UNIVERSITY OF CALGARY

A new model, algorithm and computer tool to optimize overlapping of design activities in construction projects

by

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Abstract

An effective and well known technique for earlier completion of construction projects is to overlap the project activities or phases that normally would be performed in sequence. Overlapping is inherently risky because it increases project uncertainties, rework, complexity, and eventually cost. For a typical construction project, a huge number of overlapping strategies exist which all can result in the same timesaving. However, the cost of these strategies varies significantly depending on the total rework and complexity they generate. A favourable overlapping strategy is one that generates the required timesaving at the minimum cost. To find the favourable overlapping strategy, the question "Which activities have to be overlapped and to which extent to reduce the project duration at the minimum cost?" should be answered. This research aimed at answering the question through generating an overlapping optimization algorithm. The scope of the research covers any type of activities in the design phase. A combinatory research methodology, a combination of qualitative and analytical approaches, was customized to conduct the research. Interviews and focus groups were the research instruments in the qualitative part. The analytical part included developing the overlapping optimization algorithm and its associated computer tool. The research generated three deliverables: An overlapping model, an overlapping optimization algorithm, and an overlapping optimization computer tool. The overlapping model explains the overlapping mechanism. The computer tool works based on the overlapping optimization algorithm and assesses various overlapping strategies and identifies the least expensive strategies. The tool is actually a cost evaluation module linked to a commercial

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project scheduling software (MS Project). This computer tool is so user-friendly that any scheduler or cost controller can easily run it and modify the schedule accordingly. The computer tool is unique and new as so far no similar tools exist in industry or academia. It can optimize overlaps in large and complex project schedules in fairly short processing times. It is able to handle multi-path networks and all types of activity dependencies. The tool takes all activities, critical and non-critical, into account and follows the critical path if the critical path changes or new critical paths emerge. The tool can also take resource limitations and schedule constraints into account.

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Dedication

I dedicate this thesis to my father, as he always wished me push the borders of science to their limits; my mother, who provided me a delightful environment to grow, and to my beloved wife, who helped me "stand on the shoulders of giants" by giving me hope and enthusiasm.

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Table of Contents

المنارة للاستشارات
www.manaraa.com

المنارة للاستشارات
www.manaraa.com

المنارة للاستشارات
www.manaraa.com

List of Tables

www.manaraa.com

List of Figures and Illustrations

المنارة للاستشارات

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List of Symbols, Abbreviations and Nomenclature

Symbol	Definition
ACO	Ants Colony Optimization
A_{ij}	The amount (degree) of overlapping in percentage between predecessor activity *i* and successor activity *j*
AS	Ants System
B_{ef}	Daily benefits of project early finish
C_{ij}	All possible costs of overlapping activity *i* with activity *j*, including wages, overheads, wastes, damages, extra costs, etc.
C	The net cost/benefit of project resulting from an overlapping strategy
C_{lf}	Daily costs of project late finish
C_{os}	Cost of overlapping strategy
CPM	Critical Path Method
B_{pt}	Benefit of project timesaving
D_i	Duration of activity *i*
D_j	Duration of activity *j*
ECI	European Construction Institute
E_{ij}	Extra costs, other than daily wages and overheads, imposed on successor activity *j* or on other project areas (design, procurement, construction, etc.) because of the changes made by predecessor activity *i* during its overlapping with successor activity *j*

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EIA	Energy Information Administration
EOA	Evolutionary-based Optimization Algorithms
EPC	Engineering, Procurement and Construction
FF	Finish to Finish
FS	Finish to Start
GA	Genetic Algorithms
i	Index denoting predecessor activities
IP	Integer Programming
IPA	Independent Project Analysis Inc.
j	Index denoting successor activities
L_{ij}	Duration of the overlapped interval between predecessor activity i and successor activity j
$L_{ij,max}$	Maximum allowable overlapping between predecessor activity i and successor activity j
LP	Linear Programming
MAWA	Modified adaptive weight approach
MSP	Microsoft Project
P_{ij}	The probability that a change happens for predecessor activity i during its overlapping with successor activity j and the change causes some rework for successor activity j
PMBOK	Project Management Body of Knowledge guide

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PERT	Program Evaluation and Review Technique
PSO	Particle Swarm Optimization
r_{ABC}	The *change transfer ratio* from activity A to activity C through activity B
R_{ij}	The equivalent rework duration for successor activity *j,* as a result of its overlapping with predecessor activity *i*
R_j	The equivalent rework duration for successor activity *j,* as a result of its overlapping with more than one predecessor activity
SEL	Shuffled Frog Leaping Optimization
SF	Start to Finish
SS	Start to start
T	Project duration
TCQT	Time-cost-quality Trade-off
TCT	Time-cost Trade-off
T_{ij}	The extended duration added to successor activity *j,* as a result of rework originating from the changes made by predecessor activity *i,* during its overlap with successor activity *j*
T_n	Normal project duration, no overlapping applies
T_t	Project target duration
W_j	Total daily wage for successor activity *j*, including daily salaries and daily overheads

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Epigraph

"If I have seen further it is only by standing on the shoulders of giants"

Isaac Newton, 1642-1727

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Chapter One: Introduction

Reducing project duration has been often an important strategic and tactical objective of the construction business. In this regard, various motivations such as financial, social, legal and even political exist; however, most of the time, the main driver is financial: maximizing the benefit. Today, with the uncertainty of inflation and interest costs, and with the competitive business world in which owners have to do their best to beat their competitors, accelerated project delivery approaches are becoming attractive (Fazio et al. 1988). This is particularly true for oil and gas projects as a type of industrial construction. It has become increasingly important for energy companies, particularly during times of high oil prices, to reduce the investment payback time, to turn a profit as early as possible and to reduce the period of risk exposure. All of these are possible through accelerating project execution that practitioners generally call it "fast-tracking" (Figure 1-1). To them, fast tracking means utilizing any exceptional technique to reduce the execution time of projects (Eastham 2002). Completing projects in an efficient and timely manner is of interest to the contractors as well, because the shorter the duration of the project, the greater the number of projects that can be completed in the same time frame and ultimately the greater the profit (Dehghan et al. 2010).

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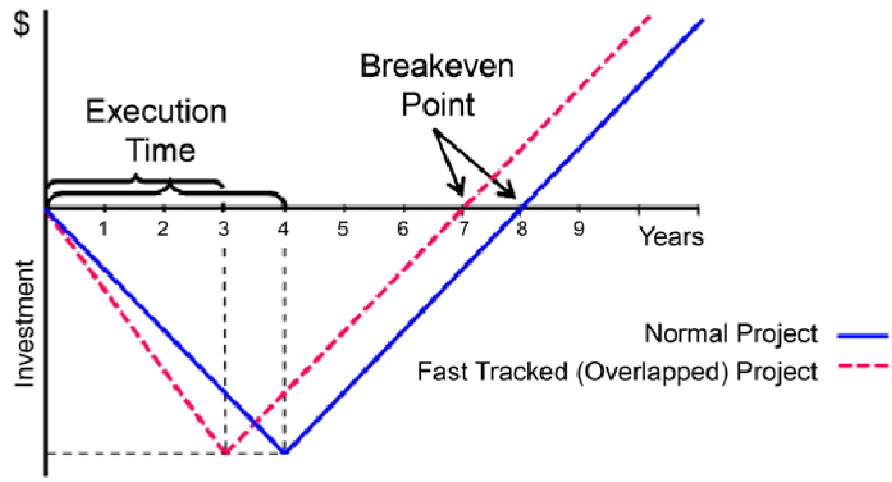

Figure 1-1: Return on investment in normal projects vs. fast-tracked projects

The demand for project completion in a shorter duration has led to various methods of schedule compression. According to A Guide to the Project Management Body of Knowledge guide (PMBOK), schedule compression techniques include crashing and fast tracking. In crashing, cost and schedule trade-offs are analyzed to determine how to obtain the greatest amount of compression for the least incremental cost. Crashing does not always produce a viable alternative and normally results in increased cost. In fast tracking, phases or activities that normally would be done in sequence are performed in parallel. An example would be to construct the foundation for a building before all the architectural drawings are complete. Fast tracking can result in rework and increased risk which are translated into extra costs. This approach can require work to be performed without complete detailed information. It results in trading cost for time, and increases the risk of achieving the shortened project schedule (PMBOK 2008). In this light, fast

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tracking is the same as overlapping dependent activities in the project schedule, and this definition is the focus of this research as well. However, sometimes practitioners in construction, oil and gas industries have a different perception of fast tracking. To them, fast tracking means utilizing any exceptional technique to reduce the execution time of projects (Eastham 2002). Although such a perception may include overlapping, it entails a broader range of techniques and therefore is not discussed in this research.

1.1 Problem statement

The main problem with overlapping lies in extra risks generated, with the risk of rework probably the greatest (Figure 1-2). Overlapping can result in more rework; more rework increases expenses and lengthens execution time of the project. This means that too much overlapping cannot be applied, because only reasonable levels of risk can be tolerated. If too much overlapping is implemented, then the time saving benefits might be offset and even superseded by the losses originating from rework and cost and time overruns. Therefore, the question is how much overlapping is desirable or which degree of overlapping is optimum, which minimizes the extra costs and rework while maximizes the timesaving. Put it differently, the research question is: **Which activities have to be overlapped and to which extent to reduce the project duration at the minimum cost**?

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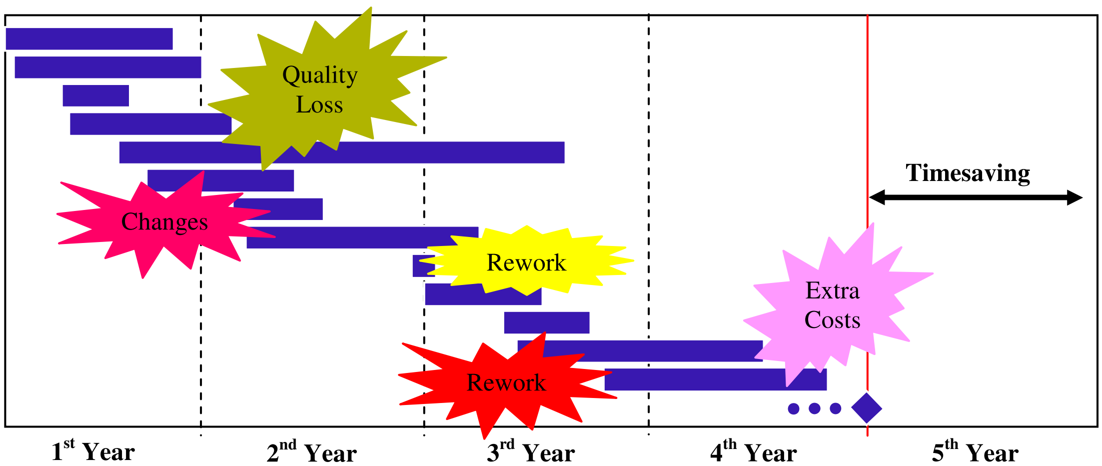

Figure 1-2: Activity overlapping reduces project duration, but generates extra risks

According to most of the research studies, sometimes the current practice of overlapping and the observed overlapping levels in projects hardly serve overlapping goals which are saving time and consequently maximizing benefits (Tighe 1991; Eastham 2002; Wang and Lin 2009). Activities to be overlapped and their overlapping levels are commonly decided on an ad hoc basis and according to the gut feelings and experience of schedulers rather than solid systematic approaches. As a result, overlapping strategies are not as efficient as they should be and sometimes act contrary to what they are supposed to serve. As of today, very few analytical models for addressing overlapping exist and most of them have been designed for “product development” (Ha and Porteus 1995; Krishnan et al. 1997; Roemer et al. 2000; Terwiesch et al. 2002; Roemer and Ahmadi 2004; Gerk and Qassim 2008) rather than “construction project management” (Pena-Mora and Li 2001; Bogus et al. 2005; Blacud et al. 2009). In addition, most of these models are hardly

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practical to be extensively and easily utilized by engineering and construction firms. Therefore, more practical models, or tools, are still required.

1.2 Problem significance

Overlapping is frequently practiced in all types of construction namely industrial, building and heavy construction. The facts and figures from oil and gas construction projects are significant. Canada is the world's third largest producer of natural gas and the seventh largest producer of crude oil. Its oil sands contain 179 billion barrels of proven reserves, second in the world only to Saudi Arabia (Energy Information Administration 2010). Canadian producers are drilling at record levels and the industry estimates that the production from Canada's oil sands alone will at least triple to over three million barrels per day (bpd) by 2015. About 80% of investment in the Canadian oil and gas industry has been spent in Alberta, the energy capital of Canada. Alberta is the largest producer of conventional crude oil, synthetic crude, and natural gas products in Canada. Oil and gas production has also spawned a major petrochemical industry as well as other related industries in this province. In 2008-2009, Alberta oil and gas royalty revenues amounted to $12.2 billion – over 30% of the Government of Alberta's total revenue. Planned energy investments in Alberta exceed $100 billion in the next 15 years (Alberta Energy Department 2010).

In such an active environment, energy companies want their projects to be finished sooner than ever, because they can generate significant profits when plants are on-stream. Therefore, they are increasingly utilizing fast track strategies and schedule reduction techniques such as overlapping as a normal way of executing projects to reduce the duration of new projects as much as possible (Knecht 2002). In fact, what these

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companies are moving towards is beyond fast track, something that can be called "extreme fast track", which is utilizing fast-tracking techniques to their extreme and reducing the project duration to the minimum practically achievable.

According to a study performed by Independent Project Analysis Inc. (IPA) in 2009, the most important single factor explaining cost overruns on major projects is the overlapping of engineering and construction not planned at the outset. In such projects, some overlap between engineering and construction is planned and predicted. However, often the engineering phase is delayed and, logically, the construction phase should start later, but owners still want to keep the same planned start date for the construction phase. As a result, engineering and construction actually overlap more than predicted. On average, 51% of the construction phase in oil and gas projects around the world is overlapped with the engineering phase. In Alberta, this value even increases to 64% (Merrow 2009).

Putting all the above facts and figures together, the importance of acceleration and overlapping strategies in project expenses and profits is revealed. Proper overlapping helps to reduce the project duration and can bring huge benefits to the project whereas improper overlapping may even result in longer project duration and jeopardise the project profitability.

1.3 Research objectives

This research aims at developing a systematic and practical approach to assessing and determining the optimal overlapping in construction projects. For this purpose, several sub-objectives will be fulfilled:

1. To explore the characteristics and mechanism of overlapping

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2. To formulate the activity overlapping time-cost trade-off
3. To review optimization techniques suitable for optimizing overlapping
4. To develop an algorithm to optimize overlapping considering its costs and benefits
5. To implement the algorithm in a computer environment
6. To verify and validate the algorithm and the computer tool

1.4 Literature review

A preliminary literature review revealed a gap in the literature about overlapping. The research question about overlapping optimization emerged out of the gap. A secondary literature review aimed at exploring the characteristics and mechanism of design activity overlapping. The literature related to various topics directly or indirectly related to overlapping, both manufacturing and construction projects, were reviewed. In general, the newer literature, published after 2000, was given priority to the literature published before 2000.

In addition, a part of the literature review was allocated to reviewing available optimization techniques for solving time-cost-tradeoff problems in construction. The intention was to choose a suitable optimization technique for this research.

1.5 Scope of research

The scope of this research covers any overlaps in the design phase of construction projects in general and industrial construction projects in particular. However, the impacts of the design overlaps on the procurement and construction phases are studied as well. The nature of overlapping procurement and construction activities is different from

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the design activities and is more affected by physical dependencies between activities. Therefore, procurement and construction overlaps are excluded from the scope.

Determining overlapping cost functions and rework functions for various project activities is not the objective or in the scope of this research. Obtaining such functions requires separate extensive research studies based on experts opinions and industry practices. However, a few such functions have been determined for a real world ongoing project by the researcher in order to validate the performance of the developed overlapping tool.

In addition to time and cost impact, overlapping may generate quality concerns. However, impacts other than time and cost are not studied in this research. It is assumed that the subject overlaps are in a range that do not violate the minimum quality and safety requirements. This assumption is close to reality, as although many times projects face time and cost overruns, they are often delivered in compliance with the required codes, standards and acceptable quality levels.

Reviewing various optimization techniques and selecting the most suitable technique for this problem is another part of the scope.

Developing the computer tool for performing the optimization and practical application of the overlapping algorithm is included in the scope and therefore some computer programming is required as well.

1.6 Research deliverables

The deliverables of this research are:

1. *An overlapping model:* The model explains and clarifies the characteristics and mechanism of overlapping between design activities in construction projects.

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2. *An overlapping optimization algorithm:* The algorithm, based on the model, provides a roadmap on how overlaps in the project schedule can be optimized to keep both project time and cost at the minimum.

3. *An overlapping optimization computer tool:* The tool uses the algorithm and physically performs overlapping optimization.

1.7 Research methodology

The research methodology has two parts (Figure 1-3). First, a qualitative research approach was taken to generate the overlapping model. Second, an analytical approach was taken to create and develop the overlapping optimization algorithm and the computer tool. Phenomenological study was used as the appropriate design for the qualitative part.

Research tools were interviews and focus groups. Semi-structured interviews with experts were used to understand the characteristics and mechanism of design activity overlapping. Also, focus groups were used to generate, modify, and validate the overlapping model. The model followed the principles of generating requisite models (Phillips 1982b, 1984).

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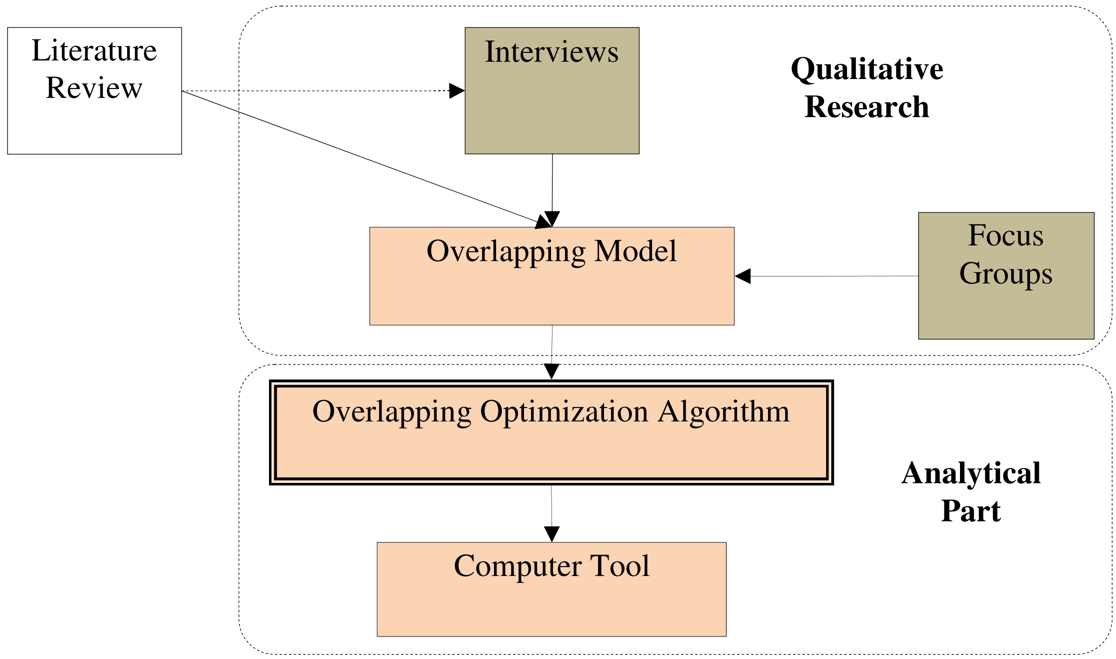

Figure 1-3: High level research methodology format

To validate the research, both internal and external validity of the research were addressed. Internal validity was performed by using two methods, *feedback from others* and *respondent validation*. External validity was achieved by implementing the suggested overlapping optimization algorithm on a real world project.

Totally, 43 individuals from 11 international owner and contractor companies mainly active in oil and gas projects contributed to this research. The majority of these people were seniors in their professions as the least experienced among them had 15 years of work experience.

1.8 Research contribution

The overlapping model developed in this research provides a comprehensive view of the mechanism of overlapping, overlapping and rework relation, and the side effects of

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overlapping. The model uses this to formulate the overlapping time-cost trade-off as well. Consequently, the overlapping optimization algorithm was developed. The implementation of the algorithm is very practical as it has been computerized and the computer tool can be used by practitioners. The overlapping optimization computer tool created in this research is unique and no similar tool exists so far in industry or academia. It can optimize overlaps in large and complex project schedules in fairly short processing times. It is able to handle multi-path networks and all types of activity dependencies (Finish-to-Start (FS), Finish-to-Finish (FF), Start-to-Start (SS), Start-to-Finish (SF)). The tool takes all activities, critical and non-critical, into account and follows the critical path if the critical path changes or new critical paths emerge. This is one step ahead of other overlapping optimization methods introduced by previous researchers. The tool can also take resource limitations and schedule constraints into account. Time and network calculations are performed very effectively as the overlapping tool takes advantage of a commercial scheduling software, MS Project, for network calculations. The computer tool performs cost evaluations and minimization using genetic algorithms. In fact, the overlapping optimization algorithm developed in this research is inherently a genetic algorithm. An algorithm of this type is capable of handling numerous cost evaluations quickly and effectively and is fit for complex problems with several variables. Therefore, the optimization process (time minimization or cost minimization) is performed effectively.

Another important advantage of the optimization algorithm is that if all of the information about all overlaps is not available, the algorithm is still able to find the best

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arrangement for those overlaps whose information is available. This is a partial optimization due to lack of some of the overlaps' rework or cost functions.

1.9 Thesis structure

The rest of the thesis is organized in the following manner: Chapter 2 is designated to the literature review. Chapter 3 highlights the research methodology. Chapter 4 introduces the overlapping model and provides in-depth knowledge about the characteristics and mechanism of overlapping. The overlapping time-cost trade-off is formulated and the need for utilizing an optimization technique to solve such a trade-off is shown. In a step-by-step manner, Chapter 5 explains how the Genetic Algorithms technique is utilized to develop the suggested overlapping optimization algorithm. Also, the computer implementation of the algorithm is described. In Chapter 6, the results of the experiments with the computer tool on two sample networks are shown. One sample is a hypothetical network with seven activities, and the other one is a real network with 35 activities. Finally, Chapter 7 is the conclusion chapter which summarizes the contribution and achievements of this research and suggests future studies.

Some of the information or documents are presented in appendices. Copies of ethics approval and ethics extension approvals are in Appendix 1. A copy of the questionnaire used during interviews along with the consolidated and finalized answers to those questions is provided in Appendix 2. Within chapters and wherever required, the results of the interviews are noted and used to enrich the suggested information or reasoning. A print of the PowerPoint slides used to develop the requisite model during focus groups or interview meetings is shown in Appendix 3. Appendix 4 encompasses the list of questions (criteria) used to validate the model. The complete list of contributors to

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the research, both individuals and companies, with their pseudonyms, professions and years of experience is provided in Appendix 5. Various snapshots from the computer tool, plus Visual Basic codes in Macros environment have been provided in Appendix 6.

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Chapter Two: Literature Review

The primary purpose of the literature review was to find gaps in previous research regarding project fast tracking and fast execution of projects. The following keywords were variably used to find the relevant literature:

Fast-tracking, flash tracking, project acceleration, schedule compression, schedule reduction, agile project management, project fast execution, phased construction, overlapping, concurrent engineering, parallel engineering, project time management.

As a result of the primary literature review, various techniques were identified which could be used for project fast execution. These techniques included but were not limited to overlapping (Roemer et al. 2000; Bogus et al. 2005), crashing (Roemer and Ahmadi 2004), substitution (Grek and Qassim 2008), decomposition (Hurink et al. 2006), overdesign, standardization (Eastham 2002), prototyping (Li et al. 2008), modularization, prefabrication, scope simplification, early scope freeze (Eastham 2002), constructability review, scenario planning (Al-Bataineh 2008), and single office execution (Eastham 2002). Further review showed that overlapping, if practiced correctly and efficiently, supersedes other techniques in saving project time. Also, overlapping is broadly practiced by engineering and construction companies. Therefore, the review narrowed down to activity overlapping. Further review revealed that a gap exists in activity overlapping optimization in the design phase of construction projects.

Since the main function of the current research is to address overlapping optimization, overlapping and optimization are two main areas of the literature review.

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However, the literature review in these two areas serve slightly different objectives. The literature about overlapping is primary and the literature about optimization is secondary to the current research. Literature related to overlapping is reviewed to capture general knowledge about overlapping, to know what other researchers have researched, and to find gaps in the literature. However, literature related to optimization is only reviewed to capture general knowledge about optimization and find a suitable and applicable optimization technique for optimizing activity overlapping. Finding a gap in the literature addressing optimization is not the objective.

Analogues to the above introduction, this chapter is divided into three main sections. The literature directly addressing overlapping is reviewed in section 2.1, overlapping in product development, and section 2.2, overlapping in construction projects. The majority of literature around overlapping is related to product development. Literature addressing overlapping in construction is less and newer. Section 2.3 addresses the literature on applicable optimization techniques for construction time-cost trade-off problems.

To better show interdependencies of the research studies in the above literature areas and the relation of the current research with those studies, a *literature review map* is provided in Figure 2-1. The map follows the same classification explained earlier, i.e. the reviewed literature is divided into two main areas: overlapping and time-cost trade-off optimization. Overlapping is further divided into overlapping in product development and overlapping in construction projects. Inside each area are the specific studies which are reviewed in the current literature review.

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Further, the map represents some subjective measures as well. The distance of each research study from the central circle representing the current research indicates the proximity of that study to the current research. This proximity is quite subjective and based on the candidate's gut-feelings. The proximity can be with regard to different components of the research such as scope, objectives, methodology, and the results. For instance, the research by Roemer et al. (2000, 2004) is more proximate to this research than the research performed by Pena Mora and Li (2001).

Arrows connecting studies represent the precedence of studies. To avoid complexity, only important contributions are shown to provide a general picture of research streams.

Some of the studies sit on interfaces between areas. This means that those studies are related to both areas. The current PhD research sits on all areas. Although this research variably uses the results of most of the literature shown in the map, it is more inspired by the research conducted by Hegazy (1999) and Roemer et al. (2004) than other studies.

