An Optimization Model for Maximizing the Benefits of Fast-tracking Construction Projects

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ABSTRACT

Fast-track construction projects have become more popular in recent years in response to growing industry demand. By allowing a downstream activity to start with incomplete information from upstream activities, fast-tracking allows for shortening the project duration at the expense of an increased likelihood of rework. This leaves practitioners with the challenge of determining the optimal fast-tracking strategy, which meets project schedule requirements and does not cause excessive amounts of rework. This paper presents an optimization based model that serves as a decision support tool in scheduling fast-track construction projects. The model takes into consideration information exchange between upstream and downstream activities. The objective function of the model is to maximize the net benefits from fast-tracking. Rework time and cost are deduced from the literature on rework in construction projects. The model is illustrated on a small scale case study, which was analyzed under various scenarios. The paper concludes with a discussion of the applicability of the model on complex construction projects.

INTRODUCTION

Traditionally, construction projects were executed under the Design-Bid-Build (DBB) method, which consists of starting execution after the full design package is acquired. In DBB projects, the successor activity starts only when its predecessors are fully completed. This method is time consuming and therefore cannot meet the obligation of emerging sharp deadlines. Fast-tracking, a.k.a. overlapping is a replacement to the DBB approach and has become more popular in recent years in response to growing industry demands (Blacud et al. 2009). It consists of starting the downstream activity before the completion of its upstream (predecessor) activities. Therefore, the downstream activity starts based on unfinished information exchanged from the upstream activities. Sharing incomplete upstream information with downstream activities effectively results in overlapping between upstream and downstream activities, thereby reducing the total project execution period.

Nonetheless, starting a downstream activity based on unfinished information introduces the risk of rework in the downstream work should there be a change in upstream information. The information exchanged is also associated with a level of
uncertainty depending on the type of the upstream activity in question. Future upstream information modifications require rework in the downstream activity to address the changes of the initial information based on which the downstream has started. The resulting rework usually consumes resources (e.g. time and money) and is disruptive to the flow of the downstream work. A practical example is starting excavation and foundation when the Electro-Mechanical (E/M) design is still ongoing. Future modification in E/M design may require rectifications in the foundation design and execution. Therefore, the challenge is to identify the optimal overlapping strategy which meets the project’s deadlines and does not cause excessive amounts of rework.

The goal of this research is to develop an optimization based model that serves as a decision support tool in scheduling fast-track construction projects. The model takes into consideration information exchange to account for the dependency between upstream and downstream activities. Time and cost impacts of rework, which results from the occurrence of a change in the upstream activity, are deduced from the literature on rework in construction projects. The proposed model assesses the total cost and benefits from overlapping at each point in time during the maximum allowable overlap period. The model maximizes the net benefits of shortening the project’s duration diminished by the expected cost of rework resulting from the uncertainty of information exchanged at the beginning of construction. The model provides the optimal earliest time at which construction activities may start. The following sections present a review of the literature in the areas of fast-tracking and rework, followed by a discussion of the proposed model.

BACKGROUND

Rework: a Costly Bi-Product of Fast-Tracking

Rework is defined as an unnecessary effort or work performed to redo or correct the execution of a certain task (Love et al. 2009). It is at the core of schedule and cost overruns of many construction projects. Fast-tracking is a major source of rework which might jeopardize the benefits from time savings. Therefore, quantifying the cost and time impact of rework in projects, as well as identifying the causes behind this rework, become a true challenge. Hwang et al. (2009) identified two major causes of rework: owner changes (OC) and design errors (DE). Love et al. (2002), Love et al. (2004) and Love et al. (2009) added another set of terms including: site management and subcontracting, project communication, and contract documentation. To quantify the impact of rework on construction projects, Hwang et al. (2009) and Love et al. (2004) used the total field rework factor (TFRF) which is equal to the total direct cost of field rework divided by the construction phase cost. Similarly, Love et al. (2010) measured the percentage of cost growth which is the original contract value subtracted from the contract value on practical completion and divided by the original contract value. Using this information, they conducted a statistical analysis on a large number of projects to assess and quantify the cost and time impact of rework.
Rework Reduction Tools

