AN ACTIVITY OVERLAPPING ALGORITHM FOR CONSTRUCTION

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ABSTRACT

Concurrent engineering has been used to reduce project completion time. Although several studies have been directed toward the issue of concurrent engineering in construction engineering and management, they have primarily focused on the process in the design phase and examined the information dependencies between overlapping of design activities. Concurrent engineering principles are also applicable to construction activities, but these activities are more subject to physical constraints rather than the aforementioned information constraints. Physical constraints can be classified into strong logical dependencies (inflexible constraints) and weak logical dependencies (flexible constraints). Overlapping of activities with strong logical dependencies requires additional resources or unnatural re-sequencing of the activities. Whenever a natural sequencing constraint is circumvented there is an increased risk of rework, delay, or additional cost. These uncertain consequences and costs of overlapping or re-sequencing must be considered when applying concurrent engineering to the construction process. This paper presents an algorithm for overlapping construction activities based upon concurrent engineering overlapping techniques for design. A pilot case study demonstrates the applicability of the proposed algorithm into the construction industry.

KEY WORDS

Construction, Concurrent Engineering, Scheduling, Production, Sensitivity

INTRODUCTION

Concurrent engineering has been used to reduce the project completion time. A fundamental concurrent engineering strategy for reducing project time is to overlap sequential activities. Previous research studies in the construction engineering and management domain have primarily focused on the design process and examined the information dependencies between

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overlapping activities (Bogus et al. 2005). This study proposes the application of emerging concurrent engineering theories and techniques to the construction phase in order to develop a framework for overlapping physical construction activities to reduce project time.

ACTIVITY OVERLAPPING

CONCURRENT ENGINEERING

Concurrent engineering is a production management philosophy that has received much attention in manufacturing, and to a lesser extent construction, over the past several decades. Concurrent engineering has been proven to shorten product development times and improve quality, especially in the automotive industry (Clark and Fujimoto 1991; Sobek et al. 1999). In order to achieve the desired goals, concurrent engineering advocates concurrent, parallel processes instead of sequential product and process design (Prasad 1996).

Concurrent engineering classifies the overlapping framework in terms of upstream task *evolution* and downstream task *sensitivity*. By defining the characteristics of upstream and downstream activities, it is possible to formulate an overlapping strategy to perform activities in parallel (Bogus et al. 2005; Krishnan 1996; Krishnan et al. 1995, 1997; Pena-Mara and Li 2001).

DEFINITION AND CHARACTERIZATION OF ACTIVITY DEPENDENCY

An initial task of this study was to define evolution and sensitivity within the construction industry, given the accepted definition in the manufacturing industry, and then to use these definitions to characterize construction activities. The concepts of evolution and sensitivity as characteristics of product development activities were defined in work by Krishnan et al. (1995, 1997) and Krishnan (1996). The concept of *sensitivity* expresses the consequence of changing upstream information after a downstream activity has already begun. The *degree of evolution* is defined as the measure of how close the upstream information is to the final value (Fig. 1).

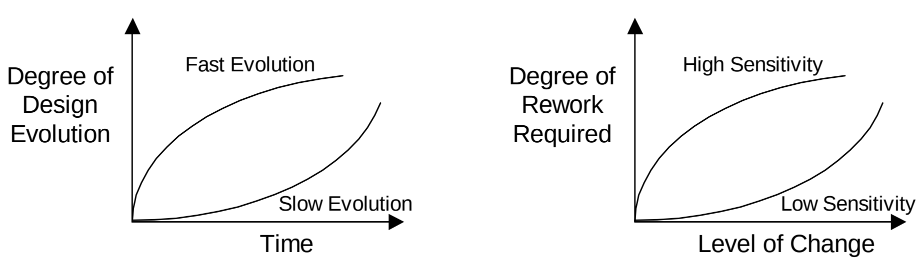


Figure 1: Concept of Evolution and Sensitivity

Activity sensitivity is a measure of the rework required in the activity due to changes in upstream activities (Bogus 2004; Bogus et al. 2005). Defining activities simply by their sensitivity characteristics – degree of sensitivity from high to low – is helpful when choosing activities to overlap. If an activity has low sensitivity, it will not be subject to large amounts of rework as a result of erroneous upstream work. Conversely, a highly sensitive activity will be subject to extensive rework if changes are made to an upstream task. In either case, a reliable fast upstream production will lead to less rework.

