A Robust Planning and Control Methodology for Design-Build Fast-Track Civil Engineering and Architectural Projects

by

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ABSTRACT

A robust planning and control methodology is developed by integrating the applications of
axiomatic design concept, concurrent engineering, graphical evaluation and review technique
(GERT), and the system dynamics modeling technique. The goal of the proposed methodology is
to help create a robust project plan for design-build fast-track civil engineering projects where
unforeseen changes can be absorbed in the project schedule without creating major interruptions.

The axiomatic design concept is applied to formulate and evaluate various work methodologies,
and to compose the project plan based on the selected work methodology. The concept of
concurrent engineering is adapted to develop a fast-tracking framework based on the task
production rate, the upstream task reliability and downstream task sensitivity to upstream error.
The duration of the project can be shortened by applying the recommended fast-tracking
strategy. The GERT diagramming scheme is used to calculate the project duration
probabilistically by incorporating the possible branches and loops in the project. The system
dynamics modeling technique is applied to analyze the causality links of relevant factors in the
construction system, and further identifies the important variables that determine the success of a
particular overlapping strategy.

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EXECUTIVE SUMMARY

Effective fast-tracking in a construction project can help reduce the duration and lower the cost of the project. The proposed robust planning and control methodology focuses on the planning and implementation of fast-tracking on design-build projects where it is applicable and effective. Design-build is re-emerging as a trend of project delivery strategy. It reduces the burden on the owner by delegating the responsibilities of the design and construction tasks to one single party, who is wholly responsible for the entire delivery process of the project. The team approach as a result of the collaboration between the design and construction crew can further enhance the fast-tracking practice to speed up the delivery process. Thus, understanding and improving the design-build method will become more important to effectively manage civil engineering projects as more projects are delivered by this method.

However, as the design-build firm speeds up the delivery process, planning and coordinating activities becomes more complex and difficult. For example, on the physical side, the constructibility of a design becomes important because the firm has to build it eventually. Therefore, a design evaluation criterion has to be established and the available resource for construction be constantly monitored. On the management side, information transfer becomes important because the design and construction teams are working in parallel. The information feedback process between the two is critical in determining the progress of the project. The proposed robust planning and control methodology is developed based on the hypothesis that by streamlining a carefully structured design process early in the design phase, together with a rigorous project management technique, it is possible to reduce schedule and cost overruns experienced by most projects today.

The goal is to develop a strategy to achieve robust project planning and control where unforeseen changes can be absorbed in the plan without creating major disruptions. The primarily backbone of this integration method is to combine the application of the concepts of axiomatic design, concurrent engineering, graphical evaluation and review technique (GERM) and finally system dynamics. Each of
these control tools has been utilized extensively across different disciplines and industries. Axiomatic design is mainly applied in mechanical engineering and manufacturing to help bring better product realization. It breaks the complex design process into hierarchy and further into work packages which can be performed independently in an ideal situation. Concurrent engineering is developed to resolve "coupled" events by managing the iteration, overlapping and integration of those events. GERT is a graphical tool that incorporates probabilities into the duration of activities and the precedence relationship of anticipated events. Both concurrent engineering and GERT are used when the independent axiom does not hold true and a more rigorous technique is needed to manage complex interdependencies. At last, the system dynamics modeling technique is applied to simulate the progress of fast-track activities over time. The impact of each factor in a system of construction events is explicitly modeled by this technique. Consequent, the different overlapping strategies developed in this thesis can be tested and compared using this modeling method.

Above all, the integration of these applications can help deliver an effective and robust project plan. With a rigorous and systemized methodology to help project planning, unforeseen problems can be addressed early before construction. As a result, the time and energy of the construction crew can be used on the important tasks instead of having to deal with conflicts, claims, and/or justifying added costs and schedule delays. The overall increase in productivity and efficiency as a result of a better planning process can consequently promote the competitiveness of the construction industry.
Many of today's large-scale civil engineering projects are subject to cost and schedule overruns. There has been a tremendous effort in academia to explain the inefficiency of the construction industry, both quantitatively and qualitatively, in the project delivery process. For example, the results of a survey distributed by Lee et al. suggest that large-scale civil engineering projects incur an average of more than 7% of cost overruns [Lee et al., 1997]. In fact, delays and cost overruns have become the rule rather than exception for various types of projects in construction, aerospace, power generation and product development [Sterman, 1992]. Among the various industries, perhaps construction is the oldest industry known to mankind. However, despite its long history, the construction industry has been unable to master the management skills necessary to improve competitiveness and promote overall industrial advancement [Kubal, 1995].

With this alarming trend in the construction industry, owners from both the public and private sectors are beginning to look for more promising project delivery strategies than today's traditional design-bid-build. Among the many different project delivery systems, design-build has re-emerged by delegating responsibility to one single party and effectively reduces the owner's burden [Loulakis, 1996]. The merging of design and construction allows design and construction crews to function as a team, hence facilitating efficient scheduling, streamlined coordination of design and construction phases and effective fast-tracking.

The concept of fast-tracking was introduced to reduce project duration by overlapping sequential tasks in a project. The application of fast-tracking can be described at two levels. One of which is to perform the design and construction tasks in parallel, so that the site can be mobilized before the design is
fully completed. The focus of this thesis will be on the other fast-tracking method, which is to overlap a set of sequential construction activities to reduce the construction duration. The difference between the two methods is that although the first method can reduce the overall project duration as well, the cost after fast-tracking might be higher due to design uncertainties leading to additional rework in construction. In this scenario, the timing of the project is more important than cost, which means that the project has to be completed within the given time at any cost. This method is usually deployed for emergency projects such as earthquake retrofit and environmental cleanup, or for time sensitive projects such as stadium construction that has to be completed before the season starts. The tradeoff between time and cost can be another interesting topic for further pursuit in future research.

On the other hand, the focus of this thesis is on streamlining the construction planning process based on a given set of drawings, and consequently lowers the fixed costs of maintaining the site office, supporting staff and equipment. Regardless of either or both fast-tracking methods are used in a project, having the design-build delivery arrangement allows the engineers to influence the design so that the facility can be easily and effectively fast-tracked. For example, a facility consisting of many identical parts, such as columns of the same size, concrete mix of the same strength and precast panels of the same shape, can be readily overlapped compared to another facility comprised of many unique objects. The intuition suggests that a continuous flow of reliable production would be an important factor for successful fast-tracking, but the exact interaction between production reliability and activity progress after fast-tracking has to be fully understood and analyzed before the fast-tracking practice can be improved.

Furthermore, the design-build arrangement can help reduce conflicts among project participants because priority is judged based on overall benefit to the team. Less conflict can lead to a higher quality because the team must respond to problems regardless to whether they are caused by defects in design, material or craftsmanship [Loulakis, 1996]. Based on the design-build benefits derived from the team approach to problem solving, Kubal [Kubal, 1995] forecasts that design-build will be the only contracting method in the future. Design-build can utilize a network linkage as a common denominator for all project participants in all future successful construction projects [Kubal, 1995]. A network linkage will consist of companies in different specialty fields with teaming relationships with their suppliers and contractors. Such coalition can provide services or products that are superior in quality, quickly produced and less expensive [Kubal, 1995]. As design-build continues to re-emerge as one of the popular delivery system in both the public and private sectors, its implications to project planning and control has become
increasingly important to understand and improve the management process in the future.

The need to deliver construction projects on time and on budget has also driven the software industry to market products capable of managing construction-related tasks. Various commercial software can help monitor and review the status of cost accounts, resource allocation, budget expenditure and event scheduling. However, these software can't take one step further to deal with the complexity of schedule reduction by fast-tracking. Before developing the next generation software with this capability, a fast-tracking methodology has to be carefully structured and fully tested to act as the foundation of such application. This fast-tracking methodology would have to address issues such as the interdependencies among the activities, important activity characteristics for effective fast-tracking, formulation and evaluation of work methodology, performance measurement of fast-tracking, and the causality links with other factors that may change the activity performance.

This thesis addresses those issues by integrating the application of axiomatic design concept, concurrent engineering, graphical evaluation and review technique (GERT), and system dynamics modeling in the planning, monitoring and control processes of design-build projects. The basic assumption of axiomatic design is that there exists a fundamental set of principles that determines a good design practice. During the design process, the best product is selected from many available alternatives, considering factors as valued added, cost, accuracy, delivery time, and consumer preference [Suh, 1990]. Appropriate technology can be applied when needed by creating a design hierarchy in this process. The proposed methodology in this thesis adapts this vary same set of principles to help achieve an effective construction planning process.

Furthermore, the concept of concurrent engineering was developed to deal with the necessary information transfer among a set of parallel activities, considering factors such as activity information certainty and sensitivity to errors. This concept can be applied to develop a fast-tracking framework that recommends the best fast-tracking strategy based on certain activity characteristics. The impact of fast-tracking can then be measured probabilistically in GERT, using the pre-defined activity characteristics to assess the probabilities in the GERT network diagram. In addition, the causality links of activity characteristics on the production can be modeled and simulated by the system dynamics modeling technique. This modeling and simulation process can help understand the changing behaviors of activities as a result of different fast-tracking strategies and further identify the important factors that could affect
the activity characteristics. Consequently, the effectiveness of various fast-tracking strategies can be tested and evaluated by this modeling technique.

1.1 THE IMPORTANCE OF THIS RESEARCH

Pre-construction planning is the most important task throughout a project cycle because a project can only be implemented and controlled to the level of detail that it is planned. The proposed robust planning and control methodology in this thesis provides a rigorous and effective guideline for construction planning, so that unforeseen changes in a project can be absorbed without creating major disruptions to the schedule. Furthermore, without a rigorous and systemized tool to develop a project plan, unforeseen problems within a plan can be difficult to detect beforehand. If these problems can be effectively addressed early in the planning stage instead of in the middle of construction, the project can be carried out smoothly, eliminating conflicts, claims, added costs and schedule delays. This research effort is to realize this goal of effective construction planning by integrating the concepts of axiomatic design concepts, concurrent engineering, graphical evaluation and review technique (GERT), and system dynamics modeling.

The concept of axiomatic design was developed by Professor N. P. Suh at MIT to fulfill the need to unify and generalize available knowledge in the design field [Suh, 1990]. The application of the axiomatic design concept to construction was developed to address the problems arise from the current approach to project delivery [Albano, 1992]. The current approach in the construction industry can be characterized as a fragmented approach to design and construction planning, and a non-homogeneous decision-making process within each organization. Problems arise because design experts responsible for conceptual design are often senior engineers whose thought processes are internalized. Conceptual planning is viewed as a skill that can only be learned through experience without an explicit expression of objectives [Albano, 1992]. Axiomatic approach to planning allows the development of an objective basis for externalizing the intent of the planning process and for evaluating solution alternatives.

One important function of axiomatic design [Suh, 1990] is the ability to map out the interdependencies among various design and construction tasks. It is able to systematically make the
inherent complexities explicit. However, these interdependencies can become very complex and difficult to manage. Successfully managing these relationships early during design process will eventually ease up construction of the facility. When these complexities become too difficult to manage, the concept of concurrent engineering helps to implement the design process. Concurrent engineering categorizes activities by its position in design flow (upstream or downstream), rate of information evolution and sensitivity to changes. Then, appropriate recommendation for information transfer can be made according to the combination of the characteristics of upstream and downstream activities. The concept of concurrent engineering is adapted in this thesis to develop the necessary framework for effective fast-tracking. The goal of the fast-tracking practice is to reduce the overall project duration by overlapping a set of activities in a construction project.

Once the fast-tracking practice is implemented in a project, the effectiveness of fast-tracking can be measured by several conventional network schemes, including CPM, PERT and GERT. The GERT approach is selected is this thesis because of its added capability of incorporating loops and branches in the network. Most of the schedulers in the construction industry build any buffer for loops directly into the activity duration itself without making them explicit in the schedule for review. The GERT network scheme helps calculate the appropriate amount of contingency based on the probabilities leading to rework loops. This capability can enhance the effectiveness of construction planning by a better understanding and anticipation of the undesirable events that may occur.

The fast-tracking practice can be further analyzed and simulated by the use of the system dynamics modeling technique. This modeling technique is applied in this thesis to map out and analyze the causality links among the different variables in a construction system. System dynamics models are treated as formal models to replace mental models. A mental model is typically the understanding and intuition of the construction process derived from years of experience and observation in the field. However, a mental model's implicit nature limits objective analysis on specific issues such as the fast-tracking practice. As a result, these issues can not be easily examined and measured against standards, their assumptions are hard to identify, and ambiguities intensify. Sterman [Sterman, 1992] suggests that no mental model can adequately assess the impact of exogenous factors and allocate responsibility for delay and disruption. He further suggests that computer modeling techniques are preferred to mental models for the following reasons [Sterman, 1992]:

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• Computer models are explicit, and their assumptions are open to all for review;
• Infallibly compute the logical consequences of the modeler's assumptions;
• Ability to interrelate many factors simultaneously;
• Can be simulated under controlled conditions, allowing analysts to conduct experiments which are not feasible in the real system.

The ability to access the quality and validity of a formal model allows managers to identify, analyze and explain the problems raised during construction. The team approach of design-build projects provides a feasible framework for its application because a single party is responsible for project delivery, thus eliminates the role of intermediary between the architect/engineer (A/E) and contractor.

Above all, the integration of these concepts can bring together the necessary elements to develop the robust planning and control methodology. From conceptual planning using axiomatic design principles to simulating the construction process by system dynamics modeling, the proposed robust planning and control methodology can help realize the goal of effective planning. Consequently, by minimizing the impact of unforeseen changes to increase the productivity and efficiency of construction, the proposed methodology can promote the overall competitiveness of the industry.

1.2 THE RESEARCH OBJECTIVES

The goal of this thesis is to develop a methodology that produces robust project planning. As project complexity increases, so does the need for communication and coordination between people involved in all stages [DeBaradelab, 1998]. Compare to other industries, a civil engineering project is particularly difficult to plan for because each project is unique and non-replicable. As a result, project managers are constantly facing new challenges coming from both external environment and internal organization. To name a few, the external environmental posts difficult tasks such as unexpected site conditions, unanticipated weather changes and equipment breakdown. As for internal organization, the combining effects of improper documenting procedure, inappropriate design evaluation and insufficient communication, post even more difficulties for a project manager. It is important for a project manager to realize the causes and consequences of these unforeseen circumstances, both internal and external, and
how they impact the project as a whole.

1.3 RESEARCH HYPOTHESIS

The hypothesis of this research is that by applying an appropriate project control methodology and integration technique, most of the causes and effects of changes on project schedule and cost can be identified and managed. The traditional project planning process is often based on the best estimates allowing little contingencies for unforeseen changes. The proposed methodology in this thesis is a rigorous control technique such that most of the aftermath to changes, including project delays and cost overruns, can be absorbed and minimized by a rigorous planning process. A common scenario in most construction projects today is that one change initiates a chain of reaction, and eventually a series of activities are affected. Therefore, any change to the project should be anticipated early in planning stage to minimize the negative effect later in construction. The proposed methodology will establish a rigorous and systemized planning process so that appropriate measures can be taken beforehand. Consequently, the construction process can proceed according to the schedule as sufficient contingencies are incorporated early in the planning stage.

Furthermore, this thesis will identify the important factors that determine the success of a particular fast-tracking strategy. The integration of different concepts can help evaluate the effect of these factors on fast-tracking. Once the implications of these factors on fast-tracking implementation is fully understood, the effectiveness of fast-tracking can be enhanced to substantially reduce the overall project duration and costs.

1.4 BENEFITS OF THIS RESEARCH

A major difficulty for most construction projects today is to manage changes, which often results from unexpected situations and unforeseen circumstances. Changes comprise the single major source of delays and cost overruns for projects of any kind [Lee et al., 1997]. The negative impact of any change on
project implementation is difficult to manage because of the difficulties to accurately forecasting change beforehand. In addition, people tend to schedule projects based on best estimates because they often believe that they are more capable than others to perform the same tasks. Thus, the impact of possible changes are often overlooked and ignored during the conventional planning process. Without a rigorous tool to systemize the construction planning process, the same errors will be observed in one project after another as it is now.

Change order management is a highly debated issue in academia that deals with the aftermath of changes. Although changes are hard to forecast, this thesis takes the active role of incorporating and preparing for changes in project planning even before they occur. An important aspect of the proposed robust planning and control methodology is to establish a series of techniques to effectively absorb those changes in the project plan without creating major disruptions. Therefore, if unforeseen changes occur during the project, a series of guidelines are available to manage and treat these changes. In fact, there is little research been conducted on how to capture and prepare for changes during project planning. The results of this thesis will enhance the current project management techniques by providing a proactive and systematic approach to plan, monitor and control a project.

1.5 ORGANIZATION OF THE THESIS

This thesis focuses on the application of the proposed robust planning and control methodology on design-build fast-track civil engineering projects. Chapter 2 of this thesis introduces the phenomenon and trend of the construction industry today. The problem within the construction industry is defined and the goal of this thesis is to propose a methodology by which these problems can be managed, if not solved. Following that, Section 2.1 describes in detail the different components involved in the proposed methodology. It begins by describing the differences in organizational structure between design-build and traditional design-bid-build projects, such as the legal environment and project delivery system. It also defines the context within which the proposed control methodology is applied. From Section 2.2 to Section 2.6, this thesis examines the elements involved in the proposed robust planning and control methodology, including the principles of axiomatic design, concurrent engineering, graphical evaluation and review technique (GERT), and finally the system dynamics modeling technique.
Chapter 3 develops and describes the integration of these concepts in the proposed methodology. As the role of each concept is introduced in this Chapter, its application will be demonstrated in a typical water dam construction project. In Section 3.1, the axiomatic design concept will be applied to develop and evaluate various work methodologies for the project. Subsequently, in Section 3.2, the project plan based on the selected work methodology will be fast-tracked using the overlapping framework derived from concurrent engineering. In Section 3.3, the effectiveness of fast-tracking will be measured by applying the GERT network scheme, which will also probabilistically incorporate the different branches and loops in the schedule. In Section 3.4, a system dynamics model will be developed to analyze the impact of various factors on the fast-tracking practice in a construction system. This modeling technique will also be applied to test the overlapping framework developed in Section 3.2. Consequently, the modeling and simulation process can help project planners identify the important factors that determine the success of a particular overlapping strategy.