Scholars and practitioners in the construction industry have started to search for tools and methods to reduce rework thereby avoiding unnecessary expenditures. Love et al. (2004) presented a conceptual procurement model to reduce rework in construction projects. Their model relies on the feedback loops among different sets of activities during construction, good record-keeping of contract documents, and a smooth flow of information throughout the project cycle. Zhao et al. (2010) used the concept of dependency structure matrix (DSM) as a platform for predicting change. This tool helped identify the relationships among activities, and therefore the risky activities which cause rework. Lee et al. (2006) found that buffers, which are time durations within the downstream activity reserved to inspect and assess the information exchanged from the upstream activity’s team, can absorb perturbations resulting from the uncertain information exchange. As such, they presented a buffering approach within the downstream activity, and proved a potential for protecting the schedule performance. Bogus et al. (2006) presented a qualitative study based on the work of Krishnan et al. (1997) in the product development literature on how to overlap traditional dependent sequential construction activities. Using the concepts of upstream evolution and downstream sensitivity, Bogus et al. (2006) identified a conceptual qualitative framework to overlap dependent design and construction activities and minimize rework. The following section elaborates on relevant work in the present development literature, which has a long history of studying fast-tracking and rework.

Rework and Fast-Tracking in the Product Development Literature

The concepts of sensitivity, evolution, and dependency are at the core of the discussion of overlapping upstream and downstream activities within the product development literature. Dependency refers to the information exchange that takes place between an upstream and a downstream activity. Sensitivity is the difference in percent progress of an activity divided by the perceived progress after a change is introduced due to a change in upstream information (Blacud et al. 2009). Evolution is defined as the rate of generation of design information from the start until the fulfillment of an activity. Loch and Terwiesch (1998) added a fourth relevant term, i.e. uncertainty in terms of the number of changes that can take place in the upstream activity while causing changes in the downstream activity. The occurrence of these changes was assumed to follow a non-stationary Poisson arrival process with a variable rate defined all along the duration of the upstream phase. The resulting mathematical model is a non-linear program (NLP). The model has three decision variables: pre-communication intensity, expected communication frequency, and amount of overlap. Pre-communication intensity is the total number of meetings which are held throughout the whole overlapping period. Expected communication frequency is the rate at which these meetings should be held. The objective function consists of assessing the benefits of the overlapping period against the additional cost of rework generated from uncertainty in the information as well as the cost of frequent meetings. Lin et al. (2008) followed a similar approach by assuming a non-homogeneous Poisson process for the upstream changes occurrences and the dependency function. The proposed model is also non-linear. However, in this case,
there are two decision variables: start time of downstream work, and functional interaction duration. Lin et al. (2009) presented a modified version of the proposed model by introducing new decision variables. Overall, the updated model included five decision variables. These are start time of the downstream stage, number of information exchanges, time interval between two successor information exchanges, time of the ith information exchange, and information exchange policy.

The literature review points to a lack of availability of mathematical models that quantify the amount of time saved versus rework for fast-track construction projects. The following section presents a model, which addresses this need and helps practitioners make optimal overlapping decisions.

STUDY OBJECTIVES AND PROPOSED MODEL

Problem presentation

This paper addresses the problem of determining the optimal overlapping strategy of traditionally sequential activities in construction projects. It builds on the work of Dehghan and Ruwanpura (2011) who presented a generic mathematical model illustrating the cost and benefit of overlapping activities. The paper builds a similar but more detailed model and illustrates its use on a case study.

Figure 1 illustrates the problem for the simple case of a single upstream design activity and a single downstream construction activity, which have a duration of overlap of “Dd-t". “Dd” is the duration of the upstream activity, “Dc” is the duration of the downstream activity, “t” is the time at which the downstream activity starts, “r” is the duration of rework in the downstream activity as a result of modified information in the upstream activity, and “x” is a continuous variable starting with the start date of the upstream activity and referring to the time at which time savings and rework are analyzed.

![Figure 1](image)

**Figure 1. Simple problem: one upstream and one downstream activity**

This paper formulates, solves, and validates an optimization model that maximizes the benefit of fast-tracking. The model helps industry practitioners make proper scheduling decisions for fast-track projects, by giving them an estimate of the potential savings from overlapping and the potential cost of rework performed in downstream activities.

