# DYNAMIC PLANNING AND CONTROL METHODOLOGY FOR DESIGN/BUILD FAST-TRACK CONSTRUCTION PROJECTS

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**ABSTRACT:** A dynamic planning and control methodology is developed by integrating the applications of axiomatic design concepts, concurrent engineering concepts, the graphical evaluation and review technique (GERT), and the system dynamics modeling technique. The goal of the proposed methodology is to help create a dynamic project plan for design/build fast-track civil engineering and architectural projects where unforeseen changes can be absorbed in the project schedule without creating major interruptions. The axiomatic design concepts are applied to formulate and evaluate various work methodologies, and to create a 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 the upstream error. 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. Consequently, with a rigorous and systemized methodology to help project planning, potential problems can be addressed early before construction. The overall increase in productivity and efficiency as a result of a better planning process can consequently promote the competitiveness of the construction industry.



## INTRODUCTION

Effective fast-tracking in a construction project can help reduce the duration and lower the cost of the project (Tighe 1991; Williams 1995). However, these savings are not always realized due to the adhoc approach taken on developng a fast-track plan. This paper presents a proposed dynamic planning and control methodology, which focuses on the planning and implementation of fast-tracking on design/build projects. This methodology is developed based on the hypothesis that by implementing a carefully structured planning process before construction, it is possible to reduce schedule and cost overruns experienced by most projects today.

The goal is to develop a methodology by integrating the applications that can help absorb potential changes in the plan without creating major disruptions. The primary backbone of this integration method is to combine the application of the concepts of axiomatic design (AD), concurrent engineering (CE), the graphical evaluation and review technique (GERT), and system dynamics (SD). Each of these concepts 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. Concurrent engineering is developed to resolve ''coupled'' events by managing the iteration, overlapping, and integration of those events in manufacturing. GERT is a graphical tool that incorporates probabilities into the duration of activities and the precedence relationship of anticipated events. And last, the system dynamics modeling technique is applied to simulate the progress of fast-track activities over time.

Above all, the integration of these applications can help deliver an effective and dynamic project plan. With a rigorous and systemized methodology to help project planning, potential problems can be addressed early before construction. The overall increase in productivity and efficiency as a result of a better planning process can consequently promote the competitiveness of the construction industry.

## BACKGROUND

### Axiomatic Design

The axiomatic design concept provides a systematic approach to gather and process design information in order to develop a product (Suh 1990, 1995). This concept will be adapted in the present paper to develop a systemized and rigorous construction planning process. The two design axioms below are the fundamental rules of the axiomatic design concept, and they are going to be the cornerstone for the dynamic planning and control methodology.

- Axion 1: the independence axiom. Maintain the independence of functional requirements.
- Axiom 2: the information axiom. Minimize the information content of the design.

The independence axiom defines three categories of dependence matrices (Suh 1990; Albano 1992)—namely, 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, as shown in Fig. 1. The best possible design is the uncoupled design, where each functional requirement (*FR*) is satisfied independently by a corresponding design parameter (*DP*); hence, the tasks can progress in parallel to save time. The second best design is the decoupled design, whereby the

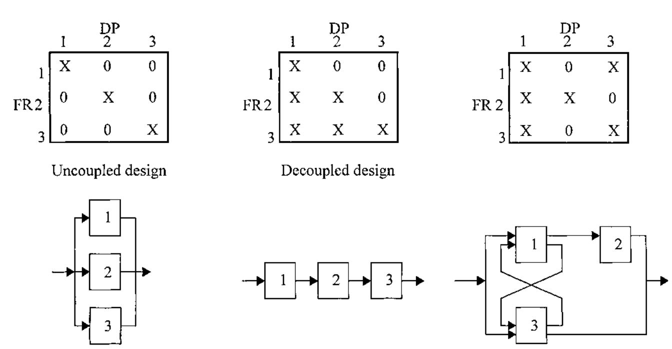


**FIG. 1. Examples of Dependency Matrices**

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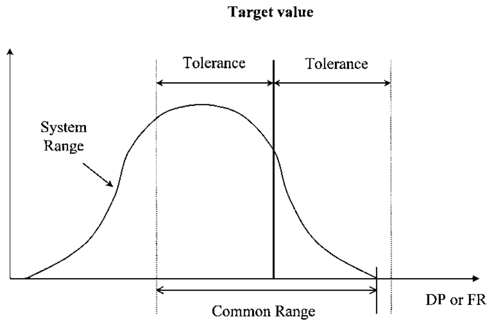


**FIG. 2. Probability of Success**

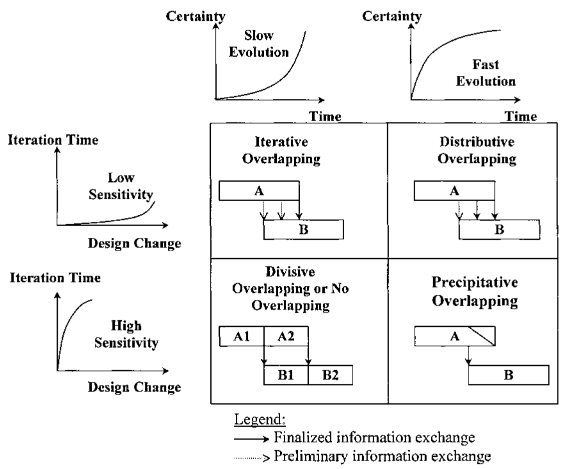


**FIG. 3. Overlapping Framework [Adapted from Eppinger (1997)]**

tasks must be carried out in series. Lastly, the coupled design is highly undesirable because the productions of the two activities are interdependent and must be conducted concurrently. Subsequently, the second axiom of the axiomatic design concept is stated next to help evaluate the effectiveness of various design schemes with respect to the *FR*s and/or constraints. Axiom number 2 (the information axiom) states that among all designs that satisfy the functional independence [axiom number 1], the best design is the one with the least information content (Suh 1990; Albano 1997).

The general definition of information content is $I = \log_2(1/p)$, where $P$ is the probability of $DP_I$ satisfying $FR_I$. This is also called probability of success. The probability of success can be measured by comparing the ''system range'' with the ''common range'' (Fig. 2). The design range is the target value with tolerances in which *FR*s are satisfied. The system range is what the *DP*s are able to achieve, expressed in probabilistic terms. The overlapping area between the design range and system range is called the common range, which represents an acceptable design. Consequently, the probability of success can be calculated as $P$ = common range/system range.

## Concurrent Engineering

Concurrent engineering focuses on the challenges facing large projects that require collaboration of interdependent tasks. It classifies the overlapping framework in terms of upstream task evolution and downstream task sensitivity. Upstream evolution describes how fast an upstream activity requires information in order for it to be completed. In contrast, downstream sensitivity describes how sensitive a piece of upstream information is to a downstream activity (Eppinger 1994, 1997). By defining the characteristics of upstream and downstream activities, it is possible to formulate an overlapping strategy to perform activities in parallel. There are four possible combinations, as illustrated in Fig. 3.

## GERT

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 the critical path method, Precedence Diagramming Method, the program evaluation and review technique, and GERT. The GERT approach (Moder et al. 1983) is selected in this paper because it allows the project planner to probabilistically incorporate the possible loops and branches in the network (Fig. 4). Therefore, an appropriate amount of contingency can be assigned to ensure timely completion of the project.

## System Dynamics Modeling

Once the project schedule is calculated by applying the GERT approach, the factors that can affect the success of a particular overlapping strategy have to be identified and analyzed. The system dynamics modeling technique (Sterman 1992) can incorporate the causality links between the variables in a construction system and the activity production process (Fig. 5). The model explicitly delineates and simulates the relationships between each variable mathematically. 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.

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 various ''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 the necessary parameters to achieve a successful fast-tracking strategy.

## METHODOLOGY

The purpose of this section is to present the methodology that integrates the different components of dynamic planning and control into a 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 *FR*s and *DP*s. However, in the context of construction project planning, one of the general concerns of the planner is to build the facility quicker with lower costs based on the given set of drawings. Consequently, the planning process would begin by identifying the key parameters or *DP*s of the project based on the preliminary design drawings and other relevant information, and then formulating the possible construction methodologies or process variables (PVs).