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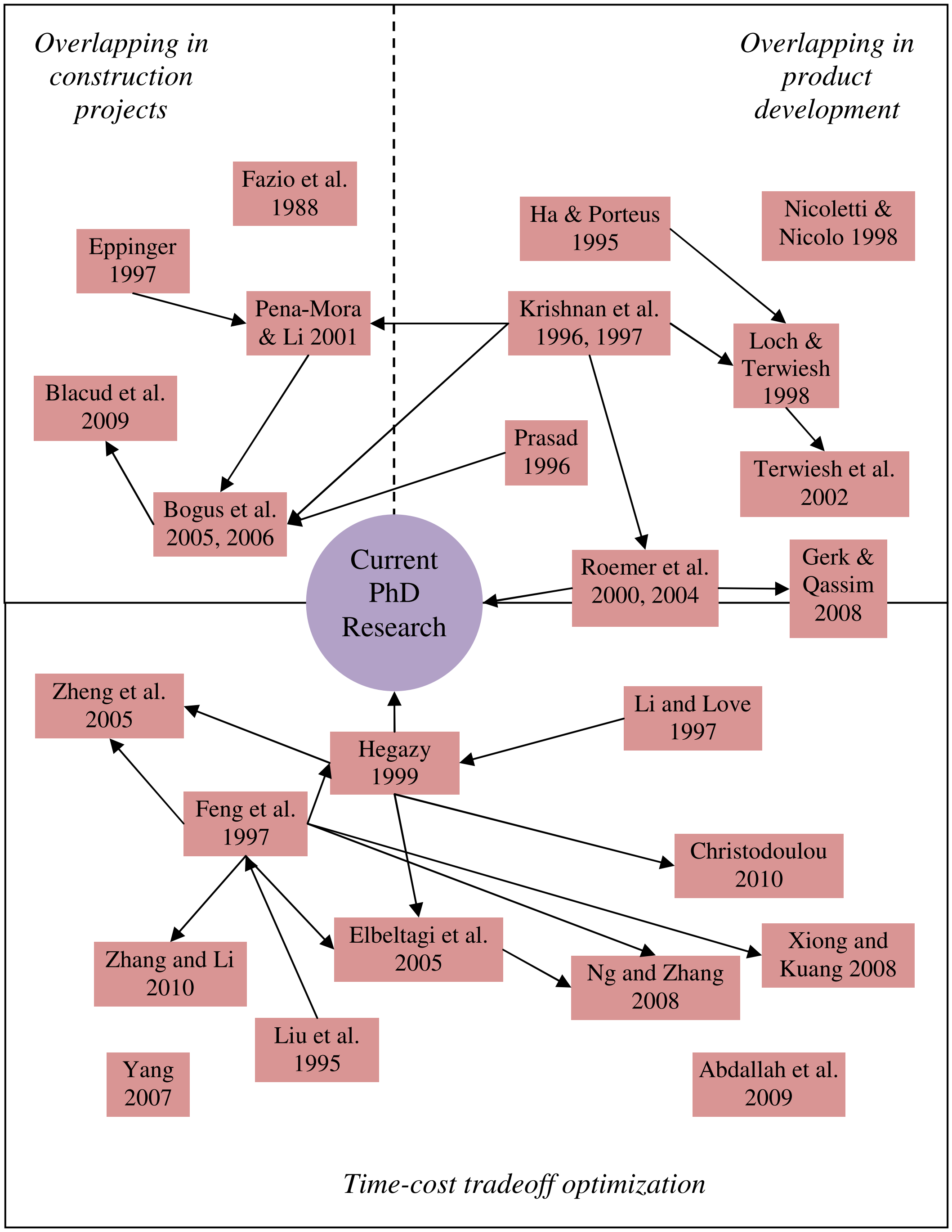

Figure 2-1: The literature review map

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2.1 Overlapping in product development

The first step for all research about activity overlapping is identifying the relationship and the type of dependencies activities have with each other. Prasad (1996) has classified the relationship between design activities into four different types:

1. Dependent activities: In order to start, one activity requires the final information from another activity.
2. Semi-independent activities: To start, one activity requires only partial information from other activities.
3. Independent activities: No information dependency exists between two activities.
4. Interdependent activities: A two-way information exchange between the activities occurs until they are complete.

Prasad's classification is important to researchers researching overlapping as it is starting point to classifying different types of overlapping. In other words, overlapping is possible for the same four types of relationships. Some of the researchers have focused on the possibility and the extent of overlapping dependent and semi-independent activities (Krishnan et al. 1997, Bogus et al. 2005, Roemer et al. 2000, Loch and Terwiesch 1998), and the others have focused on the necessity and the extent of overlapping between interdependent activities (Nicoletti and Nicolo 1998, Terwiesch et al. 2002). Overlapping independent activities has been researched only when a resource dependency between activities exists (resource levelling studies). Prasad's classification will be explained more in Chapter 4 of the current thesis.

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2.1.1 Overlapping and information exchange

Nicoletti and Nicolo (1998) investigated overlapping interdependent activities. This type of activities have to overlap to some extent, otherwise information exchange between them cannot properly take place. According to Nocoletti and Nicolo, each activity consists of several operations and each operation generates some information that can impact operations of other activities. Therefore, a flow of information exists between activities. Nicoletti and Nicolo argued that "two activities A and B are informatively linked if the information flows of the operations belonging to A can influence the operations belonging to B or vice versa (or both)" (Nicoletti and Nicolo 1998, p 116). Through this definition, they noted that a two-way information exchange between the activities exists. They believed the more two activities are informatively linked, the more it is required to execute them concurrently and coordinated.

Consequently, Nicoletti and Nicolo defined an *information link coefficient* as the number of the operations of activity A that impact activity B plus the number of operations of activity B that impact activity A. This coefficient is very critical in their research which aims at developing a decision support model to decide which activities have to be overlapped and to what measure to enhance the information exchange between activities and promote project execution in general.

To develop their model, they also defined *the atomic level of a project* which is the minimum decomposition level of activities that further disaggregation beyond it is useless. They added that such a level is typically lower than the level in which project control and monitoring take place. However, Nicoletti and Nicolo developed their model at the atomic level of the project.

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Although the research by Nicoletti and Nicolo contributes to planning concurrent execution by enhancing information flow between interdependent activities, and aims to identify which activities are to be performed concurrently and to what extent, its main concept is different from the current research for two reasons. First, the current research focuses on overlapping dependent and semi-independent activities, not interdependent activities. Second, Nicoletti and Nicolo have tried to attain their objective through the maximization of a total concurrent information index without taking the cost of overlapping into account.

Ha and Porteus (1995) discuss how to optimally schedule design reviews between two overlapping stages. They argue that in concurrent design, frequent progress reviews have to be conducted during the product design process. Therefore, sufficient information is exchanged between the activities and flaws in the design are revealed soon, saving time and preventing rework. However, each review has a setup time. Ha and Porteus managed to find an optimal policy for the review periods.

Loch and Terwiesch (1998) and Terwiesch et al. (2002) studied the importance of communication and information exchange in concurrent engineering. Loch and Terwiesch (1998) presented an analytical model of concurrent engineering to address two questions: 1) How much is the optimal overlap and 2) how should the overlapped activities be coordinated. They highlight that the main drawback of overlapping is rework and rework can be reduced if more communication exists between activities. However, communication carries a cost. According to Loch and Terwiesch, team meetings are the prominent means of communication that consume valuable engineering time. Their model uses the above argument for two purposes. First, to derive the optimal

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communication frequency (or team meeting schedule) as a function of the frequency of engineering changes, uncertainty, and dependence. Second, to define the optimal degree of overlapping, provided that the optimal communication frequency is applied. It is noteworthy that optimal overlap is low if uncertainty and dependence are high.

The model offered by Loch and Terwiesch (1998) is more analytical than numerical. In addition, they do not include the cost of rework in their model, which is very important as often the cost of rework is higher than the cost of extra communication.

Terwiesch et al. (2002) performed a similar study about exchanging preliminary information in concurrent engineering. Their objective was to develop and compare alternative coordination strategies. They introduced a time-dependent model in which the exchange of preliminary information between two interdependent activities is described in three perspectives: 1) the format of the information which has to be passed from upstream activity to downstream activity, 2) the downstream adjustment costs to change from upstream activity and 3) possible substitutes for preliminary information that may be better overall.

The format of information includes two characteristics: information accuracy and information stability. Information accuracy refers to the precision of the information, while information stability refers to the likelihood of the upstream activity information remaining unchanged during the overlap. Information accuracy and information stability conflict with each other. The more accurate the information, the more likely the information will be changed (less stability).

According to Terwiesch et al., the downstream activity adjustment costs have two sources. One is too little stability in the preliminary information that causes rework for

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downstream activity. The second source is called *starvation*, which is a result of too little precision. Starvation means that the downstream activity "runs out of work" because the information coming from the upstream activity is not precise enough to continue the work. Therefore, valuable time passes while the downstream activity remains idle waiting for the precise information.

In the third perspective, Terwiesch et al. investigate the possibility of diminishing the role of preliminary information. They believe that it might be possible to weaken interdependence between upstream and downstream activities, or to make the downstream activity so flexible that it can absorb changes and therefore adjustments become almost costless.

Taking the tension between information precision and information stability into account, they suggest two coordination strategies: Set-based coordination and iterative coordination. Figure 2-2 shows the role of precision and stability in selecting coordination strategies. If the information is communicated in a very stable manner, the downstream risk is minimum. However, the downstream activity may not continue at all due to very low information precision. If the information is communicated very precisely, the downstream activity can continue with the information, but at the risk of having to rework and iterate. Between the two extremes, intermediate points exist that represent various combinations of the two strategies.

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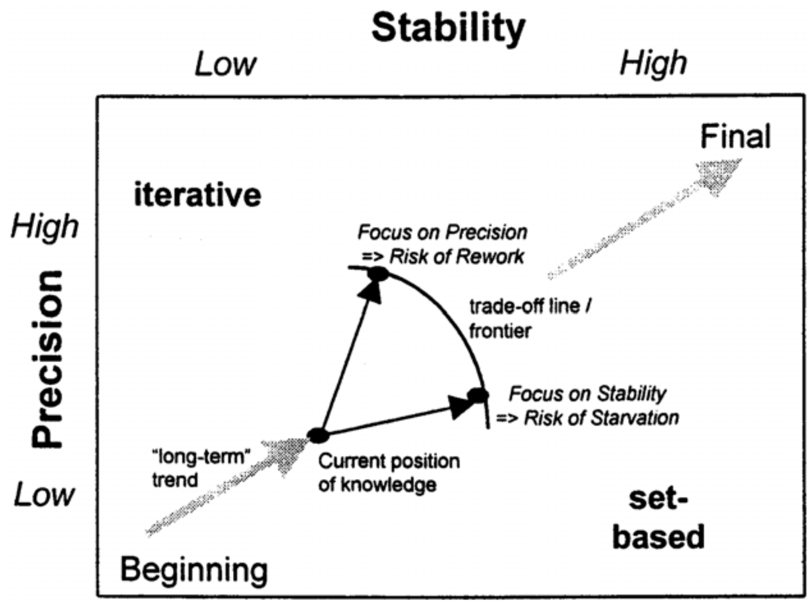

Figure 2-2: Trading off information precision with information stability in theory (Terwiesch et al. 2002)

The path shown in the matrix of Figure 2-2 represents choosing between information precision and information stability. If the path gravitates toward the lower-right, information stability is emphasized; Terwiesch et al. call it set-based coordination strategy. If the path gravitates towards the upper left, the emphasis is on information preciseness and the strategy is called iterative coordination. Terwiesh et al. state: "our study suggest that an organization should master and apply both coordination strategies within a single development project" (Terwiesch et al. 2002, p 413).

Information exchange and coordination are the focus of all research performed by Prasad (1996), Ha and Porteus (1995), Nicoletti and Nicolo (1998), Loch and Terwiesch (1998) and Terwiesch et al (2002). Activity characteristics are less investigated in their

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research. However, other researchers have focused on activity characteristics to find out which activities are more suitable for overlapping.

2.1.2 Activity Evolution, Activity Sensitivity

One very important study about overlapping has been conducted by Krishnan et al. (Krishnan et al. 1995; Krishnan 1996; Krishnan et al. 1997). Their case studies are from the automotive industry and their research results have been the base for most of the research in the area of overlapping, concurrent engineering, and accelerating product development. Their research has even been extensively referred to by the researchers who did not investigate product development, but construction projects.

In their paper, a model-based framework to overlap product development activities, Krishnan et al. (1997) presented a model-based framework that determines the most suitable type of overlapping for a pair of coupled activities. According to them, the flow of information between activities is mostly sequential. To overlap activities, the flow of information should be either removed or changed. If the flow of information is removed, then activities are actually decoupled, and can be performed in parallel. They believe this requires a change in the inherent nature of activities which is not always possible and argue that an alternative way is to increase the information exchange between coupled sequential activities. Therefore, three types of process exist: Sequential, parallel, and overlapped (Figure 2-3).

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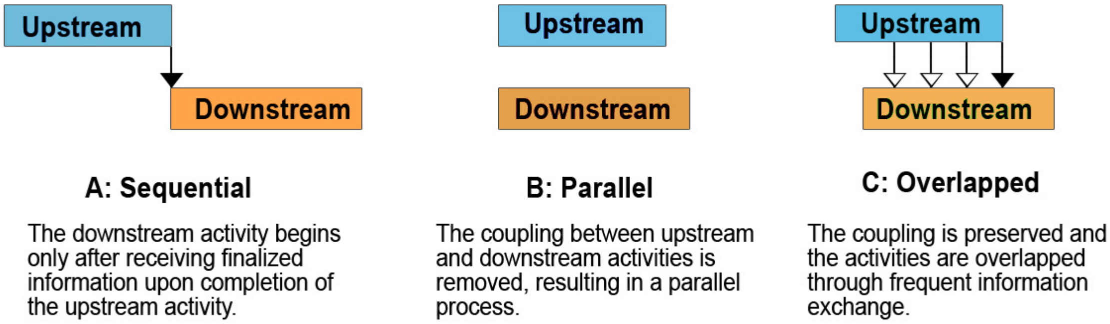

Figure 2-3: Sequential, parallel and overlapped processes (Krishnan et al. 1997)

To increase the information exchange between sequential activities, one batch of information transfer should be divided into two or more batches (Figure 2-4).

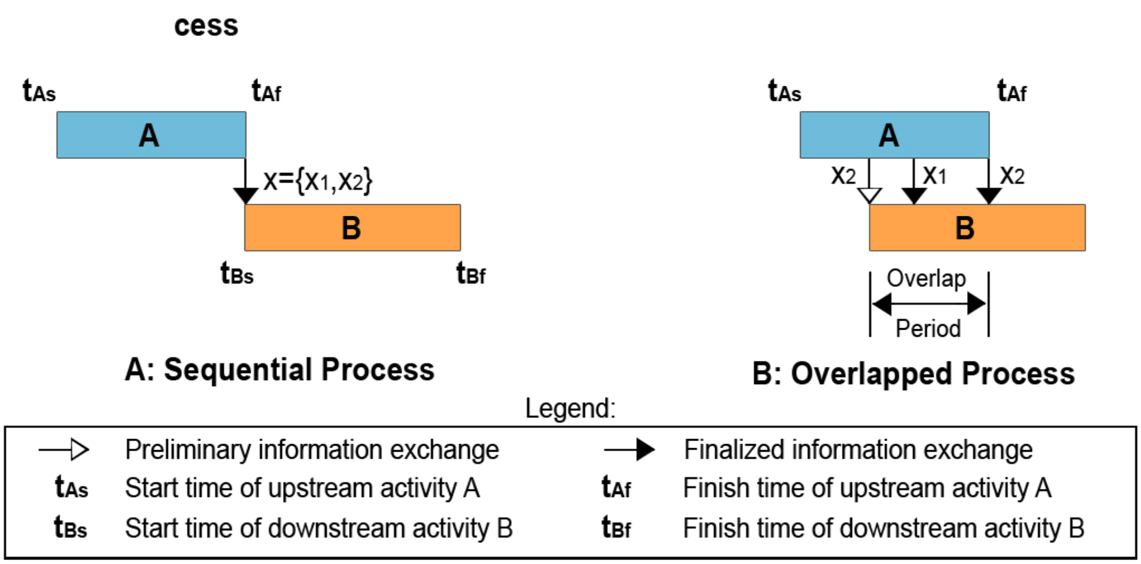

Figure 2-4: Transforming a sequential process into an overlapped process (Krishnan et al. 1997)

According to Krishnan et al., this process does not always result in the preferred time saving, as the duration of the downstream activity after overlapping might be different from its duration before overlapping. The downstream activity needs to acquire

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and absorb changes in the upstream activity during overlapping; this leads to an increase in both duration and effort. The other disadvantage is the possibility of quality loss. Since the changes in the upstream activity should be absorbed by the downstream activity and it takes time and effort, the upstream activity should limit its changes. Therefore, after early release of preliminary information to the downstream activity, the upstream activity loses the flexibility to incorporate more changes and modifications, and this is interpreted as loss of quality.

In addition, Krishnan et al. (1997) introduce and formulate two characteristics for upstream and downstream activities, and use them to determine how activities must be overlapped. The first characteristic is upstream evolution, which refers to how fast the upstream information is refined and finalized. Activities can be either fast evolution or slow evolution. The second characteristic is downstream sensitivity that refers to how much downstream activity is sensitive to possible changes in upstream activity and how quickly downstream activity can accommodate those changes. Activities can be either high sensitive or slow sensitive. The easiest and least risky overlapping is when a fast evolution upstream activity is coupled with a low sensitivity downstream activity. On the other hand, the riskiest overlapping is when upstream activity is slow evolution while downstream activity is highly sensitive. In general, Krishnan et al. proposed that four extreme situations exist (Figure 2-5):

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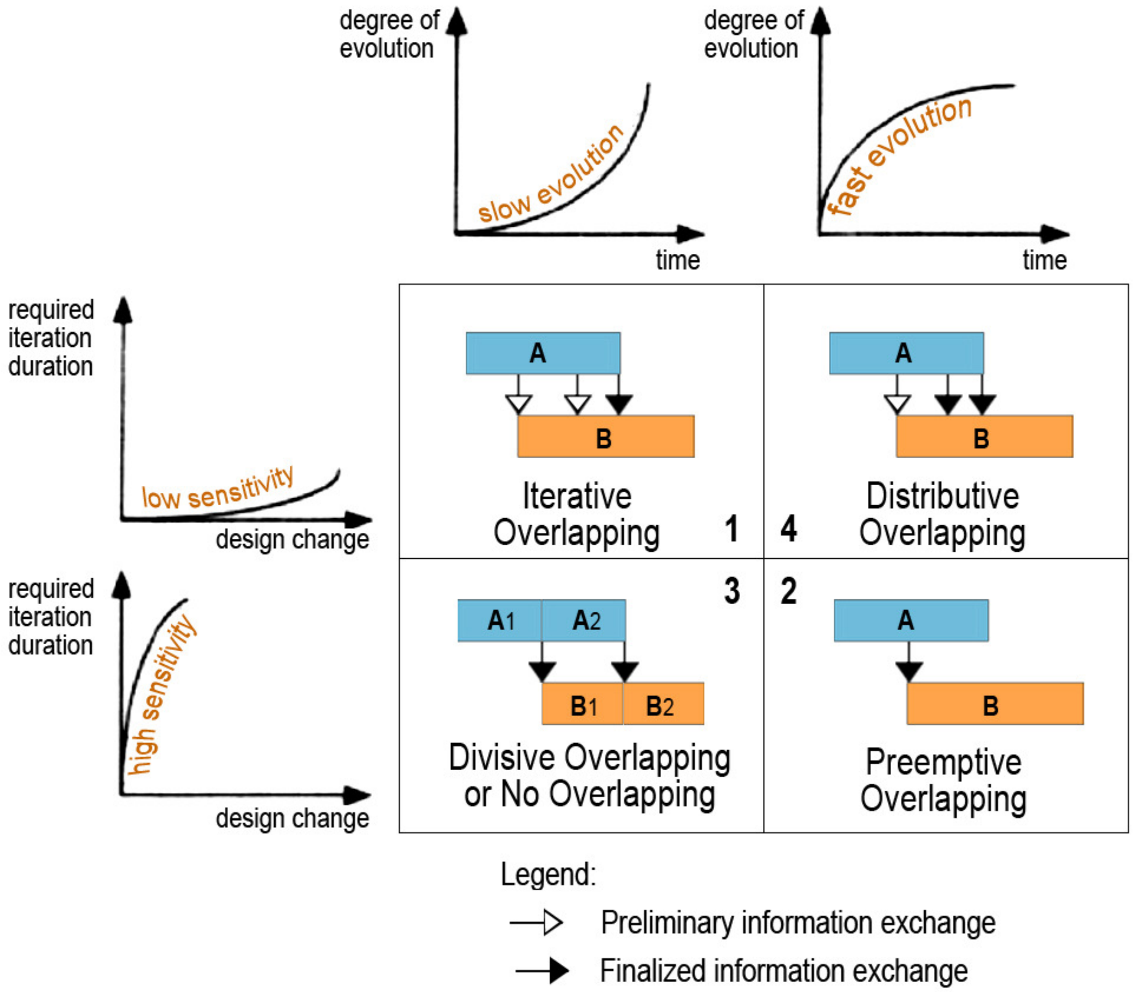

Figure 2-5: Types of overlapping based on evolution and sensitivity (Krishnan et al. 1997)

1. Slow evolution upstream and low sensitivity downstream: downstream activity is not sensitive to changes in the upstream activity and can start upon receiving the preliminary information from the upstream activity. However, it should adjust itself on an iterative basis with the changes from upstream activity, until receiving the final information. This kind of overlapping is called “iterative overlapping”.

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2. Fast evolution upstream and high sensitivity downstream: Downstream activity starts earlier by receiving the finalized information from the upstream activity, but there is no subsequent iterations. In this case, the exchanged information is to be pre-empted by taking its final value; therefore, it is called "pre-emptive overlapping".
3. Slow evolution upstream and high sensitivity downstream: This case is the least desirable for overlapping. To overlap, activities should be divided into smaller parts to see if information exchange between them is possible. This is called "divisive overlapping". If information exchange is not possible, then overlapping should be avoided.
4. Fast evolution upstream and low sensitivity downstream: In this situation, it is possible to start downstream activity with the advanced information from upstream activity, and to pre-empt later changes in the exchanged upstream information. Since the impact of overlapping is distributed between the activities, this type of overlapping is known as "distributive overlapping".

Earlier, Krishnan (1996) investigated the simultaneous execution of coupled phases in concurrent product development. He introduced a conceptual framework for concurrent execution of design and construction phases in product development. He specifically used a case study in which the completion of an automobile instrument panel is expedited by overlapping the mock-up construction with design. According to Krishnan, when mock-up construction begins before design drawings are finalized, it is quite possible substantial reworks happen for the construction, due to significant changes in design. This increases both the duration and cost of production.

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The significance of Krishnan's model is that in spite of its simplicity, it is a good representation of real world practice. The concepts of evolution and sensitivity, and their combination to define different situations for overlapping, made a large contribution to understanding the real mechanism of overlapping. This is why the research by Krishnan et al. is a reference for many studies about overlapping and concurrent engineering in product development.

2.2 Overlapping in construction projects

One of the highly contributing studies about overlapping in construction projects has been conducted by Pena-Mora and Li (2001). Their intention was to help create a dynamic project plan for construction design-build projects. They have used the concepts of upstream task evolution and downstream task sensitivity formerly developed by Eppinger (1997) and Krishnan et al. (1997), to generate a framework suitable for construction activities. In their research, Pena-Mora and Li give a priority to activities that are on the critical path or have high criticality index, and activities with high duration or resource requirement. They reason that these activities have the biggest contribution to schedule reduction if they are overlapped.

Instead of the concepts of upstream task evolution and downstream task sensitivity in product development, they considered upstream/downstream production rate, upstream production reliability, and downstream task sensitivity. The latter is the same concept as in product development and refers to the fact that the sensitivity of a downstream task to changes and errors in an upstream task will increase the rework and duration. The upstream/downstream production rate (upstream/downstream progress) is also similar to task evolution in product development and shows if a task, either upstream

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or downstream, has a higher production rate at its early stages or late stages. If a task makes good progress during its early stages, then it is called a fast production task. The opposite is true for a slow production task (Figure 2-6). Upstream production reliability means that if the work performed or information generated by the upstream task are reliable, then there is less room for mistakes and the downstream task can proceed with minimum rework.

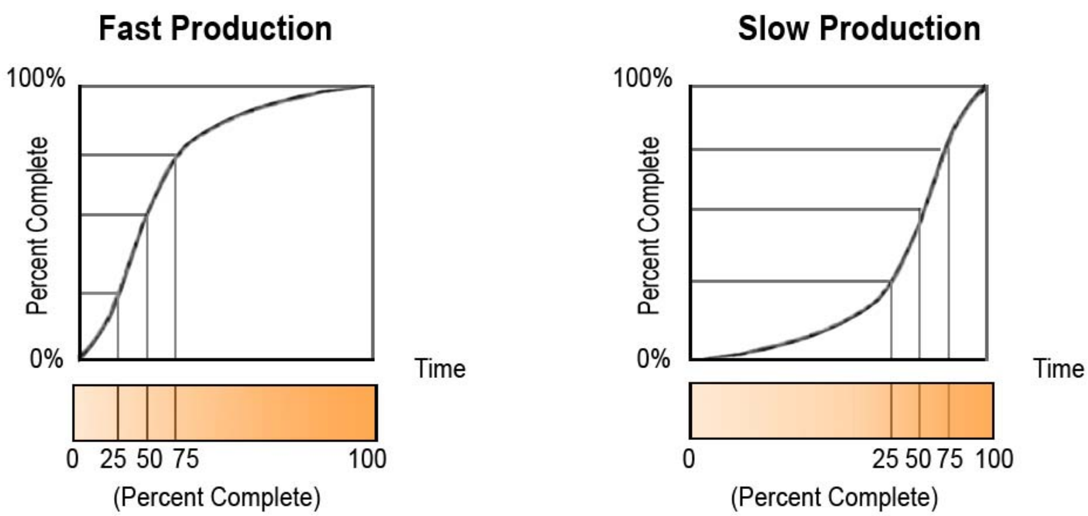

Figure 2-6: Production Rate (Pena-Mora and Li, 2001)

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Figure 2-7 shows the progress curves of a fast production upstream task with a slow production downstream task and presents why their combination is ideal for overlapping.

