AMERICAN UNIVERSITY OF BEIRUT

AN OPTIMIZATION BASED MODEL FOR MAXIMIZING BENEFITS OF FAST-TRACK CONSTRUCTION PROJECTS

by

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AN OPTIMIZATION BASED MODEL FOR MAXIMIZING BENEFITS OF FAST-TRACK CONSTRUCTION PROJECTS

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The author would also like to convey thanks to MAN Enterprise Group, in particular Mr. Joe Kiriakos and Mr. Abdallah Mardelli, Managing Partner and Area General Manager, respectively, for their understanding and support during the master’s degree process.

Special thanks are also extended to his treasured family and friends for their endless love and support.
Concurrent engineering (CE) is the process of completing tasks in parallel, in order to reduce project durations. This overlapping of traditionally sequential activities is becoming a requirement for fast-tracking complex construction projects. The nature of the information exchange, also known as the dependency between activities, determines the level to which two dependent activities may be overlapped.

Fast-track construction projects have become more popular in recent years in response to growing industry demand. By allowing downstream construction activities to start with incomplete information from upstream design activities, fast-tracking (through overlapping) allows 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 thesis presents an optimization based model, which serves as a decision support tool in scheduling fast-track construction activities. The model takes into consideration information exchange between upstream and downstream activities using the concepts of activity sensitivity and evolution in order to maximize the net benefit of fast-tracking.

The model is illustrated on an ongoing construction project, which was analyzed under various overlapping scenarios. The results indicate substantial time savings depending on the speed of evolution and sensitivity.
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ABBREVIATIONS

DBB: Design Bid Build
DB: Design Build
CM: Construction Management
DE: Designer Error
CE: Constructor Error
OC: Owner Change
TFRF: Total Field Rework Factor
MEP: Mechanical, Electrical, and Plumbing
DSM: Design Structure Matrix
LP: Linear Program
NLP: Non Linear Program
AIF: Activity Based Information Flow
NAF: Non Activity Based Factors
RIIF: Rework Iteration Information Flow
RP: Rework Probability
RIM: Rework Impact Matrix
RPM: Rework Probability Matrix
To Mom, Dad, Brothers and Sister... a family small in number... big in heart...
CHAPTER 1
INTRODUCTION AND METHODOLOGY

1.1 Background and Problem Statement:

Traditionally, construction projects are executed in a sequential manner, i.e. an 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 is a viable alternative to the sequential approach which has gained popularity in recent years (Blacud et al. 2009). As shown in Figure 1.1.1, fast-tracking is addressed when owners and developers set sharp schedules deadlines for contractors. Fast-tracking is also addressed when late design modifications occur. In fact, late design modifications do occur in construction projects at early and late stages. Thus, industry practitioners adopt the fast-tracking approach, either to meet schedule deadlines or to prevent future schedule delays, as a result to late design changes.

![Figure 1.1.1: When and why do we fast-track](image)

Figure 1.1.1: When and why do we fast-track
Fast tracking can be achieved through two processes: crashing and overlapping. As shown in Figure 1.1.2, crashing is the process of assigning more resources to an activity in order to get it done in a shorter duration. However, crashing is bounded by the availability of assigned resources and the crowding problem. In turn, crashing faces a lot of limitations which does not make it a general feasible solution for fast-track projects. On the other hand, and as shown in Figure 1.1.2, overlapping is the process of starting the downstream activity before the completion of upstream (predecessor) activities. Therefore, the downstream activity starts on the basis of unfinished information exchanged from upstream activities and effectively resulting in overlapping between upstream and downstream activities, thus reducing the project execution time (Bogus et al. 2006 and 2009).

![Diagram of fast-tracking processes]

Figure 1.2.2: Fast-tracking processes
As shown in Figure 1.1.3, fast-tracking through overlapping increases the likelihood of rework which is a result of the increased likelihood of change due to the partial information exchange at early stages. As a result, industry practitioners face the decision of whether to overlap or not to. If yes, at what time is the optimal overlapping strategy achieved? This, in turn, can only be accomplished by understanding and quantifying the amount of rework generated in downstream work which is evaluated by the amount of rework cost and duration.

![Diagram](image)

**Figure 1.3.3: What is overlapping and what defines it?**

In order to understand and achieve a fast-tracking strategy through overlapping, we distinguish between two types of dependencies among various construction and design activities: physical dependency and the informational one. Physical dependency is when the downstream successor activity cannot start until its predecessor upstream activity is entirely completed. A
practical example is the activity “install form shutters” prior to the activity “pour concrete”. Informational dependency, on the other hand, is when the downstream successor activity may start before its predecessor upstream activity is entirely completed. For example, a construction activity such as “install reinforced steel bars” can start before its related design work (e.g. shop drawings) is completed. In this context, overlapping can be only applied on activities with informational dependencies, whereas crashing can be used for physical dependencies.

Overlapping all projects’ activities is often not feasible or necessary. For example, overlapping non-critical activities does not contribute to the reduction of the project’s duration because, by definition, such activities have a total float; and thus, they do not define the duration of the project. On the contrary, overlapping activities, which lie on the critical path, offer potential for time savings. By definition, the critical path of a project is comprised of sequential activities which have no float. Thus, overlapping pairs of (sequential activities) on this path (e.g. “issuance of shop drawings” and “start of corresponding field work”) are likely to result in overall project time savings because the latter might be overshadowed by rework. This is the case unless the path becomes non-critical as a result of a significant time reduction.

Overlapping can, nonetheless, be costly. Starting a downstream activity based on unfinished information introduces the risk of downstream rework should there be a change in upstream information. Future upstream information modifications require rework in the downstream activity to address the changes of the initial information or assumptions, on the basis of which downstream has started. The resulting rework usually consumes resources (e.g. time and money), and is disruptive to the flow of the downstream work. In real construction projects, changes in upstream design information are recorded in early and late project phases.
A practical example of design modifications in the late construction phases is in residential type projects, where end users tend to modify the interior design of their apartments to suit their expectations and needs, which are often different from the Engineer’s specifications. End users’ modifications typically arise in the last few months of the project’s construction period. This is due to several reasons. The majority of residential apartments are not sold until construction is well ahead; and therefore, there is limited chance to incorporate end users’ expectations in the project design. Also, end users often change their opinion regarding various features (e.g., mechanical and electrical systems, finishing), as they gain a better understanding of the built facility. In most cases, the interior distribution of rooms is modified whereas the shell remains intact. Modifications can entail additional engineering work, construction, and demolition. The project manager, who is often given tight schedule requirements, has to decide whether to wait for the revised design package to be delivered or start earlier with a risk of downstream rework.

Similarly, design modifications may occur at early project phases. Owners and designers tend to release the final structural tender drawings for the contractor before the mechanical/electrical/plumbing (MEP) design is fully completed, in order to start civil works on site, which are more critical. A pre-tender of MEP drawings is often submitted for concrete works only. When the time comes for the contractor to submit the corresponding shop drawings and get the consulting engineer’s approval, the latter tend to delay the reply on these drawings so he can slip the ongoing design changes in the comments on the same. Such action can be time consuming especially when all the contractual duration (e.g., 21 days) is sacrificed to reply on the drawings. The contractor, who is operating under tight constraints, can reach a point where civil works are undertaken on site whereas no MEP shop drawings for a specific level are issued.
To prevent the delay in the concrete pouring of a slab, which is very critical, the MEP coordinator develops a shop drawing draft and sends it to site for execution. Then, the consulting MEP engineer is called for a site meeting to discuss the drawing. By the time the drawing is approved, works on site have evolved considerably and changes made to the original draft have contributed to a substantial amount of rework.

Therefore, the challenge is to identify the optimal overlapping strategy which meets the project’s deadlines and does not cause excessive amounts of rework.

1.2 Scope of Work and Research Objectives

This study examines constructs and relationships among dependent construction activities allowing, i.e. upstream evolution, downstream progress and downstream sensitivity, for a fast-tracked construction phase to overlap the pre-requisite design of construction activities. This study also examines the effect of the exchanged partial information on the amount of rework generated in the downstream activity. Rework is investigated on the level of causes and consequences. Rework duration and costs are mathematically evaluated. This study also uses an optimization procedure through building a non-linear program (NLP) to determine optimal overlapping strategies. After thoroughly defining and mathematically evaluating those constructs, attributes governing the construction start lag and the overlap between dependent construction activities are studied. The questions that are addressed include: what upstream design pre-requisite information is needed for each downstream package before going into construction and how much is the maturity level of the exchanged information? What is the likelihood of rework resulting from a partial information exchange? What is the amount of rework cost and duration as a function of the start of overlap?
1.3 Outline of the Document

The organization of the document is as follows:

Chapter 2: presents a general review of rework quantification in the construction industry, rework reduction tools and conceptual frameworks to overlap dependent design and construction activities. This chapter also includes guidelines on how industry practitioners and scholars deal with the overlapping process.

Chapter 3: presents the detailed methodology used to achieve proposed objectives.

Chapter 4: presents the general mathematical formulation of the proposed model. It also presents mathematical methods evaluating models constructs and rework cost and duration.

Chapter 5: describes the case study example presented to validate findings of the proposed model. The case study is an ongoing residential tower in Beirut. It is a 25 story building with six basements and a total built up area of 45000 square meters. The case studied is late design modifications to purchased apartments due to end users perspectives. The decision analyzed is the start of subsequent construction activities prior the finalization of their predecessor design requirement, i.e. issuance of shop drawings in order to prevent future delays in the construction schedule.

Chapter 6: includes conclusions and recommendations for future work. This chapter touches on findings and results of the research in addition to suggestions for upcoming research.
1.4 Methodology of Work

1.4.1 Purpose and Context of the Study

This section examines the overlapping strategy of dependent construction activities under the fast-track approach through a case study. The case study consists of an ongoing residential tower in Beirut: a 25 story building with six basements and a total built up area of 45000 square meters.