Among the many available solution alternatives, the best set of PVs will be selected based on the two principles of the 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 task errors, will become the key parameters in formulating a good overlapping strategy. Based on the concept of concurrent engineering, a detailed overlapping framework will be developed by facilitating the activity characteristics and recommending 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 shorten the project sched-



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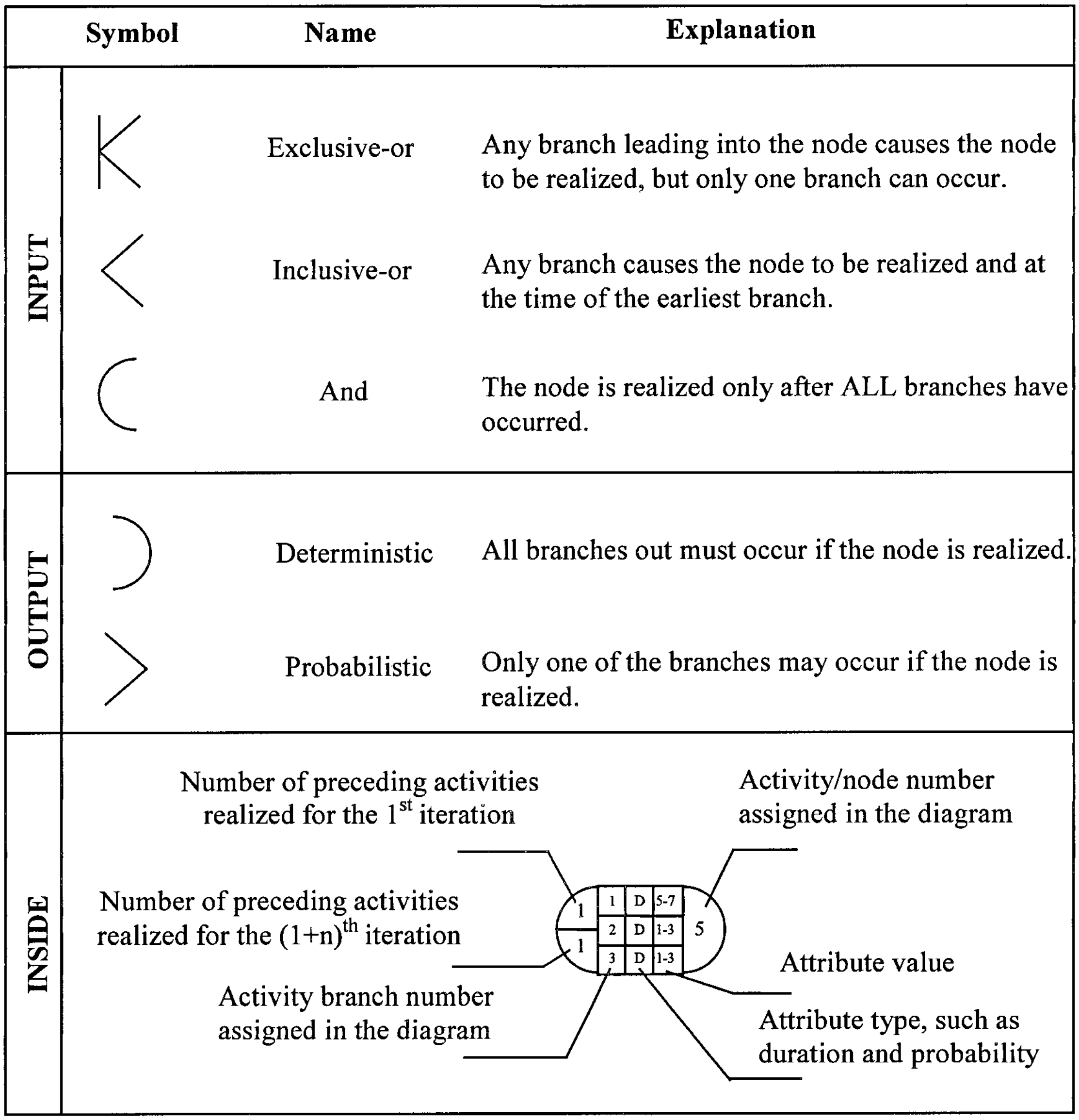


**FIG. 4. GERT and Q-GERT Symbols [Adapted from Moder et al. (1983) and Taylor and Moore (1980)]**

ule. Even if they are not on the critical path, an additional buffer can be generated as a result of overlapping and can absorb changes or reworks to protect the project from delays. Consequently, applying this overlapping framework where it is applicable can ultimately create an efficient and dynamic project plan to minimize the impact of changes on the 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 dates. Finally, the system

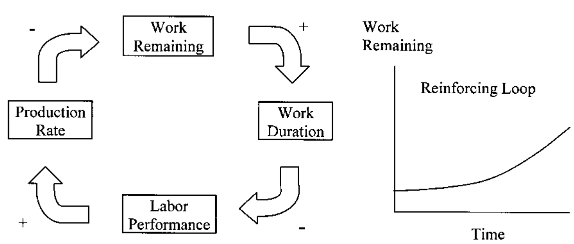


**FIG. 5. Example of System Dynamics Feedback Loop**

dynamics modeling technique will be applied to determine the causal relationships between actions and reactions in a particular set of activities. The simulation process can also help identify the important factors that determine the success and effectiveness of the overlapping framework developed in this paper.

## Role of Axiomatic Design Concept

Following this methodology, the first task is to define the objectives of the project as *DP*s. The selection of *DP*s for the project can be derived from design drawings, specifications, owner's objectives, and other relevant information. Because the role of *DP*s in construction project planning is similar to that of *FR*s in engineering design, a set of *DP*s can be defined as the minimum set of independent parameters that completely characterize the objective of the project. Redundant *DP*s may add unnecessary functions to the proposed work methodology, hence adding extra costs to the project.

Furthermore, the *DP*s 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. To better demonstrate this *DP* and PV formulation process, along with other concepts from the meth-



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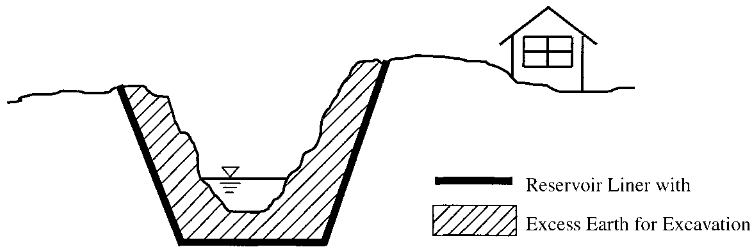


**FIG. 6. Cross-Sectional View of Reservoir**

odology, a single water reservoir construction project, as shown in Fig. 6, will be used as an example to emphasize the points needed to understand the methodology.

In this sample construction project, the reservoir is designed to utilize the existing valley and shave off excess earth to increase capacity. The cross-sectional view of the proposed reservoir is illustrated in Fig. 6. Along the two sides and the bottom, a layer of reinforced retaining slab with anchor bolts will be constructed to form the liner. During the construction, the near-by residents will continue living along the valley bank, so the slope stability and ground settlement have to be closely monitored during the construction process.

As in 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 dynamic planning and control methodology. Consequently, the effectiveness of both methods will be evaluated using the information content axiom from the axiomatic design.

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

- *DP*1: Remove excess earth between the existing earth surface and the new reservoir liner.
- *DP*2: Maintain slope stability and ensure the safety of participants during construction.
- *DP*3: Construct the retaining slab along the proposed location of the reservoir liner.

Along the same line as identifying *DP*s 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 making 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 later in the axiomatic evaluation process. Again, using the water reservoir example, some of the possible constraints are listed as the following:

- C1: project duration: less than two years
- C2: budgeted cost: less than $10,000,000
- C3: no displacement to nearby structures due to the construction method

With both *DP*s 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 for implementing the plan. As different sets of PVs are generated during planning, the dependence matrix can be applied to determine if there exists any undesirable coupled relationship in the work methodology.

Furthermore, as stated by the information axiom, a smaller volume of necessary information to carry out the project implies reduced project complexity, which further eases actual implementation. More important, 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 that satisfies the *DP*s and constraints. A greater common range signifies that the proposed plan has a higher probability of satisfying a certain *DP* or constraint.

Using the reservoir example again, the *DP*s 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 (Fig. 7). The scrape-and-excavate method deploys scrapers to move excess earth from the valley to the banks. Subsequently, excavators and bulldozers are mobilized to shovel the earth onto the dump trucks and carry the excess earth elsewhere. This method is reliable and safe, and there are few uncertainties about the production rate. It also requires a 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. However, the downside is that the progress is slow and involves heavy equipment usage, which implies a longer duration and possibly higher construction costs.

