the stock of \textit{Work Completed}. If works are found to be defective, the works go back to \textit{Work to Do} stock through \textit{Iterate Work Rate}. These works need to be corrected and improved through iterate work activity and return to the initial work stage for reprocesses.

In a similar manner to the determination of flow rate, the work available for quality assurance is the number of works done not checked. Therefore, \textit{Quality Assurance} rate is the lesser of the work process of quality assurance activity and its resource constraint.

\[
\text{Quality Assurance} = \min \left( \frac{\text{Work Done not Checked}}{\text{Ave. QA Time}}, \text{Quality Assurance Resource Constraint} \right) \quad \text{Eq. 5-19}
\]

However, it is impossible to discover all defective works by quality assurance activity. Hence, the rate for reprocesses by defects depends on the defects detect rate, \textit{Quality Management Thoroughness}, and the fraction of defective works, \textit{Work to be Iterative Ratio}. Accordingly,

\[
\text{Iterative Work Rate} = \text{Quality Assurance} \times \text{Quality Management Thoroughness} \times \text{Work to be Iterated Ratio} \quad \text{Eq. 5-20}
\]

In the same manner, the \textit{Work Completion Rate} is determined by non-defective work rate and works not found defects based on \textit{Work Release Rate}
Figure 5-13. Generic construction process structure under schedule compression
Work Completion Rate = (Quality Assurance * (1 – Quality Management Thoroughness) * 
(1 – Work to be Iterated Ration)) * Work Release Rate \hspace{1cm} \text{Eq. 5-21}
= (Quality Assurance – Iterate Work Rate) * Work Release Rate \hspace{1cm} \text{Eq. 5-22}

5.6 Development of Dynamic Construction Project Model

The system dynamics-based project management model has been developed through the series of progresses and plays the important role to understand the association of construction processes under schedule compression. Based on the system dynamics model, the development of project model enables to identify the interaction and mechanics of four performance drivers – process structure, resources, targets, and scope – in a dynamic construction environment.

The four performance drivers are strongly related to each other and the generic structures for the project, and which is dominant to decide the project performance. The project performance is implied by the traditional measures for the construction project: time, quality, and cost. The project model refers them with execution, which involves project duration and defects by constraints, project management and cost.

The interactions of the primary phase subsystem are depicted in Fig.5-14, including project process, resource constraints, required project goal, and its demands. Each driver has its own components to decide the role in project and they influence each other. The generic structure of the system dynamics model and the dependencies of activities in the project process dominate the project process. For example, in the foundation activity, the task of pouring concrete is totally dependent to the progress of formwork.

The stability of the activity according to the generic structure of project and dependency affects the project performance. At the same time, the foundation activity demands concrete and woods for forming and pouring works. These relationships are indicated with the solid and dashed lines in Fig.5-14. Demands and requirements to rely on another driver are represented by the solid line. Project performance is mostly influenced by the effectiveness of resource
management and can ask the adjustment of resources. The dashed line explains the return for correctness. Formwork demands woods. So, the woods are supplied for the work as return.

Consequently, process structures simulate the system dynamics model and its dependency. Resource structures simulate the effects and the allocation of workforce, material, and equipments in the development project model. Scope structures model the projected scope of targets for duration, quality, and cost relative to targets and the pressures on developers due to poor performance (Ford and Sterman 1998a).
CHAPTER 6
APPLICATIONS

The previous chapters presented the methodology of construction project management under schedule compression and the system dynamics-based project management model for the purpose of the research has been developed. Based on the method and the model structures, this chapter scrutinizes the validation of the dynamic project management model (DPM) and its applicability as project performance analysis tool by applying the model to a couple of real world case projects.

First, the verification focuses on the applicability of DPM with the application of the real construction projects. It explains how to apply the model to real project and examines how close the result of simulation represents to the actual performance. Secondly, the applicability of the model is observed as project performance analysis tool by representing the simulation results in detail. Finally, policy analysis proves the effectiveness of DPM by adapting base case with difference policy scenarios of project performance. These steps help to identify the possibility of the user-defined simulation modeling approach to the planning and control of construction project.

For the simulation, Primavera Project Planner (P3), Vensim® PLE, and Microsoft Office Excel were used. P3 is a software package for scheduling and tracking project related activities and it worked for the analysis of the performance of the real projects. Vensim® is one of the software for system dynamics and used for developing, analyzing, and packaging high quality dynamic feedback models. Vensim® PLE is the lowest version of the Vensim series. Therefore, there are so many limitations to get sufficient results for the research from Vensim® PLE. By this reason, the cooperation with other tools is required. Microsoft Office Excel analyzed the results from the simulation by Vensim® PLE.
6.1 Dynamic Project Management Model Application

6.1.1 State Route 25

For the application of DPM to real project, the construction of highway project in Florida was simulated. The project was to widen and reconstruct State Route 25 (US 27) from north of SR-530 to north of Boggy Marsh Road located in Lake county, Florida (Fig. 6-1). The contract was awarded to Ranger Construction Industries, Inc. and A+B contract was accepted. The incentive of $5,300 per day was supposed to be paid when the project was finished earlier than original project duration and should not exceed $900,000. The original bid cost was $22 million and the final cost was $22.5 million.

This case project serves to verify the validation of DPM by comparison of simulation results with real project performance and the application of DPM for analysis of work progress, the influence of latent lazy time and latency in project and their results.

![Figure 6-1. SR-25 project location](image)
In order to determine the simulation input, a series of interviews with construction managers, superintendents, and scheduler participated in the project has been conducted based on their experiences and historical data. 86 major activities based on the activities in the critical path was selected for the simulation and. The example of input variables are like as in Table 6-1 and the complete list of input variables are shown in Appendix C. Except the major input variables indicated at the above table, DPM has over hundreds variables for simulation to get simulated result close to realistic outcomes. And, some of the variables need to be defined as constant value. However, for the simulation of the SR-25 project, the rest of the input variables were given to satisfy the purpose of this research. The complete list of the variables and formula for the simulation can be referenced at Appendix B.

6.1.2 Validation

The comparison of the simulated output of DPM with the actual project process verifies the applicability of DPM as a project management tool to plan and control construction project.