The main purpose of this case study is to define the characteristics and relationships between dependent construction activities. The case study examines the level of dependencies among the different activities. Goals are twofold: 1) to understand why and when overlapping takes place; and 2) to determine the most efficient way to overlap construction activities. Most efficient, in this case, refers to maximizing net benefits from the overlap process.

Previous studies have shown that by overlapping successive activities, development of a project can be achieved with less time and this is what defines the fast-track approach (Prasad 1996 and Smith 1997). This case study demonstrates whether fast-tracking is the main reason behind overlapping dependent construction activities or not, i.e. it will help answering the question: why are construction activities overlapped? This case study also addresses several questions raised by previous studies (e.g. Bogus et al. 2006): what is the earliest optimal time at which an overlap can start between two informational dependent activities? What are the most significant activities upon which an overlap can be beneficial? The answers to these questions will provide a set of guidelines that will help answer the two remaining questions on how and when construction activities are overlapped.

Several studies have been conducted on overlapping activities in the manufacturing field, yet few studies examine the overlapping concept from the construction industry perspective.
Dependencies and sequences are two main concepts governing the overlap in all industries, whether manufacturing or construction. Therefore, this thesis attempts to study dependencies and sequencing of dependent construction activities through adopting a real construction project as a case study. Conclusions are then drawn as to why and how project managers overlap construction activities.

1.4.2 Instrument and Procedure

Several interviews were conducted with site engineers working on the project at different positions. The goal of the interviews was to collect more information on the activities’ behavior and characteristics in order to build constructs of the proposed optimization model. These questions were derived from the literature review and were then modified by the guidance, Dr. Srour and Dr. Yassine, who have experience in both academics and construction and product development industry.

Prior to initiating any of these interviews, the researcher obtained the approval of the project director and operations manager. Thirty minutes to an hour face-to-face interviews were carried out with engineers with different levels of experience. During the process of interviews and data collection, all participants were very cooperative and ready to answer any question and provide all needed data. Even during the data documenting process, they were ready to clarify any idea over a small phone conversation.

1.4.3 Limitations of the Study

One of the limitations of this study is that it relies on several assumptions. For example, we assumed a linear relationship between sensitivity and likelihood of rework. We also assumed that the amount of un-evolved information is a proxy for the probability of change or rework. Future work should address these assumptions. In addition, we assumed that the progress of an
activity is correlated with the corresponding expenditures, i.e. 80% of the budgeted cost for an activity is spent when 80% of the work is performed. Finally, the study does not address the effect of overlapping on the quality of performed work. However, presented models and associated survey instruments constitute a solid foundation for starting to think more analytically about fast-tracking and underlying constructs (of evolution and sensitivity) that enable the development of any future analytical techniques. For instance, we are currently using the presented methodology to build an optimization model which is a non-linear program (NLP) in order to define optimal overlapping strategy requirements of the engineering firm in-charge of the project and to preserve the confidentiality of the project name and other information (e.g. cost, contract details). The researcher was planning on interviewing the construction contractors; however, this was not possible due to the confidential nature of the project. The engineering firm prefers not to reveal the names of, or even contact, the contractors.

Another limitation is that the point of view of the different interviewed engineers varied slightly, particularly when asked about dependencies between design activities.
2.1 Introduction

Due to the fast evolving nature of the construction industry, practitioners and scholars have been adopting new techniques to reduce projects durations. Fast-tracking projects can be achieved through crashing or overlapping.

Crashing is obtained by assigning more resources (e.g., labors, materials, etc.) to a specific activity and thereby reducing its duration. The workload demanded by an activity is constant, so that assigning more resources will contribute to a faster execution of the workload, thus shortening the activity’s duration. This, in turn, results in an increased cost of the activity. Figure 2.1.1 (a) shows the normal sequential process of an upstream and a downstream activity with their normal durations. Figure 2.1.1 (b) shows the modified duration after the assignment of the additional resources to these activities and difference in time between Figures 2.1.1 (a) and 2.1.1 (b) represents the overall time saved from the crashing process.
Despite the effectiveness of crashing in many cases, this process is bounded by several limitations. Crashing does not take into account the availability of resources; it assumes that resources are available at any time with the required quantities. For example, one could not infinitely crash an engineering activity if there are no engineers available to do the job. Similarly, this case also applies on the availability of raw materials. Another limitation of crashing is the work space limitation. Crashing does not consider the workability of labors inside the space within which the activities are being crashed. For example, one could not crash multiple activities within the same space if workers do not have an adequate level of circulation inside the same.

As shown in Figure 2.1.2, overlapping 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 action 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 changes of the initial information upon which the downstream has started. The resulting rework usually consumes resources (e.g. time and money) and is disruptive to the flow of downstream work.
The related academic literature is divided into two major parts, construction literature and product development literature as shown in Figure 2.1.3.
Some of the academicians in the product development literature defined and introduced concepts of evolution and sensitivity in order to build model based frameworks for overlapping and simulation processes, such as Krishnan et al. (1997) and Yassine (2007). Others used these concepts to build Non Linear Programs (NLP) on series of sequential development activities in order to define an optimal overlapping strategy and the functional interaction frequency and intensity, such as Lin et al. (2008 and 2009) and Roemer et Ahmadi (2004).

On the other hand, the construction researchers adopted a different approach for fast-tracking problem. Some academicians assessed and quantified rework through statistical studies such as Love et al. (2004 and 2009). Others presented different tools and conceptual methods to reduce rework or to reveal predictors of rework, using DSM modeling approach such as Zhao et al. (2009) or buffering approach such as Pena-mora (2008). Another group of researchers presented conceptual frameworks to overlap dependent activities such as Bogus et al. (2011).

The following sections dwell in details in the different sections of Figure 2.1.3.

2.2 Rework: A Costly Bi-Product of Fast-Tracking

Rework is a destructive phenomenon that is likely to happen on any construction project. Rework is basically defined to be an unnecessary effort or work package intended to redo or correct the execution of a certain task. It is at the core of schedule and cost overruns of all construction projects. Fast-tracking, and specifically starting downstream activities with incomplete information from upstream activities, is a major source of rework which might jeopardize benefits from time savings. Therefore, quantifying the cost and time impact of rework in projects, as well as causes behind this rework resulting from the variability and the uncertainty of the information exchanged, becomes the true challenge. According to Hwang (2009), causes of rework are classified as owner change (OC), design error (DE), design change (DE), vendor
error (VE), vendor change (VC), constructor error (CE), constructor change (CC), transportation error (TE) and others (OS). Love and Irani (2004), Love and Edwards (2009) and Love and Holt (2002) added another set of terms to classify causes of rework: “site management and subcontracting”, “project communication”, “contract documentation”, “organizational management practices” and “legal causes”. Table 1 shows the various rework causes defined through the body of literature of the construction industry.

To quantify the impact of rework on construction projects, Hwang (2009) and Love and Irani (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. Love and Edwards (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. Both approaches are numerically different; yet, they lead to the same conclusions. They also defined and measured the resulting schedule growth, being the original construction period subtracted from the actual construction period and divided by the original construction period. Table 2.2.1 shows the cost and schedule growth for different project types which are also summarized from the construction literature. This statistical study was performed on 115 projects within the construction industry.

Love and Edwards (2010) conducted a statistical study on a large number of projects to assess and quantify the impact of rework. A stepwise regression and an ANOVA test were carried out to validate data reliability and accuracy of collected data.
Table 2.2.1 Sources of rework as defined in the literature

<table>
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<tr>
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<th>SOURCE OF REWORK</th>
<th>DESCRIPTION</th>
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<tr>
<td>I</td>
<td>Owner Change (OC)</td>
<td>owner changing the project definition, scope or requirement i Hwang-Thomas-Haas-Caldas (2009)</td>
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<td></td>
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<td>occupiers or operators changes (people buying from the owner) ii Love-Irani-Edwards (2004)</td>
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<td>II</td>
<td>Design Error/Omission</td>
<td>necessary items in design are erroneous or omitted i Hwang-Thomas-Haas-Caldas (2009)</td>
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<td>iii Love-Edwards-Smith-Walker (2009)</td>
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<td>III</td>
<td>Design Change</td>
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<td>iii Love-Edwards-Smith-Walker (2009)</td>
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<td>IV</td>
<td>Site management and subcontracting</td>
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<td>XVI</td>
<td>Other</td>
<td>All other sources i Hwang-Thomas-Haas-Caldas (2009)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 2.2.2 Cost growth v/s schedule growth in construction projects (Love et al. 2010)

<table>
<thead>
<tr>
<th>Industry</th>
<th>Cost growth</th>
<th>Schedule growth</th>
<th>Duration factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean %</td>
<td>Mean %</td>
<td></td>
</tr>
<tr>
<td>Road construction</td>
<td>13.0%</td>
<td>11.1%</td>
<td>0.85</td>
</tr>
<tr>
<td>Bridge construction</td>
<td>13.7%</td>
<td>10.3%</td>
<td>0.75</td>
</tr>
<tr>
<td>Tunnel and subways</td>
<td>13.7%</td>
<td>9.6%</td>
<td>0.70</td>
</tr>
<tr>
<td>Subdivision developments</td>
<td>9.4%</td>
<td>18.8%</td>
<td>2.00</td>
</tr>
<tr>
<td>Industrial waste plants</td>
<td>2.3%</td>
<td>3.6%</td>
<td>1.57</td>
</tr>
<tr>
<td>Marina</td>
<td>10.7%</td>
<td>9.9%</td>
<td>0.93</td>
</tr>
<tr>
<td>Pumping stations</td>
<td>12.0%</td>
<td>12.5%</td>
<td>1.04</td>
</tr>
<tr>
<td>Water treatment</td>
<td>9.4%</td>
<td>15.5%</td>
<td>1.65</td>
</tr>
<tr>
<td>Elevated highways</td>
<td>19.9%</td>
<td>16.2%</td>
<td>0.81</td>
</tr>
<tr>
<td>Reservoirs and dams</td>
<td>11.7%</td>
<td>1.0%</td>
<td>0.09</td>
</tr>
<tr>
<td>Sea walls</td>
<td>4.5%</td>
<td>15.0%</td>
<td>3.33</td>
</tr>
<tr>
<td>Runways</td>
<td>20.7%</td>
<td>17.6%</td>
<td>0.85</td>
</tr>
<tr>
<td>Sewer treatment plants</td>
<td>6.1%</td>
<td>10.4%</td>
<td>1.71</td>
</tr>
<tr>
<td>Wharves</td>
<td>12.6%</td>
<td>20.2%</td>
<td>1.61</td>
</tr>
<tr>
<td>Water main constructions</td>
<td>22.5%</td>
<td>19.6%</td>
<td>0.87</td>
</tr>
<tr>
<td>Other</td>
<td>12.65%</td>
<td>7.87%</td>
<td>0.62</td>
</tr>
</tbody>
</table>