In contrast, the new construction method in the example 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 the subsequent excavation task much easier. This method can effectively shorten the project duration and requires less equipment on-site to perform the task. The downside is that the slope stability is difficult to maintain as a result of the explosion, entailing increasing complexity of temporary structure design. In addition, due to the systematic unpredictable nature associated with explosives, it is more difficult to

<u>Solution One: Scrape-and-Excavate</u>

$$\left|\begin{array}{l}\text{Excavate earth}\\ \text{Maintain slope stability}\\ \text{Build retaining slab}\end{array}\right| = \left|\begin{array}{ccc}X & O & O\\ X & X & O\\ O & X & X\end{array}\right| * \left|\begin{array}{l}\text{Deploy scrapers}\\ \text{Install temporary structure}\\ \text{Pour reinforced concrete}\end{array}\right|$$

<u>Solution Two: Explosion Method</u>

$$\left|\begin{array}{l}\text{Excavate earth}\\ \text{Maintain slope stability}\\ \text{Build retaining slab}\end{array}\right| = \left|\begin{array}{ccc}X & X & O\\ X & X & O\\ O & X & X\end{array}\right| * \left|\begin{array}{l}\text{Use explosives}\\ \text{Install temporary structure}\\ \text{Pour reinforced concrete}\end{array}\right|$$

**FIG. 7. Dependence Matrices for Available Solutions**



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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 selection process can be done by applying the dependency matrices and the axiomatic evaluation method.

With the scrape-and excavate method, all of the *DP*s have decoupled relationships between each other. *DP*1, which is the excavation work, can proceed independently without receiving feedback from the other two *DP*s. The next task, which is installation of the temporary structure, has a start-to-start relationship with a lag relationship to excavation work. This is because the temporary structure can only be installed after a sufficient amount of earth has been removed to create enough space for installation. An ''X'' marked on *DP*2 in relation to *DP*1 represents the precedence relationship between the two tasks. Finally, the temporary structure will be used as the formwork for the permanent construction of the 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. An X marked on *DP*3 in relation to *DP*2 captures this precedence relationship.

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 design strength of the temporary structure to maintain slope stability. A greater amount of explosives can speed up the construction process, but the design strength for the temporary structure would have to be correspondingly increased to maintain the slope stability. Therefore, there exists a coupled relationship between *DP*1 and *DP*2 because of an information feedback loop involving the two tasks.

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 the effect on slope stability. On the other hand, if the strength of the temporary structure is predetermined, then the amount of explosives used by the construction crew has to comply with this constraint. As a result, the coupled relationship can be 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 a serial set of activities (Fig. 8).

Comparing the two methods, the scrape-and-excavate method is easier to implement but is less efficient; using explosives 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.

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 the probability of meeting the requirements. Since there is more than one evaluation criterion, different types of *DP*s and constraints imply different design ranges. For example, the design range for budget and duration constraints is anywhere between zero and 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.

Fig. 9 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 are 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 that of 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 Fig. 10.

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 than that of 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 that of 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 difficult to decide which of the two work methodologies is the better method for this project. As this example demonstrated, using axiomatic design principles enables the project planners to evaluate the pros and cons of different construction plans based on a series of relevant criteria. 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. Each company can make 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

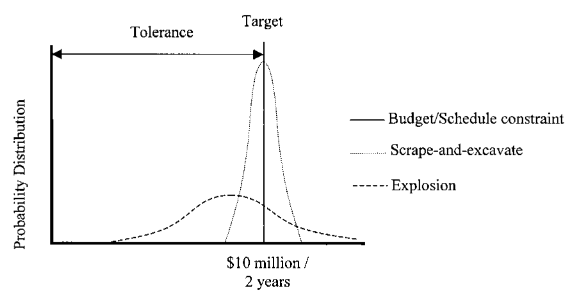


**FIG. 9. Information Content Based on Budget/Schedule Constraint**

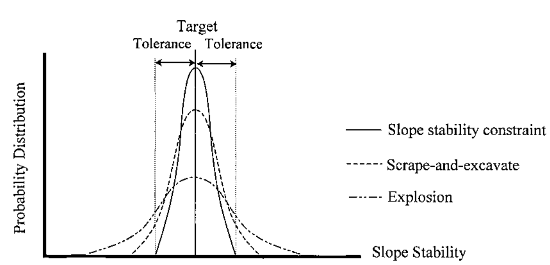


**FIG. 10. Information Content Based on Slope Stability**

**Solution Two: Explosion Method**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Excavate earth | | X | O | O | | Use explosives |
| Maintain slope stability | = | X | X | O | * | Install temporary structure |
| Build retaining slab | | O | X | X | | Pour reinforced concrete |

**FIG. 8. Dependence Matrix for Explosion Method**



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are based on a series of relevant and important criteria. In this example, the key criteria include budget, project duration, and slope stability. Consequently, the two viable work methodologies can be compared based on these criteria to ensure the quality of the final plan.

Once the top-level conceptual planning for the project is completed, the *DP*s have to be decomposed further and the zigzagging process has to be initiated to generate the detailed plan. In the water reservoir 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 an appropriate temporary structure. New constraints, such as getting a permit to transport heavy equipment and acquiring an 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.

## Role of Concurrent Engineering

In this methodology, after the detailed plan is generated, the construction schedule can be fast-tracked by applying the concept of concurrent engineering. In this section, the characteristics of the critical activities will determine if fast-tracking the project is appropriate and realistic. The activities that should be analyzed include the ones that are on the critical path, have a high criticality index, or are constrained by a high resource and duration variance. These are the activities that have the most significant impact on the project schedule if their work duration can be reduced.

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 reservoir construction example, the simplified bar chart for one stage of the scrape-and-excavate method would be similar to that given in Fig. 11.

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.

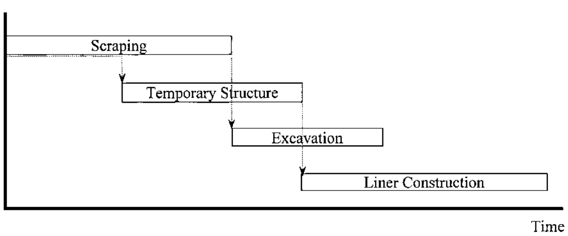


**FIG. 11. Bar Chart for One Stage of Scrape-and-Excavate Method**

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 that makes 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, productivity benefits from the learning curve as the laborers familiarize themselves with the installation procedure, materials, and geographical characteristics of the site. As a result, the productivity of the temporary structure installation would increase over time. Combining the progress curve of these two activities on the same graph, they form the ideal combination for overlapping.

The existing schedule as illustrated in the bar chart in Fig. 11 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, 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, as shown in Fig. 12.

However, the effectiveness of overlapping is not 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 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, an overlapping framework will be de-

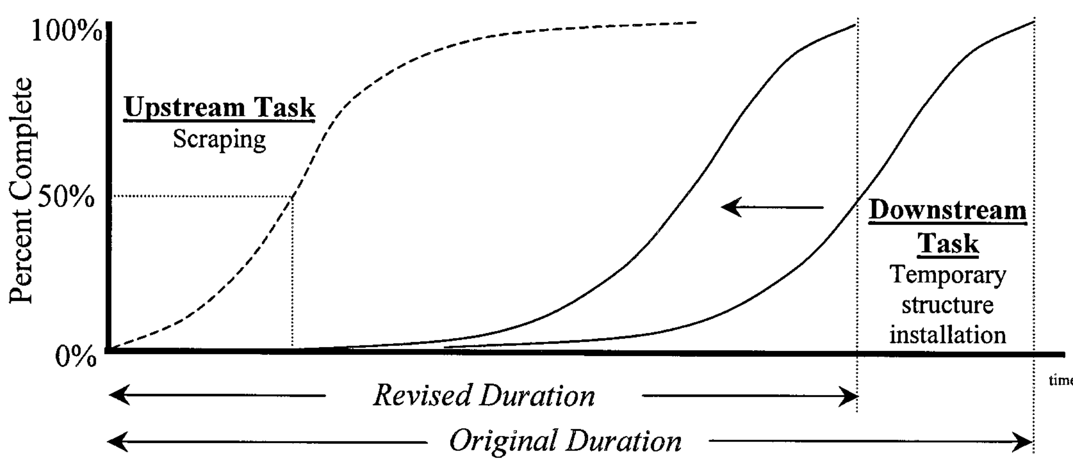


**FIG. 12. Change in Duration after Overlapping**



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veloped to suggest possible overlapping strategies based on task progress, upstream production reliability, and downstream task sensitivity. In addition, an important assumption for this framework to work is that the activities are divisible. Consequently, they can be measured by percent complete and the downstream task can proceed with the upstream task partially completed.