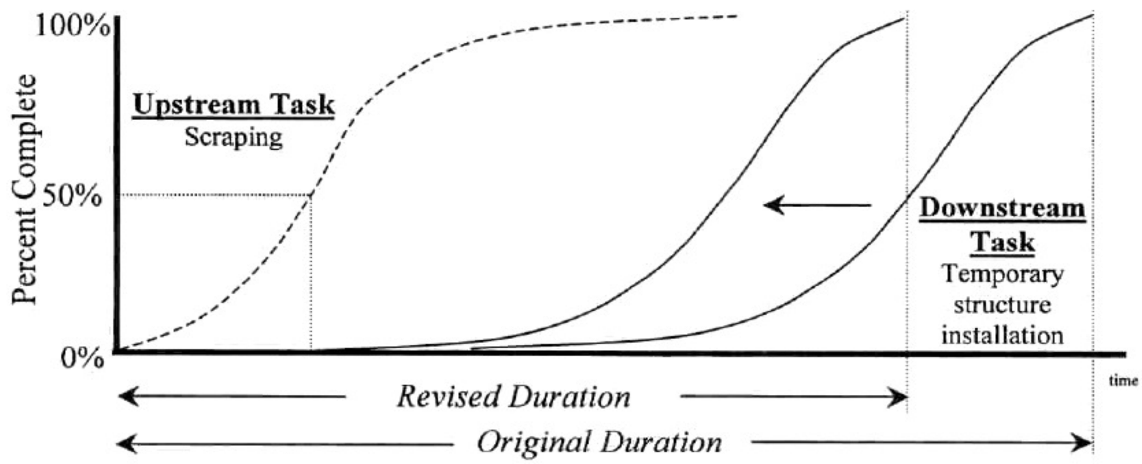

Figure 2-7: Change in Duration after Overlapping (Pena-Mora and Li, 2001)

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The framework has been developed by considering the above three characteristics and is shown in Figure 2-8. In the framework, an important assumption is that the upstream task should be finished before the downstream task. Pena-Mora and Li make the following points about their framework:

- The framework is based on dividing up activities in 25% overlapping increments. The framework is divided into four fragments and 48 scenarios.
- Upstream fast production rate means it progresses faster and 25% of work is performed sooner, giving the chance to downstream activity to start sooner.
- Downstream fast production rate lets the errors happen in upstream have higher effect on the downstream task and generate more rework.
- Within each fragment, more overlapping is possible when the upstream task is more reliable, as the possibility of changes and errors is less. On the other hand, the more sensitive is the downstream task, the less overlapping is possible.
- For certain scenarios, like the time a highly sensitive downstream task is coupled with a highly unreliable upstream task, not only overlapping should be avoided, but a schedule buffer should be considered (a finish-to-start lag). The buffer provides enough time to discover and absorb errors and omissions in upstream task before downstream task starts.
- The overlapping framework acknowledges a fast production highly reliable upstream task with a slow production insensitive downstream task as the best combination for overlapping.

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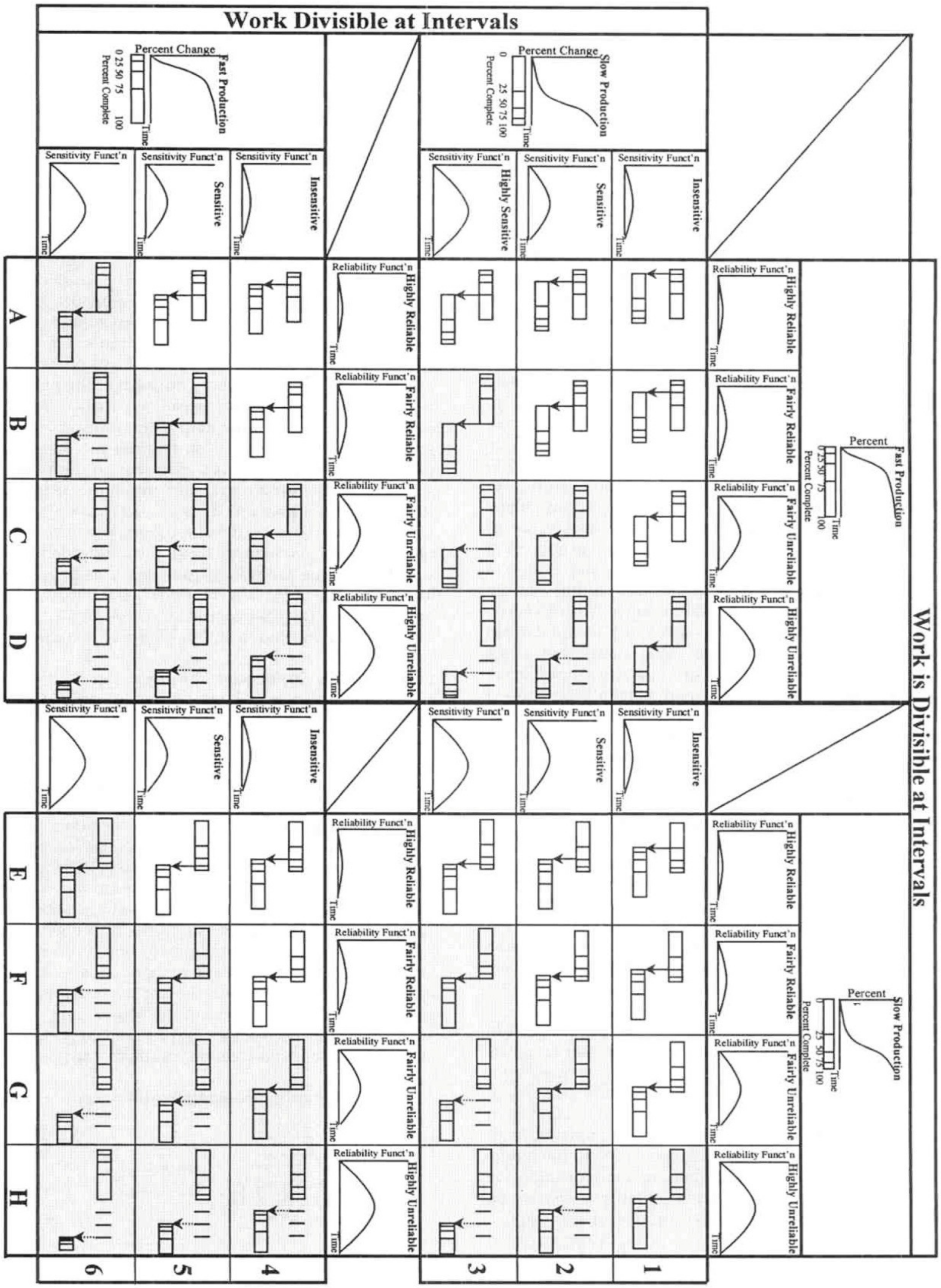

Figure 2-8: Overlapping Framework (Pena-Mora and Li, 2001)

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Pena-Mora and Li’s framework provides guidance for any type of overlapping including design-design, design-construction, and construction-construction. On the other hand, the frameworks developed by Krishnan et al. (1995, 1997) and Bogus et al. (2005) (Bogus et al.'s research will be explained later) are developed based on the exchange of information between activities and upstream information evolution and therefore are only suitable for design-design or design-construction overlapping. However, most of the time construction activities have no information dependency on each other, but they are physically dependent. Pena-Mora and Li’s framework is able to address such dependency, as it uses the upstream production rate and reliability as one of the decision criteria. The robustness of this framework has caused it to be referred to by other researchers studying overlapping in construction projects.

Bogus et al. (2005) founded their research in the qualitative framework developed by Krishnan et al. (1997), but with an orientation towards construction projects. As stated earlier, Krishnan et al. (1997) suggested using upstream evolution and downstream sensitivity to recognize the best overlapping opportunities between different activities. Bogus et al. (2005) performed exploratory interviews with design professionals to breakdown evolution and sensitivity into more detailed parameters. Consequently, they found four key determinants of evolution and three key determinants of sensitivity. These determinants provide better insight to make decisions on which activities are more suitable for overlapping.

The four key determinants of evolution are as follows:

I. Design optimization: It refers to the optimization level or number of iterations required to achieve the optimum design. One example is the balancing of the

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earthwork cut and fill quantities to minimize the amount of soil to be moved. An activity that requires a large number of iterations and evaluations is a slow evolution activity.

II. Constraint satisfaction: It describes the design flexibility in absorbing constraints, such as physical constraints. Adding a new pipe to an existing pipe gallery is an example of satisfying different constraints. The pipe should not clash with other pipes and at the same time the number of its bends should be minimized. More constraints can result in faster or slower evolution, depending on the situation.

III. External information exchange: It refers to the amount of information exchange between the designers and external sources (client, vendors, regulatory agencies, etc.). The more information exchange between activity and external sources, or the higher the number of external sources that should receive/send information from/to the activity, the slower the activity evolution.

IV. Standardization: It means the level to which design is standardized. A standard design accelerates the work and causes faster evolution. Using standard (off-the-shelf) materials and equipment in design is an example of standardization.

According to Bogus et al., activity iteration is the common element among the four determinants of evolution. High iteration causes slow evolution and low iteration results in fast evolution. Designers, if not under time or resource constraints, tend to iterate the design as much as possible to gain the best results. However, often time and resource constraints exist and designers are forced to overlook the natural evolution of activities. In the case of time constraint, a faster evolution activity can better satisfy the situation. The important point is that a faster evolution is not equal to a shorter duration. An

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activity can be either fast or slow evolution, but it keeps its original duration. The difference is that a fast evolution activity generates a significant batch of information earlier than the similar activity with slower evolution (Figure 2-9).

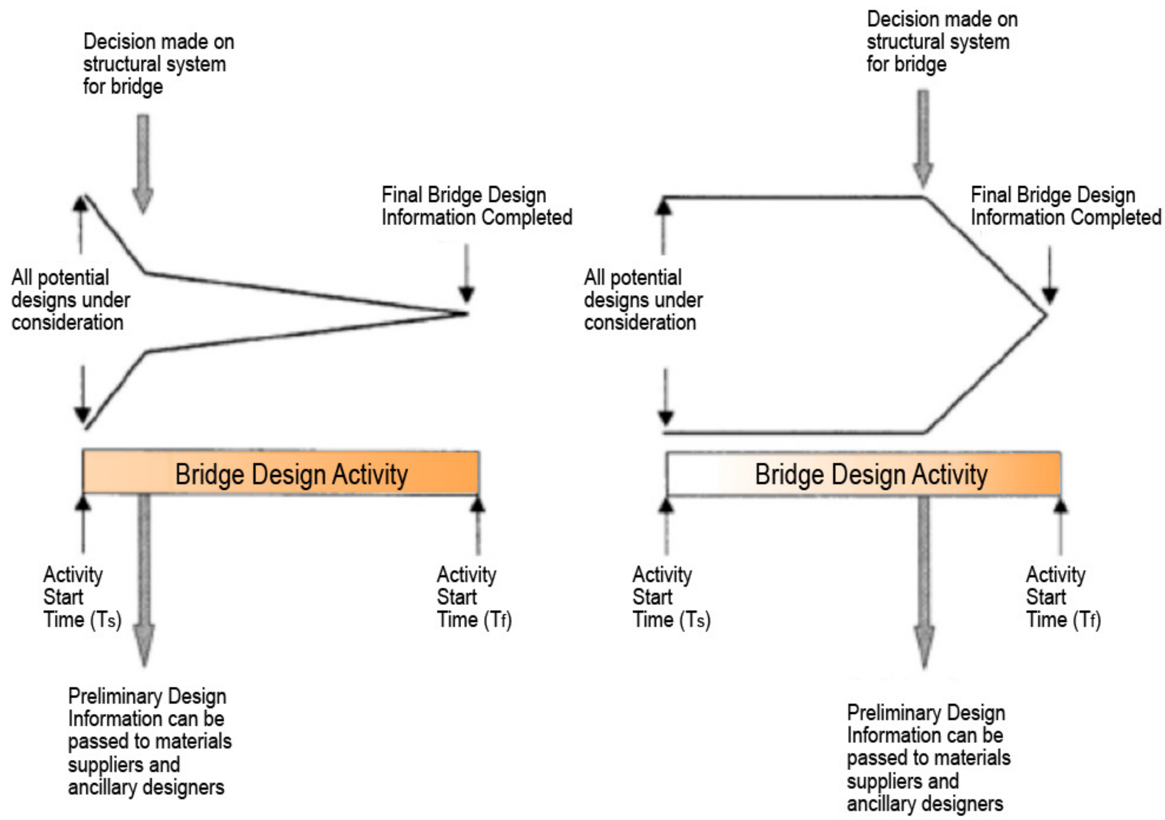

Figure 2-9: Fast (left) versus slow (right) evolution (Bogus et al. 2005)

Furthermore, the three key determinants of sensitivity are as follows:

I. Constraint sensitive: When the design is close to its tolerable boundaries, it becomes sensitive to constraints. For example, if a pump selected and designed by a mechanical engineer is near to its upper limit capacity, a small change in its flow-rate by the upstream process engineer may cause the pump not be acceptable anymore, and the mechanical engineer should select and design a different pump.

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II. Input sensitive: This refers to the level of dependency an activity has to the inputs from other activities. As an example, the selection of a generator highly depends on the amperage and voltage requirements of other electrical equipment.

III. Integration sensitive: Integration sensitive refers to the level an activity can proceed isolated from other activities. An example is designing different segments of a road as the vertical alignment of road segments are all connected to each other and cannot be performed separately.

The downstream activity sensitivity is more affected by design situation than by the inherent nature of the downstream activity.

The research by Bogus et al. (2005) adds more details and more insight to the research by Krishnan et al. (1997). In addition, it examines Krishnan's work in a different environment, construction projects. The research is limited to the design phase and considers information dependency between activities. Its results are more useful for design managers to subjectively decide if a pair of activities are suitable for overlapping.

Blacud et al. (2009) added more to Bogus et al.'s (2005) research by expanding the concept of evolution and sensitivity to the construction phase. Blacud et al. studied the overlapping of design activities as predecessor activities with construction activities as successor activities. They focused their research on determining the factors contributing to the sensitivity of construction activities. According to them, construction is a physical activity and the sensitivity of construction activities to design changes is *the amount of physical rework caused by upstream design changes*. They used semi-structured interviews to perform two case studies, cast-in-place piles and driven piles. The results was that four factors contribute to the sensitivity of construction activities:

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I. Transformation process: Some construction activities such as concrete pouring are hardly reversible or are too costly and time-consuming to repair or change. For such activities, transformation is high. Therefore, they are very sensitive to design changes.

II. Lead time: The required time to order the required resources such as raw materials and components of a construction activity to the moment they are actually delivered is the lead time. Activities with longer lead times are more sensitive to design changes.

III. Modularity: Modularity refers to the segregation of components of a construction system. The more the components are integrated, the less modularization is possible. In a high modular system, the components have minimum interdependency, so a design change affecting one part is unlikely to affect other parts. Therefore, construction activities inside highly modular systems are less sensitive to design changes.

IV. Interaction of the components: If components of a construction activity interact a great deal, the sensitivity tends to be higher. However, if low interactions exist between components, then a change in one component does not necessarily disrupt the construction process of other components.

Similar to Bogus et al. (2005), Blacud et al.'s (2009) research results are more useful for making decisions subjectively. Construction managers or supervisors can decide if starting a particular construction activity is risky with regard to the characteristics of that activity.

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Common to all research studies performed by Krishnan (1997), Pena-Mora (2001), Bogus (2005), and Blacud et al. (2009) is that they focus on one individual overlap and do not consider the overlapping in the context of project schedule and with regard to other overlaps. They do not provide any clue to which activities are better to be overlapped and which activities are not or among those which are overlapped, which activities can be more overlapped than others, as they generate less risk and less cost. Roemer et al. (2000) and Roemer and Ahmadi (2004) have tried to provide answers to these questions.

2.2.1 Overlapping Time-Cost Trade-off

Roemer et al. (2000) and Roemer and Ahmadi (2004) took a different approach from Krishnan et al. (1997) and tried to address the design costs of overlapping by evaluating the trade-off between overlapping lead times and overlapping costs. Therefore, their research has the closest proximity to the current PhD thesis in terms of the research objective: overlapping optimization through overlapping time-cost trade-off (however, the methodology is quite different and the results of their effort for the most part are not applicable to this PhD research study). Their research is the only study in the literature which focuses on overlapping time-cost trade-off. As a result, their research will be extensively reviewed in this section and the important contributions, strengths and weaknesses will be explained.

The results of the research conducted by Roemer et al. are published in two papers (Roemer et al. 2000; Roemer and Ahmadi 2004). The first paper in 2000 is about their research on overlapping time-cost trade-off. The second paper in 2004, extends on

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the first paper and discusses the combination of overlapping and crashing cost-time trade-off, or as they named, "concurrent crashing and overlapping".

The fact that overlapping can generate rework and consequently increase the duration of individual activities is thoroughly highlighted in the first paper (Roemer et al 2000). They investigated the development process of turbo-pumps at Rocketdyne, a firm that designs and develops liquid-propellant rocket propulsion systems. They argued that when different stages of a development process are overlapped, except for the first design stage (stage 0), all stages start and finish earlier than the time they were performed sequentially (Figure 2-10). Therefore, the development lead time with overlapping (L_{ovl}) is less than the same without overlapping (L_{seq}). On the other hand, since overlapping necessitates the start of each stage with incomplete information from the previous stage, rework is often necessary to absorb the unforeseen changes and developments in the previous stage. Such a rework takes time ($h_i(y_i)$) and consequently requires additional costs.

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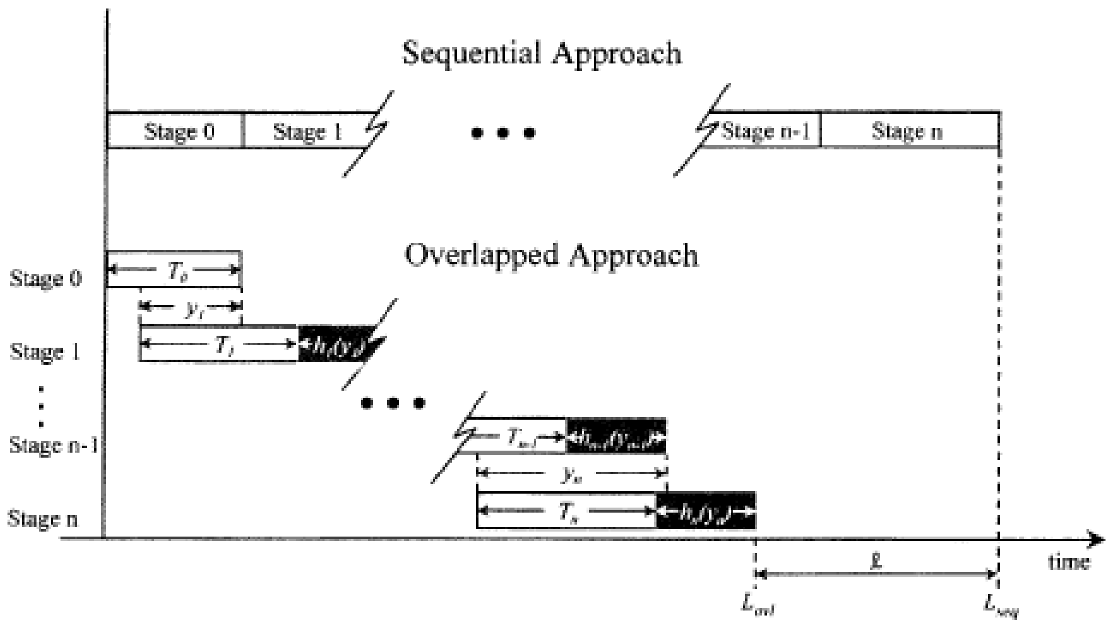

Figure 2-10: Sequential vs. overlapped design (Roemer et al. 2000)

Considering their argument, they developed an algorithm to determine the minimum product development time for a given budget. They formulated the overlapping problem as follows:

$$min \sum_{i=0}^{n} T_i - \sum_{i=1}^{n} y_i - h_i(y_i) \qquad (2.1)$$

Subject to:

$$\sum_{i=1}^{n} c_i(y_i) < c \qquad (2.2)$$

In which:

T_i: Time required to complete design stage i in isolation with full information.

y_i: Overlap duration between design stages i-1 and i.

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$h_i(y_i)$: Expected design time increase at stage *i* due to overlapping with design stage *i*-1.

$c_i(y_i)$: Expected development cost increase at stage *i* due to overlapping with stage *i*-1.

c: The additional costs incurred due to overlapping.

Equation 2.1 is the objective function and expresses that the total process duration (L_{seq}) should be minimized. Equation 2.2 is the budget constraint. For further progress, Roemer et al. had to model the extended design function, $h_i(y_i)$. They reasoned that since stage *i* starts with incomplete information from stage *i*-1, it should make predictions. According to them, "part of the design activities in stage *i* have to be repeated if predictions are wrong " (Roemer et al. 2000, p 860). They designated $P_i(y_i)$ as the probability that the prediction is incorrect. Up to this point, they thoroughly described and developed the mechanism of overlapping and the time-cost-trade-off function. However, they proposed a function to model the extended design function $h_i(y_i)$. This suggestion is criticized in the next paragraphs. They claimed that if the overlap between design stage *i* and design stage *i* - 1 be denoted by y_i and the probability function for stage *i* by $P_i(t)$, the extended time function $h_i(y_i)$ for design stage *i* is then:

$$h_i(y_i) = \int_0^{y_i} P_i(\tau)\, d\tau \qquad (2.3)$$

Roemer et al. provide the following proof:

"Suppose design stage *i* has proceeded to a point where its overlap with stage *i* - 1 is τ € [0, y_i] as demonstrated in [Figure 2-11]. A prediction is made about the outcome of stage *i* - 1 based on the available information. This prediction is updated $d\tau$ amount of time later, where the overlapping length has reduced to τ - $d\tau$. According to the definition of the probability function, the previous prediction was wrong with probability $P_i(\tau)$ and

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$d\tau$ amount of extended time will be needed to redo the design; with probability 1 - $P_i(\tau)$ the previous prediction was right and no extra time is needed. The expected additional time incurred in [τ - $d\tau$, τ] is $P_i(\tau)\, d\tau$. Equation 2.3 follows by integrating over the entire overlap y_i" (Roemer et al. 2000, p 860).

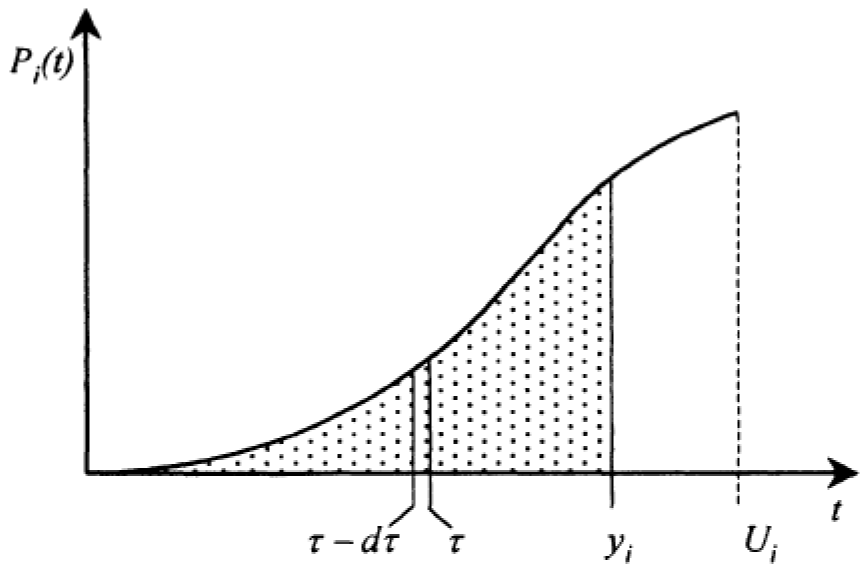

Figure 2-11: Derivation of the extended time function

In the above quotation, the notion that if predictions are wrong, "$d\tau$ amount of extended time will be needed to redo the design" is incorrect, and even contrary to what they previously stated: if predictions are wrong, "part of the design activities in stage *i* have to be repeated". In other words, if predictions are wrong, only part of the design activities have to be repeated and not necessarily all of them. Therefore, the amount of extended time needed to redo the design is not necessarily $d\tau$, but less than it. In fact, they did not consider the impact of wrong predictions in addition to the probability of wrong predictions.

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However, in their second paper in 2004, they readdress the issue with the following statement:

> "Roemer et al. (2000) introduced the probability of rework as a (non-decreasing) function P_i of the overlap between two stages. While this framework directly addresses upstream evolution through the shape of P_i, downstream sensitivity is addressed only indirectly by its magnitude and assumed to be constant over the progress of downstream. <u>In this research, we will integrate the probability of rework function with the impact function</u> to more generally address the interdependencies between upstream evolution, downstream sensitivity, rework and work intensities. In particular, we assume that under normal work intensities if stage i makes a prediction at time t, to be updated dt units of time later, then with probability $P_i(t)$ this prediction will turn out to be wrong and some portion $q_i(t).dt$ of the work performed between prediction and update must be performed again. We refer to the functions $P_i(t)$ and $q_i(t)$ as the standard probability and standard impact function respectively. In accordance with the extant literature we assume that $P_i(t)$ is non-increasing and $q_i(t)$ non-decreasing. Notice that the total rework $h_i(y_i)$ under standard work intensities can be obtained by integrating the product of impact and rework probability (PI –curve) over the entire interval $[s_i, d_i-1]$, that is over the overlap y_i as indicated in [Figure 2-12]" (Roemer and Ahmadi 2004, p 610).

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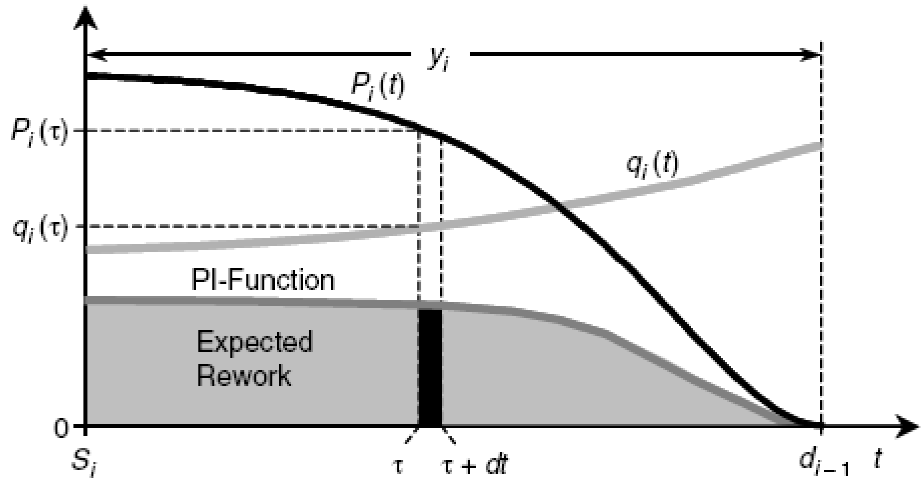

Figure 2-12: Probability of rework, impact, and PI-functions (Roemer and Ahamdi, 2004)

They continued: "Thus, whereas Roemer et al. (2000) assume that invariably all work under erroneous assumptions was futile, we acknowledge that some fraction of the work performed might be salvageable" (Roemer and Ahmadi 2004, p 610). Therefore, Roemer and Ahmadi largely modified the extended design function through introducing the rework impact and PI function. However, a number of critiques are made to their new approach in the next paragraphs.