Chapter 4 summarizes the application of the proposed robust planning and control methodology, and the benefits that can be realized by such application. By identifying problems prior to construction and plan for them accordingly, the methodology can help increase the efficiency and productivity of the construction process. Section 4.2 describes the suggested orientation for future research to further enhance the role of the proposed methodology in promoting the overall competitiveness of the construction industry.
CHAPTER 2

RESEARCH BACKGROUND

This Chapter focuses on the fundamental theories of the individual concepts in this thesis, including axiomatic design, concurrent engineering, graphical evaluation and review technique (GERT) and system dynamics modeling technique, before integrating them in the proposed robust planning and control methodology in the next Chapter. Prior to describing these fundamental theories, the implications of the design-build delivery method on the proposed methodology will be discussed in Section 2.1. Subsequently, this Chapter will explain the development of each individual concept, beginning with axiomatic design in Section 2.2 and 2.3. The axiomatic design principles were developed to help bring better product realization in mechanical engineering and manufacturing by decomposing the complex design process into hierarchy. Then, this Chapter covers the concept of concurrent engineering in Section 2.4. This concept has been applied to manage activities performed in parallel, and it specifically addresses the information flow for tasks involving iteration, overlapping and integration. The concept of concurrent engineering is widely accepted in product design and development industries, where production speed is of critical importance to the success of the product. Consequently, the application of concurrent engineering on product development will be discussed in Section 2.4.1 and 2.4.2. In Section 2.5, this Chapter will introduce the GERT network diagramming method. GERT is a graphical tool that probabilistically incorporates rework loops and branches in the schedule, so that sufficient contingency can be assigned in the project schedule. At last, in Section 2.6, the fundamental theories of the system dynamics modeling technique will be explained. This modeling technique will be applied in this thesis to simulate the progress of activities under various fast-tracking strategies over time. During the modeling and simulation process, the impact of each factor in a system of construction events can be explicitly incorporated mathematically. Consequent, the important factors that determine the effectiveness and success of a particular fast-tracking strategy can be identified and evaluated.
2.1 PROJECT STRUCTURE

The American construction industry has developed a framework that interconnects with the legal system closely. One aspect of the legal system in a civil engineering project is to arrange the project delivery system, which ultimately defines the project structure. This is because the role and responsibility of each participant in a project is bind to the contractual agreement. As a result, the project structure becomes the hybrid of the contracting strategy and project delivery system. In order to apply axiomatic control to help implement a project more efficiently, the first step is to understand the project structure and explore the function of a control tool within a project structure.

2.1.1 Design-Build VS. Design-Bid-Build

The application of axiomatic control needs to be tailored according to its context. The level of involvement from each party in a project is heavily dependent on the contracting strategy and project delivery system. For example, in a design-bid-build project, the designer and the general contractor are hired separately by the owner or the construction manager, as shown in Figure 1.

![Figure 1: Organization Structures for Design-Bid-Build Projects](image_url)
In this traditional organization, the designer and the contractor are two completely different entities with the same rank in the hierarchy. Conflicts arise due to a lack of or ineffective communication between the designer and the contractor. This lack of communication sometimes brings the need for a construction manager to help coordinate the work between the designer and contractor. For the purpose of this thesis, following the regular government laws, design-bid-build contracts preclude the designer from working with the contractor during design phase. The designer has no resource and budget information from the contractor because bidding only starts after the specifications are prepared. Furthermore, the overlapping issues in fast-tracking and concerns for using early information is removed. As a result, design-bid-build projects are beyond the scope of this research because of the legal constraints to effectively analyze the dependencies between the designer and contractor.

In contrast to design-bid-build, design-build projects allow the designer to obtain information on resource and budget early in the design phase. A typical organization structure for design-build contracts is shown in Figure 2. In this organization, the general contractor and the designer both work directly under the same engineer contractor, which is a single firm responsible for both design and construction. It is possible to design a project at its optimum configuration because the design and construction crew could work collaboratively. One way to apply the robust planning and control methodology at the management level is to restructure the organization based on how information flows among the participants. For example, a construction crew could be a member of a design team to report on the constructibilities of different design options. He/she can further prepare a cost estimate for each design option with his/her knowledge of the necessary resources. Once a design is selected, he/she can work with the project manager to plan that activity at once. As the concept of concurrent engineering suggests, the design process becomes efficient as information flow speeds up.

![Organization Structure for a Design-Build Project](image_url)

Figure 2: Organization Structure for a Design-Build Project
2.1.2 Managing a Fast-track Project

The above example leads to the possibility to "fast track" a project. The idea is to divide the design process in phases and to begin construction before the entire design process is completely finished. Fast tracking is especially popular for projects under heavy time constraints. However, it requires a carefully planned project schedule and clear channels for information feedback. The history of how and why each decision is made needs to be properly documented to minimize confusion. This is especially important when change orders are filed after the project has proceeded for a prolonged period. With an appropriate documenting procedure, change orders can be measured against early design intentions to determine its rightfulness. This thesis documents how the robust planning and control methodology can help manage fast-track projects by applying axiomatic design concepts, concurrent engineering, graphical evaluation and review technique (GERT), and system dynamics modeling.

2.1.3 Summary of Project Structure

The design-build delivery method used in this thesis provides the project planners with sufficient leverage to influence the design orientation, so that the corresponding construction tasks can be readily overlapped. After the engineers have generated the complete detailed drawings, the axiomatic approach to planning can systematically formulate and evaluate various work methodologies. The hierarchical nature of axiomatic design clearly defines the problem scope and the corresponding processes and activities that could solve the problem. Hence, the goals of each activity can be clearly documented by using the axiomatic design principles. Once a conceptual project plan is generated by axiomatic design, the concept of concurrent engineering can be applied to analyze the validity and effectiveness of fast-tracking critical activities in the project. The critical activities are either on the critical path, near-critical path or have high criticality indices. Therefore, shortening the duration of these activities can effectively reduce the overall project duration, and further leads to a lower overhead.

Subsequently, the resulting schedule after fast-tracking including the anticipated rework cycles due to undesirable circumstances, can then be calculated probabilistically in GERT. The GERT network
scheme can assign each activity with a range of duration, so that the final schedule would consist of a range of estimated completion date. Finally, the system dynamics modeling technique can be applied to simulate the activity production process under various fast-tracking schemes. Consequently, the important factors affecting the success of fast-tracking can be identified by their causality links to the rest of the construction system. The fast-tracking practice can be improved by monitoring and controlling these factors during the construction process.

2.2 FUNDAMENTALS OF AXIOMATIC DESIGN

The axiomatic design concept was originally developed to help the design process by explicitly defining the project objectives and formulating the corresponding solutions as designs. This design approach is adapted in the robust planning and control methodology to help define the project scope and formulate the necessary actions to achieve the project goals. Consequently, this set of actions can be organized and sequenced to form the work methodology for the project. This work methodology can then become the backbone of the preliminary project plan. Typically, more than one methodology can be generated to build the facility in this process. Among the many available work methodologies, the axiomatic evaluation concept can be applied to help determine the strengths and weaknesses of each work methodology, and finally select the best one for the project.

For pure design, the concept of axiomatic design provides a systematic approach to gather and process design information in order to develop a product [Suh, 1990]. This concept will be adapted in this thesis to develop a systemized and rigorous construction planning process. The two design axioms below are the fundamental rules to implement the axiomatic design process, and they are going to be the cornerstone for the robust planning and control methodology.

Axiom #1: The Independence Axiom

Maintain the independence of functional requirements.

Axiom #2: The Information Axiom

Minimize the information content of the design.

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2.2.1 Concept of Domain and Mapping

The axiomatic design process is performed in four stages, which are called Domains. There are Customer Domain, Functional Domain, Physical Domain, and Process Domain, as shown in Figure 3. The connection between two adjacent domains is called mapping, which can be described as a “what-and-how” relationship. The domain on the left posts what needs to be achieved; and the domain on right corresponds with how it can be done.

As seen in Figure 3, each domain addresses different issues by capturing various design information. The Customer Domain captures owner needs, preferences and requirements. The design engineers would then transfer these needs into engineering terms, known as Functional Requirements (FR) in the Functional Domain. Each independent FR is then satisfied by a design parameter (DP) in the Physical Domain. Finally, the very set of DP generated would be implemented in the Process Domain, which is essentially the construction phase.

Functional Requirements (FR) are defined as “the minimum set of requirement which completely characterize the design objective for a specific need” [Suh, 1990]. The FRs have to be given in a “solution-neutral environment” which specifies the function needs to be achieved, not any particular solution.

![Figure 3: Domain and Mapping](image)

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As Suh suggested, these four domains always exist regardless of the discipline in which the designer tries to apply axiomatic design. The designers can breakdown the designing process so that the design elements are consistent with the four domains. Table 1 shows how the design elements can be modified to accommodate different disciplines. For civil engineering projects, the customer domain represents attributes of the facility that the owner desires. In the functional domain, the capabilities of the facility have to be defined as functional requirements. Then, in the physical domain, engineers can design components that satisfy each functional requirement. At the end, the construction process would take place to fulfill the designs generated in the physical domain.

<table>
<thead>
<tr>
<th></th>
<th>Customer Domain</th>
<th>Functional Domain</th>
<th>Physical Domain</th>
<th>Process Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manufacturing</strong></td>
<td>Attributes which the customers desire</td>
<td>Product functional requirements</td>
<td>Physical variables which can satisfy the FRs</td>
<td>Product Variables that control the Physical Domain</td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td>Desired Performance</td>
<td>Required Property</td>
<td>Micro Structure</td>
<td>Processes</td>
</tr>
<tr>
<td><strong>Software</strong></td>
<td>Attributes desired in the software</td>
<td>Output</td>
<td>Input variables and algorithms</td>
<td>Sub-routines</td>
</tr>
<tr>
<td><strong>Systems</strong></td>
<td>Attributes desired of the overall system</td>
<td>Functional requirements of the system</td>
<td>Machines or components, sub-components</td>
<td>Resources (human, financial, and materials)</td>
</tr>
<tr>
<td><strong>Civil Engineering Projects</strong></td>
<td>Attributes which the owners desire</td>
<td>Facility capabilities</td>
<td>Design components which satisfy the FRs</td>
<td>Construction Processes</td>
</tr>
</tbody>
</table>
2.2.2 Zigzagging Design Cycle

The process that turns a conceptual design to detailed design requires interactions between Functional Domain and Physical Domain. In fact, every design that we do has a hierarchical nature to it. Therefore, decision must be made by prioritizing the level of importance and eventually decompose the problem into a hierarchy [Suh, 1990]. This process starts by specifying the general functional requirements in the Functional Domain. Then, the Design Domain responds with several design options, which are then measured against the functional requirements to select the best option. After the best design option is selected, the next level functional requirements are laid out and the same design cycles revolves until a detailed design is finally achieved. The following Figure illustrates this design process with zigzagging between Functional Domain and Physical Domain.

Figure 4: Zigzagging Design Process [adapted from Adept, 1996]

2.2.3 Summary of Axiomatic Design

The application of axiomatic design on robust planning and control methodology is to rigorously define the objective of each planning step independently. Once the objective is clearly defined, an appropriate solution can be formulated to achieve the particular project objective. The two axioms are
applied to ensure the objective is framed correctly in a solution-neutral environment, and the corresponding solution is the most effective for project implementation. The hierarchical natural of axiomatic design and the zigzagging design process will be adapted in this thesis to develop various work methodologies suitable for the project. The axiomatic design evaluation, which will be introduced in Chapter 2.3.2, can help select the best work methodology. Consequently, the application of axiomatic design concept can enhance the effectiveness of the planning process by ensuring the quality of the work methodology by which the project plan will be built upon.

2.3 DEPENDENCE MATRIX

A dependence matrix is a mathematical interpretation representing the interactions between two domains. The relationships between the FRs and DPs at a given level of the zigzagging design process are captured in a design matrix, shown below as matrix [A]. Similarly, the relationships between the DPs and PVs in the same process are captured in another mapping process, shown below as matrix [B].

\[
\{\text{FR}\} = [A]\{\text{DP}\}
\]

\[
\{\text{DP}\} = [B]\{\text{PV}\} \quad \text{where } [A] \text{ and } [B] \text{ are design matrices}
\]

Combining the two equations, we get

\[
\{\text{FR}\} = [A][B]\{\text{PV}\}
\]

Albano [Albano, 1992] defines design matrix [A] as the relationships between the design variables and the design requirements. The structure of [A] determines whether or not the proposed design maintains the independence of the individual requirements. On the other hand, design matrix [B] contains information regarding construction operations and constructibility. One important factor that has considerable influence upon constructibility issues is the complexity of the operational sequence [Griffith, 1987]. It refers to the number of steps required for construction and the inter-relationship level among the construction elements. One way to represent this information is to identify the precedence relationship of the activity, such as its duration, lag, and lead, in relation to other activities. The design matrices contain
important information regarding task relationships in an visible format.

The elements in the design matrix are determined by taking the partial derivatives illustrated in the following equation. Each element of A, the design matrix, is described by the partial derivative \( A_{ij} = \partial FR_i / \partial DP_j \). Similarly, each element of B is described by the partial derivative \( B_{ij} = \partial DP_i / \partial PV_j \).

Moreover, the overall effect of a dependence matrix can be calculated by summing up the partial derivatives. For example, the relationship between FRs and DPs can be described as the following:

\[
\Delta FR_n = (\partial FR_1 / \partial DP_1) \Delta DP_1 + \ldots + (\partial FR_1 / \partial DP_n) \Delta DP_n
\]

This mapping process must satisfy Axiom #1: The Independence Axiom. In an acceptable design, the mapping between the FRs and DPs (or, between the DPs and PVs) is such that each FR can be satisfied without affecting other FRs [Albano, 1997].

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2.3.1 Three Categories of Dependency Matrices

There are three categories of dependence matrices, which are uncoupled design, decoupled design and coupled design. The corresponding orientations of the matrices are diagonal, upper or lower triangular, or populated both above and below the diagonal. The following diagram gives an example of the three types of dependency matrices.

![Uncoupled Design](image1)

![Decoupled Design](image2)

![Coupled Design](image3)

Figure 5: Examples of dependency matrices
The best possible design is the uncoupled design, where as each FR is satisfied independently by a corresponding DP. Hence, the design tasks can be performed in parallel and be completed within the shortest duration. The second best design is the decoupled design. In this design configuration, the performance of each design task depends on the finalized information transfer from its upstream task. Therefore, the design must be carried out in series. Although a decoupled design requires a longer time frame than uncoupled design, it is still possible to perform. The least desired is the coupled design. In this scenario, the progresses of two or more design tasks are mutually dependent on each other. Therefore, the information feedback becomes not only crucial, but also difficult.

Comparing the three types of design, the uncoupled design is the most promising scheme and the coupled design is the least promising arrangement. Implementing an uncouple design can reduce the uncertainties resulting from the hard constraints among the activities in other schemes. Furthermore, eliminating the dependencies among the activities can minimize the ripple effect resulting from undesirable circumstances. The effectiveness of different design schemes can be evaluated by the information axiom introduced in Section 2.3.2.

Although the existence of a coupled design is highly undesirable, the attempt to completely eliminate all coupled relationships can be physically unrealistic and infeasible. That is, the production of two activities must be conducted concurrently. The concept of concurrent engineering introduced in Section 2.4 can be applied to effectively manage the necessary information flow to complete two tasks in parallel. This concept will be adapted in the robust planning and control methodology proposed in this thesis to address the concurrent issues when two activities are fast-tracked. Consequently, a systemized framework of fast-tracking strategy will be developed based on the concurrent engineering concept in this thesis.

2.3.2 Design Evaluation

The process of domain and mapping, hierarchical decomposition of FRs and DPs, and zigzagging design cycles, can help formulate several designs to achieve the project goal. Among the many available design alternatives, an effective evaluation method has to be established to compare the different designs.
against a benchmark. The second axiom of axiomatic design concept is stated as below to help evaluate the effectiveness of various design schemes with respect to the design or planning constraints.

**Axiom #2:** The Information Axiom states that “among all designs that satisfy the functional independence (Axiom #1), the best design is the one with the least information content” [Suh, 1990].

The general definition of information content is \( I = \log_2 (1/p) \), where \( P \) if the probability of \( DP_1 \) satisfying \( FR_1 \). This is also called probability of success. The probability of success can be measured by comparing the “system range” with the “common range.” The design range is the target value with tolerances in which FRs are satisfied. The system range is what the DPs are able to achieve, expressed in probabilistic terms. The overlapping area between the design range and system range is called common range, which represents an acceptable design. Consequently, the probability of success can be calculated as \( P = \text{common range} / \text{system range} \).

![Probability of Success](image)

**Figure 6: Probability of Success**

The sum of a design’s total information content yields the probability of success as long as the independence axiom is satisfied. This is because monotonicity and additivity of independent variables validate this operation [Albano, 1997].
2.3.3 Summary of Dependence Matrix

During the planning process for a construction project, the engineers usually can develop several work methods that are capable of achieving the project scope. Consequently, among the many available solutions, there has to be an established criterion by which the best solution can be identified and used. The application of the dependence matrix and the information content axiom can help the project planners compare the effectiveness of various work methods, and further identify the areas that could post difficulties for project implementation. Typically, these tasks can be captured as the coupled activities by which additional management attention and coordination will be required to construct these activities in parallel. Furthermore, the information content axiom helps define the probability of meeting or exceeding an important goal or constraint in the project. Hence the effectiveness of different project plans, which are developed by the zigzagging process, can be measured objectively and accurately. After the weaknesses of a project plan are identified, the planners can take appropriate measures to resolve the problems and ensure smooth implementation during construction. Finally, the application of these evaluation techniques can improve the overall effectiveness of the planning process by making each decision based on a series of important and effective criterions.