The model’s objective function is divided into two main parts. The first part consists of the time saved from overlapping multiplied by an estimate of the monetary value of time. The time saved is equal to the difference between the
duration of overlap and the duration of rework in the downstream activity due to modified information in the upstream activity. We use the liquidated damages,\( L \), which are typically set by the project owner, as a proxy for the monetary value of time. The second part of the objective function is equal to the cost of rework. The amount of rework is directly related to the level of uncertainty associated with the information exchanged at each point in time. Similar to Lin (2008), we assume that the arrival process of modified information follows a Poisson distribution. To estimate the second part of the objective function, several parameters are needed. The following section elaborates on these parameters.

**Problem parameters**

The expected cost of rework is directly related to the evolution of the upstream activity, the progress of the downstream activity, and the dependency of the downstream activity on upstream information, which is also called downstream sensitivity.

Evolution is the rate at which the information in the upstream activity accrues until it reaches its final value. A rate which decreases over time indicates that the (upstream) activity has a high evolution. In other words, in an upstream activity with high evolution, most of the work is done in the early phases. Conversely, activities with increasing work rates have a slow evolution. Work on these activities is done in the later phases. This is the case of activities which require significant amount of data collection at the beginning (e.g., foundation design which relies on the results of soil testing among other information). In the proposed model evolution is denoted by \( E \), which is a function of time. We assume two types of evolution functions: low evolution \( \frac{t^2}{d^2} \) and high evolution \( \sqrt{1 - \frac{(t-d)^2}{d^2}} \), where \( d \) is the duration of the upstream activity, and \( t \) is the time at which the evolution is evaluated (0 < \( t < d \)). These functions are commonly used in the literature to describe the low and high graphical layout of the problem’s parameters (Bogus et al., 2006).

Progress has the same definition as evolution, however applies to the downstream activity. In an activity with low progress, the major amount of work is performed in the later stages of the activity’s duration (e.g., pouring concrete). Conversely, in an activity with high progress (e.g., electrical wire installation) most of the work takes place in the early stages. In the proposed model, progress is denoted by \( P_r \), which is represented by the previously discussed evolution functions.

Sensitivity is the amount of rework in a downstream activity during the overlap period as a result of a unit change in the amount of upstream information. In the proposed model, sensitivity is denoted by \( S \), which is a function of information change. In turn, the change of the information exchanged during the duration of the upstream activity is a function of time and is a characteristic of the upstream activity. Therefore, sensitivity is also a function of time. We also assume three types of sensitivity functions: low sensitivity \( \frac{t^2}{d^2} \), high sensitivity \( \sqrt{1 - \frac{(t-d)^2}{d^2}} \), and linear sensitivity \( bxt \) where \( b \) is a scalar factor representing the slope of this function to differentiate the degree of sensitivity.
Problem formulation

As mentioned earlier, the objective of the proposed model is to maximize the net benefits of fast-tracking. This is represented by $G$, which is comprised of two major components: the value of time saved and the expected cost of rework ($EV$).

$$
G = [(Dd + Dc) - (t + Dc + r)] \cdot L - EV
$$

(1)

The direct cost of rework is assumed to be a linear function of the number of changes. In other words, the cost of rework in a downstream activity resulting from 10 changes in an upstream activity is equal to 10 times the cost of one change. Uncertainty is associated with the occurrences of these changes. Therefore, a probabilistic distribution is needed to account for this uncertainty. Similar studies in the product development literature (e.g., Lin et al. 2009) use the non-homogeneous and homogeneous Poisson distribution to describe the process of information arrival. The Poisson process is a counting process which gives the probability of occurrence of a certain number of events during a defined period of time with an average rate $\lambda$. For the proposed model, we use the Poisson process to describe the arrival of change requests from upstream activities. The arrival rates are based on Love et al. (2002)'s study which documented the types and number of changes for various construction projects. As a first step, we address only one type of change, namely “design changes”. We assume that each sub-section of the overlap period has at least one change request. The probability of at least one change becomes equal to (1-probability of no changes). This probability is equal to:

$$
P = \sum_{n=1}^{\infty} \left\{ (e^{-\lambda x}) \left( \frac{\lambda x}{n!} \right)^n \right\} \text{ where “}n\text{” is the number of change requests.}
$$