---

Table 6-1. Example of input variables for simulation

<table>
<thead>
<tr>
<th>#</th>
<th>ID</th>
<th>Activity</th>
<th>OD²</th>
<th>LLT</th>
<th>Stability</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1090</td>
<td>Obtain temp drainage material</td>
<td>10</td>
<td>NA</td>
<td>NA</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>2265</td>
<td>FL power adjustment I</td>
<td>34</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>1010</td>
<td>Install MOT</td>
<td>2</td>
<td>NA</td>
<td>NA</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>2270</td>
<td>FL power adjustment II</td>
<td>50</td>
<td>5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>1140</td>
<td>Install 60&quot; SD trunk line to pond</td>
<td>50</td>
<td>NA</td>
<td>NA</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>1070</td>
<td>Stage I temp med &amp; RT pav</td>
<td>33</td>
<td>2</td>
<td>NA</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>1130</td>
<td>Excavate pond 1 &amp; stockpile</td>
<td>43</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>1160</td>
<td>Clear &amp; grub for stage II</td>
<td>15</td>
<td>3</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>1155</td>
<td>Excavate pond 2</td>
<td>15</td>
<td>NA</td>
<td>NA</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>1185</td>
<td>Excavate pond 5</td>
<td>15</td>
<td>6</td>
<td>3</td>
<td>NA</td>
</tr>
</tbody>
</table>

81 2110 Install remaining permanent 5 4 3 8
82 2115 Adjust traffic control signal 5 5 2 9
83 2120 Install final roadway signs 5 6 5 8
84 2125 Asphalt friction course 20 5 4 9
85 2130 Final roadway marking 20 5 4 8
86 2135 Remove construction signs 1 NA NA 9

Note: 1. Scale of 0 to 10. Higher value means more LLT included, more stable, and more sensitive to dependency 2. Original Duration 3. External Sensitivity
under schedule compression. Also, the result is compared with the Critical Path Method (CPM) planning, which enables to explain the advantage of the workability of DPM against CPM’s. Fig.6-2 illustrates the comparison of the CPM plan, the actual progress, and the simulation result of DPM of the SR-25 project at the Percentage Work Complete (PWC) level.

The construction of the project started on March 27th, 2006, and the project was planned to finish by January 4th, 2008. The original contract day was 650 days based on the analysis of CPM scheduling. The real project, however, finished earlier than 74 days, October 23rd, 2007, the actual construction period of 576 days. And, the simulated completion date of the project by DPM was November 9th, 2007, 593 days. While CPM plan is behind the actual progress, the simulated output from DPM is almost following the actual progress of the project. As of October 23rd, 2007, the value of Root Mean Square Error (RMSE) between the actual progress and the

![Image of graph showing Percentage Work Complete (PWC) for CPM, Actual, and DPM projects. The graph illustrates the comparison of the CPM plan, the actual progress, and the simulation result of DPM at the Percentage Work Complete (PWC) level for the SR-25 project. The graph shows the project started on March 27, 2006, and finished earlier than planned, completing on October 23, 2007. The graph also shows the simulated completion date by DPM on November 9, 2007. The actual progress is compared with the CPM plan, and the simulated output from DPM almost follows the actual progress of the project. As of October 23, 2007, the value of Root Mean Square Error (RMSE) between the actual progress and the simulated output from DPM is almost following the actual progress of the project.]
DPM value was estimated at 2.4039% with 2,292 data sets. On the other hand, the RMSE of the actual progress with the CPM plan was estimated at 11.4955%.

6.1.3 Analysis

The application of DPM facilitates to analysis project performance in detail and to predict and manage a project based on its results from DPM. Fig.6-3 depicts the simulated work progress rate of the SR-25 project over the CPM plan. By May 7th, 2007, the project was far behind the plan. Especially, at the initial stage, the construction project kept delaying with serious decrease rate. After August 22nd of 2006 (day 149), however, the work progress started to catch up with the original plan. Therefore, as the turning point of May 7th, 2007 (day 409), the construction progress from DPM surpassed the planned progress, and finally expected to finish 4.95% earlier than the original plan at work progress rate.

The identification of the possibility of schedule compression is introduced by the work quantity for latent lazy time and latency. In accordance with the schedule compression management process represented in Fig.5-12, the works in the ‘Work Awaiting Redesign’ stock

Figure 6-3. Work progress rate
Figure 6-4. Net redesigned work and net work to be checked
decide the possibility of work to be redesigned for schedule compression and also decide the
possibility of work to check any latency causing and defects on activities and delay of project.
Fig.6-5 demonstrates the cumulative quantity of the work that has possibility for schedule
compression and Fig.6-4 illustrates the net redesigned work that could be removed or could be
the reason to reduce project duration by raising work rate according to latent lazy time that the
project originally involves and the net work to be checked that could generate delay from
changes or errors caused by latency. The simulation result of DPM predicts that the works for

Figure 6-5. Total work awaiting redesign
possible schedule compression converge on around day 410 (E in Fig. 6-4), while the works for potential delay by the fail of schedule compression are distributed in the initial and final phases of the project (F and G in Fig. 6-4). Further, the concentration of the net redesigned work on E in Fig. 6-4 and the net work to be checked on F in Fig. 6-4 introduces the rapid increase of cumulative work quantity on E and F in Fig. 6-5 (Using the same alphabet letters in different figures signifies the same causes on the area.)

The introduced works by net redesigned work and net work to be checked could reduce the total project duration with elimination of latent lazy time or expand the duration caused by latency as delineated at the previous chapters in detail. Their effects on productivity are entailed in Fig. 6-6, and the total effects of latent lazy time and latency on productivity are shown in Fig. 6-7. LLT effects on productivity are highly concentrated on H and I in Fig. 6-6. According to the net redesigned work, the effects of controlling LLT increased work performance. It resulted in the boost the total work progress and it led the reduction of project duration. A in Fig. 6-2 and Fig. 6-3 is the consequence of the LLT effect on productivity, I in Fig. 6-6. As the same reason, the LLT effect on H in Fig. 6-6 brought the augment of C in Fig. 6-4 on work progress. Even though LLT effect of H picked more than that of I in Fig. 6-4, the reason why the increase of C is

Figure 6-6. LLT and latency effects on productivity
Figure 6-7. Total schedule compression effect on productivity smaller than the increase of A in Fig.6-3 is that the average LLT effect on A is higher than the average LLT effect on C. Moreover, net redesigned work and LLT effects on productivity started to increase gradually from day 149, and this turned into the motive to convert negative work progress to positive one with the ongoing decline in latency effects on productivity.

LLT effect existed from the initial stage. The total schedule compression effect on productivity, however, did not work at the initial phase of the project, L in Fig.6-7. This is because the redesigned work was curtailed by work to be checked and that consequently eliminated the LLT effect with the absence of net redesigned work even though LLT could have affected the project performance. In addition, the major effect of latency on J in Fig.6-6 is the other reason of no impact of total schedule compression on L in Fig.6-7.