2.4 CONCURRENT ENGINEERING

Once all the feasible work method are identified and tested against the axiomatic evaluation process, the best work method can be selected to develop the preliminary project plan. The subsequent step in the proposed planning and control methodology is to identify where fast-tracking can be applicable and effective to reduce project duration. Along with this concept, the concurrent engineering practice has been applied by manufacturing firms to meet the challenges coming from intense competition to develop and market products faster. In the case of a civil engineering project, it can help a design-build firm to deliver better products quicker than its competitor and beat the estimated completion date. The application of concurrent engineering can be adapted in the proposed robust planning and control methodology to develop an overlapping framework to help implement fast-track activities.
The applications of concurrent engineering, depending on the context, are qualified as "in the small" and "in the large" [Eppinger, 1994]. Concurrent engineering in the small is usually conducted by allowing design engineers to work closely with construction engineers and field engineers. This multi-functional team integration approach gains success by working closely together to solve for challenging and complex technical issues by mutual understanding.

Concurrent engineering in the large is of the main interest for this thesis. It focuses on challenges facing large projects that require inputs across disciplines. Many of which are broken down into work packages, and are conducted by a small project team or outsourced to a consultant. What makes this process difficult is the fact that none of these tasks can be performed in complete isolation. Each decision made by an engineer will ultimately affect the decision of another engineer in the same project team and/or in a different team. Tradeoffs between decisions require efficient information transfer in the form of a consistent documenting procedure. The major challenge in the development process is how to integrate the various planning tasks into a system solution.

By incorporating the concept of concurrent engineering in this thesis, its capabilities will allow the proposed methodology to capture and manage the iterative nature of the planning process. Iteration processes are usually observed in the case of coupled activities because two or more design/construction tasks must be carried out at the same time. Reducing the complexities of coupled activities will not only ease up the planning process but will ultimately reduce the difficulties of construction.

2.4.1 Iteration among Overlapping Tasks

The concept of concurrent engineering evaluates the effectiveness of an overlapping practice based on the characteristics of the upstream and downstream task, and the type of information exchange that is required to maintain the production of the two activities. The same type of analysis can be applied to develop an overlapping framework for the robust planning and control methodology based on a defined set of activity characteristics. However, the type of activity characteristics and other relevant factors that might influence the effectiveness of overlapping has to be considered in this overlapping framework as well. Furthermore, the implication, value and usefulness of concurrent engineering has to be fully
understood before it can be applied to help develop the proposed robust planning and control methodology.

Figure 7 shows how the different overlapping practices can arise to represent two coupled tasks in the construction phase. Nominally sequentially tasks are typically observed in design-bid-build projects and typical design-build projects with little time constraints. A poor overlapping practice involves transferring immature data that still requires a substantial amount of rework and time to finalize [Eppinger, 1997]. Consequently, the downstream task becomes inefficient by producing dubious results based on inaccurate upstream data. On the other hand, an effective overlapping practice can be achieved by freezing upstream parameters before transferring information to the downstream task. Then, the downstream crew can begin their work based on the frozen parameters. One pitfall of this approach, however, is that if the finalized information released by the upstream crew actually contains a substantial amount of undiscovered rework, then the production downstream based on this unreliable information might need additional rework.

![Diagram of overlapping practices]

**A to B: Nominally Sequential Tasks**
- Downstream task is delayed until upstream data transfer.

**B to C: Poor Overlapping Practice**
- Wasteful iteration results from transfer of preliminary data which subsequently changes.

**C to D: Effective Overlapping Practice**
- Upstream task freezes early, permitting downstream to begin earlier.

**D to E: Effective Overlapping Practice**
- Analogous to B to C; however, downstream task uses preliminary data to begin early, and finalizes with fast iterations.

Legend:
- Finalized information exchange
- Preliminary information exchange

Figure 7: Versions of overlapping practices [adapted from Eppinger, 1997]

An alternative to achieving effective overlapping practice is to use preliminary data from upstream and generate work units that are flexible and have high tolerances for error. In this scenario, the
upstream parameters are not frozen when transferred. Therefore, the downstream task must be flexible enough for fast iterations as upstream data finalizes. This process is represented as D to E in Figure 7. Comparing the two methods to achieve effective overlapping practice, the engineering firm and the owner must make a tradeoff among time, quality and money. In order to overlap two sequential tasks, the production of upstream task entails compromising quality in terms of value engineering because the upstream task must ensure the parameters meet or exceed the specified performance, hence creating a greater common range for the downstream task. As a result, the upstream task could possibly incur higher material costs. Consequently, the tradeoff between time and cost has to be analyzed before two tasks are overlapped.

2.4.2 Overlapping Evaluation and Implementation

The application of concurrent engineering specifically deals with the interaction between two design crews collaboratively produce a design work. Therefore, concurrent engineering addresses the issue of transferring information that is derived from design parameters. In contrast, the construction planning deals with the production of physical units. The transformation from intangible information in the context of concurrent engineering to production of physical units in construction planning will be addressed, after the concept of concurrent engineering is introduced in this Chapter. Although the type of activity characteristics used to describe intangible information and physical production units are substantially different, the implication of concurrent engineering on collaborating and coordinating two parallel tasks can be applied to plan for fast-track activities in construction projects.

Concurrent engineering classifies the overlapping framework in terms of upstream task evolution and downstream task sensitivity. Upstream evolution describes the required time for an upstream activity to finalize its design parameter. Some crews are able to produce results quickly, and others slowly. Downstream sensitivity describes how sensitive is a piece of upstream information to a downstream activity. Some downstream activities are sensitive to changes in upstream information, and others are less sensitive [Eppinger, 1997]. The following diagram in Figure 8 represents the interactions described above in graphical forms.
After defining the characteristics of upstream and downstream activities, it is now possible to select an overlapping strategy based on its framework. There are four possible combinations as illustrated in Figure 8.

In the case of slow upstream information evolution and low downstream sensitivity, the best approach is to transfer as much preliminary information as possible to initiate the downstream design process. Since it takes time for upstream activity to generate finalized results, the downstream activity can utilize available information to develop the general design parameters. It is easy to modify and improve these parameters because the downstream activity is not particularly sensitive to information from the upstream activity.

![Diagram showing upstream and downstream tasks with certainty, duration, and information sensitivity](image)

**Upstream (Information) Evolution**
Some upstream tasks develop certainty in (evolution of) their output information quickly, others slowly.

**Downstream (Iteration) Sensitivity**
Some downstream tasks are very sensitive (in duration) to changes in input information that is transferred early, others may be insensitive.

Figure 8: Evolution and Sensitivity [adapted from Eppinger, 1997]

The similar strategy can be applied to the situation with fast upstream information evolution and low downstream sensitivity. The upstream activity still transfers preliminary information when first available. However, since parameters can be developed quickly by fast evolution, finalized information
can replace preliminary information readily for effective overlapping. This is the best context for the application of concurrent engineering.

For a situation that has slow upstream evolution and high downstream sensitivity, it is recommended to either perform overlapping in stages or no overlapping at all. Due to the nature of high downstream sensitivity, only finalized information should be transferred. Dividing design process in stages allows upstream activity to generate intermediate finalized results for downstream activity. If the task does not allow upstream development in stages, then it is better not to overlap the activities at all.

![Overlapping Framework Diagram](image)

Legend:
- → Finalized information exchange
- ← Preliminary information exchange

Figure 9: Overlapping Framework [adapted from Eppinger, 1997]

The last situation is where fast upstream information evolution meets high sensitivity downstream activity. Similar to the last case, preliminary information should not be transferred because the downstream activity is highly sensitive. However, overlapping is still feasible since upstream activity is
able to generate finalized results quickly and transfer the information to downstream activity. Such overlapping practice is called precipitative overlapping [Eppinger, 1997] to describe the process which upstream activity produces and immediately transfers the finalized results.

2.4.3 Summary of Concurrent Engineering Application

The transformation from intangible information described in concurrent engineering to physical production units in construction planning involves redefining the parameters set forth by concurrent engineering, and restructuring the information transfer process in terms of production of physical units. For example, the role of preliminary information exchange from upstream design task might represent an unreliable upstream construction activity containing a great amount of errors and reworks. The evolution of upstream design task certainty can represent how quickly the errors in the upstream construction task can be discovered and fixed. Furthermore, the different overlapping strategy developed in concurrent engineering, such as iterative, distributive, divisive and precipitative overlapping, can delineate the amount of fast-tracking that should be implemented on two sequential construction activities. In this thesis, the concept of concurrent engineering will be adapted to develop various overlapping strategies based on certain activity characteristics to effectively reduce the overall project duration and costs.

2.5 GERT (GRAPHICAL EVALUATION AND REVIEW TECHNIQUE)

Once a set of construction activities is identified as being suitable for fast-tracking, the amount of duration reduction can be calculated by several conventional network schemes, including CPM, PDM, PERT and GERT. Along with the concept of robust planning and control methodology, the scheduling uncertainties related to unexpected circumstances and rework loops should be incorporated in the schedule, so that an appropriate amount of contingency can be assigned to ensure timely completion.

However, the conventional CPM/PDM approach assigns each activity with a deterministic duration, neglecting the uncertainties and variation of production efficiency within the activity itself. The
PERT approach includes these uncertainties by assigning a range of duration for each activity, including both the pessimistic and the optimistic duration. Hence, the resulting schedule would have a range of possible completion date for the project. However, situations such as multiple branching, probabilistic branching and activity reworks through feedback loops are typical events confronted in project planning that can not be modeled in a CPM/PERT network [Taylor and Moore, 1980]. Consequently, this drawback can be taken care of by applying the GERT approach to scheduling. The GERT approach explicitly defines the rework loops and branches for different outcomes in the project schedule. A probability is assigned for each loop and branch in the schedule, so that its impact on the overall schedule can be incorporated and adjusted accordingly. Furthermore, each activity can be assigned with an estimated duration to also yield a range of possible completion date. The GERT concept follows along the same line of robust planning and control methodology, where the possible interruptions to project schedule are accounted for in the planning stage. The GERT approach to scheduling will be applied in this thesis to probabilistically calculate the project schedule, so that the effectiveness of fast-tracking can be represented mathematically in terms of duration reduction.

2.5.1 GERT Node Types

Graphical Evaluation and Review Technique (GERT) was developed to incorporate both branching and looping to capture different project end events and alternative project policies. This is achieved by including new node type for branching events to graphically portray alternative paths in a network. Consequently, a project planner can assign probabilities to different paths. The probabilities are estimated on the basis of judgement and experience with similar circumstances. The nodes used in GERT are illustrated in Figure 10.

The input parameter the GERT network describes the relationships of predecessor events to the current activity. For some activities, all of the predecessors have to be completed before the current activity can begin, and the others don't. Similarly, the output parameter describes the successor events after the current activity is finished. Again, some activities must have successor events, while others might or might not have them. The symbols in the GERT network explicitly classify the relationship of each activity to its preceding and succeeding events. Therefore, the schedulers and the reviewers can
clearly understand where probabilities should be assigned to represent the possible loops and branches in the GERT network.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exclusive-or</td>
<td>Any branch leading into the node causes the node to be realized, but only one branch can occur.</td>
</tr>
<tr>
<td></td>
<td>Inclusive-or</td>
<td>Any branch causes the node to be realized and at the time of the earliest branch.</td>
</tr>
<tr>
<td></td>
<td>And</td>
<td>The node is realized only after ALL branches have occurred.</td>
</tr>
<tr>
<td></td>
<td>Deterministic</td>
<td>All branches out must occur if the node is realized.</td>
</tr>
<tr>
<td></td>
<td>Probabilistic</td>
<td>Only one of the branches may occur if the node is realized.</td>
</tr>
</tbody>
</table>

**Figure 10: GERT [adapted from Moder et al, 1983] and Q-GERT Symbols [adapted from Taylor and Moore, 1980]**

2.5.2 Planning Under Uncertainties

GERT is typically applied to anticipate the uncertainties in the project schedule, so that an appropriate amount of contingencies can be assigned to prepare for these unforeseen circumstances.
Especially for construction projects that the overall duration is highly dependent on the actual site conditions, such as waste containment, environmental cleanup, and earthquake retrofit, the GERT approach is particularly useful to accommodate the different scenarios that the construction crew might encounter.

The following example demonstrates how probabilities can be incorporated in developing a project schedule. The example begins by performing inspection of the construction site for the presence of hazardous materials, prior to excavation work [Primavera Systems, Inc. 1995]. If hazardous materials are found, counter measures such as waste containment or removal would be required before excavation can proceed. If the possibility of uncovering hazardous materials is not properly accounted for, then the resulting schedule might be overly optimistic. However, fully allowing remedial action might not be necessary because it would result in too conservative a schedule, which allocates too much resource for this project. The GERT approach helps define the appropriate amount of contingency probabilistically, so that the project planner can decide the final resource allocation and/or counter measure technique that is suitable for the project.

Figure 11 illustrates how to account for the different scenarios probabilistically. The diagram starts with an estimated probability of finding hazardous materials. There is a 4% chance that the construction crew would uncover hazardous materials. If such materials are uncovered, then the crew needs to spend a range of five to thirty days on remedial action. Otherwise, they can proceed with the schedule as originally planned. The range of schedule variance from the original plan can then be calculated as $96\% \times (0 \text{ day}) + 4\% \times (5 \text{ to } 30 \text{ days})$, which is equal to 0.2 to 1.2 day long.

A strong connection exists between the GERT network diagramming method and the concurrent engineering concept. The activity characteristics used to define the overlapping framework in concurrent engineering can be converted to become the probabilities used in the GERT diagram. For example, a reliable upstream task would have a small probability leading to a rework cycle. For a sensitive downstream task, the range of duration would be substantially greater compared to an insensitive downstream task. Consequently, the implication of the overlapping framework on the resulting project schedule can be represented numerically in the GERT network diagram.
2.5.3 Summary of GERT

Above all, the GERT approach is applied in this thesis to account for the undesirable circumstances in the project schedule. The application of GERT helps the project planner to assign appropriate amount of contingencies in the schedule to prepare for unforeseen changes in the project. Furthermore, the branches and loops in the network incorporate these events probabilistically and yield a range of estimated completion date. The integration of GERT and concurrent engineering will be used in this thesis to calculate the impact of a particular overlapping strategy on overall project duration. Consequently, the effectiveness of overlapping can be evaluated and the undesirable circumstances can be properly incorporated in the planning process.

2.6 SYSTEM DYNAMICS MODELING

Once the project schedule is calculated by applying the GERT concept, the factors that can effect the success of a particular overlapping strategy have to be identified and monitored. The system dynamics modeling technique incorporates the causality links between the variables in a construction system and the activity production process. The model explicitly delineates the relationships between each variable
mathematically, which can be infallibly maintained during the computer simulation process. Once the critical factors are identified by the system dynamics modeling technique, the chances of successfully implementing a set of fast-track activities can be greatly increased.

The initial role of system dynamics on project management was to determine the effect of errors on the overall project progress. There is a list of factors that relate to the generation of errors in a construction project, such as staff experience, craftsmanship, schedule pressure, worker’s morale, weather, available equipment and design drawings accuracy. In many instances, projects often appear to be going smoothly until near the end, when errors made earlier are discovered, necessitating costly rework, expediting overtime, more hiring, schedule delays, and reduction of work quality. One methodology to identify and resolve problems that arise in a project is the application of a system dynamics model. System dynamics has been demonstrated as an effective analytical tool in project management, including large-scale projects in shipbuilding, defense, aerospace, power plants and construction. System dynamics models help manage projects more effectively by analyzing the causality relationships of a problem raised during construction. The models are also used to assess the magnitude and sources of cost and schedule overruns in the context of litigation [Sterman, 1992].

A construction system for typical large-scale civil engineering projects could involve thousands of activities and variables in both design and construction. The interdependencies among these activities and the effect of different factors on the production of each activity can not be completely visualized mentally alone. The complexities of these projects entail that they belong to the category of complex dynamic systems [Sterman, 1992]. Such systems have the following characteristics.

1. They are extremely complex, consisting of multiple interdependent components;
2. They are highly dynamic;
3. They involve multiple feedback processes;
4. They involve nonlinear relationships.
2.6.1 Interdependent Components

The foremost utilization of a system dynamics model is to represent the interdependencies among the different project components. Such interdependencies often complicate the problem because a subtle change in one part of the system can trigger a domino effect in other parts of the system. For example, changing the location of ethernet sockets in an apartment complex cause changes in both mechanical and electrical systems. The amount of work required is far beyond adding an extension cord. As a result, workers might need reassignment from other tasks, causing more delays. The worst scenario happens when such changes lead to delays on other tasks, which find themselves dependent on completion of the deferred activity. These are called “coupled” activities in axiomatic design. In this context, system dynamics models are capable of representing such interdependencies by tracing the causal impacts of changes.