Roemer and Ahmadi claim that "in accordance with the extant literature we assume that $P_i(t)$ is non-increasing" (2004, p 610). Therefore, $P_i(t)$ is shown as a non-increasing function of time in Figure 2-12. However, Roemer and Ahmadi do not provide a reference for their claim. During the literature review, a reference was not found to support the claim. In fact, the probability of rework is not necessarily non-increasing. The probability of rework can be decreasing or increasing or both depending on the

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conditions. However, if $P_i(t)$ represents the cumulative probability, then $P_i(t)$ is decreasing. In other words, the cumulative probability that the assumptions are wrong and change is required decreases as the overlapping time passes. In that case, integrating $P_i(t)$ or $P_i(t)q_i(t)$ is meaningless and the shaded area in Figure 2-12 cannot be the expected rework.

Roemer and Ahmadi also assumed that the impact function, $q_i(t)$, is non-decreasing. As before, no reference could be found to support this assumption in Roemer and Ahmadi's work (2004). However, assuming a non-decreasing function for impact is reasonable as the more work performed, the more rework will be required if a change is required. Therefore, $q_i(t)$ is shown as a non-decreasing function in Figure 2-12. But a question remains: why $q_i(t)$ does have a nonzero value at the outset (at S_i), when overlapping has just started? At S_i, overlapping has just started and the successor activity has made no progress. Therefore, if it is revealed that assumptions were wrong and change is required, the amount of rework is zero because the amount of work performed is zero. Hence, $q_i(t)$ has to start from zero at S_i.

The major critique goes back to assigning one single impact function to various degrees of overlapping. In Roemer and Ahamadi's model, a unique probability function, $P_i(t)$, and a unique impact function, $q_i(t)$, are allocated to the overlapping between stage *i* (activity *i*) and stage *i*-1 (activity *i*-1). These functions are fixed for different degrees of overlapping and what changes are the upper (d_i-*1*) and lower (S_i) boundaries. In other words, Roemer and Ahamadi address different degrees of overlapping by changing the upper (d_i-*1*) and lower (S_i) limits over the same probability function, $P_i(t)$, and impact function, $q_i(t)$. The researcher believes that this approach is incorrect. One impact

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function cannot represent different degrees of overlapping. Actually, each degree of overlapping has its own impact function. For further clarification, Figure 2-12 is regenerated in Figure 2-13 with a difference; a lower degree of overlapping (a smaller overlap) for the same two stages (activities) is also shown. The smaller overlap starts at S'_i. According to Roemer and Ahmadi, the probability and impact functions for the smaller overlap are parts of $P_i(t)$ and $q_i(t)$ which are surrounded by S'_i and d_i-*1*. Therefore, the expected rework is the area under PI function bounded by S'_i and d_i-*1*. However, the impact function must be less than the part of $q_i(t)$ bounded by S'_i and d_i-*1*. In fact, the impact value for the smaller overlap at S'_i should be the same impact value for the bigger overlap at S_i. The reason is that the impact value is predominantly dependent on how much stage *i*-1 (successor activity) has progressed already (Loch and Terwiesch 1998; Roemer and Ahmadi 2004). Both cases have very similar work progresses for stage *i*-1. Therefore, the amount of rework, or the impact, should be very similar as well. As explained earlier, the impact functions for both cases should be zero at S_i and S'_i.

According to the above discussion, the functions used by Roemer and Ahmadi to address different degrees of overlapping cannot be correct. In the rest of their paper, they have tried to formulate and solve the overlapping time-cost trade-off problem by means of the erroneous rework functions. In addition, in both papers (Roemer et al. 2000; Roemer and Ahmadi 2004), tedious and complicated mathematical equations and proofs have been used which are difficult to follow and repeat.

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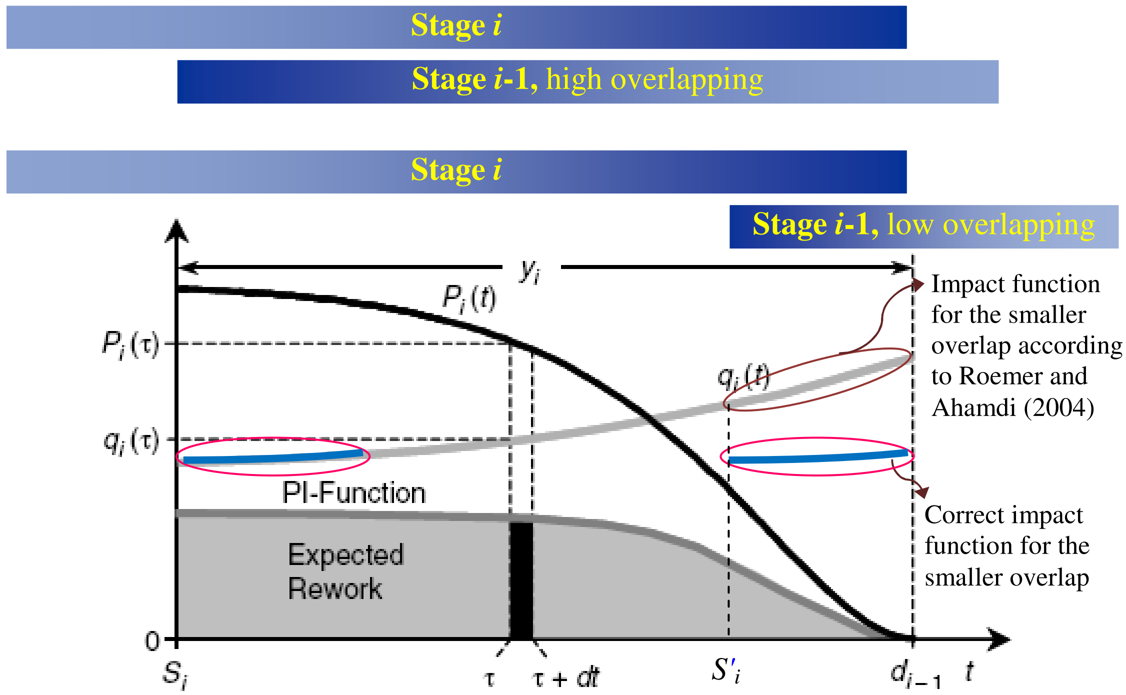

Figure 2-13: Probability of rework, impact, and PI-functions for two degrees of overlapping (Adapted from Roemer and Ahamdi, 2004)

Despite the above critiques about the mathematical link between overlapping and rework, Roemer and Ahmadi could clearly explain the concept of generating rework as a result of overlapping. Furthermore, their effort to optimize overlaps in a full chain of activities distinguish them from the majority of researchers who only investigated overlapping between two activities isolated from other activities.

It should be remembered that Roemer and Ahmadi's research has a focus on product development, not construction projects. In addition, they limited their research to one chain of activities (one path). Therefore, they did not study a network of activities

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with multiple paths and with multiple predecessors to some activities. Consequently, they were not concerned about the critical path, the activities on the critical path and the activities not on the critical path, or the fact that the critical path may be changed during project execution. Another limitation is that their optimization does not cover the condition in which two overlaps overlap (concurrent overlapping or cascade of overlaps). In the current PhD research it has been tried to overcome such limitations.

Another research which has a close proximity to the current PhD thesis has been conducted by Gerk and Qassim (2008) who introduced a mixed-integer nonlinear programming model for the acceleration of projects. In their research, they suggest that project acceleration is possible through three different techniques: activity crashing, activity overlapping, and activity substitution. According to them, each of these techniques is associated with additional costs to the project. With activity crashing, the additional costs are incurred as more resources are allocated to the activity. In activity overlapping, the additional costs are mainly related to the possible rework. In activity substitution, where a different technology or method is utilized to perform the activity, unplanned acquisition costs are the source of additional costs. To accelerate a project at minimum costs, which activities are to be crashed, overlapped, and substituted and to what extent need to be clarified. Gerk and Qassim modeled this problem and developed an objective function aimed at minimizing the total cost of project acceleration, and a large number of constraint functions. For the overlapping cost, they have assumed that a linear relation between overlapping cost and overlapping duration exists and is available (which is an optimistic assumption).

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Gerk and Qassim noted that they have used a time-based network (TBN) in model development, and utilized software package LINGO for the computational implementation of the model. However, they did not provide further information about the computational implementation and how the numerous objective and constraint functions are calculated and how the project network calculations are performed. Finally, they have examined the application of their model with four examples to show the efficiency of the model. In the examples, Gerk and Qassim have focused on critical path activities to accelerate the project and disregarded the rest of activities. However, in the real world noncritical activities may become critical when the project is accelerated.

The research by Gerk and Qassim is the first research in which all three types of project acceleration techniques, i.e. crashing, overlapping, and substitution, are simultaneously investigated. Like similar research studies about overlapping, the challenge of overlapping functions is still unsolved in their research. They explain this classic challenge as follows:

> "In so far as input data are concerned, they are normally available or easy to estimate with the exception of L_{ip} (fraction of overlapping time of activities i and p that is consumed in rework). This parameter has received significant attention (in the literature). In view of the continuously increasing interest in concurrent engineering, it is natural to expect that reliable models would be available in the near future with a view to predicting and/or estimating L_{ip} with confidence" (2008, p 593).

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As noted earlier, unfortunately, the details of network calculations and optimization computations have not been explained in Gerk and Qassim's paper. But the examples they have offered indicate that their model does not address the changes in critical path due to changes in the duration of overlaps and/or activities. From this point of view, Gerk and Qassim's model is similar to Roemer and Ahamadi's model (2004). However, Gerk and Qassim's model has one advantage to Roemer and Ahmadi's model which is related to the ability of considering more than one path in calculations. In other words, Gerk and Qassim's model takes all activities, either sequential or parallel, into account for network calculations.

The current research study is, to some extent, inspired by the models developed in the research studies by Roemer et al. (2000), Roemer and Ahamdi (2004) and Gerk and Qassim (2008), in that all of them have proposed models which optimize overlaps all together, not separately. However, a common criticism exists to all these research studies: The assumption is that either the project has only one chain of activities which naturally is the critical path (Roemer and Ahamdi 2004), or at least the overlaps under study are on the critical path of the project (Gerk and Qassim 2008). However, construction projects have several paths, one or some of the paths are critical, and new critical paths emerge when different overlapping strategies are applied. The current PhD research tries to circumvent some of the above criticisms and find a comprehensive answer to the research question: **Which activities have to be overlapped and to which extent to reduce the project duration at the minimum cost**? Specifically, the current PhD research tries to develop an *overlapping optimization algorithm* which is able to:

- Determine which activities have to be overlapped

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- Determine the degree of overlapping
- Handle multi-path networks
- Take all activities, critical and non-critical, into account and follow the critical path if the critical path changes or new critical paths emerge
- Take resource limitations into account
- Take schedule constraints into account
- Handle all types of activity dependencies (FS, SS, FF, SF)

2.3 Optimization techniques for construction time-cost trade-off problems

The overlapping optimization problem is inherently a multi-objective (bi-objective) optimization problem, as both time and cost have to be minimized at the same time; while not independent, they are intricately related. Therefore, the overlapping optimization problem is also a type of time-cost trade-off problem.

Many researchers classify techniques for optimizing time-cost trade-off problems into three categories (Hegazy 1999; Zheng et al. 2005; El-Gafy 2007; Xiong and Kuang 2008; Ng and Zhang 2008):

1. The heuristic methods: Fondahl's (1961) method, structural model (Prager 1963), effective cost slope model (Siemens 1971), and structural stiffness method (Moselhi 1993)
2. Mathematical approaches: linear programming (LP) (Kelly 1961; Hendrickson and Au 1989; Pagnoni 1990), integer programming (IP) (Meyer and Shaffer 1963; Patterson and Huber 1974), a hybrid of LP and IP (Liu et al. 1995; Burns et al. 1996), and dynamic programming (Robinson 1975; Elmaghraby 1993).

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3. Evolutionary-based optimization algorithms (EOAs) or meta-heuristic algorithms (Feng et al. 1997; Li and Love 1997; Hegazy 1999; Zheng et al. 2005; Elbeltagi et al. 2005; El-Gafy 2007; Xiong and Kuang 2008; Ng and Zhang 2008).

Although the heuristic methods and mathematical approaches have strengths, they are criticised by researchers as both techniques may not always lead to optimal solutions. In particular, neither the heuristic methods nor mathematical approaches can solve the multi-objective time-cost trade-off problem efficiently.

Since the early 1960s, heuristic methods and mathematical programming models have been used as two distinct categories of solutions. In the literature, various models of both categories have been developed and their performance compared. Specific details of these efforts can be found in Feng et al. (1997) and Li and Love (1997). The main criticisms to mathematical programming models have been their complex formulations, computational-intensive nature, applicability to small-size problems, and local minimum solutions (Moselhi 1993; Feng et al. 1997; Li and Love 1997; Hegazy 1999). Heuristic approaches which use simple rules of thumb, have been criticized for not being able to guarantee optimum solutions, despite their easy-to-understand formulation and acceptable solutions (Feng et al. 1997; Li and Love 1997). They also lack mathematical rigour (Hegazy 1999).

Evolutionary Optimization Algorithms (EOA) have been utilized by researchers to cope with the weaknesses of mathematical and heuristic approaches. EOAs are stochastic search methods that mimic the metaphor of natural biological evolution and/or the social behaviour of species. The behaviour of such species is guided by learning,

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adaptation, and evolution. EOAs are robust search algorithms that are applicable to large and complex problems. However, EOAs typically have time consuming calculation processes.

Amongst various EOAs, Genetic Algorithms (GAs) have been commonly used for deriving optimal solutions for multi-objective problem domains. First introduced by Holland (1992), GAs are based on the mechanics of natural selection and genetics and search through the decision space to identify optimal solutions (Goldberg 1989). In addition to GA, other EOA techniques introduced by researchers were inspired by different natural processes. Examples include the Ant Colony Optimization (Dorigo et al. 1996), memetic algorithms (Moscato 1989), particle swarm optimization (Kennedy and Eberhart 1995) and shuffled frog leaping approach (Eusuff and Lansey 2003). Elbeltagi et al. (2005) employed all these techniques for solving discrete time–cost trade-off problems and compared their performance and efficiency.

In this chapter, a number of evolutionary-based optimization algorithms (EOAs) are introduced and discussed. At the end of the chapter, one technique which is most suitable to solve the overlapping optimization problem is introduced.

2.3.1 Genetic Algorithms (GA)

Genetic Algorithms (GA) are the most popular meta-heuristic algorithms and are able to handle any type of optimization, i.e. continues optimization, integer optimization, discrete optimization, and mixed optimization.

Genetic Algorithm is an evolutionary computation technique inspired by the principles of natural selection to search a solution space. The philosophy behind GAs is similar to the survival of the fittest principle in nature. Stronger species in nature can live

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longer, therefore they find more chances to mate and reproduce their strong genes in the next generations. Weaker species live shorter and are less likely to mate; their weak genes will die with them (Dehghan et al 2011). GAs use the same principle to solve complex multi-objective optimization problems. They randomly generate an initial population of solutions. These solutions are expressed in terms of genomes or chromosomes. Each chromosome is a string of several genes, and each gene can have several values. The strength, or fitness, of each solution is determined by evaluating its performance against an objective function.

The initial population of solutions must evolve to generate better solutions. This is possible by exchanging the solutions genes with each other (marriage or crossover) to generate new solutions (offspring genes) (Figure 2-14). The evolution is more efficient if stronger genes are given more chance to crossover than weaker genes. New solutions are evaluated and if they are better than the weakest solutions in the population, they will replace them. The result is a better generation in terms of survival abilities. This process is repeated to generate better and better solutions until a satisfactory population is generated. The fittest member of the population is the best achievable (might be absolute optimum or near-to-optimum) and final solution.

Unlike crossover that resembles the main natural method of reproduction, mutation is a rare process that resembles the phenomenon of a sudden generation of an odd offspring that might become a genius. The mutation process can break any stagnation in the evolutionary process, avoiding local optima (Hegazy 1999). Therefore, once in a while one of the offspring chromosomes is randomly selected and its genes are arbitrarily changed to generate a different chromosome.

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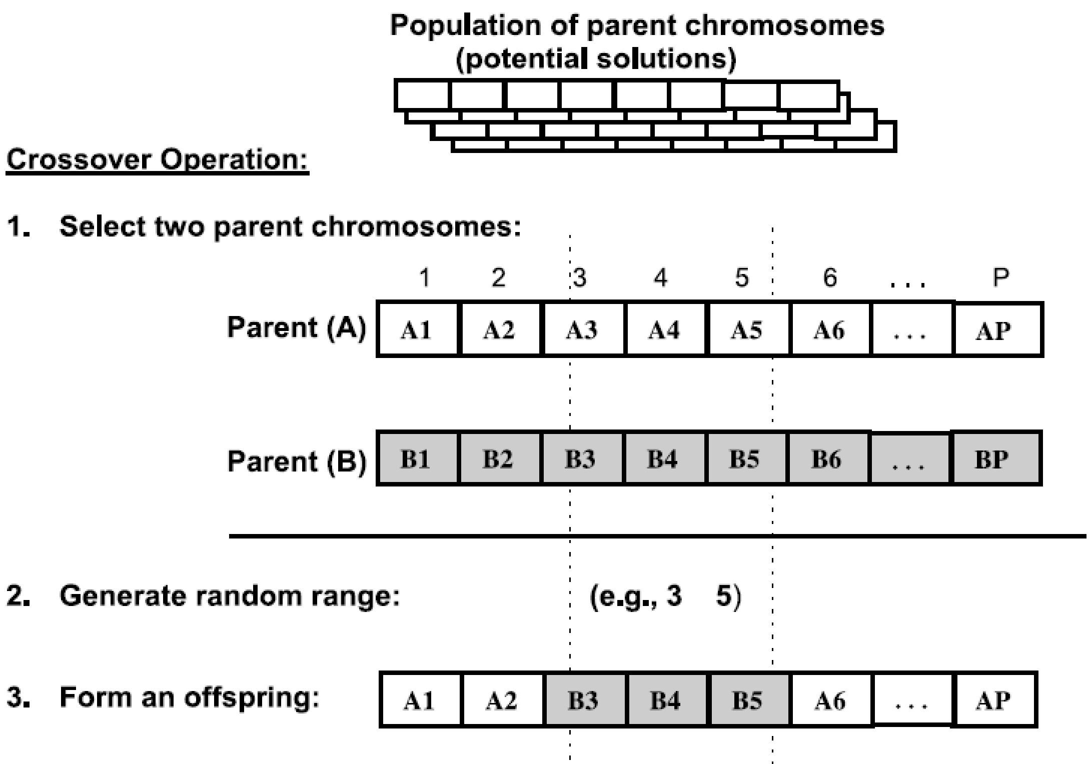

Figure 2-14: Crossover operation to generate offspring genes (Hegazy 1999)

The robustness of GAs and their ability to locate a near-global optimum in time–cost problems have been reported. For instance, Feng et al. (1997) developed a GA model that was essentially an improvement of a hybrid linear programming/integer programming model devised earlier by Liu et al. (1995). The GA model developed by Feng et al. was implemented on a spreadsheet by considering each task's construction options to generate the shape of the optimum trade-off curve for direct cost. Indirect cost was then added to determine the optimum time-cost trade-off (TCT) strategy. The model, however, is limited to simple networks with finish-to-start relationships and is not

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capable of dealing with limited resources. Feng et al. (2000) further developed a stochastic GA model for construction time-cost trade-off problems.

The model by Li and Love (1997), on the other hand, was formulated to produce the times, in real numbers, by which each critical activity should be reduced. The study also introduced some modifications to basic genetic algorithms that reduced computational time. The model, however, did not consider the formation of other critical paths during the crashing process and was limited to continuous, as opposed to discrete, variables for crashing times. Also, similar to the other study, resource-constrained situations were not taken into account.

Hegazy (1999) built on the findings of previous GA models and developed a model that circumvents some of the previous limitations. For example, his model was able to handle resource constraints and discrete values for crashing times and most importantly, could take into account the emergence of other critical paths during the crashing process. Therefore, Hagazy's model was a very robust model at the time and several researchers took the same direction. The overlapping optimization algorithm and its computer implementation in the current PhD research were highly inspired by Hegazy's research. Therefore, it is quite worthy to describe the development and implementation of Hegazy's GA model in more detail.

A clarification of what a time-cost trade-off problem really means can be helpful. Construction projects involve many individual activities or tasks. Each task can be performed in various ways in terms of methods, crew sizes, equipment, and technologies. Each alternative way has its own cost and time of execution. In general, there is a trade-off between the time and the cost to complete a task; the less expensive the resources, the

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longer the duration of the task (Feng et al. 1997). For example, using more productive equipment or hiring more workers may save time, but the cost could increase. This relationship is illustrated in Figure 2-15 (Hegazy 1999). Each of the options A, B, C or D, represents an alternative way of performing the subject activity.

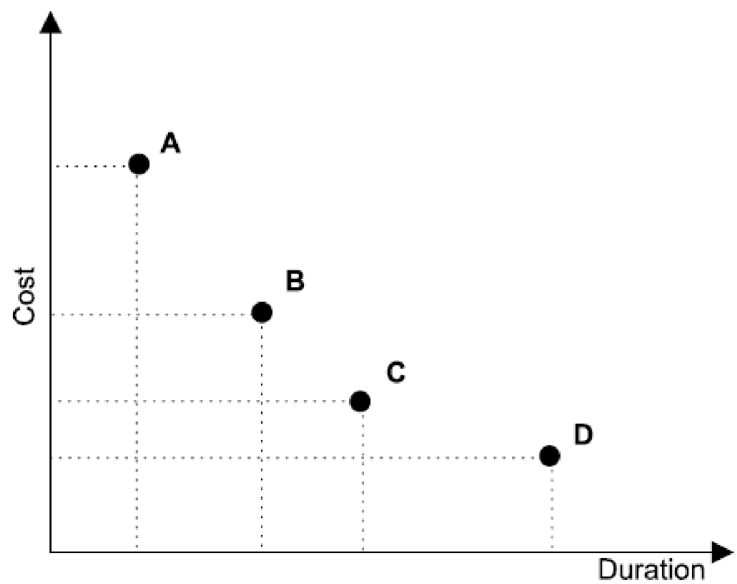

Figure 2-15: Typical relationship between time and cost of activity (Hegazy 1999)

Feng et al. (1997) used a sample network to apply their GA algorithm to investigate the algorithm's efficiency and performance. Hegazy used the same sample network which encompassed 18 activities as shown in Figure 2-16. Today, Feng et al.'s 18-activity network has become a popular network as it has been used by many researchers investigating different meta-heuristic optimization techniques as a reference example to compare the performance and efficiency of the suggested optimization techniques.

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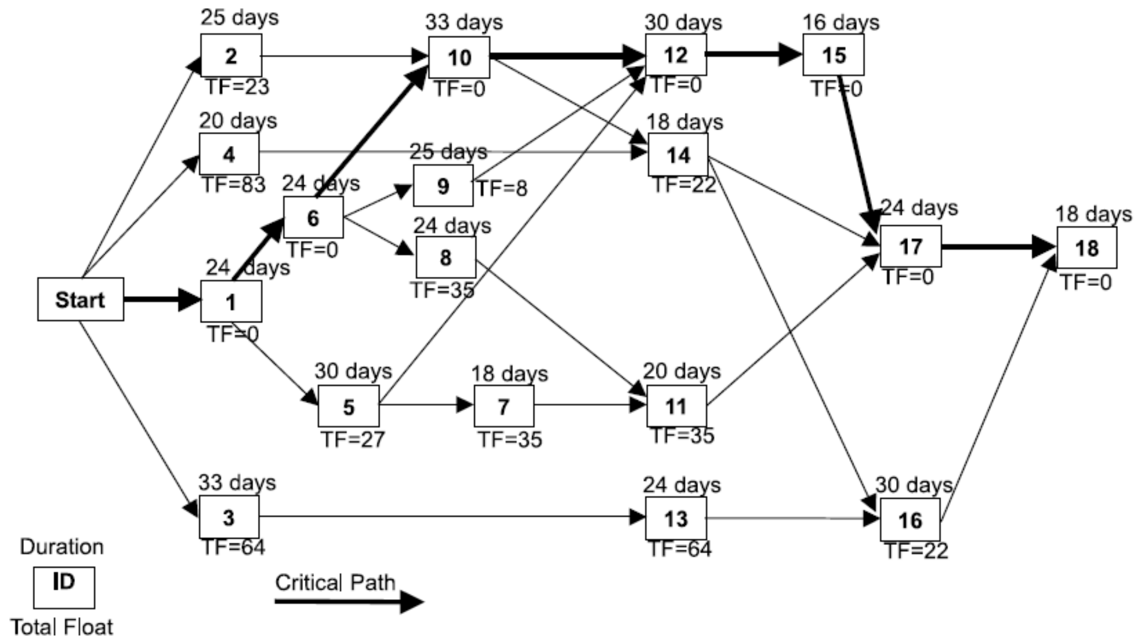

Figure 2-16: Network of the case study (Hegazy 1999)

Activities in the network have between 3 to 5 methods of construction. The associated duration and cost data for each method is also shown in Table 2-1.

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Table 2-1: Case study data (Hegazy 1999)

Activity	Predecessors	Alternative methods of construction									
		Method 1		Method 2		Method 3		Method 4		Method 5	
		Duration (days)	Cost ($)	Duration (days)	Cost ($)	Duration (days)	Cost ($)	Duration (days)	Cost ($)	Duration (days)	Cost ($)
1	—	14	2 400	15	2 150	16	1 900	21	1 500	24	1 200
2	—	15	3 000	18	2 400	20	1 800	23	1 500	25	1 000
3	—	15	4 500	22	4 000	33	3 200	—	—	—	—
4	—	12	45 000	16	35 000	20	30 000	—	—	—	—
5	1	22	20 000	24	17 500	28	15 000	30	10 000	—	—
6	1	14	40 000	18	32 000	24	18 000	—	—	—	—
7	5	9	30 000	15	24 000	18	22 000	—	—	—	—
8	6	14	220	15	215	16	200	21	208	24	120
9	6	15	300	18	240	20	180	23	150	25	100
10	2, 6	15	450	22	400	33	320	—	—	—	—
11	7, 8	12	450	16	350	20	300	—	—	—	—
12	5, 9, 10	22	2 000	24	1 750	28	1 500	30	1 000	—	—
13	3	14	4 000	18	3 200	24	1 800	—	—	—	—
14	4, 10	9	3 000	15	2 400	18	2 200	—	—	—	—
15	12	12	4 500	16	3 500	—	—	—	—	—	—
16	13, 14	20	3 000	22	2 000	24	1 750	28	1 500	30	1 000
17	11, 14, 15	14	4 000	18	3 200	24	1 800	—	—	—	—
18	16, 17	9	3 000	15	2 400	18	2 200	—	—	—	—

Hegazy set the chromosome structure as a string of elements, one for every activity, containing an index to the method of construction, as shown in Figure 2-17. As such, each chromosome has 18 values (genes) and the values in each chromosome represent one possible project solution.