The upstream task production reliability can be measured by taking the difference between the perceived output and real output of an activity, and then dividing 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:

$$F(t) = [P(t) - R(t)]/R(t_f) \quad (1)$$

where $F(t)$ = reliability function; $P(t)$ = perceived production; $R(t)$ = real production; and $R(t_f)$ = final real production = 100%. The perceived production is the amount of work that has been performed according to the schedule, but has not been thoroughly inspected and/or still contains hidden errors. The real production is the work that really added value to the project after all problems and reworks have been discovered and fixed. Fig. 13 illustrates how production reliability for different activities can be measured over time.

The left diagram in Fig. 13 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. Finally, the graph on the right represents one of the worst scenarios, when the real output falls behind the perceived output by too much and the gap between the two cannot be recovered to finish the task in time. The schedule delay is represented as $\Delta t$. 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 the sensitivity curve (Fig. 14) takes the same form as that of the reliability curve, which is $S(t) = [P(t) - R(t)]/R(t_f)$. For a downstream task that is insensitive to upstream production change, there is minimal impact on the downstream task after the change is introduced upstream, resulting in a smaller value of the sensitivity function.

Given the task production rate, upstream production reliability, downstream task sensitivity, and the task divisibility, it is possible to provide a framework by which activities with certain characteristics should or should not be overlapped. In Fig. 15, 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 a high production rate, the required time to generate 25% of the work is significantly less than that for a comparable task with a slow production rate. The percent completion bars at the bottom of Fig. 15 will be used in the overlapping framework, as shown in Fig. 16.

The overlapping framework in Fig. 16 is divided into four quadrants with respect to the production rate of the upstream and downstream tasks. Within each quadrant, the amount of overlapping is suggested based on the upstream production reliability and downstream task sensitivity. The upstream production reliability ranges from highly reliable, fairly reliable, fairly unreliable, and highly unreliable. Similarly, the downstream task is categorized into insensitive, sensitive, and highly sensitive tasks. The sensitivity of the downstream task is defined by the percent of change as a result of an error made upstream.

The overlapping framework in Fig. 16 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 the upstream task must be completed to support the production of the downstream task. The second assumption for Fig. 16 is that the upstream task always finishes before the downstream task. This is an important assumption because the production of the downstream task is based on the work generated 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 later. Finally, the third assumption is that the activities

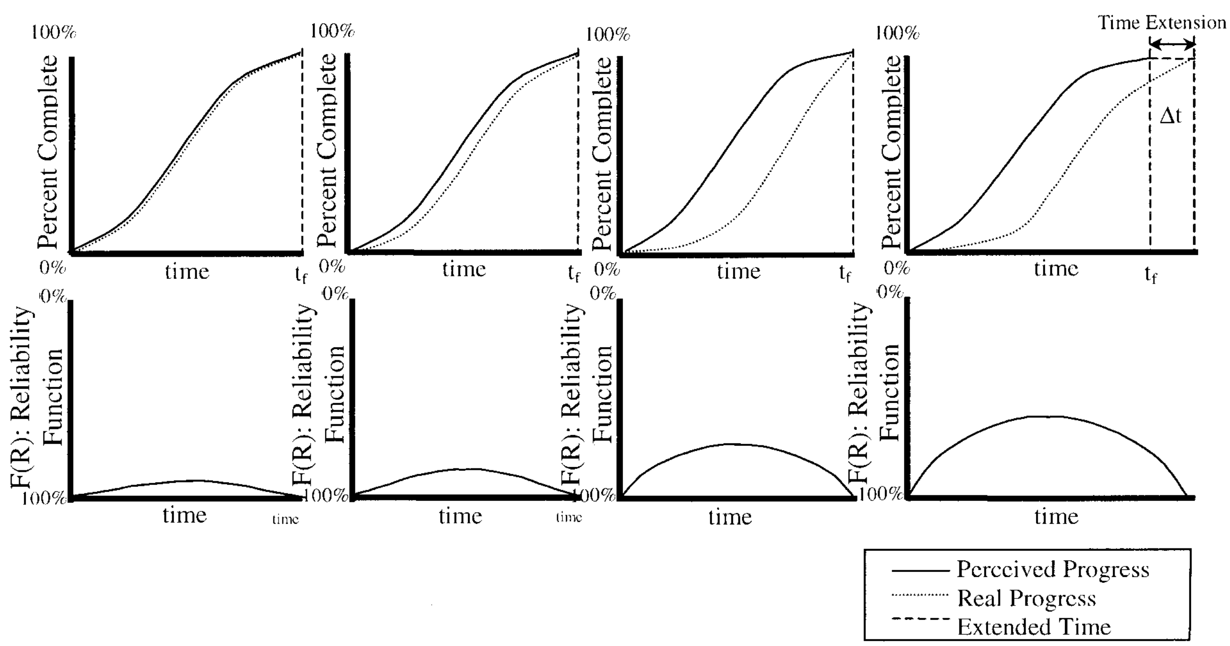


**FIG. 13. Reliability Curve**

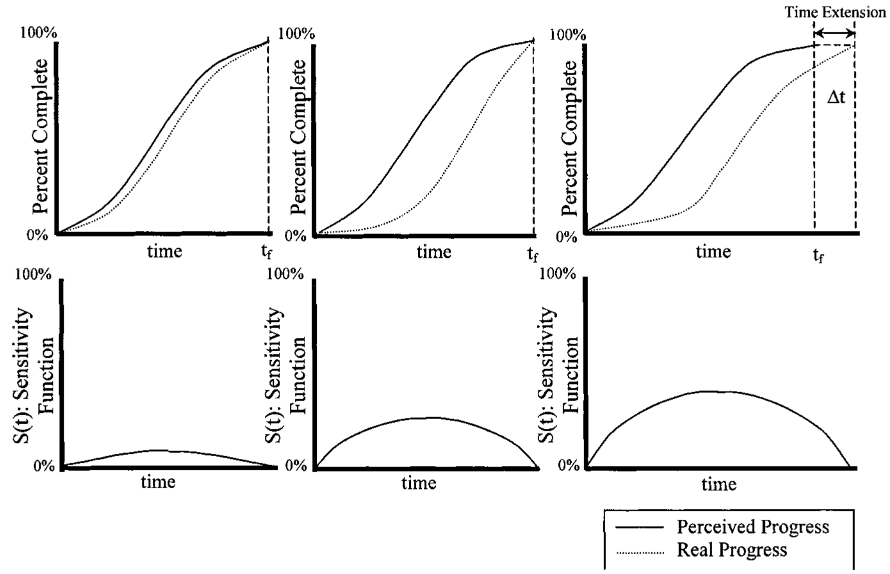


FIG. 14. Sensitivity Curve

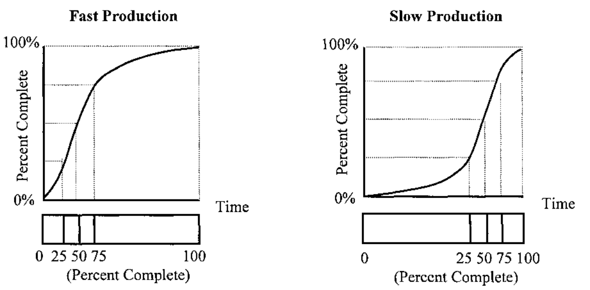


FIG. 15. Production Rate

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 increases, 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 less, 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 a multiplying effect on the downstream task. Consequently, a fast downstream task would encounter more rework compared to another task with similar duration, but with a slower initial production rate.

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 results in further delays, overlapping should be avoided to minimize the possibility of rework downstream. Similarly, the sensitivity of the 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, introducing the downstream task one increment later in the sequence reduces the amount of overlapping. 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 for 175% of upstream task completion is allowed. 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 Fig. 16, a fast and reliable upstream task together with a slow and insensitive downstream task make the ideal combination for overlapping.

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 the 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 an additional buffer within the activity. As shown in Fig. 17, the downstream task is being split into 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.