The results of the statistical study were interesting in terms of cost and time impact of rework. For example, Table 2.2.2 shows that for “other” types of construction projects, an expected average of cost growth of 12.65% is associated with a schedule growth of 7.87%. Therefore, rework is actually costly and time consuming and reflects huge expenditures and schedules delay. According to Hwang (2009), the rework impact is analyzed in two sections: “the owner reported projects” and “the contractor reported projects”. This differentiation was conducted to clarify difference between the impact on owners and contractors. Within the same category, rework was compared between types of projects and sources of rework. In owner reported projects, the mean TFRF was highest (0.093) for light industrial projects and lowest for
heavy industrial (0.044) projects. Within the same projects category and under rework causes, the mean TFRF for DE (design error) and OC (owner change) scored highest values.

Additionally, rank-order correlations for these rework causes were statistically significant, which confirm that rework generated by DE and OC contributes more to cost increase; therefore, reducing these cause will result in a remarkable decrease of rework costs. For the contractor reported projects, the mean TFRFs did not vary across the different types of projects (add-on, grass-roots and modernization). For the rework impact by sources of rework, DE and OC scored the highest values. In comparison between the owner and contractor reported projects, the cost growth for owners was over twice as high as the contractor reported projects in general, which is predictable because rework causes are demonstrated to be mostly of owners side, which explains why do the cost impact on owners is higher than that of contractors. According to Love and Edwards (2009), the mean indirect rework percentage of original contract value scored 5.26% and direct rework scored 5.13% for civil engineering projects. For building projects, scores were 5.55% and 6.09%, respectively, which means that rework is costly and destructive to projects. The findings showed that changes initiated by clients were the major determinant of rework. These changes were mostly due to omissions in documentation after work had been undertaken on site. According to Love and Edwards (2010), the direct rework cost is highest in the elevated highways projects and scored 17.25% as a mean value, whereas sea walls projects scored the lowest with a mean of 2% only. As for indirect rework costs, the same projects were listed with a highest mean value of 15% for elevated highways and runways and 1.67% mean for sea walls. Schedule growth is highest for traditional cost reimbursement contracts with a mean value of 15.4% and the cost growth is highest for traditional cost plus fixed fee contracts with a mean value of 15%.
According to Love and Irani (2004), estimates for direct rework costs were 6.4% mean and indirect rework costs 5.6% mean.

2.3 Rework Reduction Tools

As illustrated by previous studies, rework is time consuming and costly, therefore minimizing it is essential for achieving a successful project. Scholars and practitioners in the construction industry have started to search for tools and methods to reduce rework. Love and Holt (2002) used project management dynamics in construction and differentiated between attended and unattended dynamics. Attended dynamics could be controlled through a project and unattended dynamics can’t be controlled but rather only forecasted. They generated a framework to understand project dynamics and thereby have a prediction for the causes of rework. Forecasting causes of rework is essential to reducing the amount of rework.

Another tool for fast-tracking construction projects is the dynamic-planning approach. At its core are dynamics of the construction process. Peña-Mora (2001) argued that managing the information flow and the communication within the construction process is highly efficient in reducing cost increase in fast-track projects. They divided feedbacks in the construction process into two parts: “the construction-driven feedbacks” and “the design-driven feedbacks”. Flows and stock were identified for each loop and served as an input to a simulation model. A closer observation in the paper showed the following: in order to have a better management and operation of a construction project feedback, processes must be carefully monitored.

On the other hand, Love and Irani (2004) presented a conceptual procurement model to reduce rework in construction projects. Their model mainly relies on the feedback loops during construction as well as on good documentation of contract documents and a smooth flow of
information throughout the project cycle. However, their model does not quantify the amount of rework generated by projects or how much rework is reduced by using the model. Additionally, it does not present a decision tool for the overlapping duration. Zhao (2010) used the concept of dependency structure matrix (DSM) as a platform for predicting change. He mainly divided the information flow problem into major two parts: the activity-based information flow (AIF) and the non-activity-based factors (NAF). For the AIF section, he defined two DSM matrices: “the rework iteration information flow (RIIF)”, which represents the amount of rework required in downstream activity “i” due to a change in upstream activity “j”, and the “rework probability (RP)” which gives the probability of rework occurrence. Thus, the rework impact becomes the multiplication of the two previously mentioned matrices. As for modeling NAF, a dependency diagram is defined qualitatively between NAF, the change cause and the activities. It is generated into a DSM matrix, based on the project type and experience of the project team. All previous matrices are then integrated into a final RPM and final RIM DSM-based matrices. The tool presented by Zhao (2010) is useful to identify relationships among activities and, thereby, the risky activities which cause change. Zhao (2010) recognized the deficiencies in his tool and recommended improving its accuracy to become more reliable.

Another part of the body of knowledge found that a reduction of rework in the downstream activity is achieved by reducing the uncertainty of the upstream information generated through the buffering approach. Lee and Peña-Mora (2006) argued that buffers, which are time durations within the downstream activity reserved to inspect and assess the information exchanged from the upstream activity’s team, are an efficient tool to absorb perturbations resulting from the uncertain exchanged information. As such, they presented a double buffering approach within the downstream activity and proved a potential for protecting the schedule.
performance. Their work was based on a major assumption that half of the work package is done during the second buffer period, which is rarely the case in construction projects. Similarly, Sawhney (2009) discussed the importance of inspected buffers in production planning and how it contributes to a remarkable reduction of rework. His study took into consideration the inspecting passing rate (inspecting passing rate is the rate at which the work package is inspected and approved in order to move to the stock of finished work) of the inspected buffer and the workflow variability in the upstream activity. However, the study was performed in a two-way dimension, which means that only upstream and downstream activities were tested with multiple information exchanges in both directions. So it would have been more accurate if the study was on a three or more sequentially ordered activities and if a ripple effect analysis or an inter-relational effect of multiple activities was performed. Following a similar methodology, Gonzáles (2008) presented a simulation based approach of Work-In-Progress (WIP) buffer for scheduling repetitive construction projects. The buffer analysis is based on lean production principles. Results were remarkable in decreasing negative impacts of uncertainty and variability in the production process and increasing project performance. These impacts are translated through the amount of rework performed due to their occurrence.

Most studies in the construction industry dealt with fast-tracking and overlapping projects from a practical point of view, i.e. they attempted to describe, qualitatively and quantitatively, the causes and impact of rework. For example, Bogus (2006) presented a qualitative study based on the paper of Krishnan et al (1997) from the product development literature on how to overlap traditional dependent sequential construction activities. Using concepts of upstream evolution, downstream sensitivity and dependency between them, Bogus (2006) identified a conceptual qualitative framework to overlap dependent design and construction activities. Results were
based on the level of upstream evolution and downstream sensitivity. For example, it shows that when upstream activity has a high evolution and downstream has very low sensitivity, it is beneficial to perform a larger amount of overlap.

Studying fast-tracking for construction projects is a relatively new phenomenon. The major gap in the literature is the lack of a decision tool that helps project managers and schedulers select the optimal amount of overlap for these projects. Optimality refers to either minimizing the amount of rework or maximizing project quality. Other industries, such as product development, have had a longer history of studying the fast-tracking problem. The following section sheds light on some of the major studies in the area of fast-tracking within the literature on product development.

2.4 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. Pairs of activities can be classified as 1) dependent activities, 2) semi-independent activities, 3) independent activities, and 4) interdependent activities. For dependent activities, downstream activity B cannot start unless it receives information from upstream activity A. Semi-independent activities are branded by one activity requiring only partial information from preceding activities before it can begin. Independent activities require no information from the preceding activity in order to proceed. Finally, interdependent activities require a two-way information exchange between activities before either can be accomplished. Among the four relationships, only independent activities can be overlapped without any risk of rework while dependent activities carry a risk when they are overlapped.
Peña-Mora et al. (2010) describes sensitivity as the difference in percent progress on the activity, divided by the perceived progress after a change is introduced in the activity due to a change in upstream information. Thus, an activity may be highly sensitive to variation in upstream information when work on the same cannot continue without values from upstream task.

Evolution is defined as the rate of generation of design information from the minute of the activity initiation until the fulfillment of the activity. Quantitatively, the evolution function consists of the following parameters: time elapsing from the start of the activity, degree of evolution or how close the design is to final status, and the percentage of data settled.