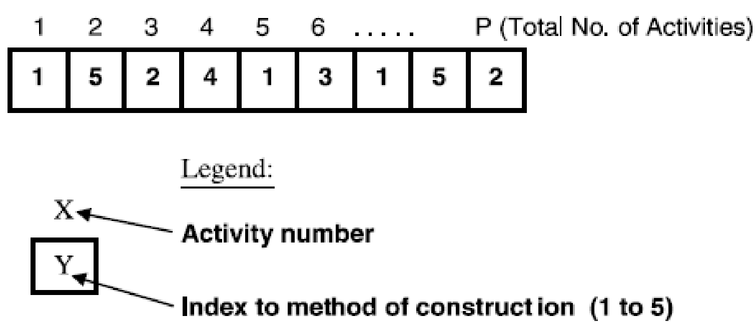

Figure 2-17: Chromosome formation (Hegazy 1999)

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Each chromosome represents a total duration and a total cost for the project. The total duration and cost depend on the methods utilized for each activity. To calculate the time, Hegazy suggested using a commercial scheduling software, Microsoft Project 1995. This facilitated the implementation process, since network calculations and resource levelling are easily performed in Microsoft Project and were not required to be programmed independently. Also, cost calculations could be programmed in the macro environment of Microsoft Project. The total cost is the summation of individual activity costs and project daily indirect costs, plus daily incentive amounts if the project is finished early, or minus project daily liquidated damages if the project is finished late. The total cost is the fitness value of the problem; therefore, the smaller the fitness value, the more fit the chromosome (less total cost).

GA's evolutionary optimization starts with random generation of a population of parent chromosomes. Then the fitness of each chromosome in this population is evaluated and, accordingly, its relative merit is calculated as the chromosome's fitness divided by the total fitness of all chromosomes. The reproduction process among the population members takes place by either crossover or mutation. Each of the two parent chromosomes is randomly selected in a manner such that its probability of being selected is proportional to its relative merit, i.e. more probability for chromosomes with lower total costs. This ensures that the best chromosomes have a higher likelihood of being selected, without violating the diversity of the random process. Also, the exchange of information between the genes of two parent chromosomes is done randomly (Figure 2-14). To ensure the evolution process is not trapped in local optima, once in a while a mutation is applied. Once an offspring is generated by either method, its total cost is

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evaluated and the chromosome can be retained only if its total cost is lower than others in the population. The process is continued for a large number of offspring generations until an optimum chromosome emerges.

As noted earlier, the way Hegazy utilized Genetic Algorithms to solve the traditional time-cost trade-off problem inspired the generation of the overlapping optimization algorithm suggested in the current PhD thesis. Chapter 4 explains how a similar approach is taken to solve the overlapping time-cost trade-off problem.

2.3.2 Swarming

Swarming, or *swarm behaviour*, is a collective behaviour exhibited by animals of similar size which move or migrate in a direction together. As a term, swarming is applied particularly to insects, but can also be applied to any other animal that exhibits swarm behaviour. The term *flocking* is usually used to refer specifically to swarm behaviour in birds, *herding* to refer to swarm behaviour in quadrupeds, and *shoaling* or *schooling* to refer to swarm behaviour in fish.

In brief, swarming is the collective motion of a large number of self-propelled entities (O'Loan, O. J. and Evans 1999). From the perspective of the mathematical modeller, it is an emergent behaviour arising from simple rules followed by individuals and does not involve any central commandment or coordination.

According to mathematical models of animal swarms, individual animals follow three simple rules:

1. They move in the same direction as their neighbours
2. They remain close to their neighbours
3. They avoid collisions with their neighbours

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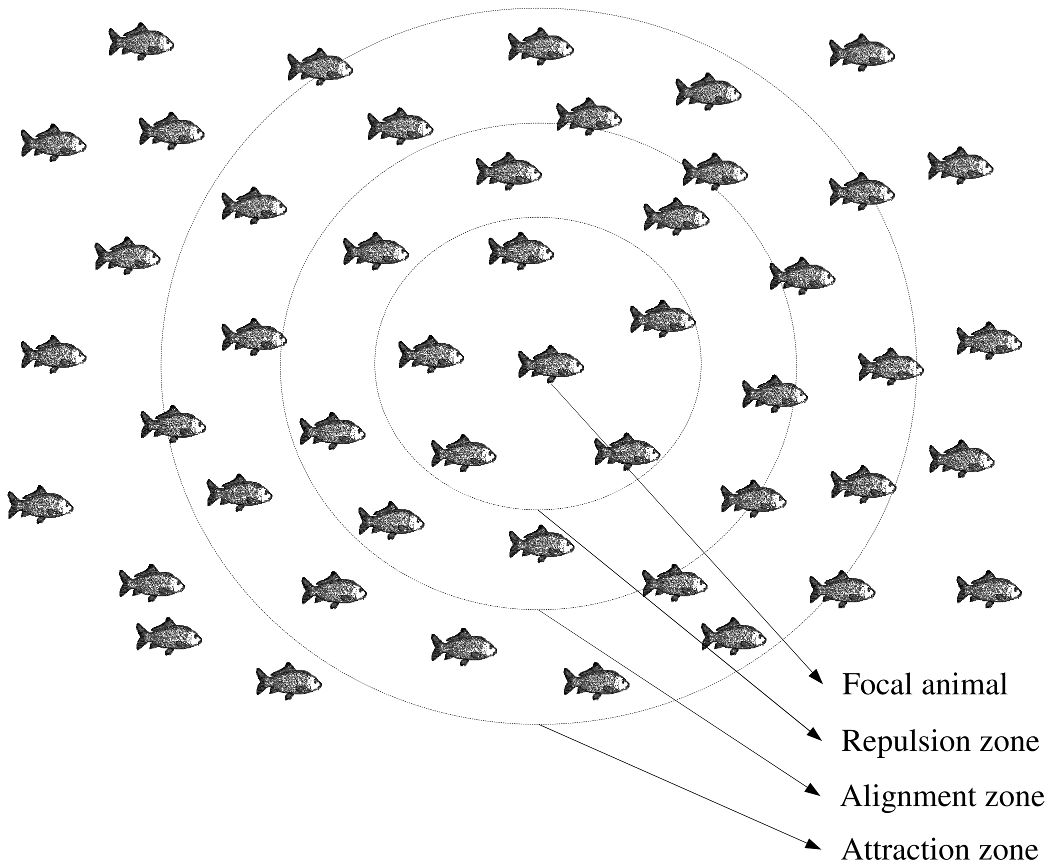

Figure 2-18: Concentric zones in swarms

Some swarming or flocking models use variations on these rules, often implementing them by means of concentric "zones" around each animal (Figure 2-18). In the zone of repulsion which is very close to the animal, the focal animal watches to distance itself from its neighbours to avoid collision. Slightly further away in the zone of alignment, the focal animal tries to align its direction of motion with its neighbours. In the attraction zone which is the outermost zone and extends as far away from the focal animal as it is able to sense, the focal animal seeks to move towards a neighbour.

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Swarm intelligence is the collective behaviour of natural or artificial decentralized and self-organized systems. The concept has applications in artificial intelligence. Swarm intelligence systems are typically made up of a population of simple *agents* or *boids* interacting locally with one another and with their environment. The agents follow very simple rules, and although there is no centralized commandment dictating how individual agents should behave, local and to a certain degree random interactions between such agents lead to the emergence of intelligent global behaviour, unknown to the individual agents.

Two popular swarm inspired methods in computational intelligence areas are Ant Colony Optimization (ACO) (Dorigo et al. 1996) and Particle Swarm Optimization (PSO) (Kennedy and Eberhart 1995). ACO was inspired by the behaviours of ants and has many successful applications in discrete optimization problems. The particle swarm concept originated as a simulation of a simplified social system. The original intent was to graphically simulate the choreography of a bird flock or fish school. However, it was found that the particle swarm model can be used as an optimizer to solve both continuous and discrete optimization problems.

2.3.2.1 Particle Swarm Optimization (PSO)

Particle swarm optimization (PSO) is a swarm algorithm that was developed in 1995 by Kennedy and Eberhart (Kennedy and Eberhart 1995; Kennedy 1997). PSO mimics a flock of birds that randomly searches for a destination (e.g. a river for fish) in an area and communicate together as they fly. The birds do not know where the destination is, but they know how far it is in each iteration. So the effective strategy is to follow the bird nearest to the destination. Each bird looks in a specific direction, and then

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when communicating together, birds can identify the bird in the best location. Accordingly, each bird speeds towards the best bird using a velocity that depends on its current position. Then each bird investigates the search space from its new local position, and the process repeats until the flock reaches the destination. It is important to note that the process involves both social interaction and intelligence so that birds learn from their own experience (local search) and also from the experience of others around them (global search).

Particle swarm optimizer uses the above scenario to solve the optimization problems. In PSO, each solution is a 'bird' in the flock and is referred to as a 'particle' in the search space. All particles have fitness values which are evaluated by the fitness function to be optimized, and have velocities which direct the flying of the particles. The particles fly through the problem space by following the current optimum particles. PSO initially seeds a population with random particles (solutions) and then searches for optima in the problem space through successive generations using stochastic optimization. In every iteration, each particle is updated by following two "best" values. The first one is the best solution achieved so far by the particle, and therefore is "particle's best value" (p-Best). Each particle stores its current position as well as the best solution it has achieved so far. The second "best" value is the best value obtained so far by any particle in the population. This best value is a global best value (g-Best). Some variations of PSO algorithms use a third value as well. The whole swarm is divided into smaller groups and particles with the best values within each group have the local best values (l-Best). Therefore, each particle has one particle best value, but only a few particles may also

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have a local best value. Only one particle in the whole swarm holds all particle, local, and global best values at the same time (Figure 2-19).

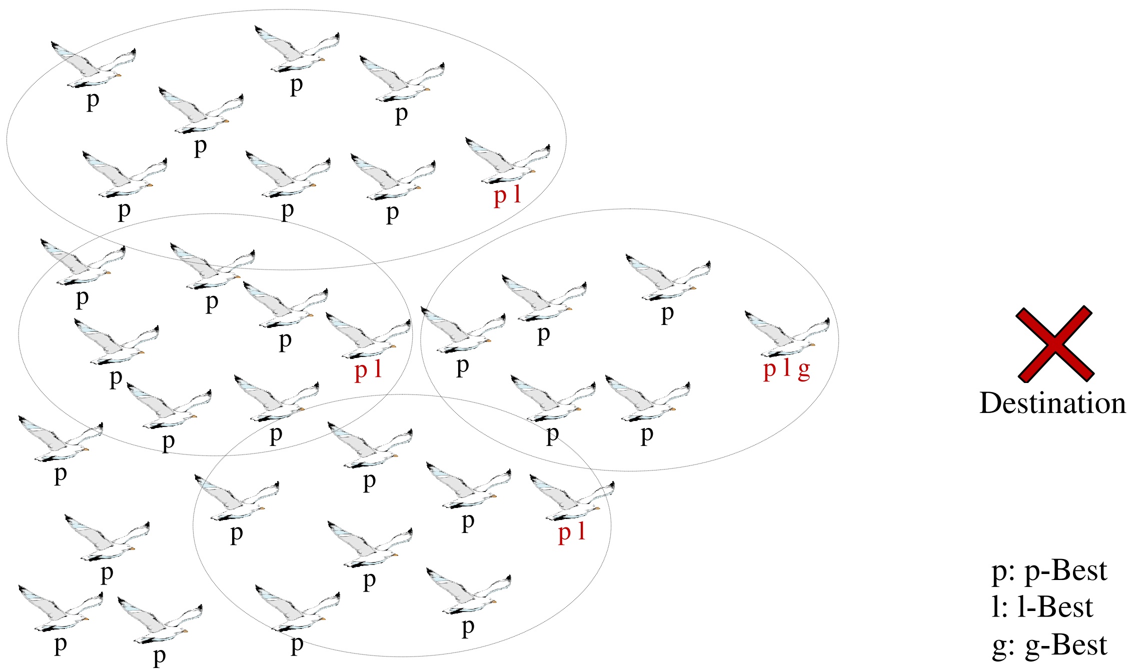

Figure 2-19: Best values in Particle Swarm Optimization

At each iteration, the particle swarm optimiser accelerates each particle toward its optimum locations according to simple mathematical rules. For this purpose, particle velocity and position is updated by the following equations 2.1 and 2.2:

$$v_{k+1} = v_k + c_1 r_1 (p - x_k) + c_2 r_2 (g - x_k) \quad [2.1]$$

$$x_{k+1} = x_k + v_{k+1} \quad [2.2]$$

v_{k+1} = new particle velocity

v_k = current particle velocity

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c_1 = learning factor

c_2 = learning factor

r_1 = a random number between (0,1)

r_2 = a random number between (0,1)

p = current particle best value (solution)

g = current swarm best value (solution)

x_k = current particle position (solution)

x_{k+1} = new particle position (solution)

Particles' velocities on each dimension are clamped to a maximum velocity v_{max}. If the sum of accelerations causes the velocity on that dimension to exceed v_{max}, which is a parameter specified by the user, then the velocity on that dimension should be limited to v_{max}.

Particle swarm optimization has been applied in many areas (Poli 2008). It has few parameters to adjust, and a version that works well for specific applications can also work well with minor modifications across a range of related applications.

Researchers have used PSO to solve time-cost trade-off problems. For example, Yang (2007) applied PSO on a fast-food outlet construction project with a focus on obtaining the entire Pareto front in a single run and treating all existing types of activity time-cost functions, such as linear, nonlinear, discrete, discontinuous, and a hybrid of the above. Zhang and Li (2010) examined PSO on Feng et al.'s 18-activity construction project (Feng et al. 1997). Rahimi and Iranmanesh (2008) used PSO; however, they added "quality" to the trade off and therefore tried to solve a time-cost-quality trade-off (TCQT) optimization problem. Zhang and Xingi (2010) also focused on TCQT problems,

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but in terms of imprecise or vague data rather than precise numbers for cost, time, and quality. Therefore they used a fuzzy-multi-objective particle swarm optimization. All of the above-named researchers reported good results and performance for PSO algorithms.

2.3.2.2 Ant Colony Optimization (ACO)

Ant colony optimization is another type of widely used swarm algorithm which was inspired by the behaviours of ants, and has been effective for solving discrete optimization problems related to swarming. The algorithm was initially proposed by Marco Dorigo (Colorni et al. 1991; Dorigo 1992; Dorigo et al. 1996; Dorigo and Stutzle 2002, Dorigo and Blum 2005), and has since been diversified to solve a wider class of numerical problems.

The social behaviour of ants is based on self-organization, a set of dynamic mechanisms ensuring that the system can achieve its global aim through low-level interactions between its elements. A key feature of this interaction is that the system elements use only local information. Therefore, any centralized control and reference to the global pattern representing the system in the external world are ruled out. Four components have to interact so that the self-organization is emerged. These components are (Shtovba 2005):

(1) Multiple renewal;

(2) Randomness;

(3) Positive feedback;

(4) Negative feedback.

Ants communicate in two ways. One way is direct communication (e.g. mandible and visual contacts) and the other way is indirect communication, which is called

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stigmergy. *Stigmergy* is a form of communication separated in time, when one participant in the communication modifies the environment, and the others make use of this information later, when they occur in a neighbourhood of the modified environment. Biologically, *stigmerg*y is realized through *pheromones*, a special chemical that is deposited as trail by ants when they move (Shtovba 2005). Ants essentially move randomly (Dorigo et al., 1996); but when ants encounter pheromone trails, they may follow the trails. Further, ants are more likely to move along paths with higher concentrations of pheromone than paths with lower concentrations. As more ants travel on a path with higher pheromone intensities, the pheromones on this path build up further, thereby making it more likely to be chosen by other ants. This form of positive reinforcement can be used to find the shortest path between the nest and a food source. Ant system optimization algorithms are inspired by the fact that ants are able to find the shortest route between their nest and a food source, even though they have poor vision and poor communication skills, and a single ant faces a poor probability of longevity (Dorigo et al., 1996).

The main difference between the artificial ant colonies (ant systems) as an optimization tool and the real ants are that artificial ants have some memory, are not completely blind, and they live in an environment where time is discrete (Dorigo et al., 1996).

Dorigo et al. explain the ant colony metaphor with an example shown in Figure 2-20. There is a path along which ants are walking (for example from food source A to the nest E, and vice versa, see (a)). Suddenly, an obstacle appears and the path is cut off. So at position B the ants walking from A to E (or at position D those walking in the

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opposite direction) have to decide whether to turn right or left (Figure 2-20(b)). The choice is influenced by the intensity of the pheromone trails left by preceding ants. A higher level of pheromone on the right path gives an ant a stronger stimulus and thus a higher probability to turn right. The first ant reaching point B (or D) has the same probability to turn right or left (as there was no previous pheromone on the two alternative paths). Because path BCD is shorter than BHD, the first ant following it will reach D before the first ant following path BHD (Figure 2-20(c)). The result is that an ant returning from E to D will find a stronger trail on path DCB, caused by the half of all the ants that by chance decided to approach the obstacle via DCBA and by the already arrived ants coming via BCD: they will therefore prefer (in probability) path DCB to path DHB. As a consequence, the number of ants following path BCD per unit of time will be higher than the number of ants following EHD. This causes the quantity of pheromone on the shorter path to grow faster than on the longer one, and therefore the probability with which any single ant chooses the path to follow is quickly biased toward the shorter one. The final result is that very quickly all ants will choose the shorter path.

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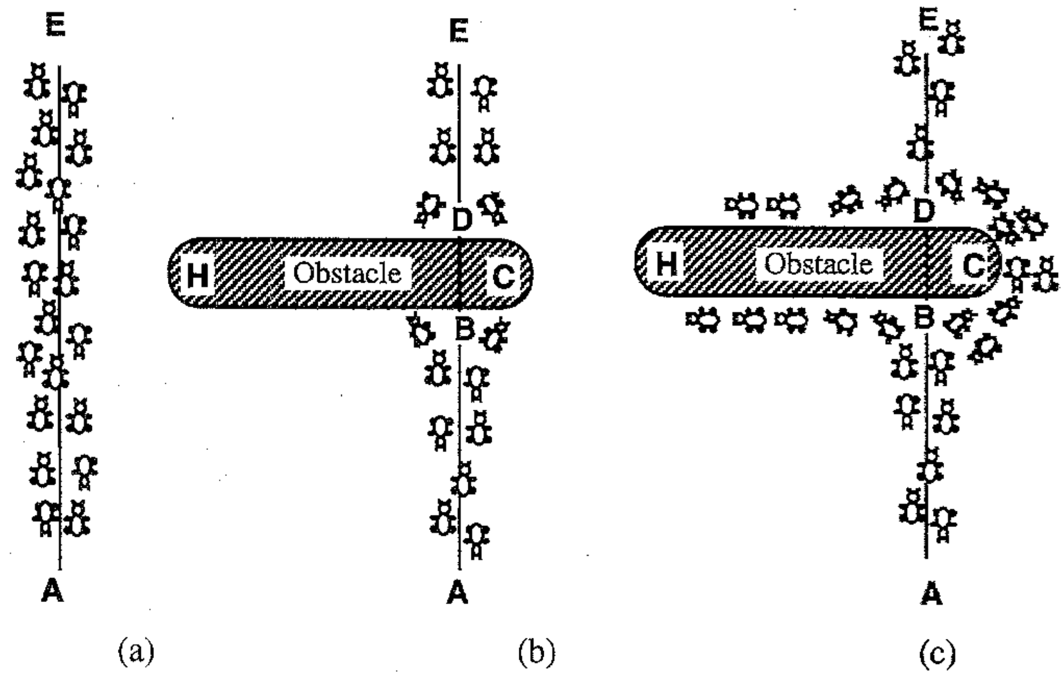

Figure 2-20: An example with real ants. (a) Ants follow a path between points A and E. (b) An obstacle is interposed; ants can choose to go around it following one of the two different paths with equal probability. (c) On the shorter path more pheromone is laid down. (Dorigo et al. 1996)

Consider the graph of Figure 2-21(a), which is a possible Ant System interpretation of the situation of Figure 2-20(b). To express the concept in another way, suppose that the distances between D and H, between B and H, and between B and D-via C-are equal to 1, and let C be positioned half the way between D and B (see Figure 2-21(a)). Now let us consider what happens at regular discretized intervals of time: t = 0,1,2, new ants come to B from A, and 30 to D from E at each time unit, each ant walks at a speed of 1 per time unit, and while walking an ant lays down at time t a pheromone

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trail of intensity 1, which, to make the example simpler, evaporates completely and instantaneously in the middle of the successive time interval (t + 1, t + 2). At t = 0 there is no trail yet, but 30 ants are at B and 30 at D. Their choice about which way to go is completely random. Therefore, on the average 15 ants from each node will go toward H and 15 toward C (Figure 2-21(b)). At t = 1 the 30 new ants that come to B from A find a trail of intensity 15 on the path that leads to H, laid by the 15 ants that went that way from E, and a trail of intensity 30 on the path to C, obtained as the sum of the trail laid by the 15 ants that went that way from B and by the 15 ants that reached B coming from D via C (Figure 2-21(c)). The probability of choosing a path is therefore biased, so that the expected number of ants going toward C will be the double of those going toward H: 20 versus 10 respectively. The same is true for the 30 new ants in D which came from E. This process continues until all of the ants will eventually choose the shortest path. The idea is that if at a given point an ant has to choose among different paths, those which were heavily chosen by preceding ants (that is, those with a high trail level) are chosen with higher probability. Furthermore, high trail levels are synonymous with short paths.

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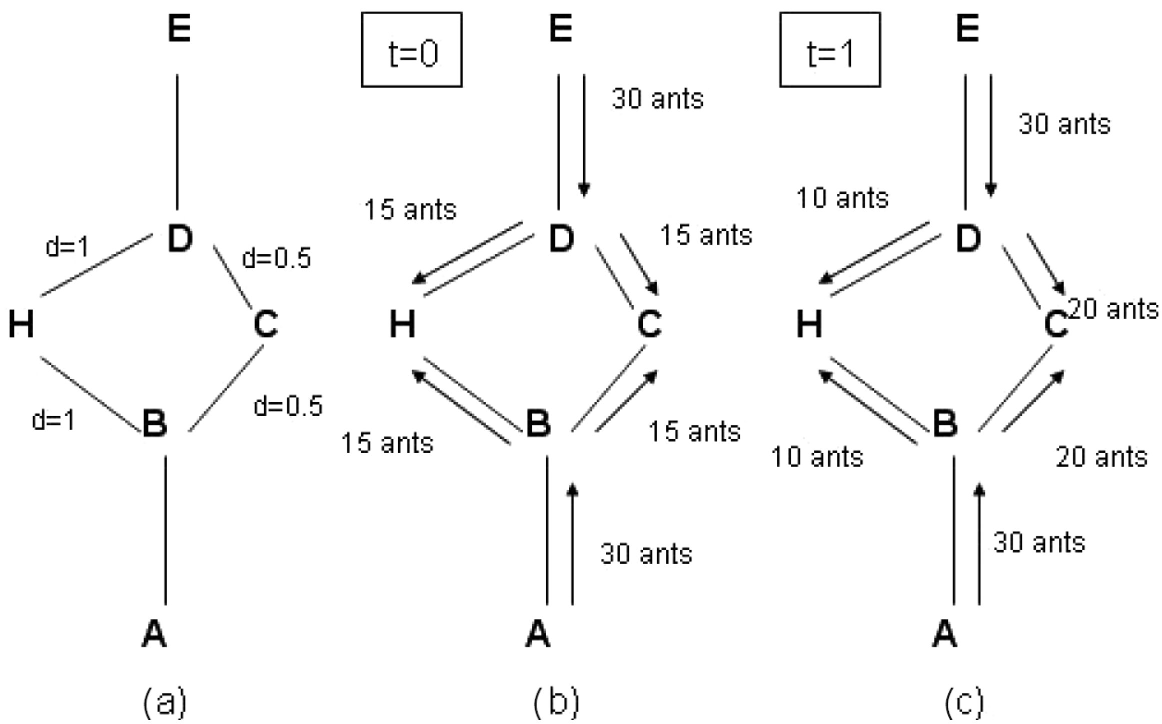

Figure 2-21: An example with artificial ants. (a) The initial graph with distances. (b) At time t = 0 there is no trail on the graph edges; therefore ants choose whether to turn right or left with equal probability. (c) At time t = 1 trail is stronger on shorter edges, which are therefore, in the average, preferred by ants. (Dorigo et al. 1996)

Ant colony optimization has been used by several researchers to solve time-cost trade-off problems to optimize the total project duration and total cost simultaneously in construction project management. Ng and Zhang (2008) used the same 18-activity construction project as previously used in several other research studies on various meta-heuristic methods (e.g. Feng et al.1997; Hegazy 1999; Zheng et al. 2005; Elbeltagi et al. 2005) to show the robustness of their algorithm, Ant Colony System - Time Cost Trade-off (ACS-TCO), which was a modified version of ACO. Referring to the results, Ng and

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Zhang claimed that the ant colony system approach is able to generate better solutions than previous GA or ACO algorithms without utilizing much computational resources.

El-Gafy (2007), Xiong and Kuang (2008), Abdallah et al. (2009) and Christodoulou (2010) conducted similar studies about ACO. In particular, Xiong and Kuang (2008) incorporated the modified adaptive weight approach (MAWA) to ACO and performed optimization for the same 18-activity network. They reported that the efficiency of ACO is better than the efficiency of GA for solving time-cost trade-off problems. Abdallah et al. (2009) presented the use of an Ant Colony Optimization (ACO) system for solving and calculating both deterministic and probabilistic CPM/PERT networks. They applied the proposed algorithm on a typical construction project. The results showed that the algorithm could be easily applied to both deterministic and stochastic project networks and could produce good optimal and suboptimal solutions. Christodoulou (2010) applied ACO to a resource-constrained construction project network and examined effects of resource availability constraints to critical path calculations and project completion time. Both Abdallah et al. (2009) and Christodoulou (2010) report that the ACO algorithms have a superiority over traditional CPM algorithms because of their capability for multiple node-to-node shortest and longest path calculations and for their suitability for parallel computing.

2.3.3 Comparison and conclusion

Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) and Genetic Algorithms (GA) share many similarities. They are like most evolutionary techniques that have the following procedure:

1. Random generation of an initial population

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2. Evaluating a fitness function which reflects the distance to the optimum solution.
3. Reproduction of the population based on fitness values.
4. Stopping if requirements are met, otherwise going back to 2.