Evolution concepts are also applicable to construction activities, but these activities are more subject to physical constraints rather than information constraints. *Production rate* instead of evolution, therefore, can be used to define physical progress for the dependency between construction activities (Pena-Mora and Li 2001). Evolution, therefore, can be equated with production in case of physical construction.

For construction activities, the production rate characteristics can be used to understand the consequences of activity overlapping. If the production rate of an upstream activity decreases over time and the productivity of a downstream activity would increase over time, they form the ideal combination for overlapping. In simple terms, the progress of work in a construction task can evolve quickly or slowly. In Figure 2, 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%, 50%, and 75% of the work is significantly less than that for a comparable task with a slow production rate (Pena-Mora and Li 2001).

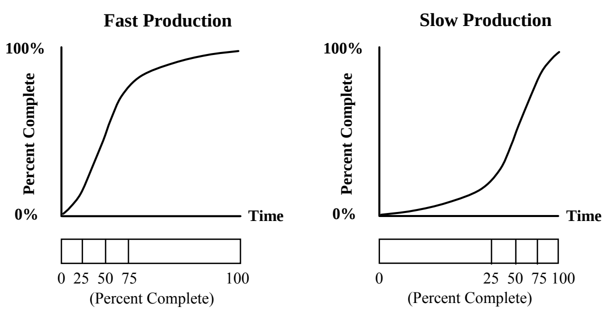


Figure 2: Illustration of Production Rates [Pena-Mora and Li (2001)]

However, the effectiveness of overlapping is not determined by the production rate alone. Downstream task sensitivity is also an important activity characteristic that governs the success of overlapping. The production rate and sensitivity functions suggested here accommodate this notion.

Figure 3 shows four probability functions that reflect different types of dependencies between two activities. Krishnan et al. (1997) suggest that dependency between activities is determined by what they call evolution and sensitivity. Thus, each of the four functions in Figure 3 represents extreme sensitivity-production combinations, where y_i indicates overlap duration and $P_i(y_i)$ indicates expected time increase due to overlapping. This information is helpful in determining which activities can be most effectively overlapped considering expected gains and risks.

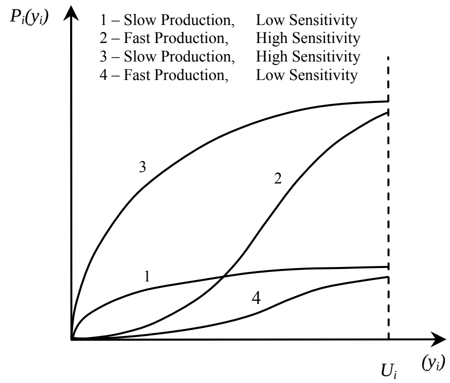


Figure 3: Different Types of Probability Functions [Adapted from Roemer et al. (2000)]

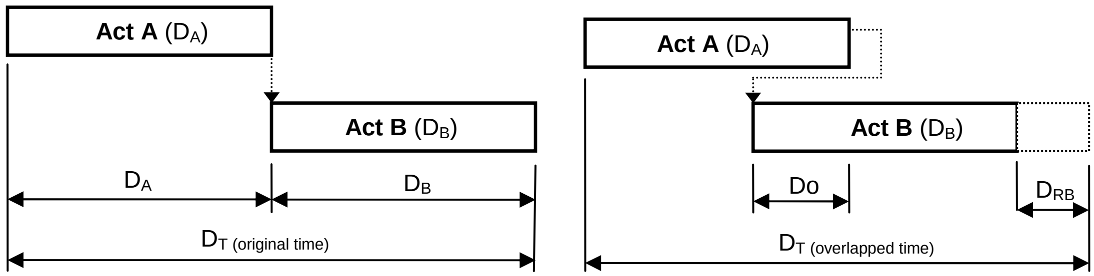
CHARACTERISTICS OF AN ACTIVITY AND ACTIVITY PAIR

Whenever a sequencing constraint is circumvented there is an increased risk of rework, delay, or additional cost. This means that additional consequences and costs of overlapping or re-sequencing are to be considered. Activity and activity pair characteristics can provide meaningful insights into these potential consequences. Two concepts, therefore, should be considered in overlapping or re-sequencing to minimize the total duration of activities. One is the degree of overlapping (or re-sequencing) and the other is the degree of rework required due to overlapping.