Several studies (e.g. Helms 2002) examined the implications of overlapping strategies on information exchange. However, only a limited number of studies addressed the problem through mathematical modeling. An example is Loch and Terwiesch (1998) whose work combines mathematical programming and probability theory. At the core of the problem they addressed is the uncertainty in the communication or information exchange process between the team working on upstream activities and the one working on downstream activities. Uncertainty refers to the likelihood of change in exchanged information. The more frequently engineers meet, the more uncertainty decreases and therefore downstream rework is reduced. Loch and Terwiesch (1998) described uncertainty in terms of the number of changes that can take place in upstream activity while causing changes in 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 justification for using Poisson process is that it is frequently used in models of quality (e.g. Lee and Rosenblatt, 1986) and reliability (e.g. Ramamoorthy and Bastani, 1982). It is justified when changes arise from many modules or
projects contributors, each being a possible source of requests for changes. The impact of changes on downstream activities is modeled using the previously discussed concept of sensitivity which Loch and Terwiesch (1998) which is quantified using an impact function of time, representing the time taken to perform the required rework. The resulting mathematical model is a non-linear program (NLP). The model has three decision variables: “the pre-communication intensity”, “the expected communication frequency” and the “amount of overlap”. Pre-communication intensity is the total number of meetings which are to be held throughout the whole overlapping period. Expected communication frequency is the rate at which these meetings should be held. In other terms, this variable defines the duration between two consecutive meetings. The amount of overlap is self-explanatory.

The objective function consists of assessing 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. A set of constraints were defined to bind the solution of the objective function such as the upper and lower bounds of the overlap duration.

Lin (2008) followed a similar approach by assuming a non-homogeneous Poisson process for upstream changes occurrences and dependency function. The proposed model is also a non-linear program (NLP). However, in this case there are two decision variables: start time of downstream work and functional interaction duration. The objective of the model is to maximize the profit resulting from overlapping. The cost of rework is assumed to be a function of its duration.
A year later, the same person presented a modified version of the proposed model. Lin (2009) updated the model by introducing new decision variables. Overall, the updated model included five decision variables. These are “the start time of the downstream stage”, “the number of information exchanges”, “and the time interval between two successor information exchanges”, as well as “the time of the information exchange” and “the information exchange policy”. An illustrative example is presented to support the model. The estimation of the problem parameters was done through observation and monitoring of a design team. For example, Figure 2.4.1 represents the graph of modifications occurred during the design phase, which helps determine the variable rate of occurrences of the non-homogeneous Poisson process. As shown in Fig.3, results showed that frequent meetings in the overlap process of a project will entail a remarkable increase in the profit “G” generated form overlapping, as seen in the first row of Figure 2.4.2.
2.5 What is missing in the construction literature

As described in previous sections, and as shown in Figure 2.5.1, the literature in the construction industry lacks the availability of: 1) mathematical evaluation of the constructs of evolution, sensitivity and progress, 2) mathematical evaluation of the rework cost and duration, 3) availability of mathematical models to reduce rework costs and durations and 4) the availability of decision support tools such as LPs and NLPs to quantify the best overlapping strategy. On the other hand, the product development literature presents a more advanced study with respect to the same issue but with another perspective.
CHAPTER 3

SCOPE, METHODOLOGY AND RESEARCH OBJECTIVES

This study examines relationships between dependent sequential construction activities. It assesses net benefits from overlapping these activities, through introducing concepts of evolution and sensitivity. It also assesses net benefits from overlapping by calculating the net profit from the saved time, diminished by the cost of rework generated due to the uncertainty of exchanged information. In turn, all previous parameters are used to formulate and solve an optimization model, which is a non-linear program, to help industry practitioners and scholars make managerial decisions about reducing projects’ durations.

This study also uses MATLAB (mathematical software) to calculate the problem’s different parameters and functions and determine optimal overlapping scenarios. After thoroughly defining those parameters and functions, attributes that govern the overlap between design and construction are studied.

3.1 Purpose and Context of the Study

This section examines overlapping between a set of pairs of sequential activities on the critical path of a construction schedule of a fast-track project through two case studies. The cases consist of two on-going projects in Lebanon. The first is in the closing phase and the second is in early phases. An investigation is made into how the project team is carrying out works on site, towards continuous changes in the design package to meet the strict deadline.

The main purpose of these case studies is to show that design modifications do occur at early stages, as well as late stages of a construction project. The goals are: 1) define and present a
method to evaluate the evolution and sensitivity of different construction activities, 2) how to use these parameters to calculate expected rework durations and costs, 3) how to calculate the optimal overlap scenario in order to make proper managerial decisions. Therefore, this thesis attempts to study dependencies and sequencing of construction activities, through adopting real construction projects as case studies. Conclusions are then drawn, as to why and how project managers overlap construction activities, in addition to creating a schedule that could be completed with most efficient overlap through a minimum duration with an increase in project benefits.

3.2 Instrument and Procedure

The case studies presented in this thesis consist of two multi-million dollar projects, currently being constructed by a well renowned engineering contracting firm. Steps followed in the analysis of the case studies are:

1- A close look on schedules of the projects which are done on primavera. An investigation on selected projects aiming at understanding projects scope and history.

2- Several interviews with site engineers working on these projects at different positions. The goal of the interviews was to collect more information on the projects scope and objectives. These questions were derived from the literature review and were then modified by the guidance of Dr. Yassine and Dr. Srour; who have experience in both academics and construction industry.

The gathered data includes detailed primavera schedules of the projects. To thoroughly examine those schedules, several interviews with projects schedulers were conducted. The data also includes the type and quantity of information exchanged between several construction activities. The data was then validated and cross checked with different group leaders.
3.3 Defining Packages and Sub-Packages:

After running the proposed model on two case studies, results are cross checked with the actual decisions taken on site by the corresponding engineers with regards to overlapping scenarios. Such action is used to assess whether the site staff has made the right decision or not. Likewise, a sensitivity study is conducted in each project to track down the optimal solution and monitor the interval inside which the solution varies. The sensitivity study is performed by changing values of the evolution, progress and sensitivity parameters.
CHAPTER 4

PROBLEM FORMULATION

4.1 Generic Multiple Formulation

We consider a generic construction process consisting of $I$ upstream activities and $J$ downstream dependent activities as shown in Figure 1. In each upstream activity $t \in I$ (e.g. design development), the design team is capable of releasing partial information to dependent downstream activity $j$. This uncertain information is subject to future change and could thus lead to downstream rework as illustrated in Figure 4.1.1. Grey squares in Figure 1 represent expected rework durations. For instance, the expected rework duration in downstream activity $j$, resulting from changes in the entire subset of upstream activities, is illustrated in the grey square next to downstream activity $j$ and is denoted by: $\sum_{i=1}^{I} r_{ij}$. Table 4.3.1 summarizes the problem’s parameters, constants and decision variable.

Figure 10.1.1: Upstream and downstream activities
The overreaching goal of the proposed model is to maximize the projects’ net benefits from overlapping. The objective function is divided into two main parts as shown in Equation 1. The first part consists of the time saved from overlapping, multiplied by an estimate of the monetary value of time. We consider liquidated damages, \( L \), which represents the dollar value of time as perceived by the project owner, a reasonable approximation 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 downstream activity, due to modified information in upstream activity (see Figure 4.1.1). The second part of the objective function, \( H \), is equal to the cost of rework which is related to the level of uncertainty associated with the information exchanged at each point in time. We assume that the likelihood of change, which is the remaining un-evolved information from the upstream activity, is a good proxy for the probability of recording modified information (Yassine et al. 2007).
Table 4.3.1: Problem’s parameters, constants and decision variable

<table>
<thead>
<tr>
<th>Decision variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t )</td>
<td>Time at which overlap starts relative to the start time of the first upstream activity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indexes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I )</td>
<td>Index of upstream activities that allow partial information exchange ( I &lt; i &lt; I )</td>
</tr>
<tr>
<td>( J )</td>
<td>Index of downstream activities ( I &lt; j &lt; J )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constants</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D )</td>
<td>Total duration of upstream (design) phase</td>
</tr>
<tr>
<td>( M )</td>
<td>Total duration of downstream (construction) phase</td>
</tr>
<tr>
<td>( D_i )</td>
<td>Duration of upstream activity ( i )</td>
</tr>
<tr>
<td>( M_j )</td>
<td>Duration of downstream activity ( j )</td>
</tr>
<tr>
<td>( \alpha_i )</td>
<td>Lag between the ( i^{th} ) and the ( (i+1)^{th} ) upstream activities. ( \alpha_3 = 0 )</td>
</tr>
<tr>
<td>( \beta_j )</td>
<td>Lag between the ( j^{th} ) and the ( (j+1)^{th} ) downstream activities. ( \beta_0 = 0 )</td>
</tr>
<tr>
<td>( L )</td>
<td>Money value of time, assumed to be equal to the liquidated damages</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G )</td>
<td>Objective function</td>
</tr>
<tr>
<td>( E_i )</td>
<td>Evolution function of upstream activity ( i )</td>
</tr>
<tr>
<td>( P_{ij} )</td>
<td>Probability of having rework in downstream activity ( j ) due to modifications in upstream activity ( i ) (continuous function)</td>
</tr>
<tr>
<td>( C_j )</td>
<td>Total execution cost of the whole downstream activity ( j )</td>
</tr>
<tr>
<td>( P_j )</td>
<td>Progress function of downstream activity ( j )</td>
</tr>
<tr>
<td>( S_{ij} )</td>
<td>Sensitivity function of downstream activity ( j ) due to changes in upstream activity ( i )</td>
</tr>
<tr>
<td>( R )</td>
<td>Expected rework duration</td>
</tr>
<tr>
<td>( r_{ij} )</td>
<td>Partial rework duration in downstream activity ( j ) due to changes in upstream activity ( i )</td>
</tr>
<tr>
<td>( H )</td>
<td>Expected Rework cost</td>
</tr>
<tr>
<td>( x )</td>
<td>Continuous variable representing the time at which the objective function is evaluated</td>
</tr>
<tr>
<td>( \alpha_{ij} )</td>
<td>Amount of downstream work leveraged in downstream activity ( j ) if the whole upstream information in upstream activity ( i ) is modified</td>
</tr>
<tr>
<td>( \beta_{ij} )</td>
<td>Calibrating constant of ( r_{ij} ) function</td>
</tr>
</tbody>
</table>
The objective function, which is the net benefits from overlapping, becomes:

\[ \max G = (D - t - R) \times L - H \]  

(1)

“\(D\)” and “\(L\)” are usually known constants while “\(t\)” is the major decision variable. The following section explains the remaining two terms: expected rework duration “\(R\)” and expected rework cost “\(H\)”.