In addition, PSO, ACO and GA do not guarantee success. A particle in PSO is analogous to an ant in ACO and a chromosome (population member) in GAs. As opposed to GAs, PSO and ACO do not have genetic evolution operators like crossover and mutation and do not create new particles from parent ones. Rather, the particles or ants in the population only evolve their social behaviour and accordingly their movement towards a destination.

Compared with genetic algorithms (GAs), the information sharing mechanism in PSO and ACO is significantly different. In GAs, chromosomes share information with each other. So the whole population moves like a one group towards an optimal area. In PSO, only global best value (or local best value) gives out the information to others. In ACO also, new ants take the information from the ants previously found solutions. Therefore, a one -way information sharing mechanism exists in PSO and ACO and the evolution only looks for the best solution.

Performance and convergence aspects of meta-heuristic optimizers are often demonstrated empirically in the research literature. For example, Elbeltagi et al. (2005) have compared the formulation and results of five types of evolutionary-based algorithms including genetic algorithms, memetic algorithms, particle swarm, ant-colony systems, and shuffled frog leaping. Elbeltagi et al. performed bench mark comparison to investigate processing time, convergence speed (success rate), and quality of the results. They reported that PSO method was generally found to perform better than other

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algorithms in terms of success rate and solution quality, while shuffled frog leaping (SFL) was better than others in terms of processing time. Such empirical comparisons have been criticized by Wolpert and Macready (1997) who prove that all optimizers perform equally well when averaged over all problems.

In addition, meta-heuristic methods do not have a rigid mathematical ground; therefore, prioritizing them in terms of their performance, effectiveness and quality cannot be proved using solid mathematical proofs. Particularly, the performance and quality of meta-heuristic optimization methods highly depends on how their proprietary parameters have been adjusted. Changing these parameters may significantly improve the performance.

Meta-heuristics are not guaranteed to find the optimum or even a satisfactory near-optimal solution. All meta-heuristics will eventually encounter problems on which they perform poorly and the practitioner must gain experience of which optimizers work well on different classes of problems.

Many researchers have tried to use evolutionary algorithms (or meta-heuristic methods) to solve time-cost trade-off problems, in which the best alternative of each activity is searched for. However, the literature review shows that none of the researchers have tried to use meta-heuristic methods to solve overlapping optimization. The current PhD research is the first trial. In the current research, the performance, effectiveness, quality of results, and success factor of the optimization technique to be utilized are important factors; however, they are not the first priority. Instead, the main purpose of this research is to model and formulate the overlapping optimization problem and for the

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first time apply a suitable and easy-to-implement meta-heuristic optimization technique which can optimize overlapping.

Although ACO has been repeatedly reported to be able to provide the best performance among other optimization techniques, it is only applicable for discrete optimization and it is not able to solve continuous optimization problems. Since the nature of overlapping is continuous, the overlapping optimization problem is also a continuous problem. Therefore, ACO is not a suitable technique unless the overlapping degrees are converted to discrete values. This is not necessary as other optimization techniques are able to handle continuous optimization. GA, on the other hand, is quite suitable for the purpose of overlapping optimization. In GA, each gene can include as many as attributes as required. In overlapping optimization, each overlap encompasses several attributes. Therefore, each overlap can be suitably resembled by a gene. Further, differences in terms of processing time or result quality are insignificant between GA and other evolutionary techniques such as ACO. GAs might be slower than some other methods, but with today's computers the speed is not a big problem as will be experimented in Chapter 6. Therefore, GA is the selected optimization technique for the purpose of the current research.

2.4 Summary

This chapter was allocated to the literature review of the current research. The primary purpose of the literature review was to find gaps in previous research regarding project fast tracking and fast execution of projects. As a result of the primary literature review, various techniques were identified which could be used for project fast execution. Further review showed that overlapping, if practiced correctly and efficiently, supersedes other

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techniques in saving project time. Also, overlapping is broadly practiced by engineering and construction companies. Therefore, the review narrowed down to activity overlapping. Further review revealed that a gap exists in activity overlapping optimization in the design phase of construction projects. Consequently, the literature about overlapping and optimization were reviewed to find a capture general knowledge about overlapping and optimization, to know what other researchers have researched, to find gaps in the literature about overlapping, and to find a suitable and applicable optimization technique for optimizing activity overlapping. Specifically, the overlapping in product development, the overlapping in construction projects and the applicable optimization techniques for construction time-cost trade-off problems were reviewed.

To better show interdependencies of the research studies in the above literature areas and the relation of the current research with those studies, a *literature review map* was generated (Figure 2-1) The map shows the literature review areas, main research studies in the areas, the proximity of various research studies to the current research and the precedence of studies.

In the last part of this chapter, important optimization techniques applicable to construction projects were reviewed. These techniques included Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) and Genetic Algorithms (GA). A comparative study and an investigation on the mechanism of these techniques led to selecting Genetic Algorithms as a suitable optimization technique for the purpose of this research.

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Chapter Three: Research Methodology

As discussed in the literature review in Chapter Two, the gap in the literature is related to the inability or weakness of available models and frameworks to determine the activities to be overlapped and the extent of overlapping. Therefore, the current PhD research tried to answer this question: **Which activities have to be overlapped and to which extent to reduce the project duration at the minimum cost**? The answer to the question was an *overlapping optimization algorithm* and the current research aimed at developing such an algorithm. Therefore, the main deliverable of the research was the overlapping optimization algorithm. However, the algorithm had to be built on a solid foundation; the fundamentals, attributes, and mechanism of activity overlapping had to be well known first and then the algorithm could be reliably made. For this purpose, an *overlapping model* was required. In addition, due to the complexity of the overlapping optimization algorithm and the fact that manual implementation of the algorithm is impossible, a *computer tool* was developed. As such, the overlapping model, the overlapping optimization algorithm, and the computer tool became the three deliverables of the current research. The deliverables are shown in Figure 1-3 with the overlapping optimization algorithm double framed as the main deliverable.

Figure 1-3 elaborates how the literature review and research tools (interviews and focus groups) were used to generate research deliverables. The research had two parts. First, a qualitative research approach was taken to generate the overlapping model. Second, an analytical approach was taken to create and develop the overlapping optimization algorithm and the computer tool.

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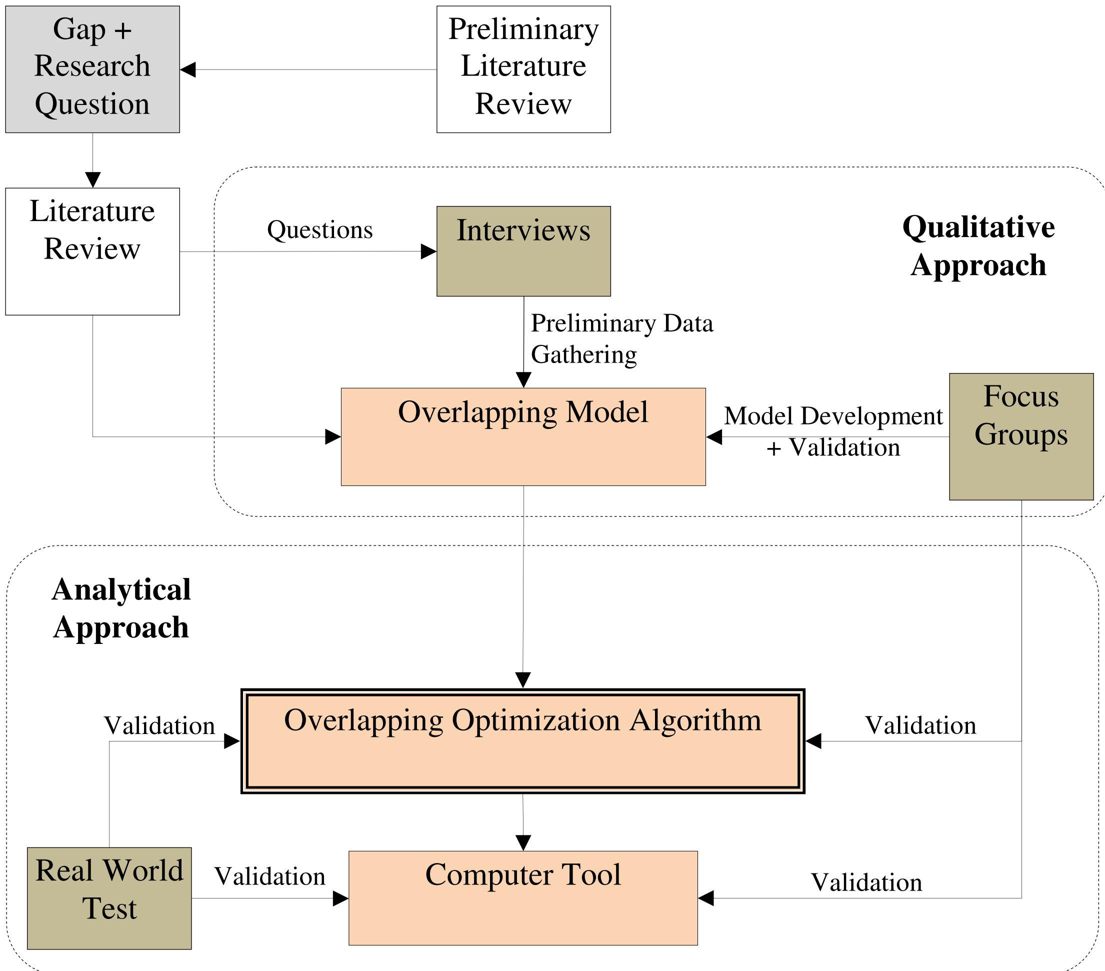

Figure 3-1: Research methodology format

As shown in Figure 1-3, a preliminary literature review revealed a gap in the literature about overlapping. The research question about overlapping optimization emerged out of the gap. A further literature review was performed to gain more knowledge about the overlapping and optimization. The literature review helped to generate a list of detailed questions about overlapping mechanism. These questions were used to interview a number of experts to obtain some preliminary information about the

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characteristics, attributes and mechanism of overlapping. The results of the interviews and the information extracted from the literature review were used to generate the overlapping model. Then, the model was further developed by means of focus groups. The focus groups served a second function as well; they validated the model.

The overlapping optimization algorithm was developed in compliance with the overlapping model. The algorithm was a genetic algorithm and included recursive and numerous calculations. Therefore, a computer tool was developed to implement the algorithm. The focus groups contributed to validating the computer tool and the algorithm as well. In addition, the tool was tested on a real world project network to prove the validity.

Figure 3-2 further elaborates on the lifecycle of the research methodology. The diagram, from top down, represents the start to end of research. The diagram's width represents the average duration of interview or focus group sessions which was approximately 1.5 hours. The research started by interviewing nine experts to gather preliminary data. During the interviews, the researcher talked about 5 to 10 minutes to ask questions and lead the session; the respondents on the other hand, were given the opportunity to talk as long as they wanted to provide as much information as possible. The plain white area and the dotted white area on top of the diagram represent the durations the researcher and respondents talked respectively. Following the interviews, the first draft of the overlapping model was generated using the interview results and the information extracted from the literature. With the first draft of the overlapping model at hand, the next step, which was using focus groups to enhance and validate the model, could start.

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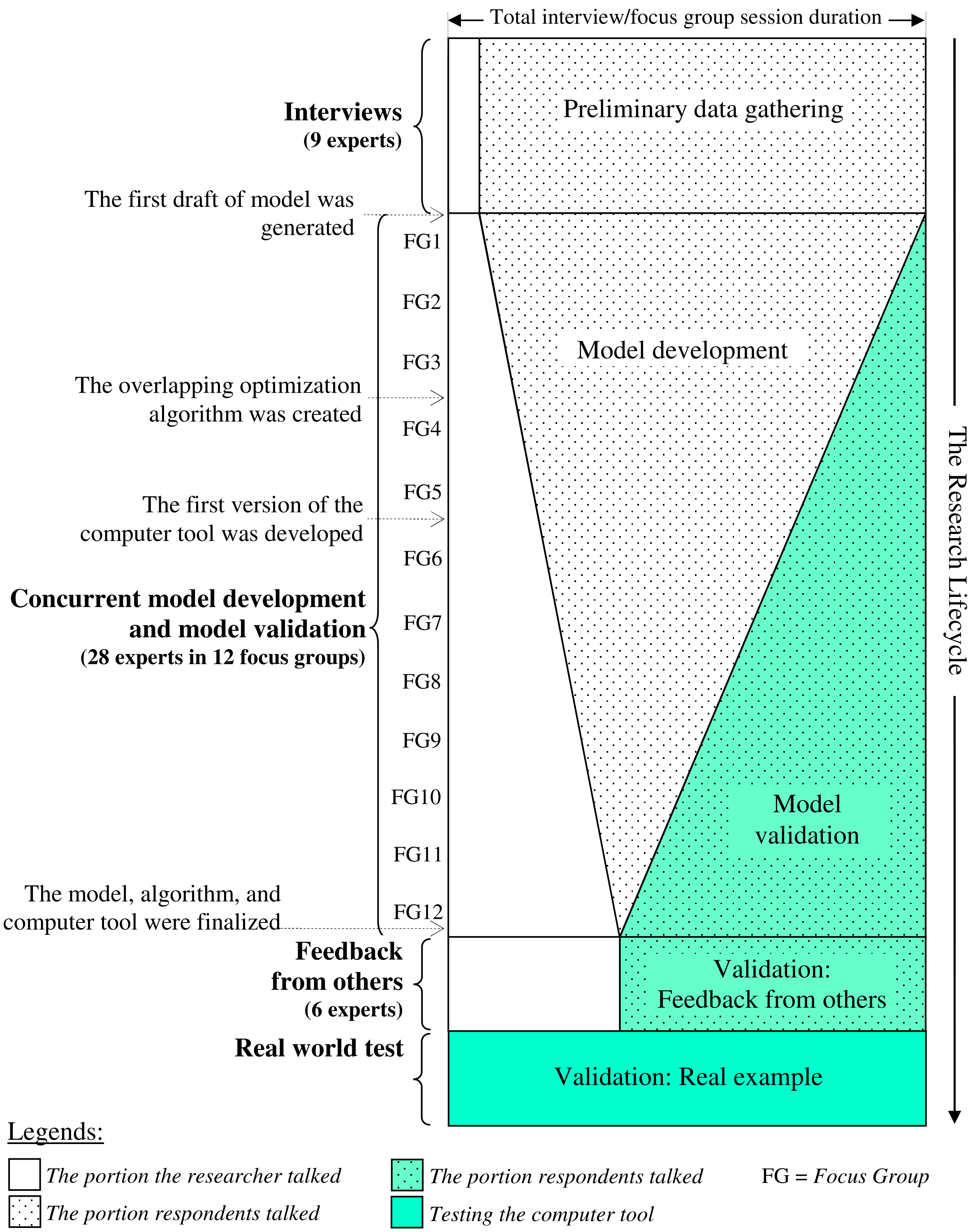

Figure 3-2: The research methodology lifecycle

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A total of 28 experts participated in 12 focus groups, shown as FG1 to FG12 in Figure 3-2. Participants in each focus group were different from participants in other groups. As stated earlier, the focus groups served two functions: (1) further developing the model and (2) validating the model. Both functions were performed concurrently. However, earlier focus groups contributed more in model development than model validation, because the model was still incomplete and more information had to be added. On the other hand, later focus groups contributed more in model validation than model development, as the model was almost complete and respondents mainly expressed their opinions on the practicality, performance and efficiency of the model. Therefore, the green dotted area (model validation) in Figure 3-2 expands while the white dotted area (model development) shrinks as the research proceeds through focus groups. Furthermore, in each focus group session, first the researcher presented the overlapping model, and then respondents discussed the model. As the research proceeded, the model became more completed and extensive and the duration that the researcher talked (presented the model) increased. Therefore, the plain white area (the duration the researcher talked) in Figure 3-2 expands while the dotted area (the duration respondents talked) shrinks as the research proceeds through the focus groups.

During the same period, the qualitative research through focus groups was under progress, the overlapping optimization algorithm and its associated computer tool were generated and developed by the researcher (focus groups did not contribute in generating or developing the algorithm and the tool). Specifically, the overlapping algorithm was generated after the 3rd focus group and the first version of the computer tool was created

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after the 5th focus group. Therefore, there was an opportunity to partially validate the performance of the algorithm and the computer tool in addition to the overlapping model, by presenting them to participants in the remaining focus groups (FG6 to FG12).

After the 12th focus group, the model, the algorithm and the computer tool were considered to be final. Then, two further validation steps were taken. The first step was another qualitative validation in which the model, the algorithm and the computer tool were presented by the researcher to six experts who had not participated in the focus groups or interviews before and their opinion about the reliability and validity were sought. Therefore, these experts only contributed in validation, not information provision or model development. The second step was an analytical validation in which the overlapping optimization computer tool was tested on a real world project.

Overall, 43 individuals from 11 owner and contractor companies mainly active in oil and gas projects contributed to this research. All these companies are international companies. Appendix 5 provides the complete list of contributors with their pseudonyms, professions and years of experience.

Figure 1-3 and Figure 3-2 presented a general view about the research methodology and the sequence of research activities. The following sections provide further details about the research steps taken. Furthermore, research approaches used in the current PhD study are justified.

3.1 Qualitative research

In order to develop the overlapping model, a rich and meaningful picture of the complex problem of design activities overlapping had to be constructed. The following difficulties existed in carrying out this part of the research:

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- Little information existed on the topic: As shown in Chapter 2, the majority of literature around overlapping was related to product development. Literature addressing overlapping or overlapping optimization in construction was less and newer.
- There were many unknown variables: For example, many factors affected overlapping benefits and costs. Also, overlapping rework was affected by miscellaneous factors. These factors had to be identified during the research.
- A relevant theory base was missing or weak: A comprehensive model or framework addressing activity overlapping was still required, because the available models about overlapping were not sufficient to answer the research question and develop the overlapping optimization algorithm intended in this study.

When one or all of the above difficulties exist, Leedy and Ormrod (2005) suggest using a qualitative approach to carry out the research. Also, according to Leedy and Ormrod (2005), when research serves descriptive, interpretative and evaluative purposes, then a qualitative research approach is appropriate. In this research, the design activity overlapping mechanism had to be described, interpreted and evaluated in order to develop the overlapping model. In particular, the overlapping characteristics had to be discovered, insights into the current practices in activities overlapping had to be gained and a new model and algorithm for activity overlapping optimization had to be developed. Therefore, it was appropriate to choose qualitative research approach for this part.

Qualitative research designs include case studies, ethnographies, phenomenological studies, grounded theory studies, and content analysis (Leedy and

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Ormrod 2005) (Figure 3-3). A phenomenological study was the most appropriate design for developing the overlapping model because a phenomenological study attempts to understand experts' perception and perspectives of a particular situation (Leedy and Ormrod 2005). In this research, the particular situation or phenomenon was the *design activity overlapping*.

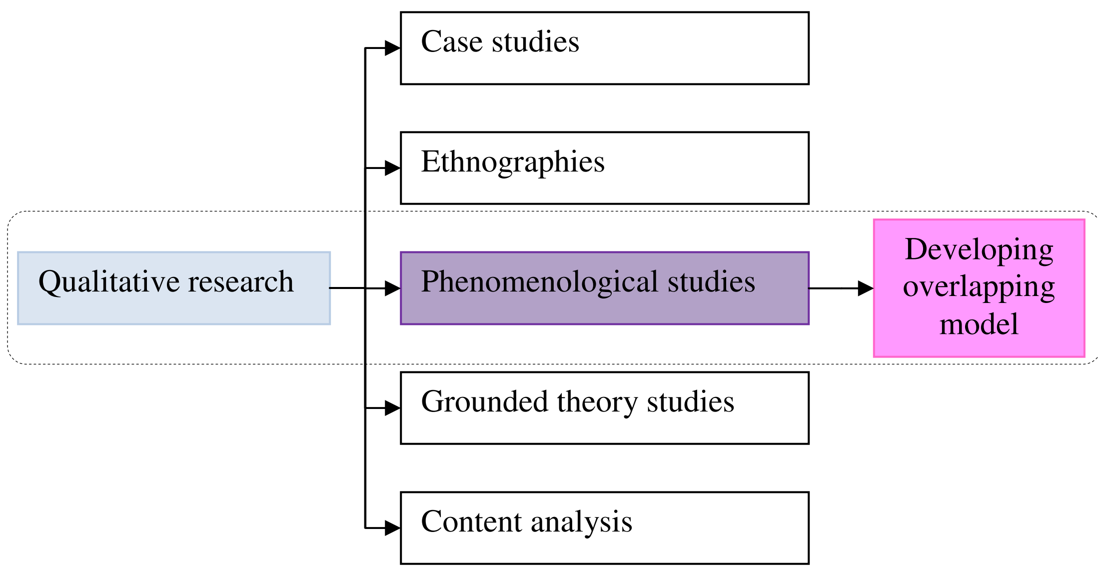

Figure 3-3: Qualitative research designs

In addition, the researcher had 8 years real world experience in project engineering and project planning and control and witnessed interactive planning and scheduling sessions in engineering and construction companies. However, he also wanted to enrich his understanding of the overlapping mechanism by taking the advantage of other professionals' experience. By looking at multiple perspectives of the same subject, a robust model for design activities overlapping could be built.

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3.1.1 Interviews

Interviews assisted in gaining and increased understanding of the current overlapping practices and issues. According to Cresswell (1998), phenomenological study depends on lengthy interviews, perhaps one or two hours in length, with a carefully selected sample of participants who have direct experience with the phenomenon being studied. A typical sample size is between 5 to 25 individuals (Cresswell, 1998). In the current research, exploratory interviews with 9 experts from the construction industry were performed to collect overlapping characterization information. The sampling was quite purposeful and non-random. Mostly experienced individuals from project planning and scheduling, project engineering and project management disciplines of reputable owner and contractor companies were chosen to yield the most information about the topic (a list of individuals with their pseudonyms, professions and years of experience is provided in Appendix 5).

One objective of the interviews was to explore the interviewees' ideas and opinions about the overlapping mechanism. However, the direction of questions was not completely clear to the researcher from the outset. At the beginning of the investigation, it was very difficult to ask specific questions and asking open-ended questions proved more helpful. Therefore, semi-structured interviews were found to be suitable for this step of the research. According to Yin (1994), semi-structured interviews are suitable for probing of views and opinions. Such probing could allow for the diversion of the interview into unknown pathways that were unknown at the beginning, but could help meet the research objectives. Using semi-structured interviews is in compliance with Leedy and Ormrod (2005) and Tesch (1994) who believe that the phenomenological

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interview is often an unstructured or semi-structured one in which the researcher and participants work together to arrive at the heart of the matter.

Furthermore, questions were not straightforward and interviewer explanation greatly helped the interviewee to understand the essence of the questions and provide reasonable answers (It is noteworthy that the process of information gathering was first started by distributing questionnaires among engineering and construction experts. However, this method failed as respondents had difficulties understanding questions and left them unanswered. In spite of several adjustments and modifications of the content and format of the questionnaire, the problem persisted. Therefore, interviews were deemed to be a better way of preliminary information gathering).

Gray (2009) explains the process of conducting semi-structured interviews. In semi-structured interviews the interviewer has a list of pre-planned issues and questions when he/she starts the interview; however, the list may not be exactly followed during the interview. Depending on what direction the interview takes, the interviewer may skip some questions, change the order of questions, or even ask extra questions including some which were not anticipated before the interview. Responses are noted or tape-recorded and documented consequently (Gray 2009).

In the current research, the initial list of questions was derived from the background literature review. The list of questions was then refined and modified throughout the course of interviews. Responses were briefly noted during interviews and completed after interviews. The interviews continued until no new information could be extracted. At this point, information saturation was reached and further interviews were not required.

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With the results of interviews at hand and the information extracted from the literature, the researcher generated the first draft of the overlapping model. In the next step, the model had to be developed using focus groups.

3.1.2 Focus groups

One advantage of focus groups is that sometimes interaction among participants is more informative than individually conducted interviews. The focus groups helped to modify, develop, and validate the model simultaneously. Overall, 28 experts from owner and contractor companies participated in 12 focus groups. Each focus group included 2, 3, or 4 experts. The intention was to ensure that all aspects of overlapping mechanism were considered in the overlapping model. For this purpose, three different groups of very experienced professionals who had at least 15 years of work experience were selected. The professionals were knowledgeable about different aspects of activity overlapping.

The first group were engineers and engineering discipline leads. These experts are expected to know best the nature of activities, the estimated durations, types of dependencies between activities, activity sensitivities to changes, and the side-effects and consequences of activity overlapping.

The second group were project planners and schedulers who initialize and develop the project schedule and monitor it regularly. They apply overlaps and witness the effects of all types of overlaps from various engineering disciplines on the schedule during the whole project lifecycle.

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The third group were project managers and senior managers. These individuals, due to their experience and positions, are capable of seeing the big picture of projects. They know the pros and cons of overlapping with regard to the project as a whole.

To enhance the quality of the focus groups, enrich the discussions and ensure that the respondents were suitably aware of the subject and objectives of the focus groups, a special approach was taken. With the general insight obtained from the background literature review and the results of the interviews, a “Microsoft PowerPoint” presentation was prepared and presented to the participants. The slides include objectives of the research and the overall overlapping model. The intention was to (1) make participants familiar with the fundamentals of the research and help them understand the objective of the research and (2) explain the overlapping model to them and obtain the feedbacks. Therefore, the PowerPoint slides were used as an auxiliary means to facilitate the focus groups and enhance the quality and richness of discussions.

The overlapping model was developed and completed during the above process. Therefore, PowerPoint slides also evolved during the process and at the later stages the slides actually represented the final overlapping model (PowerPoint slides can be found in Appendix 3).

The model generated and developed during focus groups was done in compliance with the process of generating *requisite models*. The next section explains the similarities of the overlapping model and requisite models.

3.1.2.1 Requisite model

Requisite models were introduced by Phillips (1982b). In general, the whole point of using models is to create simplifications of the real world in such a way that analysis

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of the model yields insight regarding real-world situations. A *requisite model* is a type of judgmental modeling, because it is about the *judgements* of a group of experts. The model attempts to capture the value judgements and their relative importance to the group of experts. Although no person in the group would necessarily agree with all the judgments, the model expresses a *shared social reality* that is evolving as the group works. The Latin root of *model* means *small measure*. In this respect, a requisite model is truly a model as it is a small measure of reality, a lesser reality (Phillips 1984). In brief, requisite models capture many, but not all, features of the problem through experts' judgements to facilitate the subsequent construction of a new reality. Several researchers have used the concept of requisite models in their studies (Barcus and Montibeller 2008; Holt and Barnes 2010; Lu and Druzdzel 2009).