## Role of GERT

The overlapping framework developed in Fig. 17 can be applied to help shorten a project schedule based on the activity progress rate, upstream task reliability, downstream task sensitivity, and task divisibility. Furthermore, this overlapping framework and the GERT network diagramming method (Moder et al. 1983) are good complements to each other. The shape of the 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.



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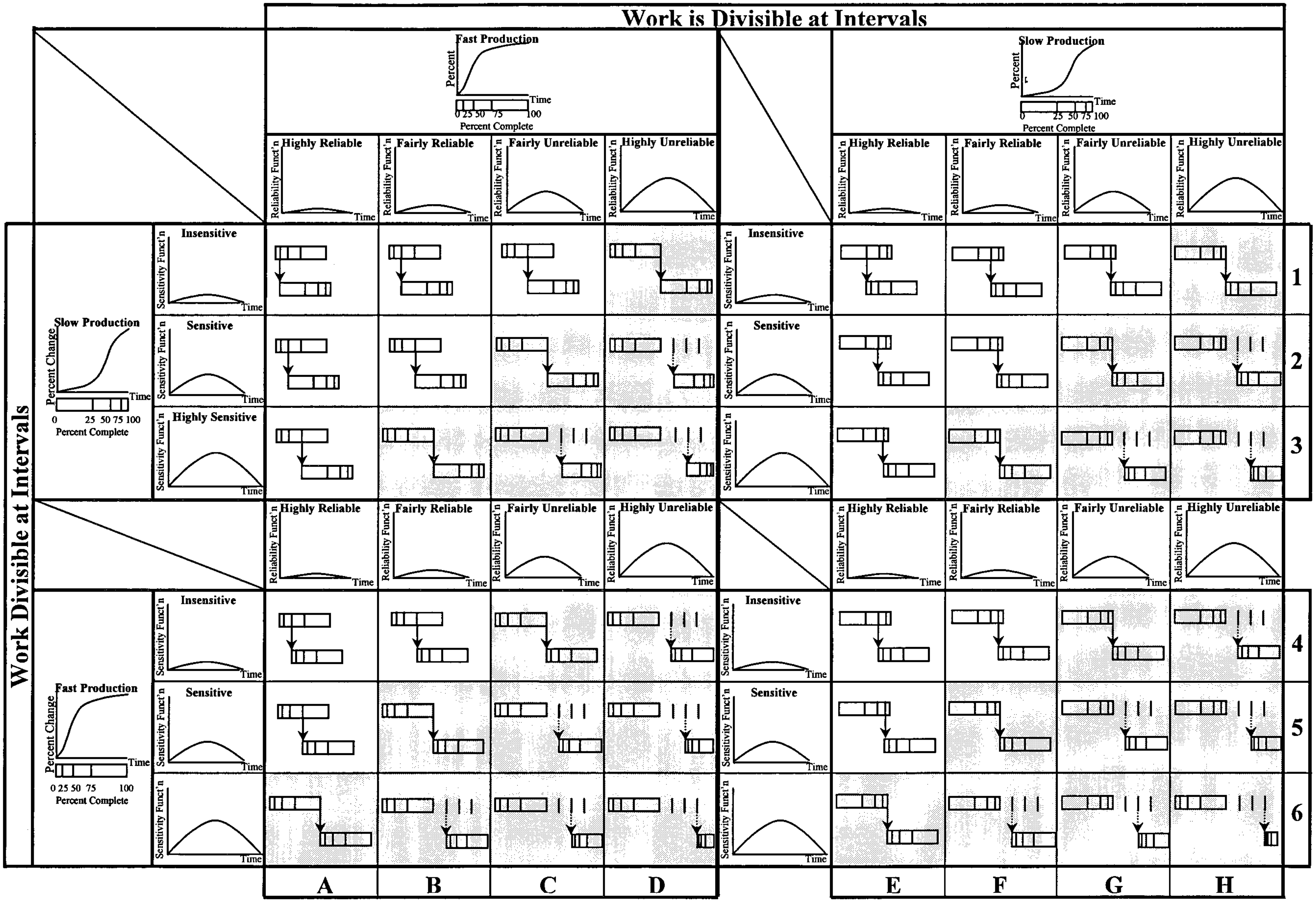


**FIG. 16. Overlapping Framework (for Upstream Task Completing before Downstream Task)**





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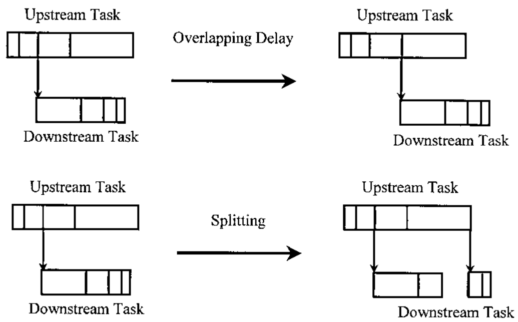

**FIG. 17. Overlapping Delay and Splitting**

In Fig. 18, the GERT diagram incorporates the possible outcomes of the two-stage explosion method for the water reservoir example. The values of duration and probability for each branch in stage 1 explosion and stage 2 explosion are recorded in node 4 and node 5, respectively. In each node, numbers 1–17 are the activity identification (ID) that corresponds to the branch or loop of the same number in the diagram. Within nodes 4 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 parentheses that follow each construction activity, the first letter in the parentheses represents the activity attribute, and the second number is the assigned activity ID. The "AT" in each set of parentheses represents the activity attribute of duration, and the letter "A" represents the activity attribute of probability. For example, in explosion stage 1, the duration of the loop going around the explosion task located in node 7 has an estimated duration range of one to three 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. Once the contractor receives the NTP, the engineers can begin the design of a standard temporary structure, given the in situ site condition and the subsequent explosion that will be deployed on the site before excavation. After the design is completed, the contractor can then proceed with the explosion task. The GERT diagram 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 does not reach 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 reexplode excess earth. In the second scenario, if the right amount of dynamite is exploded and sufficient earth is removed by the explosion, then the contractor can proceed with the original schedule as initially planned. 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.

Since the explosion is planned as a two-stage process, the same construction sequence would be repeated for the second time in the GERT network. Although stage 1 and stage 2 embrace the same sequence, the probabilities assigned to each loop and branch might be different. This is because stage 2 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 one-stage explosion task and a two-stage explosion. If the construction crew can adopt the learning curve and make a tremendous amount of improvement with each explosion, then the plan should divide the explosion task into even more stages to fully take advantage of the learning curve.

The probabilities in Fig. 18 are assigned to represent improved performance in stage 2. The duration of some tasks is assigned 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 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 Fig. 16. Typically, the temporary structure design has to be 100% completed and approved before explosion can take place. Therefore, there is no overlapping between designing the temporary structure and the explosion. Furthermore, the safety constraint might prohibit any activity from proceeding concurrently with explosion to eliminate any possible injury. Limited by this constraint, the activities left that can be fast-tracked are excavation, redesigning/installing the temporary structure, and construction of the reservoir 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 are derived based on the probabilities leading into undesirable/desirable branches and rework loops, as well as other relevant information.

The estimated characteristic for each task is illustrated in Fig. 19. 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 a field survey. As shown in the GERT diagram in Fig. 18, there is only a 5% chance that reexcavation is needed. However, the excavation work is quite sensitive to upstream production because the effectiveness of excavation is highly dependent on the results of the explosion. Following excavation, the next task is to install the 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 the temporary structure is slow because the crew is unfamiliar with the construction procedure, material, and 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 the upstream task. This is because only a small amount of excavation near the proposed liner surface is required to proceed with the temporary structure installation.

Finally, the construction of the reservoir liner is also a slow production task. Trucks carrying concrete mix might find it difficult to access 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 the formwork built upstream has a significant effect on the quality of the reservoir liner. If the temporary structure is found to be misaligned 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 the reservoir liner is highly sensitive to the upstream temporary structure installation.