4.2 Problem Parameters and Functions

As mentioned earlier, the goal is to mathematically evaluate the rework cost and duration. However, this can only be achieved by evaluating constructs of evolution, progress and sensitivity. The following sections provide a methodology to collect and analyze field data in order to derive mathematical expressions for evolution, progress and sensitivity. Finally, the mathematical expression of rework cost and duration are built based of these constructs.

4.2.1 Evolution and progress of construction activities

Several mathematical functions can be used to define the path of an evolution or progress function from 0% to 100% (e.g. polynomial functions, exponential functions). In this paper, we focus on only two paths obtained by two exponential functions, which will be explained in subsequent paragraphs. We distinguish between two types of evolution functions: high evolution and low evolution. High evolution refers to an increase in the maturity of the information generated in a decreasing rate and low evolution refers to an increase in the maturity of the information generated in an increasing rate. In other words, an activity with high evolution is an
activity where the major part of the relevant information is acquired at early stages, e.g. installation of firefighting pipes, where majorly cutting pipes to real dimensions and installing them come first and the painting and pressure testing come at the end. Conversely, an activity with low evolution is an activity where the work in early stages requires a lot of data collection or data analysis and coordination; thus, the major part of the work is done at later stages of the activity, e.g. issuing MEP shop drawings, which requires coordination among all trades before having the final layout approved. Figure 4.2.1.1.a and 4.2.1.1.b show the cases of high and low evolution. Evolution functions can be mathematically modeled through an exponential function which requires different parameters. Those parameters are calculated and estimated from site data and will be explained later in subsequent paragraphs.

![Evolution Graphs](image)

Figure 11.2.1.1: (a) High evolution, (b) Low evolution, (c) High sensitivity, (d) Low sensitivity

To distinguish between upstream and downstream evolution functions, we introduce the progress function. The progress function, $F$, is an evolution function; however, it is only dedicated for downstream successor activities. Progress functions do not give an indication of the information generated in an activity; however, they are an indication of the amount of work performed for a specific activity until a certain point in time. Progress functions abide by the
same rules of evolution functions and are classified in two categories as well: low and high progress functions.

To mathematically model evolution and progress, we introduce an exponential generic function, $Q$, presented in Equation (2) to highlight the different types of evolution and progress functions. This increases the flexibility of these constructs by allowing different combinations of functions (e.g. low and high progress), using only one functional form. One could argue that other mathematical functions, such as polynomial or square root functions could be used to solve the same problem. While this might be possible, such functions, once multiplied by each other, will yield complex functions which could be hard to solve with regular software packages such as MATLAB or MATHCAD.

$$Q(t, \Theta, \chi) = \gamma \times \left(1 - e^{\Theta \chi t}\right)$$

(2)

$Q$ is a function of three parameters: "$\chi$" is a time variable, whereas "$\gamma$" and "$\Theta$" are constants that define the shape of $Q$, and are estimated based on the problem’s conditions. "$\gamma$" Indicates the magnitude of the function and "$\Theta$" indicates the slope of the function. To numerically evaluate these two parameters, a site visit should be arranged to interview site staff to take realistic data about the performance of the studied activities through a brief questionnaire. Figure 4.2.1.2 shows two flow charts illustrating the method used to numerically evaluate progress and evolution. For instance, to evaluate the progress function of a downstream construction activity, a site engineer or a section engineer is interviewed. The downstream construction activity is first identified. Then, the engineer is requested to estimate the amount of downstream work performed when: 1) one-third of the total activity’s duration elapses, 2) half of the activity’s duration elapses and 3) two-third of the activity’s duration elapses. Knowing that
an amount of 0 percent progress is recorded when the activity hasn’t started, and a 100 percent progress is recorded when the activity is done, we build two vectors $X_1$ and $X_2$ representing the values of durations and their corresponding progress percentages. Finally, we use equation (2) and vectors $X_2$ and $X_3$ to get a best fit function for progress. MATHCAD is used to generate the best fit function by defining the corresponding values of $y$ and $\delta$.

Figure 12.2.1.2: Flow chart for evaluating upstream evolution (right) and downstream progress (left).
Similarly, evolution is estimated following the same methodology, however, the interviewed person is a design team leader and he is required to estimate the percentage amount of valuable information which could be transferred to the construction team on the same dates defined in the previous section.

Referring to Figure 3, the flow chart describes the evaluation method we developed to measure progress and evolution functions using five points to estimate each vector (described in the above flow chart) in order to have a reasonable amount of accuracy for the parameters. However, for simplicity, one could use any set of points within the allowable domain and build the vectors $X_1$ and $X_2$ with a minimum dimension of 3 for a unique vector. $D$ is the total duration of an activity, for which we are estimating the evolution or sensitivity function. $n$ is the total number of points in time selected to evaluate the $Q$ function. In turn, these vectors are denoted as follows:

\[
X_1 = \{x_1, x_2, \ldots, x_i, \ldots, x_n\}
\]
\[
X_2 = \{Q_1, Q_2, \ldots, Q_i, \ldots, Q_n\}
\]
\[
0 \leq x_i \leq D \quad 0 \% \leq Q_i \leq 100\% \quad 3 \leq i \leq n.
\]

To numerically illustrate this method, we consider a simple example using only three points. For instance, to study upstream activity “issuance of mechanical shop drawings”, we interviewed the MEP project engineer of an ongoing residential tower in Lebanon. The project is a 26 story building with six basements and a total built up area of $35,000 \text{ m}^2$. The project engineer stated that the information released from the issuance of all mechanical shop drawings is minimal in the first half of the activity’s duration, and maximal in the second half. This is
because; data for each mechanical plan, especially the inverted level and routing of all utilities, are finalized only after the coordination with all trades together is performed. Using this information and following the flow chart process shown in Figure 3, we estimate the evolution function using the minimum requirement of three points. The collected constructed vectors are as follows:

\[ X_1 = \left\{ 0; \frac{2}{3}; D; D \right\} \text{ and } X_2 = \left\{ 0; 30\%; 100\% \right\} \]

Vector "\( X_1 \)" represents different times during the entire activity process where the maturity level of the information is evaluated. Vector "\( X_2 \)" represents the maturity level of the information evaluated at the times of vectors "\( X_1 \)" respectively. For instance, for this specific example, when two-third of the activity’s duration has passed, the information generated has matured only 30%. Similarly, to illustrate the evolution profile we followed the same methodology using the flow chart shown in Figure 3 using also three different points. The two vectors constructed are:

\[ Y_1 = \left\{ 0; \frac{1}{2}; D; D \right\} \text{ and } "Y_2" = \left\{ 0; 80\%; 100\% \right\} \]

According to these vectors, the information generated from the upstream activity has a maturity level of 80% midway through the activity duration. As mentioned earlier, the elements in the previous vectors reflect the amount of work performed (progress), or the amount of generation of information (evolution) with respect to the total duration of the related activity. Thus, when a different problem is studied, the previous assumptions should be modified.
accordingly. Table 4.2.4.1 summarizes the general formulation of the high and low evolution and progress. It is essential to mention that Table 4.2.4.1 only builds on the vectors mentioned in the previous section which only apply to the specific example considered in this paper. For other problems one should follow the flow chart depicted in Figure 3 and recalculate the parameters in table 1 to suit the addressed problem.

Table 4.2.4.1: Values of parameters "δ" and "γ"

<table>
<thead>
<tr>
<th></th>
<th>High evolution/Progress</th>
<th>Low evolution/Progress</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q(\gamma, \delta, \alpha) = \gamma \cdot (1 - \delta) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma = 1.07 )</td>
<td></td>
<td>( \gamma = -0.04 )</td>
</tr>
<tr>
<td>( \delta = \frac{-2.77}{D} )</td>
<td></td>
<td>( \delta = \frac{3.38}{D} )</td>
</tr>
</tbody>
</table>

4.2.2 Sensitivity of downstream construction activities

Sensitivity refers to the amount of additional work or rework required in a downstream activity as a result of a change in the information exchanged from its (predecessor) upstream activity. We describe the amount of rework as a percentage of downstream completed work up until the time at which a modification in the upstream information is recorded. We model this dependency through a mathematical function, starting from 0 percent corresponding to an evolution 100 percent, to a certain percentage amount, not necessarily equal to zero corresponding to an evolution of 0 percent. We define sensitivity as a function of the magnitude of changes occurring in the upstream activity. That is, the more changes are recorded in the upstream activity the more sensitive the activity is. As shown in Figures 4.2.1.1.c and 4.2.1.1.d, sensitivity does not necessarily reach 100 percent. This is the case of activities which require preparation work which could be leveraged even in case of a complete information change. A
practical example of such event is a change in the steel reinforcement of a slab with respect to setting the slab. In this case, a major part of the work done is leveraged no matter how large the changes in the slab are, scaffolds and form work remain intact with limited change.

Similar to evolution and progress functions, we distinguish between two types of sensitivity functions, high and low sensitivity functions. High sensitivity function refers to the case where a small amount of change in the upstream information contributes to a large amount of downstream rework. Low sensitivity function refers to the case where a large amount of change in the upstream information contributes only to a small amount of downstream rework. A practical example of activities with high sensitivity functions is the execution of the masonry walls inside an apartment towards the receipt of a modified interior layout for some of the rooms. On the other hand, a practical example of activities with low sensitivity functions is the previously discussed example of the setting of scaffolds and formwork to a slab and a design change of the steel reinforcement of that slab.