2.6.2 Objectives are Highly Dynamic

Civil engineering projects are highly dynamic. To name a few elements, unexpected site conditions, quality inspection failure, and change of project scopes, all are possible causes of schedule and cost overruns. In the case of schedule delays, most project managers would respond by assigning overtime or hiring more workers to increase productivity. However, in the short run, experienced workers must divert time from their work to train the new worker and hence reduce overall productivity. To avoid such incidents, a system dynamics model can be designed to deal with such complications and answer “what if” questions posed by the management when considering alternative policies. The different policies can be tested in the model by altering the values of the variables in the model, and then simulate the resulting effect on the construction system. Furthermore, the system dynamics modeling technique is particularly suitable to analyze a system that the variables dynamically evolve across time. The fast-tracking issues addressed in this thesis are highly sensitive to the timing of overlapping a set of activities. Consequently, the ability to capture the activity progress across time by applying system dynamics is particularly useful to analyze the effectiveness of the overlapping strategies developed in this thesis.
2.6.3 Multiple Feedback Processes

The term “feedback” used in a system dynamic model refers to the self-correcting side effects of decisions. For example, working overtime and hiring new workers to make up for schedule delays are both self-correcting actions. In the short run, the extra hours from working overtime help bring the project back on schedule. However, if the amount of overtime remains high for a long period of time, workers become fatigued, leading to lower productivity, higher rate of errors, and more employee turnover. As a result, the project is further delayed and requires even more work time. This situation creates a reinforcing loop, as demonstrated by Figure 12. An arrow with a positive sign means that, all else being equal, a change in the first variable causes a change in the second variable in the same direction. An arrow with a negative sign means just the opposite. The message from this simple example is that instead of focusing on creating solutions to solve problems, maybe the problems are actually created by our solutions.

The ability to capture the multiple feedback processes by applying system dynamics is important because it realizes the interactions among a set of activities in a construction system. In particular, the effect of different factors on the implementation of fast-tracking will be the focus of this thesis. As mentioned in Section 2.4.3, an overlapping framework will be developed based on the concept of concurrent engineering. This framework will be categorized depending on the upstream and downstream activity characteristics. The effect of these activity characteristics on the project progress can be captured by the multiple feedback process in system dynamics. Furthermore, this process helps identify the important factors that the success of a particular overlapping strategy depends upon.
2.6.4 Non-Linear Relationships

Causes and effects in a complex system often do not have linear relationships. One simple example is diminishing return of working long overtimes. Fatigue lead to additional errors and lower production rate. Another example is the effect of learning curve, which helps increase productivity by assigning workers to the same task, allowing them to gain experience through work repetition. In order to understand the effects of these nonlinear relationships in civil engineering projects, system dynamics models help portray the range and consequences of these relationships in complex systems. The causality links between each variable can be defined mathematically in the model and infallibly retained during the simulation process.

The combined effects of large-system characteristics suggest that a system dynamics model is preferred to a mental model. A mental model does not serve sufficiently to capture and analyze problems in a complex system. In addition, a system dynamics model is a good complement to axiomatic design by utilizing the interdependencies defined during the design process. It enhances the application of the tool by adding a formal analytical element to model and analyze problems raised during construction.
2.6.5 Summary of System Dynamics Application

The application of system dynamics modeling technique on robust planning and control methodology helps the planners to understand how a set of fast-track activities would progress with respect to time. Using this technique, a model demonstrating the progression of two sequential activities will be developed and simulated in this thesis. This model will include the factors that could possibly affect the activity characteristics, and by simulating the model, the important factors that determine the success of an overlapping strategy can be identified.

Furthermore, the system dynamics modeling technique allows the construction crew to test the different overlapping strategies in a controlled environment. Once the critical factors in the system are identified, the construction crew can simulate the model under several "what if" situations. For example, the crew can test the amount of quality improvement by raising the average experience level variable in the model. With this process, the crew can realize what kind of parameters they have to strive for in order to successfully fast-track a set of activities.
CHAPTER 3

METHODOLOGY

The purpose of this Chapter is to present the methodology that integrates the different components of robust planning and control methodology into one single solution to help streamline the construction planning process. Comparing the differences between engineering design and construction planning, for a typical engineering design project, the detail design is generated by zigzagging between the functional requirements (FRs) and design parameters (DPs). However, in the context of construction project planning, the planner focuses on how to build the facility quicker with lower costs based on the given set of drawings. Consequently, the planning process would begin by identifying the DPs of the project based on design drawings and other relevant information, and then formulate the possible work methodologies in terms of process variables (PVs).

Among the many available solution alternatives, the best set of PVs will be selected based on the two principles of axiomatic design concept: the independence axiom and the information content axiom. Furthermore, the characteristics of these PVs such as production rate, production reliability and sensitivity to upstream errors will become the key parameters in formulating a good overlapping strategy. Intuitively, the ideal overlapping situation is a pair of sequential tasks having a highly reliable and fast producing upstream task combined with an insensitive and slow progression downstream task. Based on the concept of concurrent engineering, a more detailed overlapping framework will be developed and evaluated in Section 3.2.4 based on the activity characteristics and recommends the appropriate overlapping strategy. Consequently, if the two overlapped activities are either on the critical path or have high criticality indices, then overlapping the two can effectively shortened the project schedule. Even if they are not on the critical path, additional buffer can be generated as a result of overlapping and absorb changes or reworks to protect the project from delays. Consequently, applying this overlapping
framework at where it is applicable can ultimately create an efficient and robust project plan to minimize the impact of changes on project schedule.

Furthermore, this overlapping framework will be evaluated by the GERT approach, using the probabilities of branching and looping as references for task production progress, reliability and sensitivity. The difference in project duration as a result of fast-tracking can be measured probabilistically in GERT with a range of completion date. Finally, the system dynamics modeling technique will be used to determine the causal relationships between actions and reactions in a particular set of activities. By explicitly incorporating the feedback structure of the system, the planner can analyze the behaviors of task progression under various “what if” conditions. The simulation process can also help identify the important factors that determine the success and effectiveness of the overlapping framework developed in this thesis.

3.1 ROLE OF AXIOMATIC DESIGN CONCEPT

Following this methodology, the first task is to define the objectives of the project as design parameters (DPs). A simple way to describe the functions of DPs with respect to PVs, is that the DPs are the questions and the PVs are the solutions. The selection of DPs for the project can be derived from design drawings, specifications, owner’s objectives and other relevant information. Because the role of DPs in construction project planning is similar to FRs in engineering design, a set of DPs can be defined as the minimum set of independent requirements that completely characterizes the objective of the project. If two DPs are dependent on each other, they should be collapsed to one independent DP. Redundant DPs may add unnecessary functions to the proposed work methodology, hence adding extra costs to the project.

Furthermore, the DPs must frame the problems in a solution-neutral environment so that there is no bias in evaluating alternative project plans or work methodologies later in the planning process. The choice of DPs and PVs varies from company to company and project to project, because each company has a different level of expertise, concentration of resources, delivery arrangement and management goals. Therefore, an acceptable set of DPs or PVs is not necessary unique, even if similar types of projects
are planned with this vary same technique. Planning for construction is similar to design with respect to the iterative trial-and-error process before an optimal set of DPs and PVs can be derived. To better demonstrate this DP and PV formulation process along with other concepts from the methodology, a typical water dam construction project, as shown in Figure 13, will be used as an example.

![Cross Section View of the Water Dam](image)

Figure 13: Cross Section View of the Water Dam

In this sample construction project, the dam is designed to utilize the existing valley and further shave off excess earth to increase the dam capacity. The cross section view of the proposed water dam is illustrated in Figure 13. Along the sides and the bottom of the dam, a layer of reinforced retaining slab with anchor bolts will be constructed to form the liner. During the construction, the inhabitants will continue living along the valley bank, so the slope stability and ground settlement have to be closely monitored during the construction process.

Like most projects, the designers have suggested a construction method in the specification, which is the traditional scrape-and-excavate method. At the same time, the owner has provided the incentive to share the benefits gained from an alternative work methodology, given that the constructor can prove sound engineering, and the project can be completed with lower costs and shortened duration. In this example, an alternative construction plan from the scrape-and-excavate method will be developed using the axiomatic design principles and robust planning and control methodology. Consequently, the effectiveness of both methods will be evaluated using the information content axiom from axiomatic design. Furthermore, the integration and application of other concepts on robust planning and control
methodology, including concurrent engineering, GERT, and system dynamics, will be demonstrated in this example as they are introduced in the rest of Chapter 3.

### 3.1.1 Independence Axiom and Zigzagging Planning Process

Following along this methodology, the objectives of this project have to be completely described in terms of DPs. In the conceptual planning stage for this sample project, there are three major DPs that have to be satisfied.

- DP1: remove excess earth between existing earth surface and new dam liner
- DP2: maintain slope stability and ensure safety of participants during construction
- DP3: construct retaining slab along the proposed location of dam liner

Forming the DPs in a solution-neutral environment is a difficult but important task. A typical mistake is wording the solution as a part of the requirements. For example, "remove excess earth" might be wrongfully expressed as "scrape excess earth," because the term "scrape" already limits the solution to one work methodology. "Maintain slope stability" might be mistakenly expressed as "install temporary structure," which also suggests a solution to the actual problem in the statement. Above all, phrasing DPs incorrectly could limit the effectiveness of this planning process and add to the difficulty of obtaining the best solution. Furthermore, the list of DPs would expand as the planning zigzags between DPs and PVs. If the selected set of DPs in the current level does not effectively reflect the objective of the particular problem, all subsequent DPs based on this level will be inappropriately chosen and the resulting work methodology will not be as effective. Therefore, it is important that the selected set of DPs describes the project objective clearly and completely, without giving away any possible solution in this process.

Along the same line as identifying DPs in axiomatic design, realizing the constraints imposed upon the project is just as important. Some of the systematic constraints that every project encounters include estimated project duration, budgeted cost, available resources, expertise of the team, geographical/geotechnical limitations, weather, access restraints and environmental concerns. Identifying key constraints in the planning stage is an important task because discovering them later during
construction and make subsequent changes to accommodate the constraints can become very costly. Furthermore, some of these constraints will define the parameters to develop PVs and evaluate the outcomes of different sets of PVs in axiomatic evaluation process, which will be introduced in Chapter 3.1.5. It is sometimes difficult to distinguish a constraint from a DP. Suh [Suh, 1990] defines that a DP describes a particular design that the PV must produce, and a constraint defines the range of performance for that particular PV. After all, a constraint is not independent because it relies on a DP to delineate its range. Similar to DPs, the list of constraints expands as the planning zigzags between DPs and PVs. Moreover, what used to be PVs at a higher level of the PV hierarchy may become constraints at a lower level of the DP or PV hierarchy [Suh, 1990].

Constraints in the context of axiomatic design can take many different forms, such as specified materials, costs, size, geometric shape, capacity and even the laws of nature. For civil engineering projects, these constraints can be categorized into two types. First, the constraints can represent certain functions that the project plan must satisfy; and second, they represent the necessary parameters, such as duration and cost, that make the plan realistic and competitive. Again, using the water dam example, some of the possible constraints are listed as the following:

- C1: Project duration: less than 2 years
- C2: Budgeted cost: less than 10 million dollars
- C3: No displacement to nearby structures due to the construction method

The first two constraints can be derived from owner's expectation, industry average, competitor's capability and previous experience in similar projects. In order to make the project plan attractive to the owner and competitive against other potential competitors, the estimated cost and duration have to be closely monitored during the planning process. Assigning the first two constraints is similar to setting a hurdle that the project plan must meet or exceed to be realistic and also maintain its competitiveness. The third constraint is specified as a requirement that the developed project plan must satisfy. In this example, inhabitants will stay on the valley banks throughout the construction period. Therefore, it is necessary to maintain zero displacement to nearby structures to ensure the safety of the inhabitants. The work methodology must be carefully designed and chosen to meet this safety requirement, because the project manager assumes great responsibility in assuring sound engineering and safety to the participants and neighbors living around the project.
With both DPs and constraints in place, the next task is to come up with acceptable solutions or PVs that satisfy the design parameters and meet the constraints. A set of PVs represents a work methodology in the form of specifications, drawings, resources, tolerances, and knowledge required implementing the plan. This set of PVs should be as simple as possible so that it can be carried out with minimal amount of effort. Hence, as different sets of PVs are generated during planning, they have to be evaluated to determine if there exists any undesirable coupled relationship and contains the minimal amount of information.

As mentioned in Chapter 2.3.1, a good solution set has uncoupled relationships among all the DPs, so that each DP can be satisfied independently. Different types of interdependencies within each set of PVs can be classified by applying the dependency matrix. However, even if the solution involves several coupled relationships, it is sometimes possible to improve the solution through a decoupling process. Some of the decoupling techniques include altering the work sequence, assigning additional constraints, forming a new set of DPs, or simply to come up with an entirely new solution. A better solution does not imply a completely unique one compare to the previous solution. It is a better solution as long as the strength of the coupled relationship is weakened to an acceptable level that does not disturb the concurrent progression of the two activities.

3.1.2 Information Content Axiom

As stated by the information axiom in Section 2.2, a smaller volume of necessary information to carry out the project implies reduced project complexity, which further eases actual implementation. For example, in order to build a water dam, the construction crew must chose a work methodology and deploy sufficient labor hours and equipment usage. If a wrong work methodology or equipment is chosen for the project, the construction task can become quite complex and inefficient, hence entailing a greater amount of information to carry out the project plan. By the same token, if the appropriate work methodology is formulated and the right tools are chosen, the project can be constructed much easier and quicker.
An effective measure of the PVs' soundness is its common range of information content, which is the overlapping area between the system range and design range. More importantly, the common range is the core of planning because it refers to the range of solutions produced by the selected set of PVs, that are within the allowable range specified to accomplish the DPs and constraints. A greater common range signifies that the proposed plan has a higher probability of satisfying a certain DP or constraint.

Before the common range of a project plan can be measured, a piece of relevant information must be chosen as the evaluation criterion. Information exists in all types of shapes and forms and is constantly being produced throughout the planning process. Hence, the type of information required as the measuring criterion depends on how the utility associated with the information can be used during planning. More specifically, it means that a piece of information serving as an effective evaluation measure would have a greater impact on the outcome of the planning process. For example, in a location where the weather is highly unpredictable, a good information measure would be the sensitivity of production rate to the weather.

3.1.3 Application of Axioms on the Robust Planning and Control Methodology

Using the water dam example again, the DPs and constraints have been identified earlier as the parameters to generate another work methodology, or a new set of PVs. In addition to the original scrape-and-excavate method, the engineers have developed another work methodology, which is to use explosives instead of scrapers. The scrape-and-excavate method deploys scrapers to move excess earth from the valley to the banks. Subsequently, excavators and bulldozer are mobilized to shovel the earth onto the dump trucks and carry the excess earth elsewhere. This method is reliable, safe and has little uncertainties about the production rate. It also requires minimal amount of temporary structure because there is little impact on underlying geotechnical properties. Furthermore, slope grading can be maintained and monitored easily during scraping and excavation. The downside is that the progress is slow and involves heavy equipment usage, which implies longer duration and possibly higher construction costs.

In contrast, the new method suggests using explosives to loosen the earth in several stages, and then remove it with excavators and dump trucks. Using explosives can weaken a large volume of earth
instantaneously and make subsequent excavation task much easier. This method can effectively shortened the project duration and requires less equipment on site to perform the task. The unit cost of using explosives to remove the same volume of earth is also less expensive than using scrapers. The downside is that the slope stability is difficult to maintain as a result of explosion, entailing an increasing complexity of temporary structure design. In addition, due to the systematic unpredictable nature associated with explosives, it is more difficult to obtain an accurate estimate of the production rate compared to the scrape-and-excavate method. Although both work methodologies are capable of achieving the project goal, the selected process based on dependency matrices and axiomatic evaluation will be introduced in Chapter 3.1.4 and Chapter 3.1.5, respectively.

3.1.4 Dependence Matrices and Decoupling

After the alternative explosion method is identified in the water dam construction example, applying the dependency matrix for each work methodology can help determine the interdependencies between DPs and PVs. Furthermore, the complicated tasks in the project will be identified as coupled activities in this process. The dependency matrices are illustrated as Figure 14.

With the scrape-and-excavate method, all the DPs have decoupled relationships between each other. DP1, which is the excavation work, can proceed independently without receiving feedback from the other two DPs. The next task, which is installation of temporary structure, has a start-to-start with a lag relationship to excavation work. This is because temporary structure can only be installed after sufficient amount of earth has been removed to create enough space for installation. The precedence relationship between the two tasks is represented by an “X” marked on DP2 in relation to DP1. Finally, the temporary structure will be used as the formwork for the permanent construction of concrete retaining slab. Before the concrete mix can be poured, a portion of the temporary structure must be in place to serve as the formwork. This precedence relationship is captured by an “X” marked on DP3 in relation to DP2.
### Solution one: scrape-and-excavate

| Excavate earth | X | O | O |
| Maintain slope stability | X | X | O |
| Build retaining slab | O | X | X |

Deploy scrapers  
Install temporary structure  
Pour reinforced concrete

### Solution two: explosion method

| Excavate earth | X | X | O |
| Maintain slope stability | X | X | O |
| Build retaining slab | O | X | X |

Use explosives  
Install temporary structure  
Pour reinforced concrete

---

Figure 14: Dependence Matrices for Available Solutions

Compared to the scrape-and-excavate method, using explosives involves a more complicated construction process. The explosion method has a coupled relationship between using explosives and installing temporary structures. Similar to the scrape-and-excavate method, temporary structures can only be installed after a portion of excess earth is removed, which is by explosion in this case. However, the allowable amount of explosives is highly dependent on the designed strength of temporary structure to maintain slope stability. A greater amount of explosives can speed up the construction process, but the designed strength for temporary structure would have to be correspondingly increased to maintain the slope stability. Therefore, there exists a coupled relationship between DP1 and DP2 because of an information feedback loop involving the two tasks.