According to Phillips, "*a model is requisite if its form and content are sufficient to solve the problem*" (1984, p 35). Put differently, everything required to solve the problem is represented in the model or can be simulated by it. The content of a requisite model refers to values, judgements, and the socially-shared understanding of the problem. The form refers to the structure and to the way the various elements of the content are put together to create the model. The content is provided by specialists and experts who are familiar with the problem, but the form is the responsibility of a facilitator, e.g. the researcher.

Phillips states that requisite models are generated by the interaction between specialists and the facilitator. The process of building a requisite model is sometimes conducted in a group and at other times by a succession of discussions between the facilitator and individual experts. But in all cases, the process is consultative and

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iterative. The facilitator contributes the form of the model and specialists and experts provide content, though the facilitator also assists in encoding the content to be compatible with the form. Therefore, the facilitator has a dual role: to facilitate the work of the group by keeping it task oriented, and to contribute to those aspects of the task concerned with model form, but not content.

According to Phillips, a key feature is that the modelling process uses the *sense of unease* among the participants about the results of the model as a signal that further modelling may be needed, or that intuition may be wrong. If the discrepancy between holistic judgement and model results shows the model to be at fault, then the model is not requisite; it is not yet sufficient to solve the problem. *The model can be considered requisite only when no new intuitions emerge about the problem*. This criterion of *requisiteness* is necessitated by a model-building process that is generative. The participants' understanding evolves during the course of modelling.

Phillips summarizes requisite decision models by introducing several features (Phillips 1984, p 40, Table 1). The features are presented here using the same explanations provided by Phillips; at the same time, it is shown how the generated overlapping model maps those features:

"Definition: Model is requisite when its form and content are sufficient to solve the problem" (1984, p 40).

The main research question of this study was: **Which activities have to be overlapped and to which extent?** The generated overlapping model was sufficient to answer the question as it resulted in developing an overlapping optimization algorithm.

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"Representation: Requisite model represents a shared social reality" (1984, p 40).

The social reality, or the content, shared by the project experts in current research, was the characteristics, mechanism, and attributes of activity overlapping. Specifically, the shared social reality encompassed the following:

- Types of activity overlapping
- Relation between overlapping and rework
- Relation between overlapping and cost
- Effect of multi-predecessor overlaps on rework
- Effect of cascades of overlaps on rework
- Benefits of overlapping
- Risks of overlapping
- Overlapping time-cost trade-off formula

"Generation: Through iterative interaction among specialists and facilitators" (1984, p 40).

As explained earlier, successive discussion sessions were conducted between the researcher and individuals and groups of project experts including planners, schedulers, project engineers, and project managers (Figure 3-2).

"Process: Uses sense of unease arising from discrepancy between holistic judgements and model results" (1984, p 40).

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The generated model at different stages of the research was shared with project experts and their feedback was captured. The experts expressed whether they felt the model was acceptable or if it still required modifications, additions, and deletions.

"Criterion: Model is requisite when no new intuitions arise" (1984, p 40).

This feature is very similar to information saturation. At one point in time, more interviews, meetings, and discussions could not provide any further information or intuitions. The model had become requisite.

"Goal: To serve as guide to action, to help problem owners construct new reality" (1984, p 40).

The new reality was the *overlapping optimization algorithm* and the *overlapping model* helped to generate the algorithm (Figure 1-3).

The above analogy shows that the suggested overlapping model is actually a requisite model. Further, a requisite model is a simplified representation of a shared social reality. The to-be-created reality is more complex and so contains more elements than the shared representation of the problem which, in turn, is more complex than the requisite model. According to Phillips (1984), the requisite model is simpler than the reality in three respects: (1) elements of the social reality that are not expected to contribute significantly to solving the problem are omitted from the model, (2) complex relationships among elements of the social reality are approximated in the model, and (3) distinctions in either form or content at the level of social reality may be blurred in the model. Similarly, the overlapping model is a simplified representation of a more complicated reality, as unnecessary complexities were removed from the model. For example, the timeliness of the information exchange between activities did not

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significantly contribute to solving the problem; therefore, it was omitted from the model. Secondly, the overlapping cost functions included several cost elements. The cost of rework formed the major portion and was kept as one element, but the rest of the cost elements were merged and approximated into a second element. Thirdly, no distinction was made between types of changes from predecessor activity that cause rework for the successor activity (Chapter 4 provides the details).

The requisite model does not prescribe action; rather, it is a *guide* to action. In other words, the requisite overlapping *model* does not make the overlapping optimization *algorithm*. Instead, the model is used as a guide to develop the algorithm. The process of model development is described in Chapter 4. The algorithm development is explained in Chapter 5 and the computerized algorithm is presented in Chapter 6.

3.1.3 Data analysis

The main task during data analysis is to identify common themes in people's descriptions of their experiences despite diversity among them (Barritt 1986). For this purpose, Leedy and Ormrod (2005) explain a 4-step procedure suggested by Creswell (1998) to analyze the gathered data from the phenomenological study. The same approach was taken in the current research to analyze the information gathered from interviews and focus groups and was as follows:

1. *Identify statements that relate to the topic:* Relevant information were separated from the irrelevant information obtained from interviews or focus groups. Then, the relevant information was broken into small segments or phrases. Each segment represented a single specific thought.

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2. *Group statements into meaning units:* The segments were categorized into groups that reflected various aspects of the phenomenon of activity overlapping.
3. *Seek divergent perspectives:* Different perspectives in which different experts experienced the phenomenon were considered.
4. *Construct a composite:* The various perspectives identified in the previous step were used to develop an overall description. The final result was a general description of the activity overlapping as experienced by different experts.

The results of the above approach are the consolidated and finalized answers to the questions in Appendix 2 and the overlapping model explained in Chapter 4. The answers and the model reflect the general perception of individual professionals who participated in interviews and focus groups.

3.2 Analytical part

The model shed light on the overlapping mechanism and the overlapping time-cost trade-off was formulated. The main objective of the research in a sense was to optimize the trade-off. Therefore, the researcher suggested an optimization algorithm. The algorithm used the principles of artificial intelligence, specifically genetic algorithms optimization. The appropriateness of genetic algorithms was investigated through the literature review. Chapter 5 provides the details of developing the algorithm.

The algorithm was implemented in a computer environment. In order to create a user-friendly and powerful computer tool, Microsoft Excel (Excel) version 2007 and Microsoft Project (MSP) version 2007 were used, as both of them were familiar to practitioners. The Genetic Algorithm module was generated in Excel as a template, and MSP was used to perform network calculations. This approach highly facilitated the

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implementation process as well, because network CPM calculations and other computations such as resource levelling were included as built-in features in MSP and not required to be programmed independently. Chapter 5 explains the computerization process and Chapter 6 investigates the performance of the computer tool.

3.3 Validation

To validate research, both internal and external validity of the research should be addressed (Leedy and Ormrod 2005). In the following sections, each type of validation is explained and the researcher's effort to enhance the internal and external validity of the research is demonstrated.

3.3.1 Internal validity

Internal validity of the research is to ensure that the conclusions drawn are truly warranted by the data (Leedy and Ormrod 2005). Based on this definition, the internal validity of this research is to ensure that the conclusions which led to developing the overlapping model are warranted from the opinions and information collected. To achieve this purpose, two methods, *feedback from others* and *respondent validation,* were used.

3.3.1.1 Respondent validation

According to Leedy and Ormrod (2005), *respondent validation* means that the researcher takes the conclusions back to participants in the study and asks quite simply, Do you agree with my conclusions? Do they make sense based on your own experiences? The same process was used for this research during simultaneous model development and validation. It is the essence of requisite models that model development and model validation proceed together. In the last stages, the gap between the results and the holistic

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judgements of experts was diminished. Participants in later focus groups expressed their sense of ease with the results.

3.3.1.2 Feedback from others

After developing the overlapping model, opinions of a number of professionals with planning and scheduling, project engineering, and project management experience were sought to determine whether they agree or disagree that appropriate interpretations were made and valid conclusions were drawn from the gathered information. These professionals had not participated in interviews or focus groups and were different from previous participants. According to Leedy and Ormrod (2005), this process is called "feedback from others" and is one of the strategies that qualitative researchers use to support the validity of their findings. The process is also very similar to the validation process suggested by Phillips (1984) to validate requisite models. Phillips believes that validating requisite models requires the application of evaluation models, which may themselves be requisite or not insofar as they solve the 'problem' of validation:

> "Validating a requisite decision model requires the development of a *requisite evaluation model*. The decision model would be requisite for one group of problem owners, while the evaluation model would be requisite for a *different group*. This difference in the referent groups also prevents an infinite regress of requisite validation models" (1984, p 42).

In the current research, Phillips' prescribed method of using another requisite model to validate the main model was used. According to Phillips, the requisite evaluation model can include objective and subjective criteria against which judgements

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are made. Therefore, in different focus groups, the criteria to validate the overlapping model were developed. These criteria ensure that the model is:

a. Realistic

b. Comprehensive

c. Logically sound

d. Suitably simplified

Consequently, five questions were designed to address the aforementioned criteria. The questions were as follows:

1. To what extent do you agree that the presented overlapping model is logically sound?
2. To what extent do you agree that the presented overlapping model reflects the real world practice?
3. To what extent do you agree that the presented overlapping model is comprehensive? In other words, To what extent do you agree that all essential elements have been addressed in the model?
4. To what extent do you agree that the presented overlapping model is too complicated?
5. To what extent do you agree that the presented overlapping model is too simple?

The overlapping model was presented to two focus groups, both of them different from all previous focus groups that had developed the model, and the five criteria questions were asked. The questions and their answers were designed according to the Likert scale (Likert 1932). The respondents unanimously endorsed the validity of the overlapping model. The list of questions and the results are provided in Appendix 4.

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3.3.2 External validity

The external validity of a research study is the extent to which the results of the study can be generalized to other situations beyond the study itself. Conducting the research on a real life setting is commonly used to enhance the external validity of a research project (Leedy and Ormrod 2005). The researcher has applied the overlapping model and optimization algorithm on a real project obtained from one of the companies involved in the research. The results showed the satisfactory performance of the overlapping optimization algorithm. The details are explained in Chapter 6.

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Chapter Four: Analysing and Discussing Interview and Focus Groups Results: Generating Overlapping Model

The objective of this chapter is to provide insights into the overlapping mechanism. The available literature about overlapping has been reviewed to identify the mechanisms suggested by other researchers, and consequently semi-structured interviews were used to gather expert opinions, from mainly planners and schedulers, about the mechanism of overlapping. Accordingly, a mechanism is suggested which is explained in this chapter. It is reminded that the research is focused on engineering and design activities.

In addition, the time impact and cost impact of overlapping on the project are investigated and the overlapping time-cost trade-off problem which is an objective function addressing the total costs of the project is developed.

4.1 Nomenclature

A_{ij} The amount (degree) of overlapping in percentage between predecessor activity i and successor activity j

B_{ef} Daily benefits of project early finish

C_{ij} All possible costs of overlapping activity i with activity j, including wages, overheads, wastes, damages, extra costs, etc.

C The net cost/benefit of project resulting from an overlapping strategy

C_{lf} Daily costs of project late finish

C_{os} Cost of overlapping strategy

B_{pt} Benefit of project timesaving

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D_i Duration of activity *i*

D_j Duration of activity *j*

E_{ij} Extra costs, other than daily wages and overheads, imposed on successor activity *j* or on other project areas (design, procurement, construction, etc.) because of the changes made by predecessor activity *i* during its overlapping with successor activity *j*

i Index denoting predecessor activities

j Index denoting successor activities

L_{ij} Duration of the overlapped interval between predecessor activity *i* and successor activity *j*

$L_{ij,max}$ Maximum allowable overlapping between predecessor activity *i* and successor activity *j*

P_{ij} The probability that a change happens for predecessor activity *i* during its overlapping with successor activity *j* and the change causes some rework for successor activity *j*

r_{ABC} The *change transfer ratio* from activity A to activity C through activity B

R_{ij} The equivalent rework duration for successor activity *j,* as a result of its overlapping with predecessor activity *i*

R_j The equivalent rework duration for successor activity *j,* as a result of its overlapping with more than one predecessor activity

T Project duration

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T_{ij} The extended duration added to successor activity *j,* as a result of rework originating from the changes made by predecessor activity *i,* during its overlap with successor activity *j*

T_n Normal project duration, no overlapping applies

T_t Project target duration

W_j Total daily wage for successor activity *j*, including daily salaries and daily overheads

4.2 Types of Activity Relationships

A typical construction project consists of many activities that have to be performed in a specific order to complete the project. Each activity is dependent on one or more activities. Generally, there are two types of dependency: Information dependency and resource dependency. When two activities have information dependency, one activity requires information (raw data, specifications, drawings, etc.) from a second activity, before the first activity can be started. When two activities have resource dependency, it means that they are using the same resource. For example both activities have to be performed by a designated designer or machinery. In either case, overlapping dependent activities can generate extra risk for the project. If two activities have no dependency of any type on each other, then their overlapping will not be risky.

To better understand the overlapping principle, the type of relationships between activities should be identified. Bogus et al. (2005) have briefly explained Prasad's (1996) classification of relationship between design activities. According to them, four types of relationships between design activities are possible (Figure 4-1):

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1. Dependent activities: In order to start, one activity requires the final information from another activity.
2. Semi-independent activities: To start, one activity requires only partial information from other activities.
3. Independent activities: No information dependency exists between two activities.
4. Interdependent activities: A two-way information exchange between the activities occurs until they are complete.

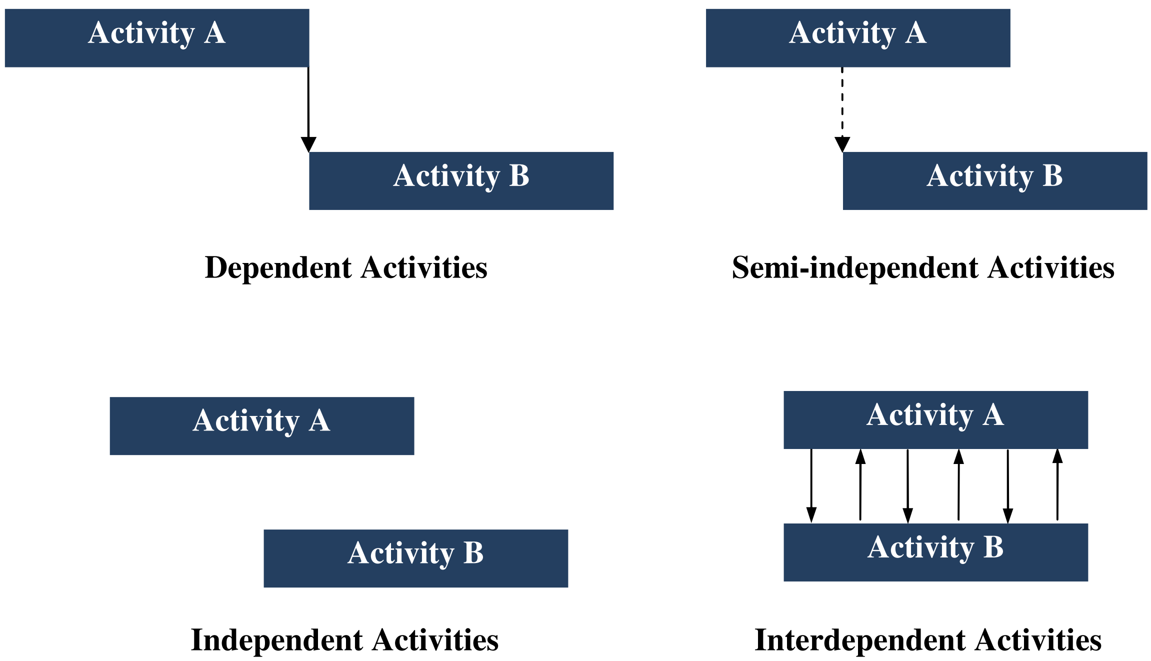

Figure 4-1: Four types of activity relationships (adopted from Prasad 1996; Bogus et al. 2005)

When it comes to activity overlapping, the above types of relationships vary significantly in terms of risk. Overlapping *dependent* activities is the riskiest. This type of relationship is also known as finish-to-start dependency, implying that the first activity

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(predecessor) should be finished before the start of second activity (successor). Otherwise, the start of the successor before the predecessor may generate rework as the successor must begin before complete information is available from the predecessor. *Independent* activities can be overlapped to any extent, without any risks. The only requirement is that both activities' resources such as human, machinery, or material be available all at the same time. *Semi-independent* activities have a specific degree of overlapping by nature. However, more overlapping will be risky, similar to dependent activities. Finally, *interdependent* activities must overlap to exchange information and make progress, otherwise they cannot proceed. In other words, overlapping is a part of their inherent nature rather than a mean to save time. Although their overlapping is associated with risks of delay and rework, overlapping should not be considered an extra risk, but a must for interdependent activities. Van de Ven and Delbecq (1974) refer to interdependent activities as "reciprocal dependence", which inherently forces overlap and joint progress because neither task can proceed without the other (Van de Ven and Delbecq 1974).

Based on the above, no specific overlapping risk exists when independent or interdependent design activities are overlapped. Risks are significant when overlapping dependent or semi-independent design activities (Dehghan et al. 2010).

4.3 Overlapping Practice in Industries

A brief write-up on how schedulers apply overlapping in project schedules is necessary. This write up is developed based on direct observations and interviews with planning and scheduling experts.

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To build a schedule, different engineering disciplines provide the list of deliverables for schedulers. Some of the deliverables are produced independently by only one discipline, and some of the deliverables are produced by several disciplines. First, the schedulers put the deliverables in the schedule, and then add dependencies between the deliverables. Four types of dependencies are possible between activities:

1. Finish-to-start dependency, in which one activity cannot start until another activity has finished.
2. Finish-to-finish dependency, in which one activity cannot finish until another activity has finished.
3. Start-to-start dependency, in which one activity cannot start until another activity has started.
4. Start-to-finish dependency, in which one activity cannot finish until another activity has started.

Of the above dependencies, finish-to-start is the most common type and a well-built schedule has mostly finish-to-start dependencies. Also, start-to-finish is the least common type and very rarely is used. Up to this point, no overlapping is applied on activities. At a later stage, the time constraint or the finish time of the project should be applied and schedulers must compress the schedule. One way of doing this compression is to overlap the activities with finish-to-start dependencies, as a predecessor may not have to be complete before its successor can start.

Overlapping can be achieved in a number of different methods. One method is starting the successor activity n days before finishing the predecessor activity by using a negative lag value, also known as a lead value (Figure 4-2).

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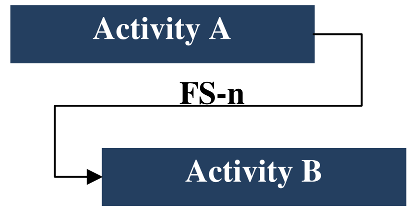

Figure 4-2: Starting successor activity n days before finishing predecessor activity

This method is rarely practiced in the real world. However, two other methods exist that are extensively practiced by schedulers. One method is starting the successor activity *n* days after starting the predecessor activity (Figure 4-3, left). The other method is finishing the successor activity *n* days after the finishing predecessor activity (Figure 4-3, right). In both cases, a positive lead time (n) is applied to generate overlapping.

Figure 4-3: Starting successor activity *n* days after starting predecessor activity (left), and finishing successor activity *n* days after finishing predecessor activity (right)

As noted, in real world practice finish-to-finish and start-to-start are more practiced than finish-to-start with a negative lag (finish-to-finish is even more widely practiced than start-to-start). The reason is not related to network logic, but related to easier understanding and judgement by engineers. A finish-to-start dependency with a negative lag makes less sense to people than finish-to-finish or start-to-start dependencies. For example, if the predecessor activity is “preparing pump layout

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drawings" by the mechanical engineer and the successor activity is "preparing pump foundation drawings" by the structural engineer, the structural engineer could say: "I will finish the pump foundation drawings ten days after I get the final pump layout drawings". He knows from experience when the final layout drawings are at hand, he needs approximately ten days to finalize the foundation drawings. Also, the mechanical engineer could say: "The structural engineer can start the pump foundation drawings ten days after I start pump layout drawings", as she knows from experience that approximately ten days are required to release the first set of preliminary information to the structural engineer. However, "the structural engineer can start foundation drawings ten days before pump layout drawings are finished" will less likely be said. Such an expression is a bit difficult to make sense of, because it is somehow against the intuitive.

4.4 Overlapping Principle

Figure 4-4 shows the mechanism of overlapping two dependent activities, in which the start of an *activity* depends on the finish of another *activity* and the second activity can only be started if the first activity is finished completely. This is because the successor needs the information generated by the predecessor. However, to compress the schedule, the successor activity may be intentionally started before the completion of its predecessor. This becomes possible if the predecessor activity releases some preliminary information before its completion to the successor activity. Therefore, the successor can start sooner, using the preliminary information and making the necessary assumptions and predictions. The two activities can proceed in parallel for a while and, during this period, some intermediate information may also be transferred until the predecessor is completed; then, the predecessor will release its final information to the successor. At this

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point, it is likely that the final information is different from the preliminary or intermediate information and therefore, changes and adjustments should be made to the successor to make it compatible with the final information. The changes and adjustments will take some additional work (rework) in form of extra person-hours (i.e. extra cost and time), which means an increase in the duration of the successor activity compared to its normal duration (Dehghan and Ruwanpura 2011).

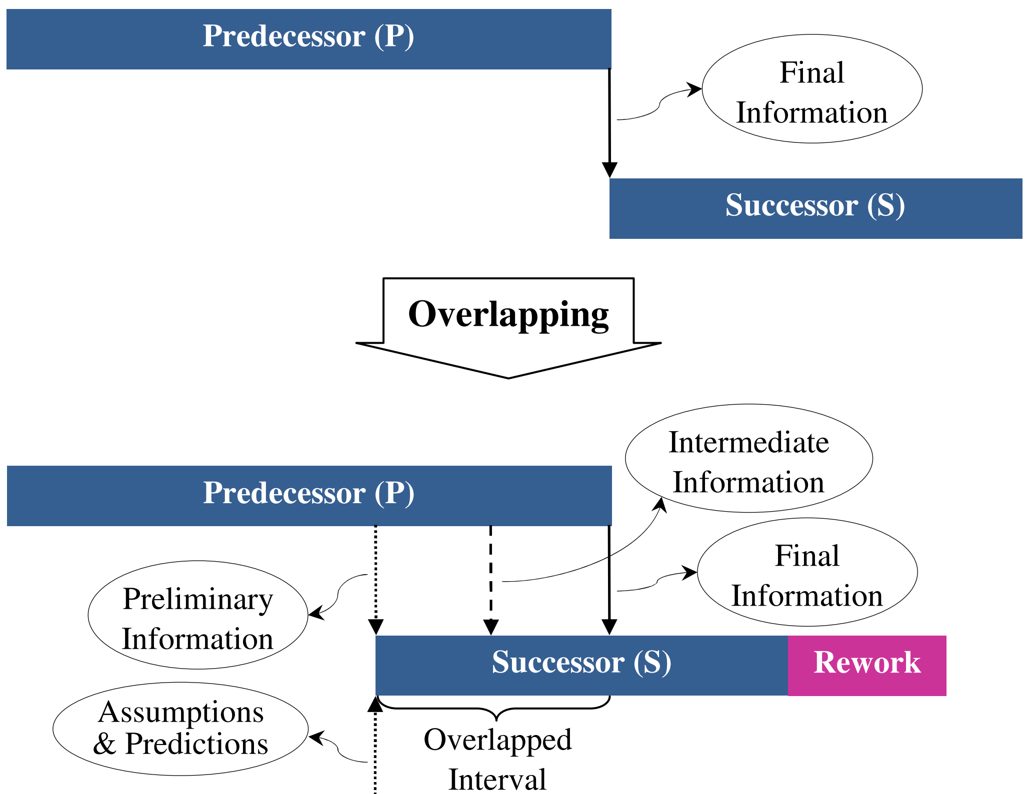

Figure 4-4: The mechanism of activity overlapping

Two points are noteworthy. First, overlapping has a maximum duration beyond which further overlapping is actually impossible because no preliminary information of

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any kind can be produced by the predecessor activity. In the current research, this amount is called *maximum overlapping* or *maximum allowable overlapping*.

Second, no rework occurs if the final, preliminary, and intermediate information are compatible. Rework is probable to take place. The *probability* of rework depends on several factors. In this research, the literature review shows and the interviews endorse that these factors are the type and complexity of overlapped activities, their relation with other activities in the project schedule, and the amount of overlapping. On the other hand, the amount (the duration) of additional work is a function of the overlapping duration, the strength of the successor activity dependency to the predecessor activity, and the intensity of nonconformity between final and preliminary information (Appendix 2). The maximum rework may happen when the final information is significantly contradictory with the preliminary information, and successor is required to apply a major change. In such a situation, the worst scenario is that the successor must disregard all its progress during overlapping and start over. Therefore, the rework duration, whatsoever, cannot be logically more than the overlapping duration (Dehghan and Ruwanpura 2011). This is also endorsed by interviewees and participants in focus groups (Appendix 2).

If a change happens in the predecessor activity and results in rework for the successor activity, the same change may result in rework for the predecessor activity as well (Appendix 2). However, the predecessor's rework is not shown in Figure 4-4, because it could happen anyway, regardless of overlapping. In other words, the source of rework for the successor activity is its overlapping with the predecessor activity, but the source of rework for the predecessor activity is not its overlapping with the successor activity.

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In addition, sometimes changes, modifications, and iterations are a part of the activity normal evolution, and sometimes changes are because of errors and omissions. In either case, an experienced scheduler predicts and applies the changes' effects in the normal duration of activities.

However, if a change has a source outside the predecessor, then it comes from other predecessors to the subject predecessor. In that case, the subject predecessor becomes a successor for its predecessors, and the resulted rework should be added to its duration. In this research, when two or more instances of overlapping happen consecutively on a chain of activities, it is called a *cascade of overlaps*. Sometimes a cascade of overlaps causes more complex situations where two or more consecutive overlaps take place concurrently and as a result affect rework periods. Such a situation is called *cascade effect* and is addressed in more detail in section 4.5.2.

Since the impact of the change on the successor activity i is the extended (rework) period for predecessor activity j, the equivalent rework can be defined by multiplying the probability of rework and the duration of rework. To formulate this expression, the following parameters are introduced:

L_{ij} Duration of the overlapped interval between predecessor activity i and successor activity j

P_{ij} The probability that a change happens for predecessor activity i during its overlapping with successor activity j and the change causes some rework for successor activity j

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T_{ij} The extended duration added to successor activity *j,* as a result of rework originating from the changes made by predecessor activity *i,* during its overlap with successor activity *j*

R_{ij} The equivalent rework duration for successor activity *j,* as a result of its overlapping with predecessor activity *i*

Lij, *Tij* and *Rij* are shown in Figure 4-5.