We describe sensitivity, $S$, as the amount of rework to be performed in a downstream activity during the overlap period as a result of a change in the information generated in the upstream activity. In other words, sensitivity is the percentage amount of downstream work to be redone as a result of modified information. Thus, $S$ is a function of the amount of un-evolved information at each point in time, i.e. it is a function of the evolution of the information at each point in time. We assume sensitivity to be a linear function of the likelihood of change, which is the amount of un-evolved information at each point in time, which is also an indication of the likelihood of having rework. This assumption could be relaxed and more complex relationships between sensitivity and the likelihood of rework could be used. For instance, one could use
exponential functions or polynomial functions; however this will increase the complexity of the problem and will, thus, require advanced software to solve it.

Sensitivity does not necessarily converge to 100% as we previously mentioned because some activities leverage some of downstream work regardless of any change in the upstream activity. Therefore, we introduce a parameter \( \alpha \) to account for this issue, \( \alpha \) represents the overall expected amount of downstream work leveraged despite the changes in the upstream activity. The amount of un-evolved information at each point in time is equal to \( (1 - \alpha^t) \) (Yassine 2007). For instance, if the information at a certain point in time has evolved 80% this means that there is still only 20% likelihood of change. As shown in equation (2), the sensitivity and evolution functions have opposite slopes. Therefore, high evolution and high sensitivity cannot be recorded conjunctionally. However, we argue that the sensitivity function is only related to the generic formulation of the evolution function and not the specific value of the function. Thus, one could have a high evolution and a high sensitivity by only using the generic function of low evolution in the sensitivity expression. Figure 4.2.2.1 illustrates a flow chart describing the method of evaluation of parameter \( \alpha \). The interviewed engineer is requested to estimate the total amount of the work leveraged in case of an extreme change in the information on which he has started downstream work. Also, he is required to estimate, in percentage of downstream work, the amount of demolishing in case there were any.

Figure 13.2.2.1: Flow chart for evaluating sensitivity
Equation 3 denotes the mathematical expression of the sensitivity function.

$$S(1 - \alpha) = (1 - \alpha) \ast (1 - \beta)$$  \hspace{1cm} (3)

A simple example is considered to numerically illustrate the methodology presented in Figure 4. We interviewed a civil section engineer of the same residential tower described in the previous section. The project engineer stated that for a downstream activity, such as the preparation of a floor slab for pouring concrete, an adequate amount of work (say 40% of the total activity) is leveraged. However, he estimated a trivial value of dismantling and demolishing of wrong work (about 10% of total activity). Thus, this activity will have an expected leveraged amount of 30% towards a change in the steel reinforcement layout. Consequently, the sensitivity function of this downstream activity with respect to changes in the upstream “steel design” activity is mathematically denoted by the following equation:

$$S = 0.3 \ast \left(1 - \left(\gamma \ast (1 - \alpha_{\text{delta}})\right)\right)$$

### 4.2.3 Expected rework cost $H$, and duration $R$

The expected rework cost, $H$, is directly related to the evolution $E_i$ of upstream activity $i$, the progress $P_j$ of downstream activity $j$, and the sensitivity $S_{ij}$ of downstream activity $j$ to changes in upstream information $i$. It is also dependent on the probability $P_{ij}$ of having rework in downstream activity $j$ resulting from changes in upstream activity $i$, which is in turn, expressed as a function of the evolution of upstream activity $i$. Similarly, the expected rework duration $R$, is dependent on the same set of previously mentioned parameters.

Equation (4) denotes the mathematical expression of the expected rework duration “$R$”. $\varphi_1$ and $\varphi_2$ are the upper and lower bounds of the integration of the elementary rework duration $\tau_{ij}$ respectively. $\varphi_2$ is the sum of the time at which the overlap starts and the total
lags of downstream activities.\(\varphi_1\) is the minimum of two expressions. The first expression, \((\sum_{i=1}^{I} \alpha_{i-1}) + D_i\), is the sum of the lags\(^1\) of upstream activities and the duration of upstream activity \(i\). The second expression, \(t + \left(\sum_{j=1}^{J} b_{j-1}\right) + M_j\), is the sum of the time at which the overlap starts, the lags of the downstream activities and the duration of upstream activity \(j\).

We consider a minimum of two expressions in the upper bound of the integration to bind it to the intersection of the upstream and downstream activities. Thus, we do not allow integration outside the intersection of an upstream activity \(i\) and a downstream activity \(j\). “\(R\)” is the integration of the elementary rework duration "\(r_{ij}\)" over the aforementioned bounds. "\(r_{ij}\)" is evaluated at \(x\) added by the sum of lags of upstream activities \(\sum_{i=1}^{I} \alpha_{i-1}\).

\[
\varphi_1 = \min \left\{ \left(\sum_{i=1}^{I} \alpha_{i-1}\right) + D_i, \ t + \left(\sum_{j=1}^{J} b_{j-1}\right) + M_j \right\}
\]

\[
\varphi_2 = t + \left(\sum_{j=1}^{J} b_{j-1}\right)
\]

\[
R = \left\{\sum_{i=1}^{I} \sum_{j=1}^{J} \left(\int_{\varphi_2}^{\varphi_1} r_{ij} \left(x + \sum_{i=1}^{I} \alpha_{i-1}\right) \, dx \right)\right\}
\]

(4)

Similarly, Equation (5) represents the expression of the expected rework cost \(H\) in downstream activity \(j\) resulting from changes in upstream activity \(i\). The integration which has the same bounds as the previous expression calculates the expected value of cost for two dependent activities. This is equal to the multiplication of four terms: 1) the progress \(F_j\) of

\(^1\) Time difference between the start dates of two consecutive upstream or downstream activities.
downstream activity $j$ which is evaluated at $x$ diminished by the time at which the overlap starts and the sum of lags of downstream activities, 2) the total cost $C_j$ of the downstream activity $j$, 3) the probability of change $P_{ij}$ and, 4) the sensitivity $S_{ij}$ of downstream work to changes. $P_{ij}$ and $S_{ij}$ are evaluated at $x$ added by the total lags of upstream activities. The discrete summation calculates the total expected cost over the whole subset of activities.

$$
H = \left\{ \sum_{i} \sum_{j} \left( \int_{x_1}^{x_2} C_j \cdot S_{ij} \left( x + \sum_{i=1}^{l} a_{i-1} \right) \right) \right\}
$$

4.3 Generic Sequential Critical Path Formulation

In the previous section we defined and formulated the problem for the most generic case which is multiple upstream and multiple downstream activities. This formulation takes into account the dependency between each activity over the entire schedule of the project. However, a lot of activities in a construction have only one dependent relationship with only one activity (upstream and downstream).

Since in a construction schedule, overlapping is beneficial only if applied on activities lying on the critical path, so we modify the previous formulation to suit the new constraint in the general problem.

In a critical path, activities are sequentially related to each other. Therefore we modify the previously defined parameter $j$ to become $i+1$. We no longer speak about upstream activities and downstream activities, but about predecessor and successor activities. Evolution, progress
and sensitivity parameters remain intact as a result to this modification. All other functions and parameters will be changed.

Equations (6), (7), (8) and (9) denote the new expressions of these functions.

\[ \varphi_1 = \min \left\{ \left( \sum_{i=1}^{l} a_{i-1} \right) + D_i \cdot t + \left( \sum_{i=2}^{l} b_i \right) + M_{l+1} \right\} \]  \hspace{1cm} (6)

\[ \varphi_2 = t + \left( \sum_{i=0}^{I} b_i \right) \]  \hspace{1cm} (7)

\[ R = \left\{ \sum_{l=0}^{L} \left( \int_{\varphi_0}^{\varphi_1} r_{l+1} \left( x + \sum_{i=1}^{l} a_{i-1} \right) \, dx \right) \right\} \]  \hspace{1cm} (8)

\[ H = \left\{ \sum_{l=0}^{l} \left( \int_{\varphi_1}^{\varphi_2} P_{l+1} \left( x + \sum_{i=1}^{l} a_{i-1} \right) \cdot C_{l+2} \cdot S_{l+2} \left( x + \sum_{i=1}^{l} a_{i-1} \right) \right. \right. \]  \hspace{1cm} (9)

\[ \qquad \left. \left. \cdot F_{l+1} \left( x - t - \sum_{i=0}^{l} b_i \right) \, dx \right) \right\} \]

The presented model is a non-linear program with a single decision variable \( t \) which is the time at which the overlap starts. A global optimal solution can be identified for instance, using the 1\textsuperscript{st} and 2\textsuperscript{nd} order conditions. However, the difficulty of the problem lies in the reliance of the different functions, on the specific problem environment. Thus, we use a numerical solution to illustrate the model. We then conclude with a discussion of the applicability of the model on complex construction projects.
CHAPTER 5

CASE STUDY: PRESENTATION AND MODEL APPLICATION

Overlapping activities that are usually planned in a sequential manner can significantly reduce project delivery times. In the case of occurrence of a late design modification, overlapping is essential to prevent potential delays in the construction schedule. However, overlapping design and construction comes with the risk of costly and time consuming rework. It is the duty of the project team to assess this risk of rework against the time-saving by fast-tracking project execution which is secured by the proposed model. To illustrate the benefits and applicability of the proposed model, we consider a simple example with two activities, one upstream and one downstream. The example is taken from an ongoing construction building project in Beirut, Lebanon.

5.1 Description of the case study

The project in question is an ongoing residential building in Beirut, with a total built up area of 45,000 m². Figure 5.1.1 shows the general problem in a bar chart schedule. The event of a notice of design change is the major milestone in the problem which contributed to the following study. As shown in Figure 5.1.1, the activities taken into account for the example are the issuance of MEP shop drawings and the related execution due to a design modification. We merge the issuance of shop drawings and the reply duration of the consultant in only one activity. The upstream activity is considered to be the issuance of mechanical shop drawings, and the
downstream activity is the execution period of the related mechanical works. These activities usually have a finish to start relationship with no lag, and, thus, they are considered sequential.