In order to decouple the relationship between explosion and temporary structures, more constraints have to be added in the planning process. For example, the construction crew can specify the maximum amount of explosives that they will use to limit its effect on slope stability. On the other hand, the engineers can impose a limitation on the maximum strength of temporary structure designed to withhold a specified amount of explosion force. If the strength of temporary structure is pre-determined, then amount of explosive used by the construction crew has to comply with this constraint. As a result, the coupled relationship is resolved by clarifying the ambiguity of the explosion effects on slope stability. After decoupling these two activities, the activity matrix for the explosion method then becomes the following. Note that there is still an “X” on DP2 in relation to DP1. That is because the physical precedence relationship between the two activities still exists regardless of this decoupling process.
Figure 15: Dependence Matrix for Explosion Method

Comparing the two methods, scrape-and-excavate is easier to implement but less efficient; and using explosive is more productive but entails a higher level of complexity. In this example, both work methodologies can satisfy the independence axiom, although the explosion method requires some additional constraints for decoupling.

3.1.5 Axiomatic Evaluation

Following the concept of axiomatic design, the next step is to apply axiom two: the information axiom, to evaluate the two possible solutions in terms of their probability distributions of meeting the requirements. Since there are more than one evaluation criterion, different types of DPs and constraints imply different design ranges as the criterion. For example, the design range for budget and duration constraints are anywhere between zero to the maximum value specified by the contract or an estimated competitive value. A different type of measure, such as the slope stability, embraces a normal distribution between the allowable minimum soil strength and the realistic maximum soil strength.

Figure 16: Information Content based on Budget/Schedule Constraint
Figure 16 utilizes the project budget and schedule as the information measures for the two available work methodologies. This diagram demonstrates that using the scrape-and-excavate method is more likely to meet the target cost and schedule, with little probability to either exceed or fail the expectation. On the other hand, the expected cost and duration of using explosives is well under the target value. However, there is a trailing part at the end that extends far beyond the target value, signaling the risk of running into longer delays and higher costs. In this diagram, the common range of the explosion method is greater than the scrape-and-excavate method; hence the explosion method is favorable using this duration/cost as the evaluation criterion. However, if another criterion is used, such as the slope stability, the information content curve would resemble a different shape, as illustrated in Figure 17.

![Diagram of Probability Distribution](image)

**Figure 17: Information Content based on Slope Stability**

Based on this evaluation criterion, the scrape-and-excavate method has a smaller spread because its procedure is less intrusive to the site, making the slope stability easier to maintain near its target value. On the other hand, the effect of explosives on slope stability is more difficult to estimate, hence its system range has a wider variance compared to the scrape-and-excavate method. Using slope stability as the criterion in this scenario, the common range for the scrape-and-excavate method is greater than the explosion method. As a result, the scrape-and-excavate method is preferred if the slope stability is used as the measuring criterion.
At this point, it is still difficult to decide between the two work methodologies as which is the better method for this project. As this example demonstrated, using axiomatic design principles enables the project managers to evaluate the pros and cons of different construction plans based on a series of relevant criterions. In reality, the final decisions will be highly dependent on the owner requirements, level of expertise, resource availability, risk preference and management goal of the firm. In the dam construction example, a higher level of risk associated with the explosion method is in coherence with a higher expected return in terms of shorter duration and lower costs, as illustrated in both Figure 16 and Figure 17.

Putting this scenario in a real context, if Company A has a higher level of equipment resources, it might select the scrape-and-excavate method to avoid the risk for slope failure. It would take advantage of economy of scale by having a fleet of equipment to generate a lower fixed/operating cost per equipment. This margin allows Company A to allocate more equipment resources at a lower cost to other companies. As a result, the information content curve in Figure 16 can be shifted to the left so that the project can be delivered faster and less expensive, while the slope stability is still easily maintained as shown in Figure 17.

Likewise, if another contractor, Company B, has a strong in-house engineering department, it might prefer the explosion method for its inherent lower cost and higher production rate. With a strong engineering department, Company B can reduce the risk involved with slope stability. Their knowledge with temporary structure design could narrow the information content curve in Figure 17 to increase the common range of slope stability. Hence, they would prefer the explosion method to fully utilize their expertise in reducing the risk associated with slope stability. Consequently, each company has made its decision based on the internal strength that can effectively alter the position of the information content curve. As this example demonstrated, the merit of applying axiomatic design principles is that a systemized planning process can ensure the quality of key decisions because they are based on a series of relevant and important criterions. In this example, the key criterions include budget, project duration, and slope stability. Consequently, the two viable work methodologies can be compared based on these criterions to ensure the quality of the final plan.
At this point, the top-level conceptual planning for the project is completed. Subsequently, the DPs now have to be decomposed down further based on the selected work methodology in the top-level and begin the zigzagging process to generate the detailed plan. In the water dam construction example, if the scrape-and-excavate method is chosen, then the next level DP should address issues such as the required volume of earth scraped and excavated per day, the necessary equipment to perform the task, and the design of appropriate temporary structure. New constraints, such as access permit to transport heavy equipment and equipment storage facility, also have to be considered. Consequently, the end result of this zigzagging process is a complete set of PVs containing sufficient information that the entire project plan can be built upon.

3.2 ROLE OF CONCURRENT ENGINEERING

After the detailed plan is generated, the construction schedule can be fast-tracked by applying the concept of concurrent engineering. In this Chapter, the characteristics of the critical activities will determine if fast-tracking the project is appropriate and realistic. If a project can be finished quicker with the same amount of resources, then the fixed costs associated with maintaining the site, office, equipment and support staff can be saved. The activities that should be analyzed using concurrent engineering include the ones that are either on the critical path, have a high criticality index, or constrained by high resource and duration variance. These are the activities that have the most significant impact on project schedule if their work duration can be reduced. In addition, activities having finish-to-start and start-to-start with a lag relationships are particularly valuable if concurrent engineering can be applied. Overlapping activities with such precedence relationships directly transcends to shortened project duration.

As mentioned in Section 2.4, the ideal activities for overlapping have high progress rate of gaining production certainty for the upstream task and low sensitivity for the downstream task, as shown in Figure 18. However, not all activities matching this criterion should be overlapped. For activities with finish-to-start relationship, the overall duration of the two tasks should be significant compared to the overall duration. Likewise, if the two activities have a start-to-start with a lag relationship, then the lag should be long enough so that further overlapping the lag can generate notable contribution to shorten the
overall project duration.

There are other issues that concurrent engineering has to address during its overlapping process, such as the limited space to accommodate additional material, equipment and labor, and the impact of an increase in the variance of system range compared to the original plan. If the overlapping task is unrealistic involving too many variables beyond the project manager's control, the risk of not meeting the specified DPs and constraints should be reevaluated using the information axiom. An example of how overlapping has been deployed in civil engineering is the construction of high rise steel building. Typically, the steel frame beams and columns are erected after the foundation is constructed. Before all the steel members are erected, the pre-cast panels could be installed in the steel frame already put in place. Furthermore, surface finishes such as tiles and windows can begin their installation in the panels that are already in place. Consequently, three tasks can be performed concurrently with some lag between their starts in this scenario.

![Graph](image)

Figure 18: Overlapping Framework Based on Progress

3.2.1 Production Rate

In order to apply concurrent engineering in actual practice to help planning, the first step is to understand the sequence of tasks specified by the work methodology. Using the dam construction example, the simplified bar chart for one stage of the scrape-and-excavate method would appear similar to Figure 19. The first task is to deploy scrapers to scrape up the excess earth between the existing surface
and designed dam surface. The excess earth will be carried by the scrapers and dumped on the banks along the peaks of the valley. Excavators and bulldozers will then be mobilized to shovel the earth onto dump trucks and transport it elsewhere. Soon after scraping begins, temporary structure must be installed to maintain slope stability. After the temporary structure is installed, liner construction can begin to complete the last portion of the dam. Although Figure 19 only illustrates the bar chart for a one-stage construction process, it is also possible to overlap between each stage to speed up construction. The important element is to determine the value of lag between each task based on the expected progress rate, reliability and sensitivity. By combining these characteristics, it is possible to evaluate the probability that a certain amount of overlapping would work by avoiding loops and reworks, and at the same time shortening the duration effectively.

![Figure 19: Bar Chart for One Stage of Scrape-and-Excavate Method](image)

The critical path of the project runs from scraping to temporary structure installation, with a start-to-start relationship; and from temporary structure installation to linear construction, with a finish to start relationship. However, overlapping temporary structure installation and liner construction is difficult because of engineering constraints. Some parts of the temporary structure also serve as the formwork for the permanent liner construction. It is safe to assume that the temporary structure and formwork must be 100% completed before liner construction can proceed, since a large amount of concrete is poured each time.

As for scraping and temporary structure installation, it is possible to further overlap the two tasks based on the behavior of the progress curves. The production rate of scraping usually decreases over time.
because soils in the bottom layer have been compressed over a long period of time, hence possessing a higher cohesive strength and that make them difficult to be scraped. Furthermore, as the scraper approaches the bottom of the valley, it takes a longer time to transport earth back to the valley banks on top. Combining these two effects, the productivity of scraping tends to decrease over time. As for temporary structure installation, the productivity is benefited from the learning curve as the labors familiarize themselves with the installation procedure, materials, and geographical characteristics of the site. As a result, the productivity of temporary structure installation would increase over time. Combining the progress curve of these two activities on the same graph, together they form the ideal combination for overlapping, as shown in Figure 20.

![Figure 20: Change in Duration after Overlapping](image)

The existing schedule plan as illustrated in the bar chart in Figure 20 instructs temporary structure installation to begin after scraping is 50% completed. Without using any progress curve, most schedulers assume a linear cumulative production level over time, hence a direct relationship between time and percent completion. However, based on the progress curve illustrated above, scraping is 50% completed at about one-fourth of its total duration. To improve the overlapping practice, temporary structure installation can begin at one-fourth of scraping’s total duration instead of one-half as originally planned. Thus, the overall project duration is reduced by an equivalent of one-fourth of scraping’s duration.
3.2.2 Upstream Task Reliability

However, the effectiveness of overlapping is not solely determined by the production rate alone. Upstream production reliability, as well as downstream task sensitivity, are also important activity characteristics that govern the success of overlapping. A reliable upstream production minimizes the mistakes that could lead to extensive rework downstream as a result of producing work based on erroneous upstream work. On the other hand, if the downstream task is insensitive to errors made upstream, then starting work early downstream might gain a significant duration reduction, while generating relatively little rework as a result of errors made upstream. Hence, in the methodology proposed in this thesis, the reliability of upstream production and downstream sensitivity to upstream errors will be analyzed and classified to add another dimension to the existing theory of concurrent engineering. An overlapping framework will be developed to suggest possible overlapping strategies based on task progress, upstream production reliability and downstream task sensitivity.

The upstream task production reliability can be measured by taking the difference between the perceived output and real output of an activity, and then divided by the final real output to normalize the curve. The function of the reliability curve, \( F(t) \), with respect to time can be written as the following:

\[
F(t) = \frac{[P(t)-R(t)]}{R(t)}
\]

Where \( F(t) = \text{Reliability Function} \), \( P(t) = \text{Perceived Production} \), \( R(t) = \text{Real Production} \), and \( R(t_f) = \text{Final Real Production} \) = 100%. The perceived production is the amount of work that has been performed according to the schedule but the work hasn’t been thoroughly inspected and/or still contains hidden errors. However, no inspection can guarantee to uncover all the problems. The difference between the perceived output and real output is really a matter of craftsmanship sloppiness, unknown effects, unclear specifications and other unanticipated circumstances. Performing inspection is only one of the passive ways to increase the work reliability. There are other method to improve work reliability and increase production, such as defining a clear scope of the project and employ experienced staff rather than new hires. Above all, the real production is the work that really added value to the project after all problems and reworks has been discovered and fixed. Figure 21 illustrates how production reliability for different activities can be measured over time.
Figure 21: Reliability Curve

The left diagram is the ideal situation in which the upstream task is almost 100% reliable, producing nearly no errors throughout the entire construction period. The middle two diagrams show the difference between the perceived production and real production, and the resulting reliability curve. As the error is discovered during construction, additional resources are assigned to bring the completion date back to the original schedule. Consequently, the percent error curve eventually declines to zero by the end of construction. The graph on the second left has a small difference between the real output and perceived output, indicating that there is little error in production and the production output is fairly reliable. The graph in the middle starts with a higher percent error, but as the error is uncovered, it is also fixed and eventually meets the original schedule. Therefore, the production is less reliable compared to the previous scenario. Finally, the graph on the right represents one of the worst scenario that the real output falls behind the perceived output by too much and the gap between the two can not be recovered to finish the task in time. The schedule delay is represented as Δt. Therefore, the percent error curve extends beyond the original time frame, and the production for this activity is highly unreliable.
Similarly, the downstream task sensitivity can be measured by taking the difference in percent progress divided by the perceived progress after a change is introduced in the activity due to an upstream change at t=0. The function of sensitivity curve takes the same form as the reliability curve, which is \( S(t) = \frac{[P(t)-R(t)]}{R(t)} \). For a downstream task that is insensitive to upstream production change, there is minimal impact on the downstream task after the change is introduced in the upstream, resulting in a smaller value of sensitivity function. The level of sensitivity can be controlled by implementing a more stringent inspection policy or performing the work in many small steps. Performing work in smaller segments allows the construction crews to adapt the learning curve more effectively because they can avoid the mistakes made in the previous segment. In addition, an increasing number of inspections enhances the chances of discovering errors. This way the difference between perceived progress and actual progress of upstream task production can be constantly verified to improve the quality of upstream production.

![Sensitivity Curve](image)

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**Figure 22: Sensitivity Curve**
3.2.4 Overlapping Framework

Given the task production rate, upstream production reliability and downstream task sensitivity, it is possible to provide a framework by which activities with certain characteristics should or should not be overlapped. In Figure 23, the rate of production is represented by the length of time to complete 25%, 50%, 75% and 100% of the task. For a task with high production rate, the required time to generate 25% of the work is significantly quicker than a comparable task with slow production rate. The percent completion bars at the bottom of Figure 23 will be used in the overlapping framework, as shown in Figure 24.

![Graphs showing production rates](image)

**Figure 23: Production Rate**

The overlapping framework in Figure 24 is divided into four quadrants with respect to the production rate of upstream and downstream task. Within each quadrant, the amount of overlapping is suggested based on the upstream production reliability and downstream task sensitivity. The upstream production reliability ranges between highly reliable, fairly reliable, fairly unreliable and highly unreliable. A highly reliable task produces insignificant errors that have little impact on downstream activity. A fairly reliable task differs from a fairly unreliable task in the amount of errors produced, although the discovered errors in both tasks can be recovered to complete the work on time. Finally, a highly unreliable task generates significant amount of errors that can’t be fixed on time, and causes a schedule delay. Consequently, overlapping is not advisable in this scenario to minimize the possible reworks as a result of the upstream errors.
Similarly, the downstream task is categorized into insensitive, sensitive and highly sensitive tasks. The sensitivity of downstream task is defined by the percent of change as a result of an error made in the upstream. Due to the interdependency relationship between an upstream and downstream task, changes made in the upstream would have an impact on the downstream task, no matter how small the change is. Therefore, there is no completely insensitive downstream task.

The overlapping framework in Figure 24 is developed based on three important assumptions. First, 25% of the upstream task must be completed before the downstream task can start, due to the inherent sequential relationship between the two activities. If the two activities are not sequentially related, then they can essentially be performed in parallel with a start-to-start relationship. Therefore, some amount of upstream task must be completed to support the production of the downstream task. The second assumption for Figure 24 is that the upstream task always finishes before the downstream task. This is an important assumption because the production of downstream task is based on the work generated by the upstream. If the schedule indicates that the downstream task would finish before the upstream task, then a separate procedure such as splitting has to be implemented. This timing issue will be addressed in Section 3.2.3 – Overlapping Timing and Activity Splitting. Lastly, the third assumption is that the activities can be divided up in increments of 25%, 50%, and 75%, so that overlapping is possible at various intervals.

In this framework, each increment of overlapping is recommended on the basis of 25% upstream work completion. This framework suggests that as the upstream production rate increase, overlapping becomes more effective because the amount of overlapping with respect to time increases. If the upstream task progresses faster, the required time to complete the first 25% of the work is shorter, hence enabling the downstream task to begin sooner. On the other hand, as the downstream task production rate increases, the amount of overlapping would decrease. If the downstream task proceeds too fast, the errors produced upstream would have multiplying effect on the downstream task. Consequently, a fast downstream task would encounter more rework compared to another task with similar duration, but slower initial production rate.
Figure 24: Overlapping Framework (for the Upstream Task Completing before the Downstream Task)
Furthermore, within each quadrant, the amount of overlapping is dependent on the upstream task reliability and downstream task sensitivity to upstream errors. As the reliability of upstream production increases, the amount of overlapping should increase as well. With a reliable upstream task, the work produced can be readily passed along the construction sequence to initiate the downstream task, resulting in a speedier construction process. On the other hand, if the upstream task is highly unreliable and resulting in further delays, overlapping should be avoided to minimize the possibility of reworking in the downstream.

Similarly, the sensitivity of downstream task also has the same effect on the amount of overlapping. For an insensitive downstream task, the amount of overlapping can be maximized at 25% upstream task completion. As the downstream task becomes more sensitive, the amount of overlapping is reduced by introducing the downstream task one increment later in the sequence. For certain scenarios in which a highly unreliable upstream task is complemented by a highly sensitive downstream task, a schedule buffer, such as a finish-to-start lag, is recommended. In this overlapping framework, the maximum amount of time allowed for upstream task completion is determined at 175%. Therefore, the errors made upstream can have enough time to be discovered and fixed, minimizing the impact of these errors on downstream activity. To summarize the overlapping framework in Figure 25, a fast and reliable upstream task, together with a slow and insensitive downstream task, make the ideal combination for overlapping.