(2)

The cost of rework resulting from the occurrence of one change is denoted by $C$. Therefore, the cost of rework, $C_n$, resulting from the occurrence of $n$ changes is equal to $(n \cdot C)$. The expected cost of rework at each point in time is denoted by $v$ and is equal to:

$$
v = \frac{\{\sum_{n=1}^{\infty} (P_n \cdot C_n)\} \cdot S \cdot Pr}{E}
$$

(3)

Since the probability follows a Poisson process, then $\sum_{n=1}^{\infty} (P_n \cdot C_n) = \sum_{n=1}^{\infty} (P_n \cdot n \cdot C)$ converges to $(\lambda \cdot C)$. Thus, the total expected value of rework cost during all the overlap period is equal to:

$$
EV = \int_{t}^{\text{Dd}} \frac{\lambda \cdot C(x - t) \cdot S(x - t) \cdot Pr(x - t)}{E(x)} \, dx
$$

(4)

Estimating the first part of the objective function $G$, which is represented by Equation 1, requires an estimation of rework duration. This is the amount of schedule overrun resulting from redoing tasks in the downstream activity to account for changes in the upstream information. The literature does not directly correlate
the duration of rework with their relative costs; however, some statistical studies (e.g., Love et al. 2002) quantified the amount of cost overrun corresponding to the amount of schedule growth for various types of projects. Table 1 shows the cost and time impacts of various types of changes that were reported by Love et al. (2002) and used in this paper to correlate cost and schedule growth. We assume that rework is the only factor that contributes to both cost and schedule growth. Therefore, we assume a certain correlation between cost and schedule growth, and we use cost growth as a proxy for rework duration. We estimate the duration of rework as a linear function of the cost of rework.

\[ r = a \times EV \]  (5)

where “a” is a scalar deduced from the literature (e.g., Love et al. 2010) by dividing the schedule growth by the cost growth for each type of projects (e.g. sea walls and wharves). It represents the amount of time units associated to the expected value of rework cost.

<table>
<thead>
<tr>
<th>Cause</th>
<th>No. of event</th>
<th>Non-productive time (days)</th>
<th>Total cost ($)</th>
<th>Mean cost per event ($)</th>
<th>% of contract value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design change</td>
<td>65</td>
<td>20</td>
<td>182,893</td>
<td>2,814</td>
<td>1.67</td>
</tr>
<tr>
<td>Design error</td>
<td>12</td>
<td>13</td>
<td>59,233</td>
<td>4,936</td>
<td>0.55</td>
</tr>
<tr>
<td>Construction change</td>
<td>14</td>
<td>2</td>
<td>72,979</td>
<td>5,213</td>
<td>0.66</td>
</tr>
<tr>
<td>Construction error</td>
<td>120</td>
<td>14</td>
<td>19,514</td>
<td>163</td>
<td>0.17</td>
</tr>
<tr>
<td>Construction omission</td>
<td>2</td>
<td>0</td>
<td>760</td>
<td>380</td>
<td>0.006</td>
</tr>
<tr>
<td>Construction damage</td>
<td>3</td>
<td>14</td>
<td>3,288</td>
<td>1,096</td>
<td>0.03</td>
</tr>
<tr>
<td>Total</td>
<td>218</td>
<td>70</td>
<td>345,504</td>
<td>1,585</td>
<td>3.15</td>
</tr>
</tbody>
</table>

The objective function, \( G \), of the proposed model becomes:

\[
[Dd - t - a \times \int_t^{Dd} \frac{\lambda \times C(x-t) \times S(x-t) \times Pr(x-t)}{E(x)} dx] \times \left[ L - \int_t^{Dd} \frac{\lambda \times C(x-t) \times S(x-t) \times Pr(x-t)}{E(x)} dx \right]
\]

(6)

where \( C \) is the cost of rework evaluated at \((x-t)\), \( S \) is the sensitivity of downstream activity evaluated at \((x-t)\), \( Pr \) is the progress of downstream activity evaluated at \((x-t)\), and \( E \) is the evolution of upstream activity evaluated at \( x \).