## Overlapping Practice

Using these parameters in the overlapping framework, the following overlapping methods are recommended, as shown in Fig. 20. 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 the ex-



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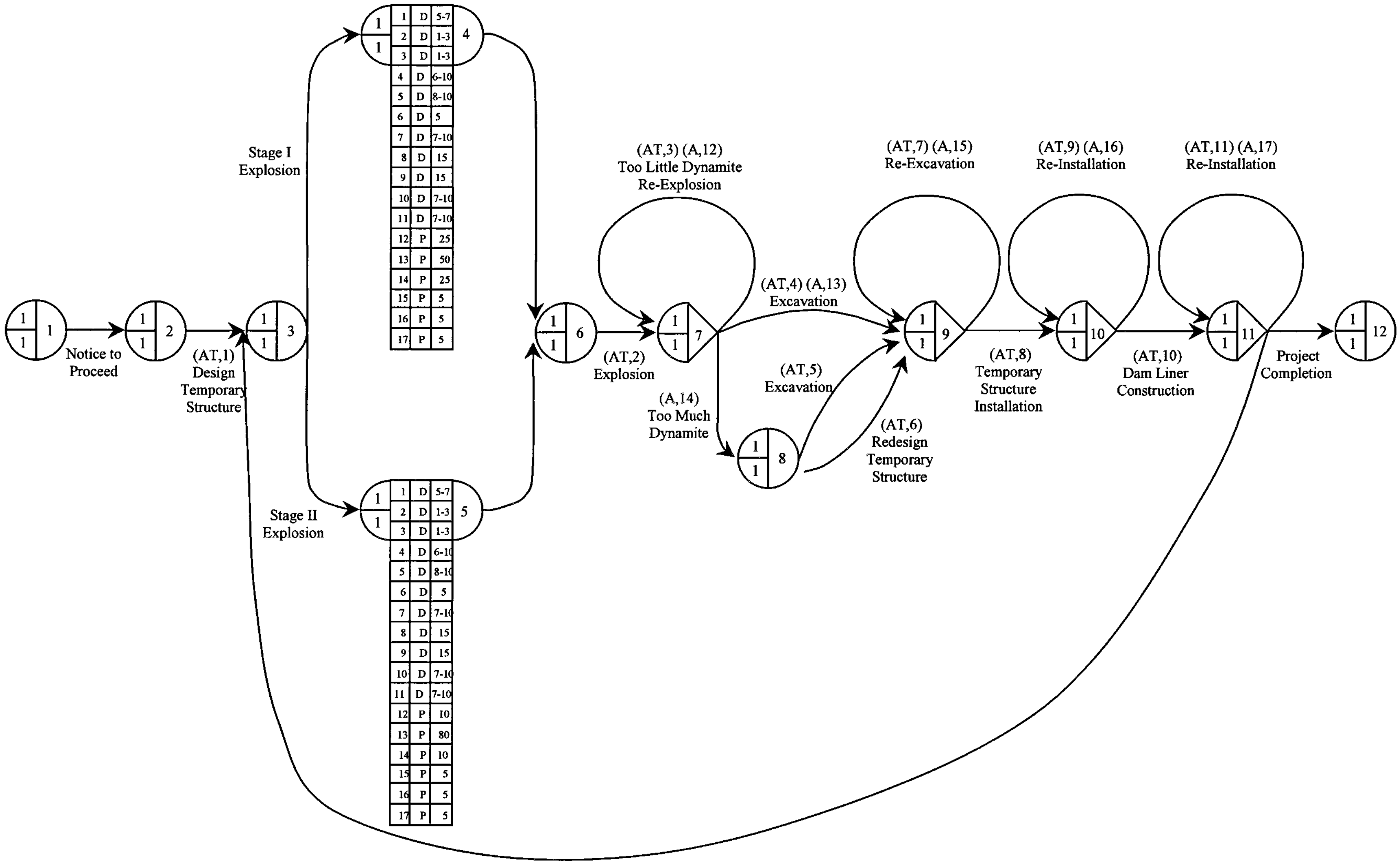


**FIG. 18. GERT Diagram for Water Reservoir Construction**

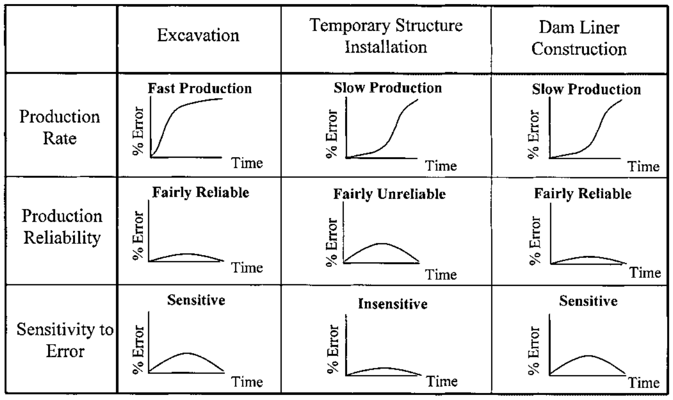


**FIG. 19. Activity Characteristics**

cavation work, resulting in a schedule reduction of approximately equivalent to 75% of the excavation time. However, if too much dynamite is used, than an additional finish-to-start relationship between redesigning and installing the temporary structure has to be considered. In this scenario, the bar chart for excavation and temporary structure installation would appear similar to that in Fig. 21. Under this circumstance, the two activities cannot be as aggressively fast-tracked as in 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. Finally, no overlapping is recommended between the temporary structure installation and reservoir liner construction according to the overlapping framework in Fig. 16.

Taking the effect of overlapping into consideration, the

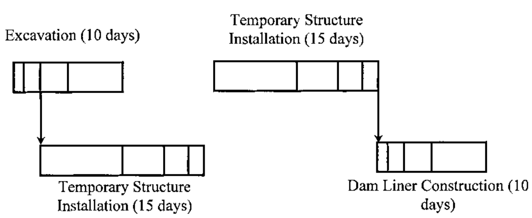


**FIG. 20. Overlapping Practice for GERT**

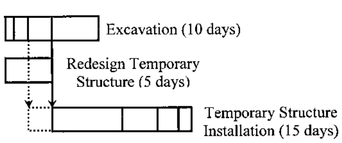


**FIG. 21. Overlapping Reduction for GERT**

amount of reduction can be reflected in the bar chart in Fig. 22. However, the amount of reduction depends on whether redesigning is required or not.

## 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. 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.

In Fig. 23, 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 Fig. 16. 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 1,000 units of work for testing purpose. On the left half of the model diagram, the progress of an upstream task is delineated with respect to its work productivity and quality.

In this system dynamics model, both the upstream and the downstream tasks have three stocks—namely, work remaining, work accomplished, and undiscovered rework. The work remaining stock begins with 1,000 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 feeds 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 adopted by the construction crew, as they become more familiar with the equipment, material, and work methodology.

The effect of the staff experience variable on work reliability 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 in-