It is necessary, therefore, to define characteristics of each activity and activity pair to determine the degree of overlapping. The concept of production rate for upstream activities and sensitivity for downstream activities or activity pairs is used to define characteristics of each activity and activity pair in this research. The sensitivity of a downstream activity or activity pair, defined as the degree of rework required due to overlapping of activities, is assumed to be a function of the degree of overlapping and to the production rate. Optimization, therefore, can be considered to satisfy both conditions to maximize the degree of overlapping and minimize the sensitivity in order to minimize the total duration of activities (Function (1), (2), and Figure 4). These production rate and sensitivity characteristics of a task suggest appropriate strategies for achieving overlap in construction.

If define $l_{AB} \equiv D_O - D_{RB}$ (l_{AB}: Time savings due to overlapping) (1)

Max $\{ l_{AB} \equiv D_O - D_{RB} \}$, where in condition of $D_{RB} = f(D_O)$ (2)



(a) Sequential pair (before overlap) (b) Concurrent pair (after overlap)

D_A: Duration of upstream activity A
D_B: Duration of downstream activity B
D_{RB}: Expected time increase due to overlapping
D_O: Overlap duration between activity A and activity B
D_T: Total duration required to complete activity A and activity B

Figure 4: Characteristics of Activity Pair [Adapted from Roemer et al. (2000)]

OVERLAPPING ALGORITHM FOR CONSTRUCTION

PROBABILITY FUNCTIONS OF REWORK

Critical for the application of this methodology are appropriate estimates of the probability of rework function. Roemer et al. (2000) applied this concept of sensitivity to the design of a rocket. In this case, sensitivity was measured through discussions with project engineers who jointly estimated the probability of rework for rocket development. In that case, obtaining the probability function relied heavily on data from similar projects in the past. Similarly, probability functions of rework, which is sensitivity, can be obtained from construction professionals.

The downstream task sensitivity in this research can be measured by taking the difference in percent progress (i.e., expected time increase) divided by the overlap duration after a change is introduced in the activity due to an upstream change [Function (3)].

$$\text{Sensitivity (\%)} = [\text{Expected time increase } (D_{RB}) \,/\, \text{Overlap duration } (D_o)] \times 100 \qquad (3)$$

TIME-COST TRADEOFF

Given the upstream task production rate and downstream task sensitivity, it is possible to provide a framework by which activities with certain characteristics can be overlapped to minimize rework considering the time-cost tradeoff. The estimates of the cost functions also can be obtained from construction professionals. Figure 5 shows the process to select a point of cost and duration tradeoffs for overlapping.

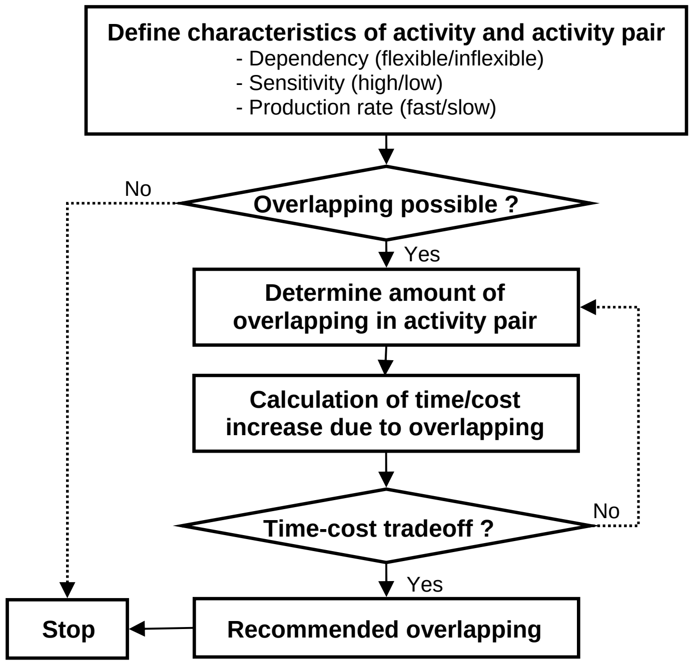


Figure 5: Algorithm for Overlapping Activities

The algorithm shown in Figure 5 begins by defining activity and activity pair characteristics. Activities pairs with flexible constraints and low sensitivity in the downstream activities will be most available for overlapping. Ideally, these pairs will also have fast production in the upstream activity and slow production in the downstream activity. The amount of overlapping will be determined by a cost-time tradeoff that maximizes overlapping while minimizing cost and the potential for rework. The following case study provides one example of how to approach this cost-time tradeoff.