In addition to non negativity, the objective function is subject to the following constraints: \( 0 < t < Dd \) and \( t < x < Dd \).
NUMERICAL APPLICATION
Parameters estimation

The proposed model is applied on a hypothetical simple example which consists of one upstream activity and one downstream activity. The duration of the upstream activity, $D_u$, is equal to 20 weeks. The duration of the downstream activity, $D_d$, is equal to 10 weeks. The liquidated damages denoted by $L$ are equal to $100,000 per week. The scalar $a$ is obtained by dividing the schedule growth (7.87%) by the cost growth (12.65%) which are obtained from Love et al. (2010) - “$a” is equal to 0.0062. The cost of rework, $C(x-t)$, is equal to $(0.077 \times (x - t) + 2814)$. The constant in this function refers to the average cost of rework resulting from a design change, also obtained from Love et al. (2002). The evolution of the upstream activity is estimated to follow a slow pattern $E(x) = \frac{(x)^2}{2a^2} = 0.0025(x)^2$. The progress of the downstream activity is also estimated to follow a slow pattern $Pr(x-t) = \frac{(x-t)^2}{2d^2} = 0.01(x-t)^2$. The sensitivity function is assumed to be a linear function of time $S(x-t) = x - t$. Finally, $\lambda$ is equal to 5 changes per week.

Problem solution

The proposed simple model was implemented and solved in MATLAB. Figure 2 shows the objective function plotted as a function of the time at which the downstream activity starts. For this case, the optimal overlap is obtained at $t = 18.8$ weeks. Therefore, the amount of overlap between the upstream activity and the downstream activity is 1.2 weeks.

![Figure 2. Objective function](image)

To validate the applicability and elasticity of the proposed model, a sensitivity analysis was performed on various parameters including the sensitivity $S$. When $S$ is increased twenty times over its original value, $t$ is increased by 0.8 weeks; therefore, the amount of overlap is decreased by 0.8 weeks. In cases with little to no sensitivity between the two activities ($S = 1$), the solution decreases by 0.2 weeks;
and therefore, the amount of overlap increases by 0.2 weeks. This indicates that \( t \) is not significantly affected by the sensitivity between the upstream and downstream activities.

**CURRENT AND FUTURE WORK**

This paper presents an optimization based model that serves as a decision support tool in scheduling fast-track construction projects. The model is particularly useful for projects executed under non-traditional project delivery methods (e.g., design-build, partnering, integrated project delivery) which allow for fast-tracking and continuous exchange of information between overlapped activities.

The model is illustrated for the case of a single upstream design activity and a single downstream construction activity. The effort to expand the model to cover multiple downstream activities is on-going. The relationships among multiple downstream activities are typically classified as “start-to-start”, “start-to-finish”, “finish-to-start” and “finish-to-finish” relationships. The most commonly used relationships are “start-to-start” and “finish-to-start”; therefore, we address only these two relationships. In a “finish-to-start” relationship, the succeeding activity starts only when its predecessor is complete. Therefore, they can be lumped into one activity, which reduces the problem to only one type of relationships which is the “start-to-start” relationship with the possibility of having a lag between the predecessor and the successor. Figure 3 shows the general layout of the problem with only one upstream and multiple downstream activities.

![Figure 3. Single upstream and multiple downstream activities.](image)

The parameter “\( a_i \)” represents the lag between the \( i^{th} \) and the \((i-1)^{th}\) downstream activities. The total overlap duration is divided into different sections. In each section, the objective function “\( G \)” has a different function due to the appearance of more downstream activities. “\( G \)” will be evaluated in each section of the overlap period, and then the optimal solution is found by inspecting the local optimum in each section.

Finally, to further improve the proposed model to reflect all the possibilities on real-world construction project, the research team is also working on developing the most generic case of the problem. This will be achieved by addressing multiple upstream activities and multiple downstream activities. The methodology is the
same as that in the previous example; however, the sub-sections inside the overlap period will be smaller and numerous due to the presence of multiple upstream activities.

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REFERENCES