On the other hand, as the other factor to influence project performance, latency effects on productivity drag on project progress under net work to be checked. The impact of latency on productivity exacerbated negative impact on project performance and asked the need of reconsideration of schedule compression. Accordingly, its concentration on J and K in Fig.6-6
delayed project as seen in B and D of Fig.6-3. The average LLT and latency effects on productivity are respectively 2.0240 and 1.3702.

Net work to be checked dose always not indicate the work that causes delay by unsuccessful schedule compression. It contains the work to be reconsidered for schedule allocation. In the case of SR-25 project, the project strolled down in the early phase and caught up with the original plan later. One of the reasons was that many activities were planned to begin simultaneously at the early step. When the project launched, however, the requisite of activity reallocation for better efficiency of work performance was detected. Actually, by moving some activities in the initial phase back to later phase, the reduction of project duration was expected and accomplished. This enables to explain the result of B in Fig.6-2 and 6-3 and also explain that the net work to be checked of F in Fig.6-4 was affected by the latency effect of J in Fig.6-6 and also needed the reconsideration of rescheduling biased-work quantity by the concentrated activities. This elucidation discussed in Chapter 5 as well.

The factors discussed so far mutually manipulate every components of project and that regenerates work rate for project performance. Fig.6-8 states and compares the work rates of CPM scheduling and DPM simulation. Latency effects on net work to be checked deteriorated

Figure 6-8. CPM vs. DPM work rates
the efficiency of planned work rate, N in Fig.6-8, on the other hand, well-managed LLT on net redesigned work reintroduced and increased work rate, O in Fig.6-8. Therefore, they respectively concluded in the delay and acceleration on project progress, B and A in Fig.6-2 and 6-3. While the average work rate of CPM scheduling was 1,500 w/Day, the one of DPM simulation was 1,710 w/Day. W is the work unit for simulation. Reintroduced work rate primarily decided by LLT effect on productivity amplified work rate and the amplification was the major cause of the reduction on project duration.

Consequently, the LLT effects on J in Fig.6-6 cause the augment of total schedule compression effect on M in Fig.6-7, and this elicited the major increment of work progress, A in Fig.6-2 and 6-3. The effect of latency on the project, J in Fig.6-6, trailed the initial project progress, B in Fig.6-2 and 6-3.

6.2 Policy Implications

The other case project is applied to DPM in order to exam scenario specification in

Figure 6-9. SR-25 II project location
different environmental conditions. Policy implications design new decision, rules, strategies, and structure that might be tried in the real world and represent how robust policy recommendations are under different scenario and given uncertainty (Sterman 2000). With this case project, how the time for Schedule Compression Thoroughness (SCT) and its reliability affect construction performance are explored.

For the objective, another highway project in Florida was simulated, which was the reconstruction of State Route 25 (US 27) from the westbound ramp at SR-50 to County Road 561-A in Lake county of Florida (Fig.6-9) (called SR-25 II project in distinction from the previous project). The original bid cost was $25.5 million and the final cost was $27.4 million. The input variables for the simulation were listed in Appendix C.

The project began on February 17\textsuperscript{th}, 2006, and was planned to finish by April 26\textsuperscript{th}, 2008. The original contract day was 800 days based on the analysis of CPM scheduling. However, the project was actually completed by February 16\textsuperscript{th}, 2008, and the actual duration was 730 days. The project duration simulated by DPM was 757 days. Fig.6-10 illustrates the PWCs of the CPM

![Figure 6-10. Percentage of work complete of CPM, actual work, and DPM (SR-25 II)](image-url)

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPM</td>
<td>800 days</td>
</tr>
<tr>
<td>Actual</td>
<td>730 days</td>
</tr>
<tr>
<td>DPM</td>
<td>757 days</td>
</tr>
</tbody>
</table>
scheduling, the actual work, and the simulation result of DPM of SR-25 II project respectively. For 540 days, the DPM progress was behind the planned progress. As of February 16th in 2008, the estimation of RMSE between the actual progress and the DPM result was 2.5024% with 2,920 data sets. On the other hand, the RMSE of the actual progress with CPM schedule was estimated at 7.5866%.

Except the input data, the values of many other variables consisting of DPM structure influence simulation results. Most of all, SCT plays an important role in the accuracy of the results analyzed by DPM. The time needed for SCT and the reliability of SCT alter the

![Figure 6-11. Percentage of work complete according to SCT time](image)

<table>
<thead>
<tr>
<th>SCT time</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 day</td>
<td>757 days</td>
</tr>
<tr>
<td>2 days</td>
<td>760 days</td>
</tr>
<tr>
<td>1 week</td>
<td>771 days</td>
</tr>
<tr>
<td>2 weeks</td>
<td>797 days</td>
</tr>
</tbody>
</table>
prediction of construction performance. The time and reliability of SCT for the base case were 1 day and 100% respectively. Under the condition, the simulated duration was 757 days. For the closer results applicable to real world project, first, the SR-25 II project was simulated under 2 days, 1 week, and 2 weeks of SCT time by DPM. When SCT process took 2 days, the project duration was 760 days. Under SCT process of 1 week, the total duration of the project was 771 days, and 797 days of project duration was generated with 2 weeks for SCT process (Fig.6-11). When SCT process needed more than 2 weeks, the simulated duration of DPM was longer than the planned duration by CPM.

The base case had 100% of the reliability on SCT. That means that errors or reconsiderations in monitoring and detecting LLT do not exist through SCT process. If SCT process is less reliable, the process will generate latency resulting in delay of project during schedule compression and iterative cycles caused by errors or reconsiderations will require additional SCT time and errors. For clear consideration, the project was simulated under different situations: 0%, 25%, 50%, 75%, and 100% of SCT reliability. The results of project
Figure 6-13. Work rate vs. SCT reliability

duration are depicted in Fig.6-12. The project durations were respectively 800 days, 792 days, 781 days, 769 days, and 757 days on the condition. The result with 0% SCT reliability was same as the one of CPM. Which means that CPM scheduling does not consider, even cannot elicit the causes and effects of schedule compression on project performance.

Fig.6-13 delineates the varied work rates on the different scenarios. As seen in the table, the more reliable SCT is, the higher work rate is. Consequently, higher work rate decreases project duration. Entirely, the rate of work rates around day 550 to 600 is high. This is caused by

Figure 6-14. Net redesigned work and net work to be checked vs. SCT reliability
Figure 6-15. Schedule compression effect vs. SCT reliability

the LLT effect on productivity within the net redesigned work. Fig.6-14 and Fig.6-15 illustrate
the considered work for schedule compression and the effect of schedule compression on
productivity against different SCT reliabilities.