3.2.5 Overlapping Timing and Activity Splitting

However, the assumption that the upstream task finishes before the downstream task when the two are overlapped might not hold true all the time. When the two activities are rigorously overlapped, the bar chart might indicate that the downstream task is completed before the upstream task. In reality, this situation is logically impossible because the downstream task is performed based on the output of upstream task. Therefore, there has to be a positive lag between the upstream and downstream task completion date. If the downstream task is completed too soon as a result of overlapping, one way to retain the logical sequence is to delay the downstream task to the next appropriate overlapping increment. Another way is to split the downstream task into two subtasks. The duration for each subtask will depend
on the early start, early finish, late start and late finish dates as calculated by the Precedence Diagramming Method [Callahan et al, 1992]. The merit of splitting is that it creates additional buffer within the activity. As shown in Figure 25, the downstream task is being split to two segments. Hence, the lag between the two segments becomes a buffer that can absorb delays generated during the first segment. In this scenario, overlapping has created additional float to increase the contingency of the project plan.

![Overlaying Tasks Diagram](image)

**Figure 25: Overlapping Delay and Splitting**

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### 3.3 ROLE OF GRAPHICAL EVALUATION AND REVIEW TECHNIQUE (GERT)

The overlapping framework developed in Figure 24 can be applied to help shorten a project schedule based on activity progress rate, upstream task reliability and downstream task sensitivity. Furthermore, this overlapping framework and the GERT network diagramming method [Modé, 1983] are good complements to each other. The shape of reliability and sensitivity curves in the overlapping framework can help define the probabilities of branching and looping used in GERT. Based on this information, the appropriate overlapping scheme can be chosen and the benefit of overlapping can be calculated probabilistically in GERT.
GERT is applicable to situations that the outcome is highly dependent on variables that have high degrees of unpredictability. This scenario is particularly common in large-scale civil engineering projects involving many unknown variables, such as geotechnical properties, weather, possible hazardous materials and environmental concerns. Using GERT can help generate a more realistic schedule because the output of GERT is an expected value with a probability or a range of possible values. Furthermore, GERT incorporates the possible rework cycles by assigning a probability to each possible loop. This feature cannot be found on the conventional PERT and CPM approach. Taking the water dam project as an example, the explosion method has a wider spread between the expected duration, maximum duration and minimum duration, because of the inherent unpredictability of explosion. To illustrate this scenario, a GERT diagram has been developed to incorporate the possible outcomes of the two-stage explosion method as illustrated in Figure 26.

![Diagram](image_url)

**Figure 26: Bar Chart for One Stage of Explosion Method (No Overlapping)**

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### 3.3.1 The Application of GERT Network Diagram

The GERT diagram illustrated in Figure 27 utilizes the symbols introduced in Section 2.5.1, Figure 10. In this diagram, the values of duration and probability for each branch in Stage I Explosion and Stage II Explosion are recorded in Node 4 and Node 5, respectively. In each Node, the number 1 to 17 is the Activity ID that corresponds to the branch or loop of the same number in the diagram. Within Nodes 4
Figure 27: GERT Diagram for Water Dam Construction
and 5, the letter “D” signifies that the following value is the duration of the listed activity. The letter “P” signifies that the following value is the probability of the corresponding branch or loop. As for the parenthesis that follows each construction activity, the first letter in the parenthesis represents the activity attribute, and the second number is the assigned Activity ID. The letter “AT” in each parenthesis represents the activity attribute as duration, and the letter “A” represents the activity attribute as probability. For example, in Explosion Stage I, the duration for the loop going around the Explosion task located in Node 7, has an estimated duration range of 1 to 3 days, and the probability for this event is 25%.

With the appropriate symbols in place, the diagram is structured to begin with the Notice to Proceed (NTP) issued by the owner, as shown in Node 1. Once the contractor receives the NTP, the engineers can begin the design of a standard temporary structure, shown as branch (AT, 1), given the in-situ site condition and the subsequent explosion force that will be deployed on the site before excavation. For Stage I Explosion, the duration for the design work can be read from Node 4 - Row 1, which has a “D” attribute representing for “duration”, and the value is estimated to range between 5 to 7 days. After the design is completed, the contractor can proceed with the explosion task at Node 6. The explosion task has a branch represented as (AT, 2), which means that the duration of 1 to 3 days is given in Node 4 – Row 2.

The GERT diagram then captures the three possible outcomes of explosion. In the first scenario, if an insufficient amount of dynamite is used and the volume of earth removed didn’t reached the desired level, then another explosion should be implemented to obtain the desired result. Hence, there is a loop going around the explosion task to capture the possible need to re-explode excess earth. The branch value of (AT, 3) represents that the duration for re-explosion can be read from Node 4 – Row 3, which has an estimated range between 1 to 3 days. The branch value of (A, 12) represents the probability for requiring re-explosion, which is described in Node 4 – Row 12, and has a 25% chance of happening. In the second scenario, if the right amount of dynamite is exploded and given that sufficient earth is removed by the explosion, then the contractor can proceed with the original schedule as initially planned, as shown in branch (A, 13). Therefore, the probability to proceed with the original schedule is described in Node 4 – Row 13, which indicates a 50% chance of happening. Finally, if too much dynamite was used and has damaged the necessary slope stability, then the original temporary structure design needs to be modified.
to accommodate the actual site condition, as shown in branch (A, 14). Hence, the probability for such occurrence is given in Node 4 – Row 14, which indicates a 25% chance of happening. If it happens, then the time it takes to redesign the temporary structure is captured by branch (AT, 6). The duration for redesigning is given in Node 4 – Row 6, which shows an estimated duration of 6 days for this task.

Following the explosion task, the next activity is excavation work, as shown in Node 7 and 8, depending on the outcome of the previous explosion task. If the explosion task were properly conducted as planned, then the expected duration for excavation work is represented by branch (AT, 4). The duration is given in Node 4 – Row 4, which has an estimated value of 6 to 10 days. However, if too much dynamite were used, then the excavation work would take the (AT, 5) path. Consequently, the duration is given in Node 4 – Row 5, which has an estimated range of 8 to 10 days. As for the excavation rework loop, it is represented by branches (AT, 7) and (A, 15). The probability for such occurrence is given in Node 4 – Row 15, which indicates a 5% chance of happening. The associated duration can be found in Node 4 – Row 7, which has an estimated range of 7 to 10 days.

Once the excavation work is completed, the temporary structure has to be installed, as shown in Node 9. The estimated duration for installation, represented by branch (AT, 8), can be found in Node 4 – Row 8, for an estimated duration of 15 days. Subsequently, the rework loop for temporary structure installation is represented by branch (AT, 9) and (A, 16). The duration for reinstallation is given in Node 4 – Row 9, which has an estimated duration of 15 days. The associated probability is described in Node 4 – Row 16, which indicates that there is a 5% chance of happening. Following the installation of temporary structure, the dam liner has to be constructed, as shown in Node 10. The duration for this task is represented in branch (AT, 10). Therefore, the estimated duration of 5 days can be found in Node 4 – Row 10. Finally, the rework loop of dam liner construction is represented by branch (AT, 11) and (A, 17). Hence, the probability of requiring rework can be found in Node 4 – Row 17, and the probability is estimated at 5%. Subsequently, the estimated duration for such rework is described in Node 4 – Row 11, which has a range of 7 to 10 days.

Since the explosion is planned as a two-stage process, the same construction sequence would repeat for the second time in the GERT network. The readings for all the branches in Stage II Explosion would be given in Node 5 instead of Node 4, following the same procedure described above. Although Stage I and Stage II embraces the same sequence, the probabilities assigned to each loop and branch
might be different. This is because Stage II explosion can adapt the results and experiences from the previous stage and modify the procedures as necessary, such as the amount and location of dynamite, to improve the chances of obtaining the desired result. Furthermore, the contractor can evaluate the difference between a n-stage explosion task versus a two-stage explosion. If the construction crew can adapt the learning curve and make a tremendous amount of improvement from each explosion, then the plan should divide the explosion task into even more stages to fully take advantage of the learning curve.

3.3.2 Project Scheduling by GERT

The probabilities in Figure 27 are assigned to represent an improved performance in Stage II. The duration of some tasks is assigned with a pessimistic and optimistic value to obtain a range of estimates. The loop of deploying insufficient dynamite is assumed to activate only once, and it proceeds directly to excavation work. The expected range of project duration without overlapping can then be calculated as the following:

**Optimistic**

**Stage I:**

\[ 5 + 1 + 25\% \times (1+6) + 50\% \times 6 + 25\% \times 8 + 5\% \times (7+15) + 95\% \times 15 + 20\% \times (15+7) + 80\% \times 7 + 5\% \times 7 = 38.45 \text{ days} \]

**Stage II:**

\[ 5 + 1 + 10\% \times (1+6) + 80\% \times 6 + 10\% \times 8 + 5\% \times (7+15) + 95\% \times 15 + 20\% \times (15+7) + 80\% \times 7 + 5\% \times 7 = 38 \text{ days} \]

*Total Optimistic Duration: 38.45 + 38 = 76.45 days*

**Pessimistic**

**Stage I:**

\[ 7 + 3 + 25\% \times (3+10) + 50\% \times 10 + 25\% \times 10 + 5\% \times (10+15) + 95\% \times 15 + 20\% \times (15+10) + 80\% \times 10 + 5\% \times 10 = 49.75 \text{ days} \]

**Stage II:**

\[ 7 + 3 + 10\% \times (3+10) + 80\% \times 10 + 10\% \times 10 + 5\% \times (10+15) + 95\% \times 15 + 20\% \times (15+10) + 80\% \times 10 + 5\% \times 10 = 49.3 \text{ days} \]

*Total Pessimistic Duration: 49.75 + 49.3 = 99.05 days*

*Total Duration Range: 76.45 ~ 99.05 days*
The next task is to determine how the GERT diagram can be used to evaluate the overlapping on the schedule. First the activities that can be overlapped need to be identified, then the characteristics of each activity can be classified to obtain the recommended overlapping scheme illustrated in Figure 24. Typically, the temporary structure design has to be 100% completed and approved before explosion can take place. Therefore, there is no overlapping between designing temporary structure and explosion. Furthermore, the safety constraint might prohibit any activity to proceed concurrently with explosion to eliminate any possible injury. Limited by this constraint, the activities left that can be fast-tracked are between excavation, redesigning/installing temporary structure and construction of dam liner. In actual practice, obtaining the activity characteristics requires previous experience in similar projects or information on published statistics. In this example, the activity characteristics is derived based on the probabilities leading into undesirable/desirable branches rework loops, as well as other relevant information.

3.3.3 Integration of Concurrent Engineering and GERT

The estimated characteristic for each task is illustrated in Figure 28. Beginning with excavation work, it can be done fairly quickly because the earth has already been loosened by explosion. The production level of excavation is reliable because the amount of excavated earth can be readily measured by field survey. As shown in the GERT diagram in Figure 27, there is only a 5% chance that re-excavation is needed. However, the excavation work is quite sensitivity to upstream production because the effectiveness of excavation is highly dependent on the results of explosion. Following excavation, the next task is to install temporary structure to maintain the slope grading and to serve as the formwork for permanent construction in a later stage. The initial production rate for temporary structure is slow because the crew is unfamiliar with the construction procedure, material and the job site. As the crew adapts the learning curve, the production rate would increase over time. For the same reason, the production level is unreliable given that the installation work is expected to repeat 20% of the time. In addition, the installation work is insensitive to upstream task. This is because only a small amount of excavation near the proposed liner surface is required to proceed with temporary structure installation.
Finally, the construction of dam liner is also a slow production task. Trucks carrying concrete mix might find it difficult to access to the formwork on the steep valley slope. Maneuvering the concrete transporting pipe might also take some skill that can only be acquired over time. As for its production reliability, it should be a reliable task because the formwork is already in place. Consequently, the quality of formwork built upstream has a significant effect on the quality of dam liner. If the temporary structure is found to be mis-aligned after the concrete is poured to form the liner, then the liner would have to be demolished and rebuilt. Hence, it can be concluded that the construction of dam liner is highly sensitive to the upstream temporary structure installation.

![Figure 28: Activity Characteristics](image)
3.3.4 Overlapping Practice

![Diagram: Excavation (10 days) -> Temporary Structure Installation (15 days) -> Dam Liner Construction (10 days)]

Figure 29: Overlapping Practice for GERT

Using these parameters in the overlapping framework, the following overlapping methods are recommended, as shown in Figure 29. For branches with an insufficient or right amount of dynamite, the overlapping practice on the left suggests installing the temporary structure at 50% completion of excavation work, resulting in a schedule reduction of approximately equivalent to 75% of the excavation time. The schedule reduction for a pessimistic estimate can be calculated as (10 days * 75%) = 7.5 days. However, if too much dynamite were used, then an additional finish-to-start relationship between redesigning and installing temporary structure has to be considered. In this scenario, the bar chart for excavation and temporary structure installation would appear similar to Figure 30. Under this circumstance, the two activities can not be as aggressively fast-tracked as the previous case. This is because of the design constraint that the temporary structure installation can begin only after redesigning is fully completed. Hence, overlapping between the excavation work and temporary structure installation is limited by the need to redesign the temporary structure. As a result, the earliest starting day for temporary structure installation to overlap with excavation work is the 6th day of excavation work. The schedule reduction as a result of overlapping is then reduced to (10 days * 50%) = 5 days instead of the 7.5 days in the prior case. Finally, no overlapping is recommended between temporary structure installation and dam liner construction according to the overlapping framework in Figure 29.
Taking the effect of overlapping into consideration, the amount of reduction can be reflected on the bar chart in Figure 31. The amount of reduction depends on weather redesigning is required or not. Based on the suggested overlapping methods, the project schedule can be calculated again in GERT after overlapping. The project duration can be calculated again as the following:

Optimistic

Stage I:  
\[ 5 + 1 + 25\% \times (1+1.5) + 50\% \times 1.5 + 25\% \times 5 + 5\% \times (1.5+15) \]
\[ + 95\% \times 15 + 20\% \times (15+7) + 80\% \times 7 + 5\% \times 7 = 34.05 \text{ days} \]

Stage II:  
\[ 5 + 1 + 10\% \times (1+1.5) + 80\% \times 1.5 + 10\% \times 5 + 5\% \times (1.5+15) \]
\[ + 95\% \times 15 + 20\% \times (15+7) + 80\% \times 7 + 5\% \times 7 = 33.38 \text{ days} \]

Total Duration: 34.05 + 33.38 = 67.43 days
Pessimistic

**Stage I:**

\[ 7 + 3 + 25\% \times (3+2.5) + 50\% \times 2.5 + 25\% \times 5 + 5\% \times (2.5+15) \]
\[ + 95\% \times 15 + 20\% \times (15+10) + 80\% \times 10 + 5\% \times 10 = 42.5 \text{ days} \]

**Stage II:**

\[ 7 + 3 + 10\% \times (3+2.5) + 80\% \times 2.5 + 10\% \times 5 + 5\% \times (2.5+15) \]
\[ + 95\% \times 15 + 20\% \times (15+10) + 80\% \times 10 + 5\% \times 10 = 41.68 \text{ days} \]

**Total Duration:** 42.5 + 41.68 = 84.18 days

**Total Duration Range:** 67.43 ~ 84.18 days

Consequently, the range of possible schedule reduction as a result of overlapping is equivalent to (76.45 - 67.43) = 9.02 days and (99.05 - 88.58) = 10.47 days, or roughly an average of 11% of the original duration.

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### 3.4 ROLE OF SYSTEM DYNAMICS MODELING TECHNIQUE

Above all, the proposed methodology suggests that the success of a particular overlapping strategy depends on the task production rate, upstream reliability and downstream sensitivity. The ideal combination for overlapping would be a fast and highly reliable upstream task, in conjunction with a slow and insensitive downstream task to achieve maximum duration reduction. However, these activity characteristics are affected by a variety of factors through a set of feedback structures in the project. As the project proceeds, the contribution of each factor to these activity characteristics varies across time in part due to the changing strength of other associated variables in the system.

Consequently, without the help of system dynamics modeling technique, it is difficult to explicitly delineate the causal effects acting among all the variables at different points of time. Since the success of each overlapping strategy is highly dependent on these activity characteristics, it is important to realize the implications of these variables on the overlapping results. The application of system dynamics modeling technique not only can simulate the overlapping process between two activities, it also helps understand the interactions between different factors and activity characteristics, as far as their final impact on the overlapping results. Through the modeling and simulation process, the important
variables that are crucial to the success of overlapping for different combinations of activity characteristics can be identified. Consequently, the project manager can use this method to improve the effectiveness of their overlapping practice to complete the project sooner.

Furthermore, the best overlapping strategy for a certain combination of activity characteristics can be obtained by specifying the variable values in the system. Different combinations of activity characteristics can be obtained by changing the variable values during simulation. For example, to obtain a highly reliable upstream production, the ratio of experienced staff can be set at 100% and at the same time assigning more buffer to reduce schedule pressure, which leads to a higher work reliability. Besides identifying the best overlapping strategy, another use of this modeling method is to realize the necessary parameters in order to achieve a certain percentage of schedule reduction as the goal. This is often the case when the owner proposes an incentive package for the contractor who completes the project ahead of schedule by a certain length of time. Indeed, the application of system dynamics is flexible and versatile enough to allow the contractor testing various “what if” scenarios, and yet it can still retain the soundness of simulation by preserving the interactions between each factor in the model dynamically.