CASE STUDY

CASE EXAMPLE

A pilot case study has been conducted on the construction of a bridge. The bridge consists of two concrete abutments, which are built in sequence due to a limited amount of resources, a steel structure between the abutments and a concrete deck on top of the abutments. Table 1 lists the activities for the bridge that are on the critical path along with their respective durations. Only those activities that were on the critical path were considered for overlapping in this simple example.

As described in the algorithm in Figure 5, the first step is to define the activity characteristics. Table 1 classifies the type of constraint as defined by the logical dependency with the preceding activity. Table 2 classifies the production rate and sensitivity of each activity. Activities in the upper right quadrant (low sensitivity and fast production) will be the best choice for overlapping. While these classifications are not yet formalized in this research study, they are provided to demonstrae the usefulness of the algorithm.

Table 1: List of Activities

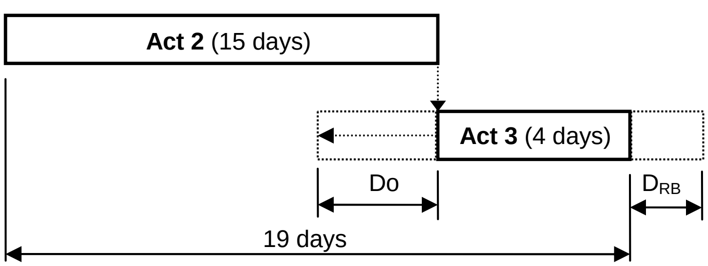
Activity	**Dur.(days)**	**Constraint (Activity Pair)**
1. Prepare & approve shop drawings of abutment & deck bar	10	N/A
2. Fabricate & deliver abutment & deck bar	15	Flexible
3. Abutment #1 Forms & rebar	4	Flexible
4. Pour	2	Inflexible
5. Strip & cure	3	Inflexible
6. Abutment #2 Forms & rebar	4	Inflexible
7. Pour	2	Inflexible
8. Strip & cure	3	Inflexible
9. Set girders	2	Inflexible
10. Forms & steel	4	Inflexible
11. Pour & cure	3	Inflexible
12. Strip deck	3	Inflexible
13. Paint	5	Flexible
14. Cleanup	3	Flexible
15. Final inspection	1	Flexible

Table 2: Level of Production Rate and Sensitivity

Upstream / **Downstream**		**Production Rate**	
		Slow	**Fast**
Sensitivity	**Low**	11-12/12-13	2-3/14-15
	High	3-4/4-5/5-6/6-7/ 7-8/8-9/9-10/10-11	1-2/13-14

Note: "1-2" means activity pair of upstream activity 1 and downstream activity 2

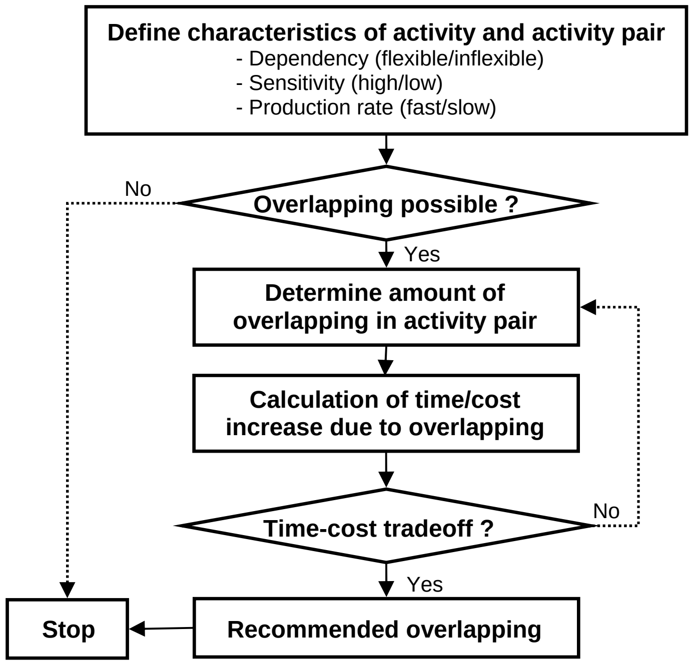
Activity pair 2-3 is a candidate for overlapping because the logic constraint is flexible, the sensitivity of the downstream activity is low and the production rate of upstream activity is high. Figure 6 shows the relationship between activities 2 and 3 and the overlapping process.