Table 6-2 enumerates the results of duration, RMSE, and the average of LLT and latency
effects under 0% to 100% of SCT reliabilities. As SCT reliability increases, the duration
decreases and the accuracy of DPM increases. The scarcity of accuracy of DPM reduces the
effect of LLT, but augments the impact of latency.

<table>
<thead>
<tr>
<th>Reliability</th>
<th>Duration (Day)</th>
<th>RMSE (%)</th>
<th>Avg. LLT Effect</th>
<th>Avg. Latency Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 %</td>
<td>800</td>
<td>7.5866</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>25 %</td>
<td>792</td>
<td>6.2164</td>
<td>1.1922</td>
<td>1.2629</td>
</tr>
<tr>
<td>50 %</td>
<td>781</td>
<td>4.7909</td>
<td>1.2485</td>
<td>1.2785</td>
</tr>
<tr>
<td>75 %</td>
<td>769</td>
<td>2.6592</td>
<td>1.2662</td>
<td>1.1706</td>
</tr>
<tr>
<td>100 %</td>
<td>757</td>
<td>2.5024</td>
<td>1.3256</td>
<td>1.0599</td>
</tr>
</tbody>
</table>

Note: 1: 2,920 data sets
CHAPTER 7
CONCLUSIONS

Construction is a living organism. Along with the requirement of its characteristics, a project is planned and created. Depending on the environment, the growing process of a project varies. The large-scale, uniqueness, and complexity of a construction project deteriorate the prediction of project progress and its performance, and aggressive project schedules and inappropriate response to delays often invite undesirable consequences on a project’s cost and schedule (Nepal et al. 2006). The uncertainty and variation demand more endeavors of contractors and construction managers as a requisite of schedule compression. Moreover, with the traditional project management methodologies, a lack of understanding of schedule pressure and the perspective considering construction as a static and linear project make the planning and control of construction under schedule compression more difficult. As an effort to address these challenge issues, Dynamic Project Management Model (DPM) has been developed in this research.

7.1 Applicability of Dynamic Project Management Model

Understanding of Dynamic Construction Process under Schedule Compression

Construction process is complex, dynamic, unstable, and replicate. Multiple feedback processes in a construction project contribute to generating indirect and unanticipated results during the project execution. A lack of management mechanism and understanding of schedule compression introduced more efficient and practical concepts of *Latent Lazy Time* and *Latency* for reliable management to accelerate schedule. The development of the frameworks for internal and external management of activities helps understand the association of construction process, latent lazy time, and latency under schedule compression and how they affect one another and construction performance in an activity and in a project.
Based on the management frameworks, system dynamics determined the causes and effects of the feedback processes, and capturing how development processes affect project performance by explicitly modeling those processes provides significantly improved descriptions of development team mental models, project constraints, and the drivers of project performance (Ford and Sterman 1998a). To understand the construction process with the point of dynamic view based on feedback process enables us to create a unique model for every required situation. The dynamic model satisfies the convenience to comprehend projects with a holistic view that traditional network-based tools cannot support.

**Realistic and Proactive Planning**

System dynamics offers a project management model that reflects the real experiences of projects, which seldom follow the simple linear route suggested by the logic of the traditional project network. Taking into account dependencies of evolution and sensitivity, production type, and soft data based on feedback processes enables to augment the reliability of the planning and managing of construction projects. In the case projects for simulation, the project type, the experience level of works, fatigue according to workhours, and the internal and external sensitivities were the critical input variables, and which are also the main input variables of the dynamic project management model and influence project performance. By understanding these information, a project manager can use that information to identify appropriate strategies for reducing or removing those dependencies (Bogus et al. 2005), and thus possibly result in the reduction of project duration.

The newly introduced concepts, latent lazy time and latency, allow to interpret the quantitative impact of schedule compression on a project. The detrimental impacts of these two factors imply the applicability of the implementation of schedule compression and the reconsideration of work rate by accelerating schedule. This interpretation facilitates to predict
project performance and streamlining information flow under schedule compression and the prediction based on the accuracy and constructability imposes appropriate strategies for better achievement of schedule compression. Through collaborative efforts directed at anticipating upcoming results and reducing potential problems in advance, opportunities for the increase in work rate and the decrease in latency can be accomplished.

**System Dynamics-based Project Management Model**

With the combination of Critical Path Method (CPM) scheduling, the DPM based on system dynamics was developed to plan and control construction projects under schedule compression. The user-defined project management model focuses on the ability to dynamically interpret construction processes and practice and analyzes the system structure to understand dynamic behavior for the great contribution to management of a project. The elaboration of the quantitative work for schedule compression and its side effects, the reintroduced work rate in accordance with schedule acceleration, and the analysis of the impacts of LLT and latency on project performance enhances the reliability of prediction and the applicability, and thus devises robust and explicit tactics for the best consequences.

**7.2 Future Research**

The dynamic project management model for schedule compression that has been developed in the previous steps facilitates to analyze the relationship of activities and their effects at the activity and project levels and to manage project performance under schedule compression. When design and construction become more complex and dynamic, concurrent process in the large scale project are developed, and projects are globalized, the associated uncertainty and complexity can introduce serious schedule, cost, quality, and safety problems. That increases the factors that must be considered and it requires the necessity of more concise
and potent utility to manage the projects. In an effort to address these issues, future researches are directed.

### 7.2.1 Standardization of Compression Concepts and Methods

Project performance operated by DPM is predicted relied on the project manager’s judgment. The input for simulation of DPM such as reliability or stability is different according to the experience and perspective of project managers or experts, which are subjective and ambiguous to make a correct decision to control the urgent situation on job site, and that creates different outcomes. For this, there is a need to create better objective judgment system into project control. In addition, more systematic and objective efforts to estimate cost and time in the condition of schedule compression must be analyzed than historical data and subjective judgment causing unpredictable results.