In the following, we address the possibility of overlapping the execution of mechanical first and second fix works with the issuance of their related design prerequisite, i.e. the shop drawings. Figure 5.1.2 shows the area of our concentration from Figure 5.1.1 which is in importance to the example study with actual numerical values. As shown in Figure 5.1.2, the execution could start along with the start of the shop drawings; however it has a risk of an increased likelihood of rework (in red).
5.2 Problem model formulation

In the following section, we apply the proposed model to solve the overlapping problem. This requires, first, estimating the rework cost $H$ and duration $R$. This, in turn, requires estimating evolution $E$, progress $\bar{P}$, sensitivity $S_{ij}$, and elementary rework duration $\gamma_{ij}$.

5.2.1 Formulation of rework cost $H$ and duration $R$

We begin by defining the example indices, $i = j = 1$, $D_1 = 8$ weeks, $M_1 = 7$ weeks, $L = 65,000 \ 8/\text{week}$. To estimate the cost of the downstream work, we assume that the dollar amount of the work performed until a certain point in time is equal to the value of the progress function at that point multiplied by the total cost of the whole activity. This is due to the assumption of the linear relationship between progress and project expenditures. For instance, we assume that 60 percent of the work is correlated with a payment of 60 percent of the total cost. In turn, the cost figure in the presented case study is a constant, and thus $C_1 = 45,000 \ \$$. 

Substituting the indices by their values yields the following mathematical expressions for $H$ and $R$.

$$H = \int_0^{D_1} \{P_{i,j}(x) \ast C_1 \ast S_{i,j}(x) \ast F_1(x - t) \ast dx\} \quad (10)$$

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5.2.2 Formulation of evolution, progress and sensitivity

Mechanical shop drawings typically remain unfinished until a composite drawing is issued to coordinate all trades with each other. Therefore, we consider a low evolution function for the upstream activity (i.e. issuance of shop drawings) as shown below. We use the methodology discussed earlier in Chapter 4 using Equation (2) to numerically evaluate the constants in equations (12), (13), (14) and (15).

\[
E_1(x) = 0.095 \times (a^{1.1286x} - 1)
\]  \hspace{1cm} (12)

As mentioned earlier, we consider the amount of un-evolved information in the first upstream activity a fair proxy of the probability of rework in the downstream activity resulting from change in the first upstream activity. This is equal to:

\[
P_{11}(x) = 1 - E_1(x) = 1.095 - 0.095 \times a^{1.1286x}
\]  \hspace{1cm} (13)

\(P_1\) is the progress function of the downstream activity, which is the execution of the first and second fix of the mechanical works inside the apartment (above false ceiling and inside masonry walls). This activity is most likely to have a moderately high evolution. All pipes and accessories and valves are cut to their dimensions and all hangers are drilled in the concrete and before installing materials. Thus, we consider a high progress function denoted by the following expression:

\[
P_1(x - \ell) = 1.067 \times (1 - a^{-0.3355 \times (x-\ell)})
\]  \hspace{1cm} (14)
As shown in Equation (14), the progress function is expressed in terms of \( \hat{x} - t \). This is because we consider the start of the upstream activity as the origin of all time variables. Thus, evaluating the progress function at point \( \hat{x} \) requires a subtraction of \( \hat{x} \) and \( t \) because progress function is related to the downstream activity only.

\( S_{14} \) is the sensitivity of the downstream activity to changes in the upstream activity. As mentioned earlier in Chapter 4 and in Equation (3), sensitivity is a function of the likelihood of changes \( (1 - E_1) \). The slope \( (1 - \alpha_{14}) \) refers to the amount of downstream work which will not be leveraged should there be a total change in upstream information. An example could be site preparation and purchasing of materials. The reason behind this assumption is that changes on the issuance of shop drawing will rarely change the utilities sizes especially for pipes, but only change routing and inverted level. Accordingly, materials (e.g., valves and corresponding accessories) could be purchased and installed. In this case, we assume that only 15 percent of downstream work will be leveraged. The sensitivity becomes:

\[
S_{14} (1 - E_1) = 0.85 \times (1 - E_1)
\]

Substituting \( E_1 \) by its generic function yields the following general expression of sensitivity:

\[
S_{14} (x) = 0.85 \times (1 - 0.95 \times (e^{1.128x} - 1))
\]

Estimating the only remaining parameter in the model, \( \eta_{12} \), requires a closer examination of actual rework durations and costs incurred in the case study due to an end user initiated design change. For this purpose, data was obtained from the contractor through an
interview with the project lead engineer. Table 5.2.2.1 summarizes the cost of rework including demolition and wasted material.

Table 5.2.2.1: Rework cost breakdown when a RR reply is recorded

<table>
<thead>
<tr>
<th>Labor</th>
<th>Number</th>
<th>Duration (Days)</th>
<th>Wage (USD/day)</th>
<th>Total labor cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineer</td>
<td>1</td>
<td>7</td>
<td>500</td>
<td>3,500</td>
</tr>
<tr>
<td>Foreman</td>
<td>2</td>
<td>17</td>
<td>150</td>
<td>5,100</td>
</tr>
<tr>
<td>Skilled plumber</td>
<td>3</td>
<td>17</td>
<td>100</td>
<td>5,100</td>
</tr>
<tr>
<td>Helper</td>
<td>4</td>
<td>17</td>
<td>50</td>
<td>3,400</td>
</tr>
<tr>
<td>Skilled pipe fitter</td>
<td>2</td>
<td>12</td>
<td>100</td>
<td>2,400</td>
</tr>
<tr>
<td>Helper</td>
<td>4</td>
<td>12</td>
<td>50</td>
<td>2,400</td>
</tr>
<tr>
<td>Skilled ductman</td>
<td>1</td>
<td>12</td>
<td>100</td>
<td>1,200</td>
</tr>
<tr>
<td>Helper</td>
<td>2</td>
<td>11</td>
<td>50</td>
<td>1,100</td>
</tr>
<tr>
<td>Skilled insulator</td>
<td>1</td>
<td>8</td>
<td>100</td>
<td>800</td>
</tr>
<tr>
<td>Helper</td>
<td>2</td>
<td>8</td>
<td>50</td>
<td>800</td>
</tr>
<tr>
<td>Total labor cost</td>
<td></td>
<td></td>
<td></td>
<td>25,800</td>
</tr>
<tr>
<td>Demolition cost</td>
<td></td>
<td></td>
<td></td>
<td>2,000</td>
</tr>
<tr>
<td>Wasted material cost</td>
<td></td>
<td></td>
<td></td>
<td>2,900</td>
</tr>
<tr>
<td>Total cost impact</td>
<td></td>
<td></td>
<td></td>
<td>30,700</td>
</tr>
</tbody>
</table>

Engineering cost is the cost of reissuance of the corrected shop drawings as well as some site work and supervision. Foreman cost is related to the supervision, and follow up of modifications on site. Labor cost is the cost of removing and demolishing (if applicable) of installed materials. For example, plumbers and pipe fitters had to remove all plumbing networks above the ceiling and relocate the sleeves inside the masonry walls. The relocation required the contractor to destroy approximately 50 cm of the walls in the sleeves location and rectify them. Some of the installed pipes were relocated; and, thus, the installed dimensions were no longer useful. The pipe fitters were obliged to redo all the preparation works. Duct workers had the biggest load. This is due to the relocation and modification of inverted levels, a major part of the ducts was modified by location and size. Insulators had only to remove some of the installed insulation on the wrongly installed ducts and pipes. As a result, Table 5.2.2.1 shows that 2.5
weeks of rework costs 30,700$. This corresponds to a sensitivity of 57 percent (i.e., (30,700-2,900-2,000)/45,000). Demolition and wasted materials costs are removed from the equation in order to get the exact amount of work reworked. As mentioned earlier, "R", the duration of rework, is a function of sensitivity and progress. We assume a linear dependency between rework duration and sensitivity. In order to estimate the dependency parameters we use the example in Figure 4.1.1. Since no work is required when sensitivity is equal to zero then the expression becomes:

\[ n_{14}(x,t) = f(S_{14}, R_{14}, P_{14}) = \beta_{14} * P_{14} * S_{14} * R_{14} \]

Using the example shown in Figure 1, we evaluate \( \beta_{14} \). Sensitivity of 57 percent corresponds to 2.5 weeks of downstream rework having 90 percent of downstream work performed. Thus, \( \beta_{14} \) is equal to 4.9. Substituting the functions and parameters by their algebraic values yields the following expression of the elementary duration of downstream rework:

\[ n_{14}(x,t) = 4.9 * \left( 0.85 * \left( 1 - 0.055 * (e^{1.12*9.30} - 1) \right) \right) * \left( 1.067 * \left( 1 - e^{-0.395*(x-0.3)} \right) \right) * \left( 1 - 0.085 * (e^{1.12*w} - 1) \right) \]

(16)

5.3 Model solution

The proposed simple model was implemented and solved in MATLAB. The first derivative \( \frac{dQ}{dt} \) of the objective function is calculated and equated to zero, which yields a potential solution of the problem. To demonstrate that the obtained solution is a local maximum in the interval of variable “t”, the second derivative is evaluated. If the second derivative is found to be always negative in the allowable domain of the variable, the objective function can be
considered a concave function having as many optima as the number of roots of the first derivative in the allowable domain for the decision variable.