D_{RB}: Expected time increase due to overlapping
D_O: Overlap duration between activity 2 and activity 3
Act 2: Fabricate & deliver abutment and deck bar
Act 3: Forms & rebar (Abutment #1)

Figure 6: Relationship of Overlapping Activities in the Example Project

Time/cost increases due to overlapping are illustrated in Tables 3 and 4 using Functions (1) and (3). In Table 4, percentage of time increase, sensitivity, is derived from each increased time divided by overlapped time (1~4 days) and percentage of cost increase is derived from each increased cost divided by total cost ($7,376). Graphs of time/cost increase percentage



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A graph of time savings/cost increase due to overlapping is illustrated in Figure 8. From this figure, time-cost tradeoffs can be examined for overlapping durations. From Table 5, if an overlap of 2 days is chosen, a likely reduction of 1.5 days would be realized (time savings (%) = 1.5 days/19 days = 7.9%). From Figure 8, a 7.9% time savings results in an 11% cost increase. Likewise, 3 days overlapping (8.7%) is possible, but there is a cost increase from 11% to 20% for this duration decrease from 7.9% to 8.7%.

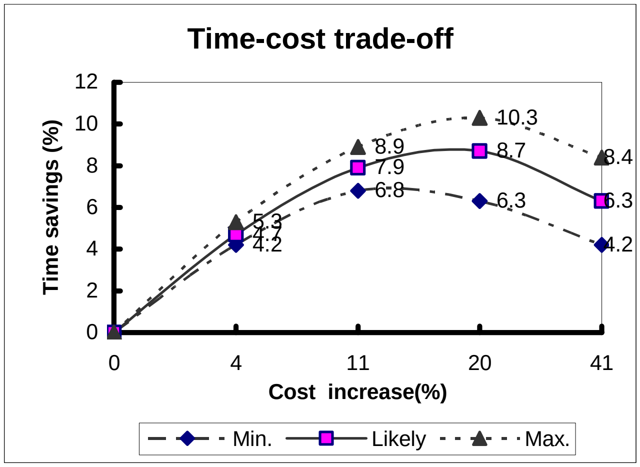

Figure 8: Results of Time-Cost Tradeoff

A primary goal of this research is to understand how overlapping activities affects schedule and cost. The algorithm shown here illustrates the time-cost tradeoff for decision makers. It compares the project schedule before and after overlapping. A reasonable overlapped time for the process is 17.5 days, compared to 19 days in the sequential process. With the overlapping approach, the construction time is reduced by 7.9% at additional costs of 11%.

CONCLUSIONS AND FUTURE WORK

This paper presents an algorithm for overlapping construction activities based upon concurrent engineering overlapping techniques for design. The algorithm appears to be feasible as demonstrated on the simple bridge example.

The model has obvious limitations at this point. The model implicitly assumes that the probability of rework is dependent only on the overlap between two consecutive construction activities. Other possible factors influencing the probability of rework should be incorporated in future work.

A formalized approach for assessing these probabilities has not yet been defined. Additionally, the classifications of activity characteristics for logical constraints, production rate and sensitivity have not been formally defined. This research relies on design and construction professionals to develop activity pair characterizations similar to work by Roemer et al. (2000), Krishnan et al. (1997), and Bogus et al. (2005), but these professionals need a formal set of directions to assess these characterization measurements.

The algorithm is a step towards developing a formalized optimization method for overlapping activities. Since the input for the overlapping algorithm is uncertain, the research team is testing various simulation methods to assist with this optimization. The future research is focusing on better formalization of the measurements for activity characteristics and the development of simulation models for more meaningful output.

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