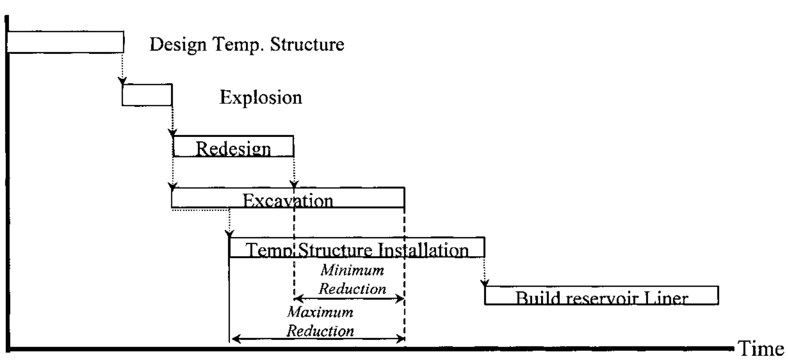


**FIG. 22. Bar Chart for One Stage of Explosion Method (with Overlapping)**



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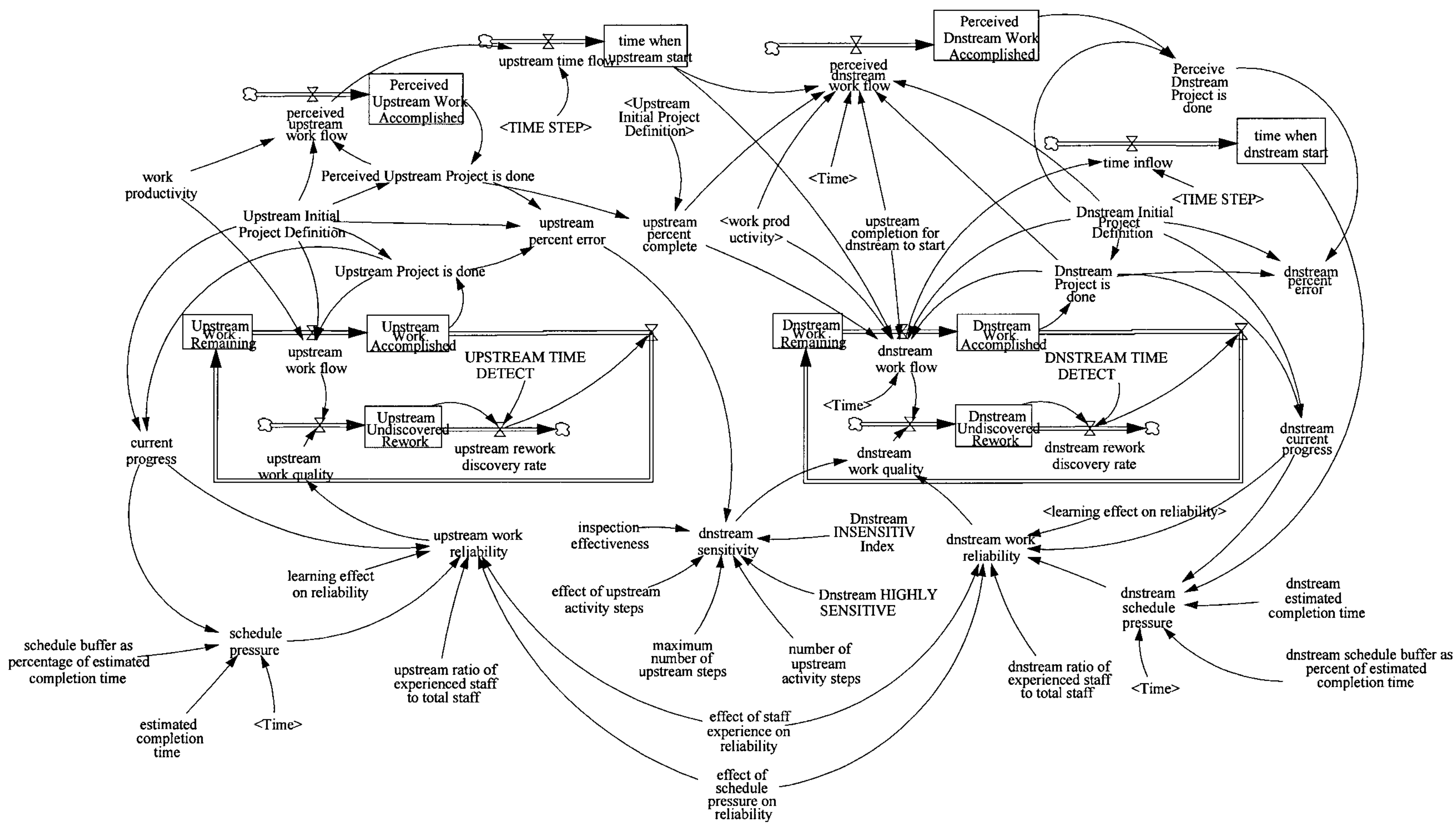


**FIG. 23. System Dynamics Model for Overlapping Analysis**





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crease 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. The assumption is that as the contractor falls behind schedule, he/she might take shortcuts as a means of completing the project on time. Consequently, more errors are generated as a result of taking shortcuts, creating additional rework that needs to be completed, further delaying the project.

Similarly, the downstream task on the right half of Fig. 23 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 affects the production rate of the downstream task. 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 in identifying 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 upstream. Consequently, implementing a more stringent inspection process can reduce the sensitivity of the downstream task to upstream errors.

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 the upstream task, and each inspection only needs to cover a small fraction of work. As a result, the chance of uncovering errors by scrutinizing the entire production process in segments is much greater than that when performing a single inspection at the completion. Second, 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.

## Simulation Process

After the model is constructed, several sets of simulations are conducted to evaluate the effectiveness of the overlapping recommendation in Fig. 16. 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 1. As the table shows, 44 out of the 48 simulation runs have results matching the overlapping recommendation in Fig. 16. 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 Fig. 24, to demonstrate how the different overlapping strategies can be compared. In this scenario, the simulation is conducted for a highly reliable and fast production upstream task, together with an insensitive and slow production downstream task. In Fig. 16, the recommended amount of overlapping is 25% upstream completion for this combination of activity characteristics. The results of the simulation in Fig. 24 reinforces this recommendation, because starting the downstream task at 25% of upstream completion actually enables the downstream task to finish first.

From the results of the 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 does not 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 the 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 Fig. 25. 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.

Similarly, the downstream sensitivity (Fig. 26) 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 of 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 the upstream segments is held constant and the inspection effectiveness is set to range from zero to 150% of the normal inspection.

To summarize the results of the simulation, for any given value of downstream sensitivity regardless of the 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 counterintuitive to the overlapping recommendations in Fig. 16. Two take place in the categories 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 the simulation show that 25% and 75% of upstream completion are better alternatives than 50% with respect to each activity characteristics combination.

Consequently, the results of the simulation suggest that in order to effectively fast-track a pair of slow production upstream and downstream tasks, the following scenario has to be considered. Either the overlapping practice has to be done early enough so that there is sufficient time to discover and fix the errors made 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.

The other two counterexamples to the overlapping framework are due to the boundary conditions of the model. One 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, in conjunction with a fast and highly sensitive downstream task. According to Fig. 16, 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. The errors made up-



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**TABLE 1. Simulation Results for Different Combinations of Activity Characteristics**

| Category (1) | Simulation identification (2) | Reliability Factors: Percent of experienced staff (3) | Reliability Factors: Estimated completion time (months) (4) | Sensitivity Factors: Inspection effectiveness (5) | Sensitivity Factors: Effect of upstream activity segments (6) | Upstream percent complete for downstream to start (7) |
|---|---|---|---|---|---|---|
| (a) Insensitive | | | | | | |
| Fast upstream production and slow downstream production | A1 | 98% | 24 | 130% | 100% | 25% |
| | B1 | 82% | 24 | 130% | 100% | 50% |
| | C1 | 60% | 24 | 130% | 100% | 75% |
| | D1 | 0% | 24 | 130% | 100% | 100% |
| (b) Sensitive | | | | | | |
| Fast upstream production and slow downstream production | A2 | 90% | 24 | 100% | 100% | 50% |
| | B2 | 85% | 24 | 100% | 100% | 75% |
| | C2 | 60% | 24 | 100% | 100% | 100% |
| | D2 | 0% | 24 | 100% | 100% | 125% |
| (c) Highly Sensitive | | | | | | |
| Fast upstream production and slow downstream production | A3 | 90% | 24 | 0% | 100% | 75% |
| | B3 | 70% | 24 | 0% | 100% | 100% |
| | C3 | 40% | 24 | 0% | 100% | 125% |
| | D3 | 0% | 24 | 0% | 100% | 150% |
| (d) Insensitive | | | | | | |
| Slow upstream production and slow downstream production | E1 | 100% | 150 | 150% | 100% | 25% |
| | F1 | 100% | 125 | 150% | 100% | 75%[a] |
| | G1 | 100% | 115 | 150% | 100% | 75% |
| | H1 | 100% | 105 | 150% | 100% | 100% |
| (e) Sensitive | | | | | | |
| Slow upstream production and slow downstream production | E2 | 100% | 156 | 100% | 100% | 25%[a] |
| | F2 | 100% | 150 | 100% | 100% | 75% |
| | G2 | 100% | 60 | 100% | 100% | 100% |
| | H2 | 100% | 35 | 100% | 100% | 125% |
| (f) Highly Sensitive | | | | | | |
| Slow upstream production and slow downstream production | E3 | 100% | 170 | 0% | 100% | 75% |
| | F3 | 100% | 150 | 0% | 100% | 100% |
| | G3 | 100% | 50 | 0% | 100% | 125% |
| | H3 | 100% | 10 | 0% | 100% | 150% |
| (g) Insensitive | | | | | | |
| Fast upstream production and fast downstream production | A4 | 80% | 24 | 120% | 100% | 50% |
| | B4 | 75% | 24 | 120% | 100% | 75% |
| | C4 | 30% | 24 | 120% | 100% | 100% |
| | D4 | 0% | 24 | 120% | 100% | 125% |
| (h) Sensitive | | | | | | |
| Fast upstream production and fast downstream production | A5 | 80% | 24 | 100% | 100% | 75% |
| | B5 | 40% | 24 | 100% | 100% | 100% |
| | C5 | 7% | 24 | 100% | 100% | 125% |
| | D5 | 4% | 24 | 100% | 100% | 150% |
| (i) Highly Sensitive | | | | | | |
| Fast upstream production and fast downstream production | A6 | 70% | 24 | 0% | 100% | 100% |
| | B6 | 30% | 24 | 0% | 100% | 125% |
| | C6 | 2% | 24 | 0% | 100% | 150% |
| | D6 | 0% | 24 | 0% | 100% | 150%[a] |
| (j) Insensitive | | | | | | |
| Slow upstream production and fast downstream production | E4 | 100% | 150 | 150% | 100% | 50% |
| | F4 | 100% | 135 | 150% | 100% | 75% |
| | G4 | 100% | 85 | 150% | 100% | 100% |
| | H4 | 100% | 35 | 150% | 100% | 125% |
| (k) Sensitive | | | | | | |
| Slow upstream production and fast downstream production | E5 | 100% | 135 | 100% | 100% | 75% |
| | F5 | 100% | 100 | 100% | 100% | 100% |
| | G5 | 100% | 40 | 100% | 100% | 125% |
| | H5 | 100% | 1 | 100% | 100% | 150% |
| (l) Highly Sensitive | | | | | | |
| Slow upstream production and fast downstream production | E6 | 100% | 100 | 0% | 100% | 100% |
| | F6 | 100% | 24 | 0% | 100% | 125% |
| | G6 | 100% | 1 | 0% | 100% | 150% |
| | H6 | 100% | 0.01 | 0% | 100% | 150%[a] |