5.3.1 MATLAB code

As mentioned earlier, the problem is solved using MATLAB software. In the following, we present the mathematical sequence and coding of the problem for calculating the optimal overlapping scenario.

```matlab
>> L = 65000
>> C1 = 45000
>> E1 = (7*exp((141*x)/125))/200 - 7/200
>> P1 = 1 - E1
>> P1 = 207/200 - (7*exp((141*x)/125))/200
>> Ev1
>> Ev1 = (87992289*exp((282*t)/125))/18649600 - (2602057689*exp((141*t)/125))/1834880 - (6995142099*t)/160000 - (78850233*exp(423/125))/30080 + (2666433*exp(846/125))/120320 - (2666433*exp(279/50)*exp((99*t)/250))/99200 +
```

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\begin{align*}
\frac{(70658001*\exp((99*t)/250))/(640*\exp(297/250))}{(78850233*\exp(549/250)*\exp((99*t)/250))/19520 + 3320926047/160000} + \\
\end{align*}

\[ \triangleright \triangleright R1 = \]

\begin{align*}
(479069129*\exp((282*t)/125))/(932480000000) - \\
(14166758529*\exp((141*t)/125))/(91744000000) - (38084662539*t)/8000000000 - \\
(429295713*\exp(423/125))/(1504000000) + (43551739*\exp(846/125))/(18048000000) - \\
(43551739*\exp(279/50)*\exp((99*t)/250))/14880000000 + \\
(384693561*\exp((99*t)/250))/(32000000*\exp(297/250)) + \\
(429295713*\exp(549/250)*\exp((99*t)/250))/976000000 + 18080597367/8000000000
\end{align*}

\[ \triangleright \triangleright H1 = E_{11} \]

\begin{align*}
(87992289*\exp((282*t)/125))/(18649600) - (2602057689*\exp((141*t)/125))/(1834880) - \\
(6995142099*t)/160000 - (78850233*\exp(423/125))/30080 + \\
(2666433*\exp(846/125))/120320 - (2666433*\exp(279/50)*\exp((99*t)/250))/99200 + \\
(70658001*\exp((99*t)/250))/(640*\exp(297/250)) + \\
(78850233*\exp(549/250)*\exp((99*t)/250))/19520 + 3320926047/160000
\end{align*}

\[ \triangleright \triangleright G1 \]
\[ G1 = \frac{461052033997t}{1600000} + \frac{210188437767 \exp\left(\frac{141t}{125}\right)}{18348800} - \frac{7107821567 \exp\left(\frac{282t}{125}\right)}{186496000} + \frac{6369346599 \exp\left(\frac{423}{125}\right)}{300800} - \frac{646165597 \exp\left(\frac{846}{125}\right)}{3609600} + \frac{646165597 \exp\left(\frac{279}{50}\right) \exp\left(\frac{99t}{250}\right)}{2976000} - \frac{5707596303 \exp\left(\frac{99t}{250}\right)}{2976000} - \frac{6369346599 \exp\left(\frac{549}{250}\right) \exp\left(\frac{99t}{250}\right)}{195200} + \frac{92635 \exp\left(\frac{99}{250}\right) \left(\exp\left(\frac{99}{250}\right) - 1\right)}{2 \exp\left(\frac{198}{125}\right)} - \frac{48003794241}{1600000} \]

\[ S11 \]
\[ S11 = \frac{3519}{4000} - \frac{119 \exp\left(\frac{141x}{125}\right)}{4000} \]

\[ E1 \]
\[ E1 = \frac{7 \exp\left(\frac{141x}{125}\right)}{200} - \frac{7}{200} \]

\[ Pr1 \]
\[ Pr1 = \frac{1067}{1000} - \frac{1067 \exp\left(\frac{99t}{250} - \frac{99x}{250}\right)}{1000} \]

\[ F1 = Pr1 \]
\[ F_1 = \frac{1067}{1000} - \frac{1067 \times \exp((99 \times t)/250 - (99 \times x)/250)}{1000} \]

\[ G = \frac{461052033997 \times t}{1600000} + \frac{210188437767 \times \exp((141 \times t)/125)/300800}{18348800} - \frac{7107821567 \times \exp((282 \times t)/125)/186496000}{36096000} + \frac{646165597 \times \exp(846/125)}{3609600} + \]
\[ (646165597 \times \exp(279/50) \times \exp((99 \times t)/250)/2976000) - (5707596303 \times \exp((99 \times t)/250)/(6400 \times \exp(297/125))) - (6369346599 \times \exp(549/250) \times \exp((99 \times t)/250))/195200 + (92635 \times \exp((99 \times t)/250) \times (\exp(99/250) - 1)/(2 \times \exp(198/125)) - 48003794241/1600000 \]

5.3.2 Optimal solution and optimal rework

As mentioned earlier, the optimal solution can be found by applying the first second order conditions. Thus, we set \( \frac{\partial^2 G}{\partial t^2} \) to zero which yields a \( t \) of 1.4 weeks, which corresponds to 1.6 weeks of overlap (53 percent) and net benefits of $70,500. The second derivative \( \frac{\partial^2 G}{\partial t^2} \) has negative values in the allowable domain of the decision variable, which confirms that the obtained solution is a global optimum. Figures 5.3.2.1, 5.3.2.2, 5.3.2.3, 5.3.2.4 and 5.3.2.5 show the function plots of upstream evolution, downstream sensitivity, rework duration, rework cost and the objective function respectively, in the allowable domain as a function of the decision variable.
variable “t” or the activity duration “x”. In the case of the objective function plot, the decision variable “t” is converted into percent of overlap.

Figure 16.3.2.1: Evolution function plot

Figure 17.3.2.2: Sensitivity function plot
Figure 18.3.2.3: Rework duration function plot

Figure 19.3.2.4: Rework cost function plot
5.3.3 Sensitivity analysis and comparison

To test the flexibility of the proposed model, we present a sensitivity analysis on all problems’ parameters (e.g. evolution, sensitivity and progress). We investigate the change in the optimal value of the decision variable and the objective function. Table 3a illustrates the percent overlap for the case of high sensitivity whereas 3b shows the case of low sensitivity. The percent of overlap is deducted from the value of the solution of the decision variable “t” having $t=0$ corresponds to a 100% of overlap period.
Table 5.3.3.1.a shows that, for high sensitivity functions and, for low progress functions, the optimal solution is to proceed with the two activities in parallel. In the presented case study, the percentage of work done after three days in a low progress pattern is nearly 10 percent, this is because the duration of the downstream activity is seven days, which is approximately twice the duration of the upstream activity. Even if a high sensitivity function is addressed, as shown in table 3.a, this amount remains a very low amount to be reworked and not very costly with respect to the money saved due to this overlap, which explains the reason why the model calculated a 100% overlap. Similarly, as shown in table 3.a, for high progress functions, high evolution patterns enhance the amount of overlap (83.5%) more than low evolution patterns (53.3%). In fact, this is due to the probability of having rework. We assumed in the proposed model that the amount of un-evolved information is a good proxy for this probability, i.e. one diminished by the value of evolution at each point in time. Thus, higher evolution values generate lower probability values, and in turn, entail lower amount of rework which contributes finally to a higher overlap. Correspondingly, Lower evolution values will contribute to a lower overlap.

Table 5.3.3.1.b shows that, for low sensitivity functions and, for low progress functions, the optimal solution is to proceed with the two activities in parallel. As shown earlier, in the presented case study, the percentage of work done after three days in a low progress pattern is nearly 10 percent. Also, as shown in table 3.b, a low sensitivity function is addressed which is in
the advantage of higher overlap because the lower the sensitivity function is, the lower rework is and thereby more overlap is advisable. The amount to be reworked remains very low and not very costly with respect to the money saved due to this overlap, which explains the reason why the model calculated a 100% overlap. Similarly, as shown in table 3.b, for high progress functions, high evolution patterns require a parallel pattern of the activities, i.e. 100% amount of overlap, whereas low evolution patterns only require 53.3% of overlap. As shown earlier, this is due to the probability of having rework. Thus, higher evolution values generate lower probability values, and in turn, entail lower amount of rework which contributes finally to a higher overlap. Correspondingly, Lower evolution values will contribute to a lower overlap. Tables 3a and 3b also suggest that the more sensitive downstream work is, the less overlap is advisable (e.g., case of high sensitivity and progress, and low evolution). This outcome is predictable for the reason that, higher sensitivity function will enlarge the amount of downstream work to be reworked and thereby increases rework cost and duration. This, in turn, results in lower overlap scenarios.
CHAPTER 6

CONCLUSIONS

6.1 Summary

This thesis presented and illustrated a mathematical model for maximizing net benefits of overlapping dependent construction activities. The model incorporates the constructs of evolution, progress and sensitivity in making overlapping decisions. The application of the model on the case study showed promising results. The amount of suggested overlap, varied between 53 and 100 percent depending on the speed of evolution, progress and sensitivity.

The obtained results can be extrapolated for multiple dependent activities. The research team is currently investigating the application of the proposed model for the case illustrated in Figure 1 where overlap is likely to occur among several dependent activities. This requires the identification of the most critical dependent activities, which are typically on the project’s critical path, and examining the nature of their dependency (e.g., progress, evolution, sensitivity). Once data is collected, running the model on the identified activities provides the amounts of overlap between each two dependent activities. This will, in turn, allow for estimating the overall time savings on the examined path and the impact on the overall project schedule.

The model relies on several assumptions. For example, as mentioned earlier, the model assumes a linear relationship between sensitivity and the likelihood of rework. Also, the model assumes unlimited resource availability to complete downstream and upstream activities. One could argue that the cost and duration of rework are also subject to the availability of resources, especially human resources. We consider that overlapping does not have any effect on the
resource loading of the upstream and downstream activities, i.e. the upstream team is different from the downstream team. Future work should address these assumptions.

6.2 Future Work

The future work that can be done on this thesis is to develop the research by addressing the model on a sequence of sequential construction activities on the critical path of a construction Primavera schedule. In turn, the aggregation of pairs of dependent activities on the critical path will contribute to large time savings which will be of a remarkable order.

Also, future researchers can build similar optimization models using the mathematical formulation of the constructs of evolution, progress and sensitivity developed in this thesis. Some of the assumption made in the presented model can be further investigated or mitigated to get more realistic solutions which reflect more the reality of construction projects. The research can be also oriented to the dynamic behaviour of construction projects by addressing variable probabilities of occurrence of rework and not only deterministic ones. Additionally, the model constants, such as the durations of different construction activities, can be considered as dynamic duration which varies over time as a result of the variance of the resources availability and productivity. Finally, quality of the work performed as a result of overlapping can be added as an additional constraint to the proposed model to maintain a certain level of quality standards.
REFERENCES