In 1990, Construction Industry Institute (CII) at University of Texas Austin published Concepts and Methods of Schedule Compression. As mentioned briefly in Chapter 3, that suggested the 94 concepts and methods for schedule compression through broad questionnaire

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Value</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.01</td>
<td>Adaptation to weather conditions</td>
<td>4.2</td>
<td>Strong</td>
</tr>
<tr>
<td>4.02</td>
<td>Realistic scheduling</td>
<td>3.8</td>
<td>Good</td>
</tr>
<tr>
<td>4.03</td>
<td>Repetitive tasks scheduling</td>
<td>4.0</td>
<td>Good</td>
</tr>
<tr>
<td>4.04</td>
<td>Schedule crashing</td>
<td>4.1</td>
<td>Good</td>
</tr>
<tr>
<td>4.05</td>
<td>Startup-driven scheduling</td>
<td>3.6</td>
<td>Fair</td>
</tr>
<tr>
<td>4.06</td>
<td>Use of float flexibility</td>
<td>3.4</td>
<td>Fair</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Value</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.01</td>
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<td>3.9</td>
<td>Good</td>
</tr>
<tr>
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<td>Realistic scheduling</td>
<td>3.7</td>
<td>Good</td>
</tr>
<tr>
<td>4.03</td>
<td>Repetitive tasks scheduling</td>
<td>3.8</td>
<td>Good</td>
</tr>
<tr>
<td>4.04</td>
<td>Schedule crashing</td>
<td>3.8</td>
<td>Good</td>
</tr>
<tr>
<td>4.05</td>
<td>Startup-driven scheduling</td>
<td>3.8</td>
<td>Good</td>
</tr>
<tr>
<td>4.06</td>
<td>Use of float flexibility</td>
<td>3.6</td>
<td>Fair</td>
</tr>
</tbody>
</table>

Note: 1: 5=Strong decrease; 4=Moderate decrease; 3=No effect; 2=Moderate increase; 1=Strong increase  
2: 4.2-5.0=Strong; 3.7-4.1=Good; 3.3-3.6=Fair; 0.0-3.2=None
surveys. In addition to the list and the definition of the schedule compression methods, CII obtained a consensus of opinion from the experienced constructors as to the impact of these 94 concepts and methods on duration and cost during engineering, procurement, and construction. The construction phase was sectioned into Construction 0-25% and Construction 26-100%. Table 7-1 shows the part of the effectiveness of methods of ‘Scheduling’ rated according to the construction phase.

Also, to increase productive time and reduce the project schedule, Noyce and Hanna delineated planned and unplanned schedule compression based on CII’s schedule compression concepts. This model contains 34 concepts and methods that are determined too most directly apply to the construction phase and the concepts and methods were conducted to explore the impacts of planned and unplanned schedule compression on labor productivity through the questionnaire surveys. The providing information was related to labor productivity, schedule duration, and project cost impacts. Table 7-2 shows the some parts out of 15 highest ranked results of most effective planned and unplanned schedule compression methodologies. The methodologies were most effective in maximizing labor productivity levels, minimizing costs, and minimizing schedule duration in order (Noyce et al. 1998).

By the rapid and magnificent achievement in construction industry over the last decade, however, some of concepts, such as ‘Computer-Aided Design and Drafting’ or ‘Fast Track Scheduling’, have been the norms of strategy. In addition, some of concepts are not suitable to

<table>
<thead>
<tr>
<th>Rank</th>
<th>Planned Schedule Compression</th>
<th>Unplanned Schedule Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Staff the project with most efficient crews</td>
<td>Staff the project with most efficient crews</td>
</tr>
<tr>
<td></td>
<td>Detailed project planning</td>
<td>Detailed project planning</td>
</tr>
<tr>
<td>2</td>
<td>Add a second shift</td>
<td>Look for short cuts in the process</td>
</tr>
<tr>
<td>3</td>
<td>Pre-work crew briefings</td>
<td>Pre-work crew briefings</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>15</td>
<td>Change to special shifts</td>
<td>Avoid interruptions during productive time</td>
</tr>
</tbody>
</table>
this research. The premise of this research is to reduce the project duration in the condition of maintenance of time and budget. For example, the concept of ‘Incentives’ proposed by CII requires cost increase, which doesn’t satisfy the requirements of this research. For these reasons, compression concepts and methods must be reestablished and reorganized for this research.

In the future research, based on the compression concepts of CII, the new and revised compression concepts and methods will be collected through diverse literature reviews and practitioner surveys. Then, new compression concepts and methods will be reorganized and divided into phases by questionnaire surveys: internal management framework, external management framework, design and engineering phases, and construction phases. Through the series of these steps, more practical and realistic concepts and methods for schedule compression will be determined.

7.2.2 Computerized Dynamic Project Management Model

The developed DPM model needs a support of diverse tools to achieve effective results. To schedule and track project related activities, Primavera Project Planner (P3) or Microsoft Project was cooperated with Vensim software for the application of system dynamics. With the results, Microsoft Office Excel was required as the final analysis of DPM scheduling. Considering complexity and uncertainty of construction project, a series of the processes need a comprehensive system to increase efficiency and applicability, and thus decrease time consumption in operation of DPM.

The computerized DPM intends to integrate several existing tools to achieve a flexible application for diverse situation. Particularly, the system dynamics model incorporated with network-based and data analysis tools creates user-friendly interface so that different kinds and types of input and output are managed in one integrated work station. Using well-designed
interface facilitates to translate the simulated results to graphic format for users familiar with CPM. Further, the system increases the accuracy of application in different policies.

Figure 7-1. Computerized dynamic project management model
Figure A-1. Generic construction process structure under schedule compression
Figure A-2. Initial work rate structure
Figure A-4. Latency modification structure
Figure A-5. Schedule pressure and work rates structure
Figure A-6. Iteration work rate and change and error structure
Figure A-7. Work release rate structure
Figure A-8. Workforce and productivity structure
Figure A-9. Resource constraint structure
Figure A-10. Dependency structure
APPENDIX B
EQUATIONS OF SYSTEM DYNAMICS MODEL

Activity Relationship = Constant (1 for default simulation)
   Units: Dmnl [0, 2]
   1: dependent; 2: interdependent; 0: independent

Actual Productivity = Work Scope / (Work Duration * Avg. Workforce)
   Units: w/(Day*People)
   Initial productivity for simulation

Actual Work Scope = XIDZ (Work Scope, Dependency, 0)
   Units: w
   An activity work scope according to its dependency to another activities

Avg. Constraint Thoroughness Time = Constant (1 for default simulation)
   Units: Day [0, ?]

Avg. Latency Modify Time = Constant (1 for default simulation)
   Units: Day [0, ?]

Avg. Quality Assurance Time = Constant (1 for default simulation)
   Units: Day [0, ?]

Avg. Quality Mgmt. Time = Constant (1 for default simulation)
   Units: Day [0, ?]

Avg. Redesign Time = Constant (1 for default simulation)
   Units: Day [0, ?]

Avg. SCT Time = Constant (1 for default simulation)
   Units: Day [0, ?]

Avg. Work Release Time = Constant (1 for default simulation)
   Units: Day [0, ?]

Avg. Work Time = Constant (1 for default simulation)
   Units: Day [0, ?]