3.4.1 Modeling Process

In Figure 33, a system dynamics model is developed to represent the interactions between a pair of sequential activities. This model will be used to simulate the overlapping framework in Figure 24. In this model, task production rate, upstream reliability and downstream sensitivity are captured as the three major determinants of the activity progress. The goal for both stocks of the upstream and downstream task is set at 1000 units of work. On the left half of the model diagram, the progress of an upstream task is delineated with respect to its work productivity and quality. The work productivity is captured as a look-up table for a fast production activity that reaches its peak production level early in the production cycle. This look-up table is illustrated as Figure 32. For an activity with slow production rate, the same table is used except that the input on the x-axis is read from the right to the left. Consequently, the production of the activity reaches its peak level later in the construction phase.
In this system dynamics model, both upstream and downstream tasks have three stocks, namely work remaining, work accomplished and undiscovered rework. The work remaining stock begins with 1000 units of work, and the outflow of the stock is equivalent to a predefined work flow, which is 100 units/month, multiplied by work productivity. The work accomplished stock is the accumulated amount of work produced, including the ones that need additional rework later to really add value to the task. Finally, the undiscovered rework stock keeps track of the errors made in the work flow. The inflow of the stock is calculated by multiplying the work flow by one minus the work quality. The rate at which the errors are discovered and corrected is calculated by taking the stock divided by the error discovery time. This rework discovery rate is equivalent to the outflow for the work accomplished stock, and it feed back to the stock of work remaining.

For the upstream task, the level of work quality is entirely dependent on the work reliability in this model. The level of work reliability is determined by three other variables: the learning effect on reliability, staff experience and schedule pressure. The learning effect on reliability factor captures the learning curve adapted by the construction crew, as they become more familiar with the equipment, material and work methodology. Hence, this variable represents the improvement in work quality over time through a repetitive work process. The amount of improvement resembles the shape of learning curve where the initial improvement is the greatest, and gradually increases at a slower rate as the project progresses.
The next variable in the model is the effect of staff experience on work reliability. It measures the impact on work quality in terms of the ratio of experienced staff to total staff. As the ratio of experienced staff on the team increases, the reliability of work would increase as well. Furthermore, a higher ratio of experienced staff can enhance the learning process for the new hires. Subsequently, the final factor is the effect of schedule pressure on reliability. In this model, the schedule pressure takes the form of a look-up table. The input to the table is measured by the ratio of the current activity percent complete to the percent of time elapsed with respect to the estimated completion time. The assumption is that as the contractor falls behind schedule, he/she might take short cuts as a means of completing the project on time. Consequently, more errors are generated as a result of taking short cuts, creating additional rework that need to be completed and further delays the project.

Similarly, the downstream task on the right half of Figure 32 also has the same reliability factors controlling its production rate. However, there is one additional variable, the downstream task sensitivity to upstream errors, which also effects the production rate of downstream task. The influence of downstream sensitivity on production is represented by two look-up table functions, one of which is called the Highly Sensitive Index and the other Insensitive Index, as shown in Figure 34. The input to these look-up tables is the upstream percent error, which is measured by taking the difference between perceived work accomplished and actual work accomplished, and then divided by the initial project definition.

Furthermore, the level of downstream sensitivity is determined by two other variables, namely the inspection effectiveness and the number of upstream task segments. The inspection effectiveness indicates how effective the inspection process is to identify errors and reworks in the upstream task. As the effectiveness of the inspection process increases, the errors made upstream can be discovered quickly before the downstream task produces units based on what was done wrong in the upstream. Consequently, implementing a more stringent inspection process can reduce the sensitivity of downstream task to upstream error.
Figure 33: System Dynamics Model for Overlapping Strategy Analysis
The model is set up so that the contribution of the insensitive index and the highly sensitive index to the overall sensitivity is determined by the inspection effectiveness and the number of upstream work segments. For example, if the inspection of upstream task is 1.2 times more effective than normal inspection, then 60% of the downstream sensitivity is from Insensitive Index and the other 40% is from Highly Sensitive Index. If the inspection is only 0.6 times as effective, then 30% of the downstream sensitivity is from Highly Sensitive Index and the other 70% is from Insensitive Index.

The other driving factor of the downstream sensitivity is the number of upstream task segments. There are two reasons why the downstream sensitivity can be reduced by breaking the upstream activity into subtasks. First of all, there would be more inspection throughout the production cycle of upstream task, and each inspection only needs to cover a small fraction of work. As a result, the chances of catching errors by scrutinizing the entire production process in segments are much greater than performing one single inspection at the completion. Secondly, implementing the activity in segments allows the construction crews to learn about the errors that they made during previous segments. Hence the same mistakes can be avoided by performing the same task over to gain expertise on it.
3.4.2 Simulation Process

After the model is constructed, several sets of simulations are conducted to evaluate the effectiveness of the overlapping recommendation in Figure 24. For each overlapping strategy, six values of upstream percent completion are tested in increments of 25%. Consequently, the value that yields the shortest completion duration is the best overlapping strategy. Therefore, there are six runs for each simulation.

The simulation results for different combinations of activity characteristics are presented in Table 2. As the table shows, 44 out of the 48 simulation runs have results matching the overlapping recommendation in Figure 24. Hence, this simulation process reinstates almost 92% of the overlapping recommendations.

The progress curves of the downstream work accomplished versus time for various overlapping strategies are shown, in Figure 35a to Figure 35f, to demonstrate how the different overlapping strategies can be compared. In Figure 35a, the simulation is conducted for a highly reliable and fast production upstream task, together with an insensitive and slow production downstream task. In Figure 25, the recommended amount of overlapping is 25% upstream completion for this combination of activity characteristics. The result of simulation in Figure 35 reinforces this recommendation because starting the downstream task at 25% of upstream completion actually finishes the downstream task first. Furthermore, the best overlapping practice of 50%, 75%, 100%, 125% and 150% upstream completion are demonstrated in Figure 35b, 35c, 35d, 35e, 35f, respectively.

During the simulation, it is necessary to change the level of reliability and sensitivity in the model to realize their effect on the overlapping strategy. The level of reliability can be controlled by altering the estimated duration of upstream completion and the ratio of experienced staff on the construction crew. A shorter estimated upstream duration inflicts a greater schedule pressure on the construction crew, hence lowering the work reliability. The ratio of experienced staff on the team is also directly related to work reliability. Consequently, there are two ways to evaluate the quality of upstream production. One of which is to control the estimated upstream task completion, and the other is to modify the ratio of experienced staff to achieve the desired
<table>
<thead>
<tr>
<th>Category</th>
<th>Simulation ID</th>
<th>Reliability Factors</th>
<th>Sensitivity Factors</th>
<th>Upstream Percent Complete for Downstream to Start</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Percent of Experienced Staff</td>
<td>Estimated Completion Time (month)</td>
<td>Inspection Effectiveness</td>
</tr>
<tr>
<td>Fast Upstream</td>
<td>A1</td>
<td>98%</td>
<td>24</td>
<td>130% sensitive</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>82%</td>
<td>24</td>
<td>130% sensitive</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>60%</td>
<td>24</td>
<td>130% sensitive</td>
</tr>
<tr>
<td></td>
<td>D1</td>
<td>0%</td>
<td>24</td>
<td>130% sensitive</td>
</tr>
<tr>
<td>Production &amp; Slow</td>
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<td>90%</td>
<td>24</td>
<td>100% sensitive</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>85%</td>
<td>24</td>
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</tr>
<tr>
<td></td>
<td>C2</td>
<td>60%</td>
<td>24</td>
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</tr>
<tr>
<td></td>
<td>D2</td>
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<tr>
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<td>24</td>
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</tr>
<tr>
<td></td>
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<td>0% sensitive</td>
</tr>
<tr>
<td>Slow Upstream</td>
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<td>150</td>
<td>150% sensitive</td>
</tr>
<tr>
<td></td>
<td>F1</td>
<td>100%</td>
<td>125</td>
<td>150% sensitive</td>
</tr>
<tr>
<td></td>
<td>G1</td>
<td>100%</td>
<td>115</td>
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</tr>
<tr>
<td></td>
<td>H1</td>
<td>100%</td>
<td>105</td>
<td>150% sensitive</td>
</tr>
<tr>
<td>Production &amp; Slow</td>
<td>E2</td>
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<td>156</td>
<td>100% sensitive</td>
</tr>
<tr>
<td></td>
<td>F2</td>
<td>100%</td>
<td>150</td>
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</tr>
<tr>
<td></td>
<td>G2</td>
<td>100%</td>
<td>60</td>
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</tr>
<tr>
<td></td>
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</tr>
<tr>
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</tr>
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</tr>
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</tr>
<tr>
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<td>B4</td>
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</tr>
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</tr>
<tr>
<td></td>
<td>B5</td>
<td>40%</td>
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</tr>
<tr>
<td></td>
<td>C5</td>
<td>7%</td>
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</tr>
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<td></td>
<td>D5</td>
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</tr>
<tr>
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<td>24</td>
<td>0% sensitive</td>
</tr>
<tr>
<td></td>
<td>B6</td>
<td>30%</td>
<td>24</td>
<td>0% sensitive</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>D6</td>
<td>0%</td>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
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<td></td>
<td>G4</td>
<td>100%</td>
<td>85</td>
<td>150% sensitive</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>100%</td>
<td>35</td>
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</tr>
<tr>
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<td>100%</td>
<td>135</td>
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</tr>
<tr>
<td></td>
<td>F5</td>
<td>100%</td>
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<td>100% sensitive</td>
</tr>
<tr>
<td></td>
<td>G5</td>
<td>100%</td>
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</tr>
<tr>
<td></td>
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</tr>
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<td>100</td>
<td>0% sensitive</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>H6</td>
<td>100%</td>
<td>0.01</td>
<td>0% sensitive</td>
</tr>
</tbody>
</table>

*Inconformity with the Overlapping Framework in Figure 24
Figure 35a: Simulation ID: A1 (best case: 25% upstream completion)
Figure 35b: Simulation ID: A4 (best case: 50% upstream completion)
Figure 35c: Simulation ID: C1 (best case: 75% upstream completion)
Figure 35d: Simulation ID: H1 (best case: 100% upstream completion)
Figure 35f: Simulation ID: C6 (best case: 150% upstream completion)
3.4.3 Model Behavioral Analysis

From the results of simulation, it was discovered that the effect of estimated duration is dependent on the upstream production rate. It was shown that the schedule pressure has a much smaller effect when a fast upstream production takes place. This is because a majority of work can be completed early in the construction phase. Therefore, the crew doesn't feel as much pressure as compared to a slow production activity with a similar duration. Due to this effect, the schedule pressure is set constant by holding the value of estimated upstream duration at 24 months for simulations with a fast upstream production. Subsequently, the desired level of reliability is determined by modifying the ratio of experienced staff on the team. The different levels of upstream reliability as a result of experienced staff are illustrated in Figure 36. On the other hand, for simulations involving a slow upstream production, the ratio of experienced staff is set constant at 100% and the work reliability can be determined by altering the estimated completion duration.

![Upstream Task Reliability](image)

**Legend**

- 98% experienced staff
- 82% experienced staff
- 60% experienced staff
- 0% experienced staff

Figure 36: Upstream Task Reliability
Similarly, the downstream sensitivity can be controlled by the same procedure during simulation. The two driving factors are the inspection effectiveness and the number of upstream task segments. Because the effect of these two variables is independent from the production rate, one factor is held constant throughout the entire simulation to simplify the process. Hence the desired level of sensitivity is determined solely by the other factor. During the simulation, the effect of upstream segments is held constant and the inspection effectiveness is set to range from zero to 150% of the normal inspection.

![Downstream Task Sensitivity](image)

**Legend**

<table>
<thead>
<tr>
<th>% Inspection Effectiveness</th>
<th>2</th>
<th>2</th>
<th>2</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% Inspection Effectiveness</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>150% Inspection Effectiveness</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 37: Downstream Task Sensitivity

To summarize the results of simulation, for any given value of downstream sensitivity regardless of upstream and downstream production rate, the amount of overlapping can be increased as the upstream reliability increases. On the other hand, for any given value of upstream reliability, the amount of overlapping can be increased as the downstream sensitivity decreases.
However, there are four counts of simulation runs that are counter-intuitive to the overlapping recommendations in Figure 24. Two of which take place in the category of slow upstream production and slow downstream production. One of them has the combination of a fairly reliable upstream task and an insensitive downstream task. The other has the combination of a highly reliable upstream task and a sensitive downstream task. The recommended overlapping strategy is to begin the downstream task at 50% of upstream completion. However, the results of simulation show that 25% and 75% of upstream completion are better alternatives than 50% with respect to each activity characteristics combination. A possible explanation is that because of the slow upstream production, starting the downstream task at 25% upstream completion can gain a significant lead-time compared to other starting times, especially for a highly reliable upstream task. As the reliability of upstream task decreases, the significance of lead-time for the 25% upstream completion mark diminishes, and the recommended strategy should shift to later starting times.

However, the increase in upstream error as a result of a lower reliability gives 75% upstream completion mark an advantage over the 50% mark. Hence, the gain for 75% mark as a result of lower work reliability outpaces the gain for 50% mark for the same amount of reliability reduction. In this unique situation, either or both the 25% and 75% upstream completion time can outperform the 50% completion time across any level of reliability as shown in Figure 38. Part of Figure 38 is truncated to show the lag of 50% upstream completion starting time compared to other starting times. This particular simulation result was not anticipated when the overlapping recommendation in Figure 24 was developed. Without the application of system dynamics modeling technique, this kind of behavior would be difficult to foresee and analyze.

Consequently, the results of simulation suggest that in order to effectively fast-track a pair of slow production upstream and downstream task, the following scenario has to be considered. The overlapping practice has to be done either early enough, so that there is sufficient time to discover and fix the errors made in the downstream; or the overlapping has to be done late in the process, so that the upstream errors can be corrected without creating too much rework in the downstream task. This phenomenon is especially significant in the quadrant of slow production upstream and downstream task because for two reasons. First, for a slow production upstream task, the difference in time between 25% completion and 50% completion is greater than a fast production activity, as shown on Figure 23. Hence starting the downstream task at 25% of upstream completion can gain a significant lead time. As a result,
there is a greater difference in work accomplished downstream between starting at 25% and 50% upstream task completion. Secondly, a more aggressive overlapping strategy is recommended for a slow production downstream task in comparison to a fast production upstream task. Consequently, this strategy further multiplies the difference in work accomplished between various starting points for the downstream task.

![Downstream Work Accomplished vs. Time](image)

**Legend**
- 25\% upstream completion
- 50\% upstream completion
- 75\% upstream completion

Figure 38: Counter-Example #1 (Simulation ID: F1)

The other two counter-examples to the overlapping framework are due to the boundary conditions of the model. One of which takes place for a fast and highly unreliable upstream task, together with a fast and highly sensitive downstream task. The other occurrence is for a slow and highly reliable upstream task, also in conjunction with a fast and highly sensitive downstream task. According to Figure 24, the recommended overlapping strategy is to begin both tasks at 175\% upstream completion. However, the simulation results show that for these combinations of activity characteristics, the best overlapping strategy is to begin the downstream task at 150\% upstream completion. This is because the learning effect
in the model can sufficiently improve the work quality, and consequently discover and fix all the errors in
the upstream task within 150% of its estimated completion time. As Figure 39 shows, the 150% and
175% upstream completion progress curves maintain the same difference throughout the production
cycle, which means that the two activities always proceed with the same production rate. The errors made
upstream no longer affect the performance of these two activities beyond 150% of upstream completion.
Consequently, creating additional schedule buffer produces no extra value to improve the robustness of
the project and can only cause delays.

![Downstream Work Accomplished vs. Time](chart)

**Legend**

- 150% upstream completion
- 175% upstream completion

Figure 39: Counter-Example #2 (Simulation ID: H6)

Above all, the modeling and simulation process can help understand the implications of the
various overlapping strategies on overall project duration. The parameters defined in the model represents
the modeler’s understanding of the interactions among the factors embraced in the model. Based on the
same set of parameters, the effectiveness of different overlapping strategies can be evaluated, and further
identify how to increase the chances of succeeding a particular overlapping strategy.
3.5 SUMMARY OF METHODOLOGY

Although a system dynamics model can not be a true representation of how a real project would evolve over time, it is still a useful technique to establish a benchmark to compare the results of different overlapping strategies developed in this thesis. To summarize the integration of different concepts in the proposed robust planning and control methodology, Figure 40 illustrates the various components by the order of its application in this integration process. The first task is to classify the different domains in the project and to define the mapping process in order to formulate the activities in each domain. In this thesis, the proposed methodology specifically deals with the interaction between the physical domain and process domain, and the mapping process between the design parameters (DPs) and process variables (PVs). In another words, the DPs would represent the project scope based on the design drawings and other relevant information, and the possible work methodologies are formulated as PVs to satisfy the project scope.

During this mapping process from DPs to PVs, various solution alternatives could arise to form the PVs. Consequently, the best set of PVs will be selected based on the two principles of axiomatic design concept: the independence axiom and the information content axiom. The fulfillment of the independence axiom can be checked by applying the dependence matrix, which is shown as the second component in Figure 40. If any coupled relationship is determined to exist, it can possibly be resolved by applying the decoupling task. Once the coupled relationship is reduced to an acceptable level that can be managed during construction, the information content axiom can be applied to further evaluate and compare the PVs against the important criterions in the project. As a result, the best set of PVs can be selected to form the preliminary project plan.

Once the preliminary project plan is developed, the next step is to identify the suitable activities for fast-tracking based on the overlapping framework in Figure 24. With this framework, the characteristics of the activities such as production rate, production reliability and sensitivity to upstream task errors would become the key parameters in formulating a good overlapping strategy. Consequently, if the two overlapped activities are either on the critical path or have high criticality indices, then overlapping the two can effectively shortened the project schedule. Even if they are not on the critical
path, additional buffer can be generated as a result of overlapping and absorb changes or reworks to protect the project from delays. In the event of activity splitting, as shown in Figure 40, additional buffer can be created once again to ensure timely completion for the first portion of the task. Consequently, applying this overlapping framework at where it is applicable can ultimately create an efficient and robust project plan to minimize the impact of changes on project schedule.