[a]Inconformity with the overlapping framework.



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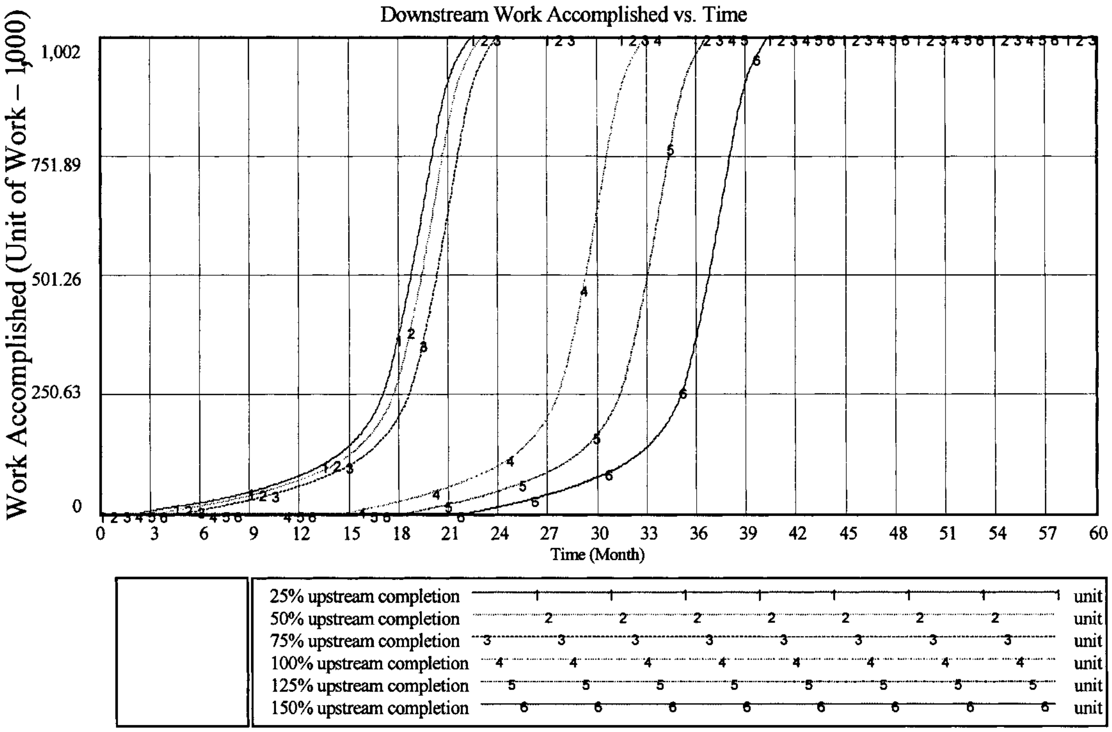


FIG. 24. Downstream Activity Simulation

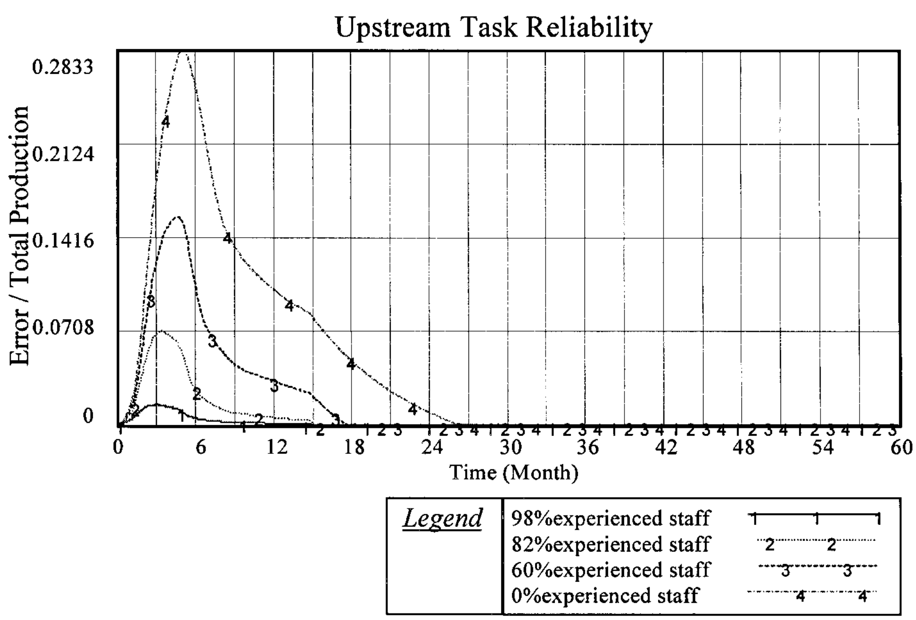


FIG. 25. Upstream Task Reliability

stream no longer affect the performance of these two activities beyond 150% upstream completion. Consequently, creating an additional schedule buffer produces no extra value to improve the dynamics of the project, and can only cause delays.

## CONCLUSION

Although a system dynamics model cannot 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 the overlapping framework. To summarize the integration of different concepts in the proposed dynamic planning and control methodology, this paper has demonstrated how a dynamic construction plan can be achieved by integration of axiomatic design (AD), concurrent engineering (CE), GERT, and the system dynamics (SD) modeling technique. The initial project plan is formulated as 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 over-lapping framework can be applied to shorten 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 dates. The results of overlapping can then be simulated using the system dynamics modeling technique



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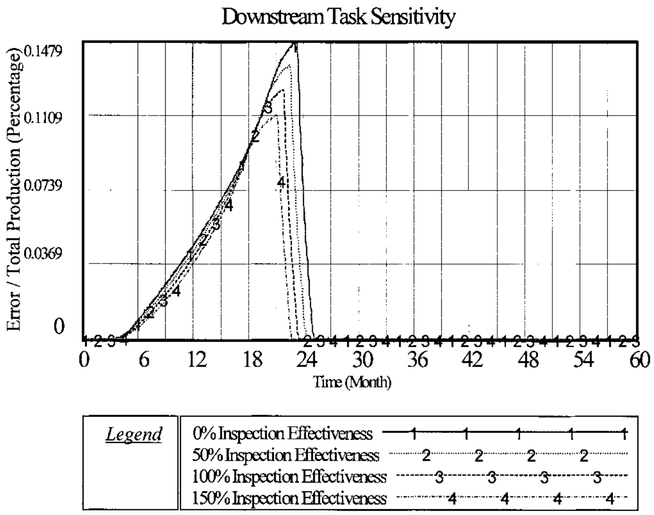


**FIG. 26. Downstream Task Sensitivity**

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. Hence, implementing the proposed methodology can create an effective fast-tracking project plan to absorb potential changes without creating major interruptions to the project schedule. Consequently, the increase in productivity and efficiency as a result of a better planning process can help promote the overall competitiveness of the construction industry.


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