Change and Error Detection Rate = Constant (1 for default simulation)
   Units: Dmnl [0,1]

Change and Error Release Rate = (Change and Error Detection Rate * Change and Error Release
Rate Amplifier * Changes and Errors * Hidden Change and Error * Quality Mgmt.
Thoroughness * (Work Release Rate)) / Avg. Quality Mgmt. Time
   Units: w/Day
Change and Error Release Rate Amplifier = 1e-007
Units: Dmnl [0,1e-007]

Changes and Errors = INTEG (Change and Error Release Rate, Constant (10 for default simulation))
Units: w

Constraint Identification Rate = Constraint Thoroughness * Discovery Rate * (Total Constraints in Work / Work Scope)
Unit: w/Day

Constraint Rate = Constant (2 for default simulation) – Managed Constraint Rate
Units: Dmnl

Constraint Subordination = Constraint Evolution * Constraint Classification * (1 – Other Constraints Subordination) / Constraint Subordinate Time
Units: Dmnl

Constraint Thoroughness = MIN ((Work to Do / Avg. Constraint Thoroughness Time), Constraint Thoroughness Restriction)
Units: w/Day

Constraint Thoroughness Restriction = Workforce * Actual Productivity
Units: w/Day

Dependency = External Dependency * Productivity Reliability * Evolution Fraction * Information Sensitivity * Constraint Rate
Units: Dmnl
1 is normal dependency, more dependent >1

Design Completion Ratio = Constant (1 for default simulation)
Units: Dmnl [0, 1]

Discovery Rate = Constant (1 for default simulation)
Units: Dmnl [0, 1]

Downstream Work Scope = Downstream Work Duration * Work Unit Converter
Units: w

Effect Identification Time = Constant (1 for default simulation)
Units: Day [0, ?]

Effect Rate on Productivity = (((Reliable Productivity on Production Type * Schedule Pressure Effect on Productivity) / Fatigue Effect on Productivity) – Perceived Productivity) / Avg. Quality Mgmt. Time
Units: w/(Day*People*Day)
Even though Work Completed is bigger than PWC, this value doesn't affect Dependency.
Only work on less than 1

Evolution Fraction = MAX (1, XIDZ (Work Completed, Perceived Work Consideration, 0)) * Standardization
Units: Dmnl
Even though Work Completed is bigger than PWC, this value doesn't affect Dependency.
Only work on less than 1

Expected Work Process = INTEG (Expected Work Rate, Initial Work Process)
Units: w

Expected Work Rate = MIN (Remaining Work / (Avg. Work Time), Expected Work Rate Constraints)
Units: w/Day

Expected Work Rate Constraints = Reliable Productivity on Production Type * Target Workforce * Reliability Effect on Work Duration
Units: w/Day

External Dependency = Lookup for Activity Relationship (Activity Relationship) * Lookup for External Sensitivity (External Sensitivity * External Information Exchange)
Units: Dmnl

External Information Exchange = Constant (0 for default simulation)
Units: Dmnl [0,1]

External Sensitivity = Constant (0 for default simulation)
Units: Dmnl [0,1]

Fatigue Effect on Productivity = Lookup for Fatigue (Time)
Units: Dmnl [0, 10]

FINAL TIME  = Given
Units: Day
The final time for the simulation.

Fraction of Change and Error = Changes and Errors / Work Completed
Units: Dmnl [0,1]

Fraction of Work Defects = Work to be Checked / Work to Do
Units: Dmnl

Hidden Change and Error = MIN ((Total Change and Error – Changes and Errors), Work Scope)
Units: w
Information Completion Ratio = Design Completion Ratio * Required Work Completion from Upstream
Units: Dmnl

Information Sensitivity = Lookup for Information Sensitivity (Work Completed * Information Completion Ratio)
Units: Dmnl

Initial Hiring Ratio = Given
Units: Dmnl
Ratio to hire people per normal productivity. Determine initial workforce

Initial Resource Constraint = Constant (0 for default simulation)
Units: w/Day [0, ?]

INITIAL TIME = 0
Units: Day
The initial time for the simulation.

Initial Work Available = Original Duration * Work Unit Converter
Units: w

Initial Workforce = (Work Scope * Initial Hiring Ratio) / (Actual Productivity * Work Duration)
Units: People

Initial Work Process = Constant (0 for default simulation)
Units: w [0, ?]

Initial Work Rate = MIN ((Initial Work Available / Initial Work Time), Initial Resource Constraint)
Units: w/Day

Initial Work Time = Given
Units: Day

Initial Work to Do = Work Duration * Work Unit Converter
Units: w

Iterative Work Rate = Quality Assurance * Work to be Iterated Ratio
Units: w/Day

Latency Modification Constraint = MIN ((Actual Productivity * Fraction of Work Defects * Motivation to Work * Quality Mgmt. Thoroughness), Initial Work Rate)
Units: w/Day
Latency Modified Rate = MIN ((Work to be Checked / Avg. Latency Modify Time), Latency Modification Constraint)
Units: w/Day

Latency Modified Rate (for Simulation) = Request to Check Rate + MIN ((Work to be Checked / Avg. Latency Modify Time), Latency Modification Constraint)
Units: w/Day

LLT Potential = Constant (1 for default simulation)
Units: Dmnl [0, 1]

Lookup for Activity Relationship ([0, 0)-(2, 6), (0, 1), (1, 1), (1, 1), (1.3, 1.4), (1.7, 3), (2, 5))
Units: Dmnl

Lookup for External Sensitivity ([0, 0)-(2, 6), (0, 1), (0.3, 1.4), (0.7, 3), (1, 5))
Units: Dmnl

Lookup for Fatigue ([0, 0) - (100, 10)], (0, 1), (100, 1))
Units: Dmnl

Lookup for Information Sensitivity ([0,0)-(200000,10]),(1,1),(70000,1),(100000,1),(200000,1))
Units: Dmnl

Lookup for Motivation to Work ([0, 0) – (100, 10)], (0, 1), (100, 1))
Units: Dmnl

Lookup for Production Type ([0, 0) - (100, 10)], (0, 1), (100, 1))
Units: Dmnl

Lookup for Schedule Pressure ([0, 0) - (100, 10)], (0, 1), (100, 1))
Units: Dmnl

Manageable Time Reduction = Work Duration * Reliability
Units: Day

Managed Constraint Rate = Constant (1 for default simulation)
Units: Dmnl [0, 1]

Min. Reprocess Time = Constant (1 for default simulation)
Units: Day [0, ?]