Subsequently, the effectiveness of a particular overlapping strategy can be evaluated by the GERT approach. With this diagramming scheme, the branches and rework loops are captured probabilistically to represent the possible outcomes that the project could encounter. Furthermore, the probability values can be derived by utilizing the activity characteristics defined by the overlapping framework. For example, a highly unreliable task would have a good chance of running into a rework cycle. Furthermore, each activity's duration can be assigned with an estimated range to incorporate both the optimistic and pessimistic estimate. Consequently, the difference in project duration as a result of fast-tracking can be measured probabilistically in GERT and yields the final duration with a range of completion date.

If the construction crew wants to further enhance the performance of a particular overlapping practice, the system dynamics modeling technique can be applied to determine the causal links among the different factors in a construction system. This modeling technique can analyze the actions and reactions by modifying the different factors in a particular set of activities. By explicitly delineating the feedback structure of the system, the planner can analyze the behaviors of task progression under various "what if" conditions. Once the important factors are determined in this modeling and simulation process, the construction crew can enhance the effectiveness of overlapping by enforcing appropriate policies to reduce project duration.

Above all, by implementing the proposed robust planning and control methodology, the planner can begin the planning process by creating an effective work methodology utilizing the axiomatic design concept. This work methodology then becomes the backbone of the preliminary project plan. Based on the concept of concurrent engineering, the project duration can be reduced in addition to create schedule buffers by recognizing appropriate overlapping practices based on the activity characteristics. Subsequently, the project schedule can be developed using the GERT diagramming scheme to probabilistically incorporate the various outcomes of the project. With the GERT scheduling approach,
sufficient contingencies can be assigned to prepare for unforeseen events that are typically neglected in conventional network diagramming methods. Following the GERT scheduling method, the overlapping practice can be enhanced by applying the system dynamics modeling technique to identify the important factors on activity progress. Hence the construction crew can address these important factors during the overlapping process to effectively reduce the project duration. Consequently, by implementing the robust planning and control methodology, a sound project plan can be delivered as the end product with a shortened overall duration in addition to providing scheduling buffer at where it is possible to minimize the impact of changes in the project.
Domain and Mapping

Axiomatic Design

\[
\begin{align*}
FR_1 &= \begin{bmatrix} X & X & O \end{bmatrix}
\end{align*}
\]

\[DP_1 = \begin{bmatrix} X & X & O \end{bmatrix}
\]

\[
\begin{align*}
FR_2 &= \begin{bmatrix} X & X & O \end{bmatrix}
\end{align*}
\]

\[DP_2 = \begin{bmatrix} X & X & O \end{bmatrix}
\]

\[
\begin{align*}
FR_3 &= \begin{bmatrix} X & O \end{bmatrix}
\end{align*}
\]

\[DP_3 = \begin{bmatrix} X & O \end{bmatrix}
\]

Axiomatic Evaluation

Concurrent Engineering

GERT (Graphical Evaluation and Review Technique)

System Dynamics Model

Figure 40: Methodology
CHAPTER 4

CONCLUSION

This thesis has demonstrated how a robust construction plan can be achieved by an integration of axiomatic design, concurrent engineering, graphical evaluation and review technique (GERT) and system dynamics modeling technique. The initial project plan is formulated as process variables (PVs) using the axiomatic design concept, and then finalized by the axiomatic information content principle. Based on the characteristics of the sequential activities in the plan, the overlapping framework can be applied to shortened the project duration on tasks where overlapping is feasible and effective. These activity characteristics can be used in GERT by transforming them into probabilities of branching and looping. Then GERT can calculate the resulting schedule probabilistically after overlapping, yielding a range of estimated completion date. The results of overlapping can be further reinforced using the system dynamics modeling technique to study the impact of different factors on the project. The system dynamics approach also helps the construction crew realize the critical factors that the success of a particular overlapping strategy depends upon, and increases the possibility of creating an effective fast-tracking project plan.

4.1 APPLICATION OF THE ROBUST PLANNING AND CONTROL METHODOLOGY

A typical bid-level project schedule might have a range of hundreds of activities. For a fully deployed detailed schedule, the number of activities might become thousands or even more. It would be inefficient and unnecessary to apply the entire robust planning and control methodology on every single activity in the schedule. Since the axiomatic design concept is used to develop the essential work
methodology to construct the project, it might diffuse throughout the entire planning process and appear in the schedule at the summary level. However, the application of concurrent engineering, GERT and system dynamics modeling should be implemented only to activities that are critical to the success of timely completion. In addition, the overlapping framework was developed based on an important assumption that the activities can be divided in intervals, so that the subsequent tasks can begin early to achieve overlapping. To fully take advantage of the proposed robust planning and control methodology, a software system should be developed to identify the activities where fast-tracking should be applied, based on the critical path, near-critical paths, criticality index and the divisibility of the task’s production. The near critical paths and activities with high criticality index should be considered because they are likely to become the actual critical path after changes are made to the original schedule.

4.2 FUTURE RESEARCH

The ADEPT System [Adept, 1996] was developed to assist the implementation of axiomatic design concept on schedule planning. The system suggested the use of a "smart cell" that includes information such as activity duration and precedence relationships. Subsequently, the information in the smart cell can be used to develop a project schedule in the Gantt chart form. The proposed robust planning and control methodology can be applied to strengthen this software application by fast-tracking a certain set of activities identified as critical. The associated activity characteristic information such as production rate, production reliability and sensitivity to upstream errors can be encapsulated in the smart cell as well. The deterministic duration in the original smart cell can be improved to incorporate a range of duration. After the original schedule is improved by fast-tracking the activities based on their characteristics and the overlapping framework developed in this thesis, the resulting schedule can be calculated probabilistically in GERT. In addition, the activity characteristics should be defined in such a way that the system dynamics modeling technique can adapt those values to perform simulation. Consequently, the progress curve of the activity can be simulated automatically according to the specific overlapping strategy and the corresponding activity characteristics.

The focus of this thesis primarily lies on the scheduling aspect of robust project control, which improves the project implementation through a more effective schedule planning process. However,
another important issue that hasn’t been addressed in this thesis is the cost-benefit analysis between a normal schedule and fast-track schedule. A schedule with minimized duration might not be the best schedule if the incremental cost to complete becomes too high. For example, the system dynamics model might suggest the construction crew to consist of at least 80% of experienced staff to successfully overlap the activities. However, the existing ratio of experienced staff might be only 50%. Now, the cost to hire an additional 30% experienced staff may exceed the gain from overlapping. Hence, overlapping creates negative value to the project and becomes undesirable in this scenario. A possible approach would be to establish a reference point where the cost of additional resources equals the benefit of schedule reduction. Consequently, this amount of additional resource can be entered in the smart cell as the maximum value. If an activity requires additional resources exceeding this value, then it should be filtered out from the list of activities for overlapping.

The scope of the proposed robust planning and control methodology can be extended to incorporate other robust design concepts. The axiomatic design principles adapted in this thesis are often compared with other design methods, such as the Taguchi Method [Suh, 1990]. The Taguchi method has proven to be useful in analyzing and improving the performance of an existing design such as manufacturing operations. On the other hand, the axiomatic design concept is more useful when new designs are being developed [Suh, 1990]. Consequently, depending on the characteristics of the project and the work methodology associated with it, whether the method is conventional or innovative, an appropriate robust design concept can be adapted in the proposed robust planning and control methodology to help develop the best project plan.

In addition, the concept of linear scheduling [Moder et al., 1983] was developed to create an efficient construction sequence based on the activity progress rate. This scheduling technique is mainly applied to help repetitive activities using the same resource to minimize resource discontinuity. Furthermore, there is an added dimension of location buffers in addition to scheduling buffers, so that it is possible to reduce activity location interference. Consequently, integrating the concept of linear scheduling to the proposed robust planning and control methodology can enhance its application by streamlining the construction phase to increase the productivity of the crews.

The final software product developed based on the proposed robust planning and control methodology is envisioned to have three major components to it. The first component is the work
methodology formulation process using the concept of axiomatic design principles. The second component focuses on the schedule reduction aspect of robust planning and control methodology by overlapping appropriate activities. Finally, the third component is applied to analyze the benefit of overlapping in actual dollar terms. The integration of these three components will serve as a rigorous project planning process. By this process, the effectiveness of the work methodology, the timeliness of schedule planning, and as far as the cost effectiveness of the project, are the subjects of critical evaluation to achieve a robust project plan. This project plan not only can reduce the time and cost for construction, but it also allocates additional schedule and budget contingencies within the plan to absorb unforeseen changes without creating major interruptions to the plan.
REFERENCES


APPENDIX

MODEL DOCUMENTATION
current progress=(Upstream Project is done/Upstream Initial Project Definition)
   Units: dimensionless

dnstream current progress=DNstream Project is done/Dnstream Initial Project Definition
   Units: dimensionless

dnstream estimated completion time=20
   Units: Month

DNstream HIGHLY SENSITIVE Index ( [0,-1)-(1,1)],(0,1),(0.00906344,0.05),(0.0151057,-
   0.4),(0.0241692,-0.675439),(0.0543807,-0.850877),(0.135952,-0.912281), (0.280967,-
   0.938596),(0.498489,-0.947368),(0.749245,-0.973684),(1,-0.991228))
   Units: dimensionless

DNstream Initial Project Definition=1000
   Units: unit

DNstream INSENSITIVE Index ( [0,-1)-(1,1)],(0,1),(0.0725076,0.394737),(0.190332,-0.149123),
   (0.377643,-0.526316),(0.564955,-0.754386),(0.746224,-0.894737),(1,-1))
   Units: dimensionless

dnstream percent error= (Perceive DNstream Project is done-Dnstream Project is done)/DNstream Initial
   Project Definition
   Units: **undefined**

DNstream Project is done=MIN(Dnstream Initial Project Definition,Dnstream Work Accomplished)
   Units: unit

dnstream ratio of experienced staff to total staff=1
   Units: dimensionless

dnstream rework discovery rate=Dnstream Undiscovered Rework/DNSTREAM TIME TO DETECT
   ERRORS
   Units: unit/Month

dnstream schedule buffer as percent of estimated completion time=0.5
   Units: dimensionless

dnstream schedule pressure=(((Time-time when dnstream start)-dnstream current progress*dnstream
   estimated completion time*(1-dnstream schedule buffer as percent of estimated
   completion time))+1e-006)/(1e-006+Time-time when dnstream start)
   Units: dimensionless

dnstream sensitivity=(inspection effectiveness*effect of upstream activity steps(number of upstream
   activity steps/maximum number of upstream steps)/2)*DNstream INSENSITIVE
   Index(upstream percent error)+(1-inspection effectiveness*effect of upstream
   activity steps(number of upstream activity steps/maximum number of upstream
   steps)/2)*DNstream HIGHLY SENSITIVE Index(upstream percent error)
   Units: dimensionless

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DNSTREAM TIME TO DETECT ERRORS=2
Units: Month

Dnstream Undiscovered Rework= INTEG (dnstream work flow*(1-dnstream work quality)-dnstream rework discovery rate,0)
Units: unit

Dnstream Work Accomplished= INTEG (IF THEN ELSE(-dnstream rework discovery rate+ dnstream work flow>1000,1000,-dnstream rework discovery rate+dnstream work flow),0)
Units: unit

dnstream work flow=IF THEN ELSE(upstream completion for dnstream to start>1,IF THEN ELSE(Time>upstream completion for dnstream to start*time when upstream start,(IF THEN ELSE(Dnstream Project is done =1000,0,100* work productivity ((Dnstream Project is done)/Dnstream Initial Project Definition)),0),IF THEN ELSE(upstream percent complete<upstream completion for dnstream to start,0,(IF THEN ELSE(Dnstream Project is done=1000,0,100*work productivity((Dnstream Project is done)/Dnstream Initial Project Definition))))
Units: unit/Month

dnstream work quality= MIN(1,dnstream work reliability*dnstream sensitivity)
Units: dimensionless

dnstream work reliability=MIN((effect of schedule pressure on reliability(dnstream schedule pressure)
*effect of staff experience on reliability(dnstream ratio of experienced staff to total staff))*learning effect on reliability(dnstream current progress),1)
Units: dimensionless

Dnstream Work Remaining= INTEG (-dnstream work flow+dnstream rework discovery rate,1000)
Units: unit

effect of schedule pressure on reliability([(-i,0)-(1,1)],(-1,1),(-0.5,1),(1,0.5))
Units: dimensionless

effect of staff experience on reliability([((0,0)-(1,1)],(0.0060423,0.434211),(0.21148,0.47807),
(0.392749,0.526316),(0.6,0.6),(0.803625,0.732456),(0.942598,0.872807),(1,1))
Units: **undefined**

effect of upstream activity steps([(0,0)-(1,2)],(0,0),(0.25,0.2),(0.4,0.5),(0.5,1),(0.6,1.5),(0.75,1.8), (1,2))
Units: dimensionless

estimated completion time=24
Units: Month

FINAL TIME = 60
Units: Month
INITIAL TIME  = 0
Units: Month

inspection effectiveness=0
Units: dimensionless

learning effect on reliability([(0,0.8)-(1,2)],(0,1),(0.111782,1.13158),(0.226586,1.26842),
(0.374622,1.37895),(0.495468,1.44737),(0.634441,1.46842),(0.746224,1.48421),(1,1.5))
Units: **undefined**

maximum number of upstream steps=6
Units: **undefined**

number of upstream activity steps=3
Units: dimensionless

Perceive Dnstream Project is done=MIN(Dnstream Initial Project Definition,Perceived Dnstream Work
Accomplished)
Units: unit

Perceived Dnstream Work Accomplished= INTEG (IF THEN ELSE(perceived dnstream work
flow>1000,1000,perceived dnstream work flow),0)
Units: unit

perceived dnstream work flow=IF THEN ELSE(upstream completion for dnstream to start>1,IF THEN
ELSE(Time>upstream completion for dnstream to start*time when upstream start,(IF THEN ELSE(Dnstream Project is done=1000,0,100*work productivity ((Dnstream Project is done)/Dnstream Initial Project Definition)),0),IF THEN ELSE(upstream percent complete<upstream completion for dnstream to start,0,(IF THEN
ELSE(Dnstream Project is done =1000,0,100*work productivity((Dnstream Project is
done)/Dnstream Initial Project Definition)))))
Units: unit/Month

Perceived Upstream Project is done=MIN(Upstream Initial Project Definition,Perceived Upstream Work
Accomplished)
Units: **undefined**

Perceived Upstream Work Accomplished= INTEG (IF THEN ELSE(perceived upstream work
flow>1000,1000,perceived upstream work flow),0)
Units: **undefined**

perceived upstream work flow=IF THEN ELSE(Perceived Upstream Project is done = 1000,0,100 * work
productivity ((Perceived Upstream Project is done)/Upstream Initial Project Definition))
Units: **undefined**

SAVEPER  = TIME STEP
Units: Month
schedule buffer as percentage of estimated completion time=0
   Units: dimensionless

schedule pressure=(Time+1e-009-current progress*estimated completion time*(1+schedule buffer as percentage of estimated completion time))/(Time+1e-009)
   Units: dimensionless

time inflow=IF THEN ELSE(dnstream work flow=0,TIME STEP,0)
   Units: Month/Month

TIME STEP = 0.05
   Units: Month

time when dnstream start= INTEG (time inflow*20,0)
   Units: Month

time when upstream start= INTEG (upstream time flow*20,0)
   Units: Month

upstream completion for dnstream to start=1
   Units: **undefined**

Upstream Initial Project Definition=1000
   Units: unit

upstream percent complete=Perceived Upstream Project is done/Upstream Initial Project Definition
   Units: **undefined**

upstream percent error=(Perceived Upstream Project is done-Upstream Project is done)/Upstream Initial Project Definition
   Units: **undefined**

Upstream Project is done=MIN(Upstream Initial Project Definition,Upstream Work Accomplished)
   Units: unit

upstream ratio of experienced staff to total staff=0.02
   Units: dimensionless

upstream rework discovery rate=Upstream Undiscovered Rework/UPSTREAM TIME TO DETECT ERRORS
   Units: unit/Month

upstream time flow=IF THEN ELSE(perceived upstream work flow=0,0,TIME STEP)
   Units: Month/Month

UPSTREAM TIME TO DETECT ERRORS=1
   Units: Month

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UPSTREAM TIME TO DETECT ERRORS 1=3

Units: Month

Upstream Undiscovered Rework= INTEG (upstream work flow*(1-upstream work quality)-upstream rework discovery rate,0)
Units: unit

Upstream Work Accomplished= INTEG (IF THEN ELSE(-upstream rework discovery rate+ upstream work flow>1000,1000,-upstream rework discovery rate+upstream work flow),0)
Units: unit

upstream work flow=IF THEN ELSE(Upstream Project is done=1000,0,100*work productivity
((Upstream Project is done)/Upstream Initial Project Definition))
Units: unit/Month

upstream work quality=MIN(1,upstream work reliability)
Units: dimensionless

upstream work quality 0=0.9
Units: **undefined**

upstream work reliability=effect of schedule pressure on reliability(schedule pressure)*effect of staff experience on reliability(upstream ratio of experienced staff to total staff)*learning effect on reliability(current progress)
Units: dimensionless

Upstream Work Remaining= INTEG (-upstream work flow+upstream rework discovery rate,1000)
Units: unit

work productivity([(0,0)-(1,3)],(0.0060423,0.5087772),(0.0755287,0.868421),(0.123867,1.47368),
(0.175227,1.76316),(0.247734,2.01316),(0.311178,2.05263),(0.404834,2.03947),(0.492447,1.92105),
(0.549849,1.80263),(0.586103,1.75),(0.655589,1.63158),(0.691843,1.48684),(0.73716,1.22368),
(0.779456,0.824561),(0.8429,0.482456),(0.909366,0.236842),(0.996979,0.0789474))
Units: dimensionless