Motivation to Work = Lookup for Motivation to Work (Time)
Units: Dmnl

Original Duration = Given
Units: Day
Perceived LLT Rate = MIN ((Work to Do / Avg. SCT Time), (Constraint Thoroughness * LLT Potential))
Units: w/Day

Perceived Productivity = INTEG (Effect Rate on Productivity, Actual Productivity)
Units: w/Day/People
with consideration of schedule pressure, fatigue, and production type

Perceived Work Consideration = Work Awaiting Redesign + Work Completed + Work Done not Checked + Work to be Checked + Work to be Stabilized + Work to Do
Units: w
All stocks in an activity

Production Type = Constant (1 for default simulation)
Units: Dmnl [0, 1]
Determine fast or slow production, closer 1, faster

Productivity Reliability = Perceived Productivity / Actual Productivity
Units: Dmnl

Quality Assurance = MIN ((Work Done not Checked / Ave. QA Time), Quality Assurance Resource Constraint)
Units: w/Day

Quality Assurance Resource Constraint = Information Completion Ratio * Quality Management Thoroughness * Workforce * Actual Productivity
Units: w/Day

Quality Management Thoroughness = Constant (1 for default simulation)
Units: Dmnl [0, 1]

Reintroduced Work Rate = IF THEN ELSE ((SCT * Stability * MIN ((Work Awaiting Redesign / Avg. Reschedule Time), Schedule Pressure Resource Constraint)) > Work Rate, (SCT * Stability * MIN ((Work Awaiting Redesign / Avg. Reschedule Time), Schedule Pressure Resource Constraint)), 0)
Units: w/Day

Release Trigger = IF THEN ELSE (Downstream Work Scope > (Work Done not Checked + Work Completed), 1, 0)
Units: Dmnl

Reliability = Constant (1 for default simulation)
Units: Dmnl [0, 1]
Reliability Effect on Work Duration = \( \frac{\text{Work Duration}}{(\text{Work Duration} - (\text{Reliability} \times \text{Work Duration}))} \)
Units: Dmnl

Reliable Productivity on Production Type = \( \text{Actual Productivity} \times (\text{Lookup for Production Type (Production Type)}) \)
Units: \( \text{w}/(\text{Day} \times \text{People}) \)

Remaining Work = \( \text{Target Work Scope} - \text{Expected Work Process} \)
Units: \( \text{w} \)

Request to Check Rate = \( \min \left( \frac{\text{Work Awaiting Redesign}}{\text{Min. Reprocess Time}}, \left(1 - \text{Stability} \right) \times \text{Perceived LLT Rate} \times \text{Schedule Compression Thoroughness} \right) \)
Units: \( \text{w}/\text{Day} \)

Required Work Completion from Upstream = \( \frac{\text{Perceived Work Consideration of Upstream} - \text{Work Available of Upstream}}{\text{Perceived Work Consideration of Upstream}} \)
Units: \( \text{w} \)

Resource Constraint = \( \text{Information Completion Ratio} \times \text{Resource Limitation Ratio} \times \text{Workforce} \times \text{Actual Productivity} \)
Units: \( \text{w}/\text{Day} \)

Resource Limitation Ratio = \( \min \left( \frac{\text{Supplied Resource Quantity}}{\text{Target Resource Quantity}}, 1 \right) \)
Units: Dmnl

SAVEPER = \( \text{TIME STEP} \)
Units: Day [0, ?]
The frequency with which output is stored.

Schedule Compression Thoroughness = \( \text{Constant (1 for default simulation)} \)
Units: Dmnl [0, 1]

Schedule Pressure Resources Constraint = \( (1 + \text{XIDZ} (\max (\text{Schedule Pressured Effect on Work Process}, 0), \text{Expected Work Process}, 0)) \times \text{Perceived Productivity} \)
Units: \( \text{w}/\text{Day} \)

Schedule Pressured Effect on Productivity = \( \frac{\text{Work Duration}}{\text{Target Duration}} \)
Units: Dmnl

Schedule Pressured Effect on Work Process = \( \text{Expected Work Process} - \text{Work Done not Checked} \)
Units: Dmnl

SCT Reprocess Rate = \( \min \left( \frac{\text{Work Awaiting Redesign}}{\text{Min. Reprocess Time}}, \left(1 - \text{Schedule Compression Thoroughness} \times \text{Perceived LLT Rate} \right) \right) \)
Units: \( \text{w}/\text{Day} \)
Stability = Constant (1 for default simulation)
   Units: Dmnl [0, 1]

Stable Work Rate for Schedule Compression = MIN ((Work Awaiting Redesign / Avg. Redesign
   Time), (Perceived LLT Rate * Stability * Schedule Compression Thoroughness))
   Units: w/Day

Standardization = Constant (1 for default simulation)
   Units: Dmnl [0,1]
   The level of standardization in the design product or the design process

Supplied Resource Quantity = Constant (1 for default simulation)
   Units: Dmnl

Target Duration = Work Duration – Manageable Time Reduction
   Units: Day

Target Hiring Ratio = Constant (5 for default simulation)
   Units: Dmnl
   Determine Final Workforce

Target Resource Quantity = Constant (1 for default simulation)
   Units: Dmnl

Target Workforce = (Target Work Rate * Target Hiring Ratio) / Perceived Productivity
   Units: People

Target Work Rate = Work Available / Target Duration
   Units: w/Day

Target Work Scope = Work Duration * ((Work Duration * Work Unit Converter) / (Work
   Duration – (Reliability * Work Duration)))
   Units: w

TIME STEP = 0.25
   Units: Day [0, ?]
   The time step for the simulation.

Time to Adjust Workforce = Constant (1 for default simulation)
   Units: Day

Total Change and Error = Constant (10000 for default simulation)
   Units: w [0, ?]

Total Constraints in Work = Constant (0 for default simulation)
   Units: w [0, ?]
Work Available = MAX (0, (Actual Work Scope – Perceived Work Consideration))
Units: w
High dependency, less work available

Work Awaiting Redesign = INTEG (Perceived LLT Rate – Request to Check Rate –
SCT Reprocess Rate – Stable Work Rate for Schedule Compression, 0)
Units: w

Work Completed = INTEG (Work Completion Rate, 0)
Units: w

Work Completion Rate = Work Release Rate * (1 – Work to be Iterated Ration))
Units: w/Day

Work Done not Checked = INTEG (Work Rate + Reintroduced Work Rate – Iterate Work Rate –
Work Completion Rate, 0)
Units: w

Work Duration = Given
Units: Day

Workforce = INTEG (Workforce Adjustment Rate, Initial Workforce)
Units: People

Workforce Adjustment Rate = (Target Workforce – Workforce) / Time to Adjust Workforce
Units: People/Day

Work Rate = MIN (MIN ((Work to Do / "Avg. Work Time"), Resource Constraint), Constraint
Thoroughness )
Units: w/Day

Work Rate of Unconstrained Work = Constraint Thoroughness – Constraint Identification Rate
Units: w/Day

Work Redesigned = INTEG (Stable Work Rate for Schedule Compression, 0)
Units: w

Work Release Rate = (Release Trigger * Quality Assurance) / Avg. Work Release Time
Units: w/Day

Work Scope = Work Duration * Work Unit Converter
Units: w

Work Stabilization Rate = Stabilized Work Release Rate * Managed Constraint Rate * MIN
(Work to be Stabilized / Avg. Constraints Management Time, Constraint Subordination)
Units: w/Day
Work to be Checked = INTEG (Request to Check Rate – Latency Modified Work Rae, 0)
Units: w

Work to be Iterated Ratio = Fraction of Change or Error * Quality Mgmt. Thoroughness
Units: Dmnl [0, 1]

Work to be Stabilized = INTEG (Constraint Identification – Work Stabilization Rate, 0)
Units: w

Work to Do = INTEG (Initial Work Rate + Work Stabilization Rate + Latency Modified Rate +
SCT Reprocess Rate + Iterate Work Rate – Constraint Identification Rate – Work Rate –
Perceived Latent Lazy Time, Initial Work to Do)
Units: w

Work Unit Converter = 1000
Units: w/Day
## APPENDIX C
### INPUTS FOR SIMULATION

Table C-1. Input variables for simulation: SR-25

<table>
<thead>
<tr>
<th>#</th>
<th>ID</th>
<th>Activity</th>
<th>OD</th>
<th>LLT</th>
<th>Stability</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1090</td>
<td>Obtain temp drainage material</td>
<td>10</td>
<td>NA</td>
<td>NA</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>2265</td>
<td>FL power adjustment I</td>
<td>34</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>1010</td>
<td>Install MOT</td>
<td>2</td>
<td>NA</td>
<td>NA</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>2270</td>
<td>FL power adjustment II</td>
<td>50</td>
<td>5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>1140</td>
<td>Install 60” SD trunk line to pond</td>
<td>50</td>
<td>NA</td>
<td>NA</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>1070</td>
<td>Stage I temp med &amp; RT pav</td>
<td>33</td>
<td>2</td>
<td>NA</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>1130</td>
<td>Excavate pond 1 &amp; stockpile</td>
<td>43</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>1160</td>
<td>Clear &amp; grub for stage II</td>
<td>15</td>
<td>3</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>1155</td>
<td>Excavate pond 2</td>
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<td>NA</td>
<td>NA</td>
<td>9</td>
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<td>10</td>
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<td>Excavate pond 5</td>
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<td>6</td>
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<tr>
<td>11</td>
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<td>SD trunk line LT 45+30</td>
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<tr>
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<td>1170</td>
<td>SD trunk line LT 20+99</td>
<td>18</td>
<td>3</td>
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<td>7</td>
</tr>
<tr>
<td>13</td>
<td>1630</td>
<td>Grass/sod pond 5</td>
<td>3</td>
<td>7</td>
<td>3</td>
<td>NA</td>
</tr>
<tr>
<td>14</td>
<td>1250</td>
<td>SD lat &amp; cross drains LT 45+30</td>
<td>22</td>
<td>3</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>15</td>
<td>1190</td>
<td>SD trunk line LT 103+40</td>
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<td>5</td>
<td>4</td>
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<td>16</td>
<td>1210</td>
<td>SD trunk line LT 162+00</td>
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<td>NA</td>
<td>NA</td>
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</tr>
<tr>
<td>17</td>
<td>1205</td>
<td>Stabilization LT 45+30</td>
<td>15</td>
<td>4</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>18</td>
<td>1255</td>
<td>SD lat &amp; cross drains LT 103+40</td>
<td>15</td>
<td>3</td>
<td>4</td>
<td>8</td>
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<td>19</td>
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<td>SD trunk line LT 196+00</td>
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<td>5</td>
<td>6</td>
<td>3</td>
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<td>20</td>
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<td>Embankment LT 103+40</td>
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<td>2</td>
<td>3</td>
</tr>
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<td>1315</td>
<td>Stabilization LT 103+40</td>
<td>12</td>
<td>3</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>22</td>
<td>1480</td>
<td>Sidewalk LT 45+30</td>
<td>13</td>
<td>3</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>23</td>
<td>1320</td>
<td>Curb &amp; gutter LT 103+40</td>
<td>6</td>
<td>2</td>
<td>6</td>
<td>8</td>
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<td>24</td>
<td>1325</td>
<td>Base LT 103+40</td>
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<td>5</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>25</td>
<td>1495</td>
<td>Sidewalk LT 103+40</td>
<td>9</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>26</td>
<td>1350</td>
<td>Base LT 142+00</td>
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<td>6</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>27</td>
<td>1375</td>
<td>Base LT 162+00</td>
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<td>7</td>
<td>4</td>
<td>7</td>
</tr>
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<td>28</td>
<td>1515</td>
<td>Gass/sod LT 142+00</td>
<td>2</td>
<td>NA</td>
<td>NA</td>
<td>7</td>
</tr>
<tr>
<td>29</td>
<td>1400</td>
<td>Base LT 180+00</td>
<td>4</td>
<td>3</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>30</td>
<td>1425</td>
<td>Base LT 182+00</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>31</td>
<td>1405</td>
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Table C-2. Continued

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LIST OF REFERENCES


Howell, G., and Koskela, L. “Performing Project Management: The Role of Lean Construction.”


BIOGRAPHICAL SKETCH

Jaesung Lee was born in 1974, in Busan, South Korea, and remained there until he graduated from Dong-A University in 2001. He had studied Architectural Engineering as an undergraduate student in Busan, South Korea, and had completed over two years of a research student in the construction engineering laboratory in Dong-A University. In the period as a research student, he worked some projects like as structural safety survey and assessment and research in construction management.

After graduation, he immediately was eager to pursue the advanced studies in the United States. He enrolled in the Fu Foundation School of Engineering and Applied Science at Columbia University in the city of New York and studied the diverse areas from planning and programming, estimating, scheduling, and coordination and control to strategies for construction management through a lot of case studies under professor Michael J. Garvin, a Ph.D. in construction engineering and management from MIT. Especially, his interests and knowledge included sustainable strategies for infrastructure delivery and management and engineering and construction markets and organization and researched the strategies for construction organizational evolution.

After receiving the master’s degree from Columbia University, he transferred to the University of Florida for Ph.D. to satisfy his thirst for knowledge about this in 2003. He had researched several projects as a graduate research assistant under Dr. R. Ralph Ellis and Dr. Edward Minchin. Also, he taught the class of technical drawing and visualization as a teaching assistant.