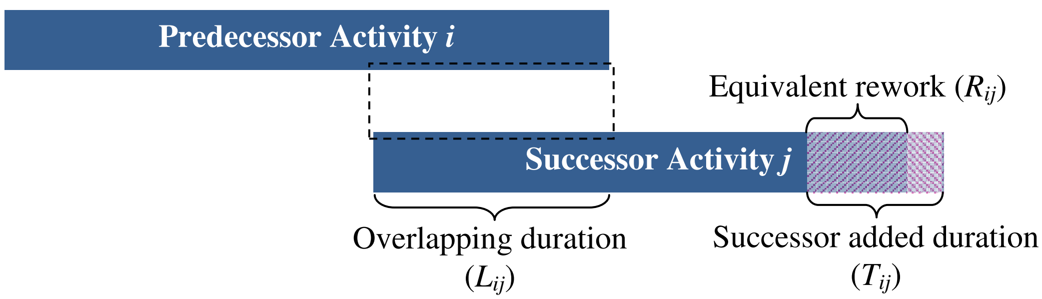

Figure 4-5: Overlapping duration vs. successor added duration

According to the above expression, R_{ij}, the equivalent rework, is defined as follows:

$$R_{ij} = P_{ij} \times T_{ij} \qquad [4.1]$$

Noting that:

$$0 \le P_{ij} \le 1 \Rightarrow 0 \le R_{ij} \le T_{ij}.$$

Based on the explanation of the mechanism of overlapping, both the probability, P_{ij}, and amount of rework, T_{ij}, are functions of the overlapping duration, L_{ij}. Therefore, the equivalent rework, R_{ij}, is also a function of L_{ij}.

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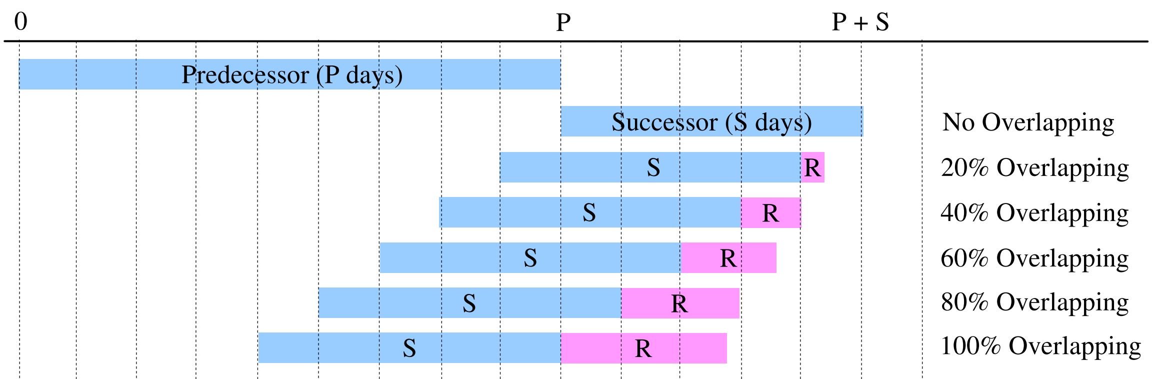
$$R_{ij} = f\,(L_{ij}) \qquad [4.2]$$

Although in this research, R_{ij} is briefly called “rework” instead of “equivalent rework”, it is important to note that R_{ij} is different from T_{ij}. During the interviews, the relation between degree of overlapping (overlapping duration) and rework duration was questioned (Appendix 2). The participants unanimously believed that more overlapping causes more rework and consequently increases the successor duration, except for very odd cases (Figure 4-6).



Legends:

P: Duration of the Predecessor (days)

S: Duration of the Successor (days)

R: Duration of the Rework (days)

Overlapping percentage = (duration of the overlapped fraction ÷ total duration of the successor activity) ×100

Figure 4-6: Relation between degree of overlapping and rework duration

The respondents also endorsed the idea that the rework or equivalent rework duration, whatsoever, cannot be more than the overlapping duration. Therefore, in Figure 4-7, the locus of the rework duration functions is in the dotted area.

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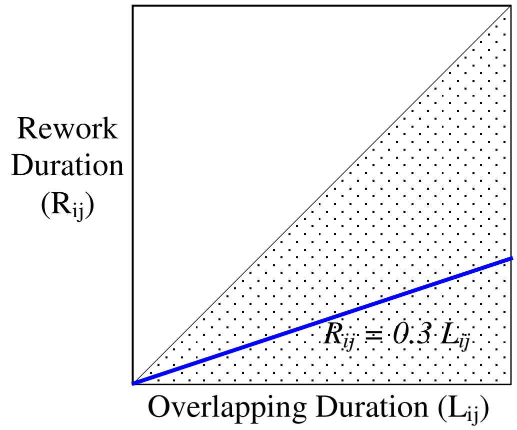

Figure 4-7: Rework duration vs. overlapping duration

of relations to show the variations of rework duration as a function of the variations of overlapping duration is extremely difficult, if not impossible. As a result, they were unable to suggest any functions. However, a few respondents referred to the current practice of *schedule risk analysis* in their companies. They stated that although no rework duration is considered for overlapping during scheduling, risk analysts perform a risk review on the schedule by means of schedule risk analysis tools such as “Pertmaster” and consider up to 30% of the overlapping duration as the rework duration, i.e. $R_{ij} = 0.3L_{ij}$ as shown in Figure 4-7. This value is a rough estimate for the resulting rework and is based on the general knowledge and experience of risk specialists.

Investigating the exact relation of rework duration with overlapping duration is out of the scope of the current research. However, in Chapter 6 the rough estimates obtained from the interviews for a few real world overlaps will be used to perform a number of experiments with the suggested overlapping optimization tool.

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4.4.1 Overlapping Semi-independent Activities

The above mechanism of overlapping dependent activities can also be applied to semi-independent activities by considering the predecessor as two separate sequential activities (A_1 and A_2), one before (A_1) and the other (A_2) after the information exchange (Figure 4-8); Activity A_1 becomes the predecessor for both activities A_2 and B. Therefore, activity A_1 and activity B may overlap with the same mechanism of dependent activities, and activity A_2 and activity B can easily overlap because they are independent (Dehghan and Ruwanpura 2011).

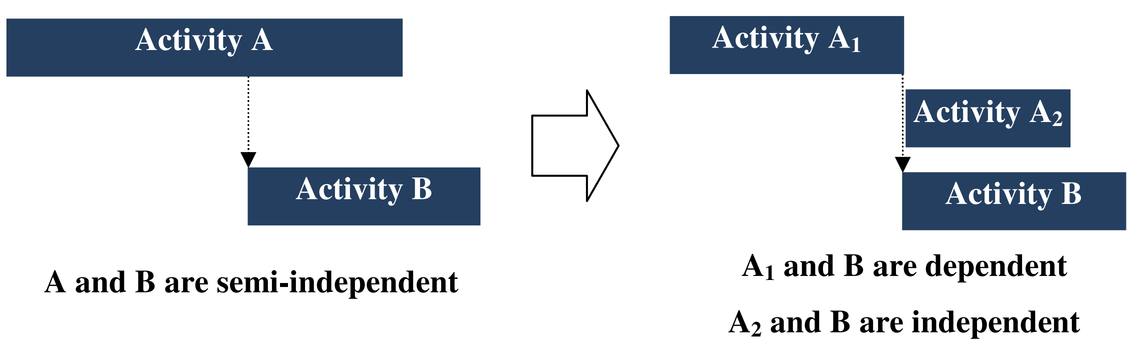

Figure 4-8: Semi-independent activities' overlapping

4.5 Overlapping Time Impact

By implementing the overlapping mechanism explained in the previous section on the project schedule, the real timesaving of design activity overlapping can be better identified (Figure 4-9). If two activities on the project critical path overlap, the actual timesaving will not be equal to the overlapping period as it may first seem. Instead, the actual time saving equals the overlapping period minus the rework period (Dehghan and

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Ruwanpura 2011). However, the survey performed in this research showed that in real world practice, schedulers do not consider the rework period during scheduling, causing their schedules to be a little unrealistic. In some companies though, risk analysts consider the risk of rework when they conduct schedule risk analysis (Appendix 2).

It is also noteworthy that activities with longer durations can potentially generate more overlapping and consequently more timesaving than activities with shorter durations (Pena-Mora and Li 2001).

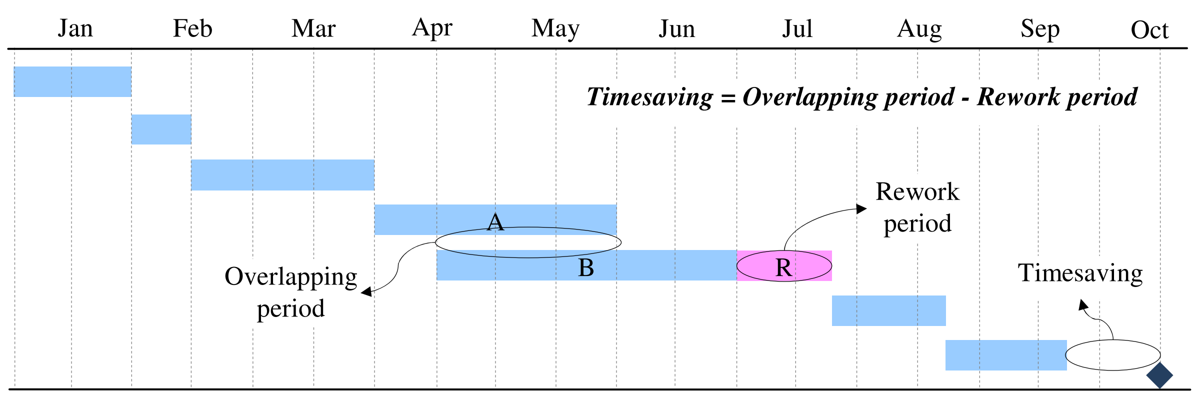

Figure 4-9: Overlapping time impact on the project schedule

4.5.1 Multi-predecessors effect

Figure 4-9 shows a project network with only one path, which is naturally the critical path as well. A single path network occurs when each activity has only one predecessor and one successor. However, a real world situation is very often different as activities may have more than one predecessor or successor. Therefore, multiple paths emerge in the schedule and many of them can potentially become critical. Overlapping critical activities (activities that form the critical path) results in project duration reduction, while

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overlapping noncritical activities does not reduce the duration, and increases project costs as well.

When an activity has multi-predecessors, what was explained so far about the equivalent rework period should be revised. Since the activity may overlap with any and all of its predecessor activities, its equivalent rework duration can be affected by any and all overlaps with the predecessor activities.

In interviews, the multi-predecessor phenomenon was discussed. Unfortunately, no concrete answer could be obtained as the mechanism of interaction among overlaps is too parametric and complex and suggesting a unique pattern is almost impossible. Despite the lack of concrete answers, the industry specialists provided some ad-hoc ideas, which were reviewed and organized and a set of guidelines were identified and used to generate a formula to address multi-predecessors effect on rework. In this section, the guidelines are noted and explained in detail and the formula is developed.

Figure 4-10 shows a successor activity ($j = 1$) with its entire predecessors (i = 1 to n). Each predecessor has an overlapping period with the successor activity (L_{ij}; i=1 to n, j=1). The rework period caused by each predecessor, if the predecessor was supposed to individually overlap with the successor, is shown as well (R_{ij}; i = 1 to n, j =1). Meanwhile, R_1 represents the rework for the successor activity 1 caused by predecessor activities 1 to n (In general, R_{ij} is the equivalent rework duration for successor activity j, as a result of its overlapping with predecessor activity i).

The three guidelines are as follows:

1- *Regardless of the number of predecessors, whatsoever, the rework duration should not supersede the longest individual overlapping duration.*

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As stated earlier, such an expression is reasonable as the worst scenario is when a major change happens and the successor must disregard all its progress during overlapping and start over. This guideline is rephrased as follow:

$$R_j \leq \max_{i=1 \text{ to } n} L_{ij} \qquad [4.6]$$

For example in Figure 4-10, the longest individual overlapping is L_{11}, therefore $R_1 \leq L_{11}$.

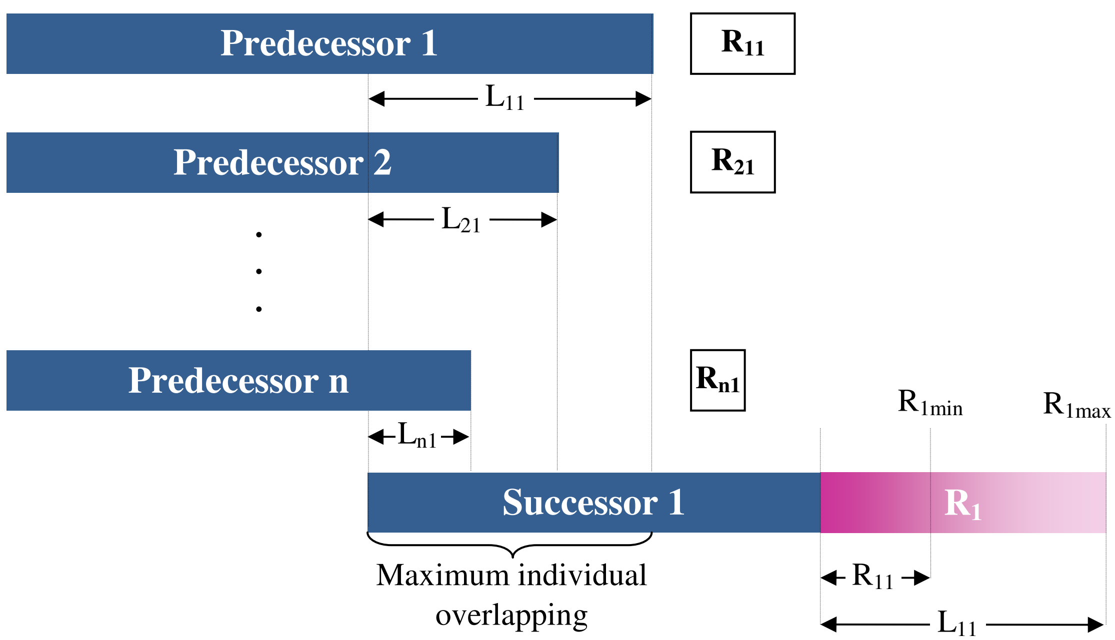

Figure 4-10: Multi-predecessor effect

2- *The rework duration, whatsoever, should not be less than the longest individual rework duration.*

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In other words:

$$R_j \geq \max_{i=1\ to\ n} R_{ij} \qquad [4.7]$$

For example in Figure 4-10, the longest individual rework is R_{11}; therefore, *min* $R_1 = R_{11}$. The justification to this guideline is that when successor 1 only overlaps with predecessor 1, the equivalent rework duration is R_{11}. If more predecessors are added to this arrangement, the resulting rework cannot be reasonably less than R_{11}.

3- *The more predecessors, the more rework.*

Except for very odd cases, the rework duration is increased as the number of predecessors is increased. Therefore, the rework duration formula should be progressive in terms of the number of predecessors.

Unfortunately, further criteria could not be obtained to make the decision more specific. A variety of formulas can satisfy the above criteria. However, considering the probabilistic nature of overlapping rework, using principles of the probabilistic theory makes a good sense in developing formula. In this regard, a suitable formula can be obtained by using the concept of *not mutually exclusive events*.

According to the probability theory, if either event X or event Y or both events occur on a single performance of an experiment this is called the union of the events X and Y denoted as P(X∪Y).

The situation, in which the occurrence of one event is not influenced or caused by another event, is called *mutually exclusive*. It is impossible for mutually exclusive events

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to occur at the same time. In such a situation, the probability of occurrence of two or more mutually exclusive events is the sum of the probabilities of the individual events.

$$P(X \cup Y) = P(X) + P(Y) \qquad [4.8]$$

Otherwise, if the occurrences of two events are independent from each other and they can occur at the same time, the events are *not mutually exclusive (*Montgomery and Runger 2003). Then:

$$P(X \cup Y) = P(X) + P(Y) - P(X)P(Y) \qquad [4.9]$$

The concept of mutually exclusive or not mutually exclusive events is valid for more than two events as well.

Since one activity can overlap with more than one predecessor at a time, the multi-predecessor overlapping is not mutually exclusive. The rework resulted from individual overlaps are considered as individual events. According to equation 4.1, $R_{ij} = P_{ij} \times T_{ij}$. For any overlapping duration (L_{ij}), at least one P'_{ij} exists that $P_{ij} \times T_{ij} = P'_{ij} \times L_{ij}$. Therefore, R_{ij} can be deliberately defined as $P'_{ij} \times L_{ij}$, (equation 4.10) which is a form of equation 4.2, $R_{ij} = f(L_{ij})$.

$$R_{ij} = P'_{ij} \times L_{ij} \qquad [4.10]$$

Or:

$$P'_{ij} = R_{ij} / L_{ij} \qquad [4.11]$$

Therefore, the rework probabilities in Figure 4-10 can be expressed in terms of individual rework durations and the maximum individual overlapping duration (L_{11}):

$$P'_{11} = R_{11} / L_{11} \qquad [4.12]$$

$$P'_{21} = R_{21} / L_{11} \qquad [4.13]$$

…

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$$P'_{n1} = R_{n1} / L_{11} \qquad [4.14]$$

The resulting rework can be expressed as a function of the maximum individual overlapping duration and the union of probabilities (equation 4.15):

$$R_1 = (P'_{11} \cup P'_{21} \cup \ldots \cup P'_{n1}) \times L_{11} \qquad [4.15]$$

For example, when $n = 2$:

$$R_1 = (P'_{11} \cup P'_{21}) \times L_{11} \qquad [4.16]$$

Since the probabilities are not mutually exclusive:

$$R_1 = (P'_{11} + P'_{21} - P'_{11} P'_{21}) \times L_{11} \qquad [4.17]$$

Substituting P'_{11} and P'_{21} from equations 4.12 and 4.13:

$$R_1 = \left(\frac{R_{11} + R_{21}}{L_{11}} - \frac{R_{11}R_{21}}{{L_{11}}^2}\right) \times L_{11} \qquad [4.18]$$

Likewise, when $n = 3$:

$$R_1 = (P'_{11} \cup P'_{21} \cup P'_{31})\, L_{11} \qquad [4.19]$$

$$R_1 = (P'_{11} + P'_{21} + P'_{31} - P'_{11}P'_{21} - P'_{11}P'_{31} - P'_{21}P'_{31} + P'_{11}P'_{21}P'_{31})L_{11} \quad [4.20]$$

$$R_1 = \left(\frac{R_{11} + R_{21} + R_{31}}{L_{11}} - \frac{R_{11}R_{21} + R_{11}R_{31} + R_{21}R_{31}}{{L_{11}}^2} + \frac{R_{11}R_{21}R_{31}}{{L_{11}}^3}\right) \times L_{11} \qquad [4.21]$$

Equations 4.18 and 4.21 define the equivalent rework for successor activity 1, when it overlaps with 2 and 3 predecessors respectively. According to these equations, only the maximum overlapping duration and individual *rework* durations are required to evaluate the *equivalent rework*. Using the probability theory principles, similar equations

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can be developed for *n= 4, 5, …* . Such equations, which all extend on equation 4.15, meet the three criteria explained earlier. In other words, the equivalent rework duration neither exceeds the longest individual overlapping duration nor is less than the longest individual rework duration. Also, the equivalent rework increases when adding more predecessor activities.

As the number of predecessors increases, the risk and amount of rework escalate; therefore, overlapping becomes less favourable. Overlapping is most favourable for activities with fewer predecessors.

4.5.2 Cascade effect

In certain occasions, when the degree of overlapping is high, more than two activities may overlap at the same time and form *a cascade of overlaps*. Figure 4-11 shows a sample cascade of overlaps. As shown in Figure 4-11, activity B has one predecessor (activity A) and one successor (activity C) and separately overlaps with them. Overlapping A with B generates rework period R_B and overlapping B with C generates rework period R_C. When the degrees of overlaps are high, then activity A and activity C may overlap as well. In other words, A and C progress concurrently for a while. However, they are not directly dependent and their dependency is through activity B. In such a condition, the duration of R_C can become longer than the time when A and C are not concurrent, because R_C duration is not only affected by changes in B, but also affected by changes in A. Therefore:

$$R_C = T_{BC}\ (P_{BC} \cup\ P_{AC}) \qquad [4.22]$$

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In which P_{BC} and P_{AC} follow the same definition as of P_{ij} which represents the probability that a change happens for i and causes rework for j.

To better understand the effect of cascade overlaps on rework durations, the source of rework should be investigated. As stated earlier, the source of overlapping rework is changes in predecessor activities that necessitate changes and modifications in successor activities.

The overlapping period between A, B and C can be divided into three distinct intervals as shown in Figure 4-11.

- Interval 1: Activity A and activity B overlap.
- Interval 2: All three activities, A, B, and C overlap and progress concurrently.
- Interval 3: Activity B and activity C overlap.

Furthermore, P_{AB} is the probability that a change happens for A and causes rework for B. P_{AB} and P_{BC} are further broken to represent the probability of change in each of the above intervals. The new probabilities are introduced as:

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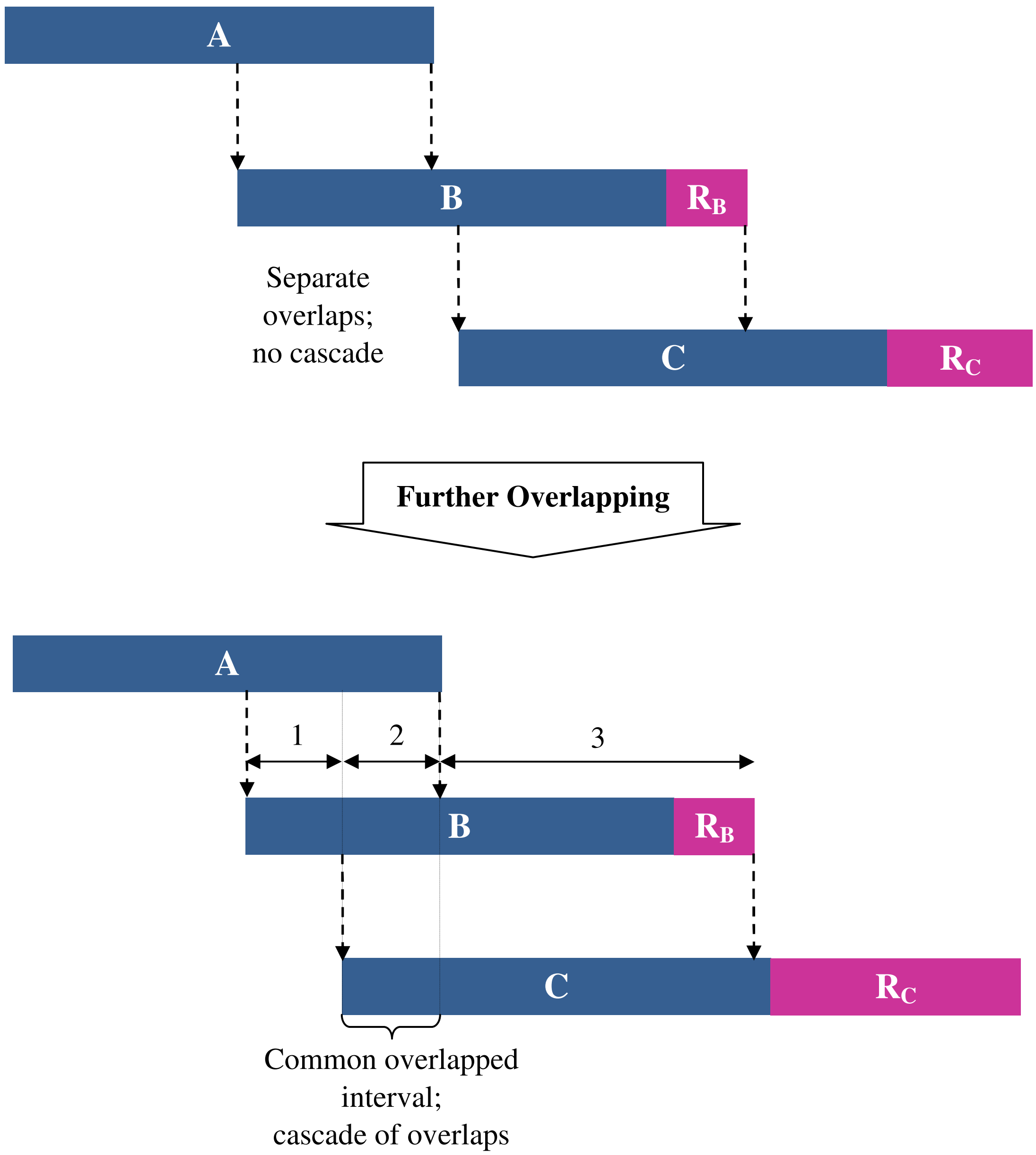

Figure 4-11: Cascade effect

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- $P_{AB,1}$: P_{AB} during interval 1 (contribution to R_B)
- $P_{AB,2}$: P_{AB} during interval 2 (contribution to R_B)
- $P_{BC,2}$: P_{BC} during interval 2 (contribution to R_C)
- $P_{BC,3}$: P_{BC} during interval 3 (contribution to R_C)

Meanwhile, it is assumed that as soon as a change happens in the predecessor that can generate rework for the successor, it is communicated with the predecessor (in form of intermediate information) to prevent further rework (Ha and Porteus 1995).

Not all of the changes happen to activity A during interval 2 are transferred to activity C through activity B. Because some of these changes are completely absorbed by activity B and never transferred to activity C, and only a fraction of the changes affect activity C. To take this fact into account, a *change transfer ratio* is defined.

r_{ABC} is the *change transfer ratio* from activity A to activity C through activity B and is the number of changes that happen for activity A during interval 2 and generate rework merely for activity B (and not for activity C), divided by the number of changes that happen for activity A during interval 2 and generate rework for both activities B and C. Therefore:

$$P_{AC} = r_{ABC}\, P_{AB,2} \qquad [4.23]$$

In which:

$$0 \le r_{ABC} \le 1 \qquad [4.24]$$

Naturally, $r_{ABC} = 0$ means none of activity A's changes affecting activity B, affect activity C; $r_{ABC} = 1$ means all activity A's changes affecting activity B, affect activity C as well.

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With r_{ABC} available, equation 4.22 can be rewritten as:

$$R_C = T_{BC}\ (P_{BC} \cup r_{ABC}\ P_{AB,2}) \qquad [4.25]$$

Since $0 \leq r \leq 1$, then $0 \leq r_{ABC}P_{AB,2} \leq 1$. Also, P_{AC} and P_{BC} are not mutually exclusive, because they are independent probabilities. Therefore, according to equation 4.9:

$$R_C = T_{BC}\ (P_{BC} + r_{ABC}\ P_{AB,2} - \ r_{ABC}\ P_{AB,2}\, P_{BC}) \qquad [4.26]$$

$$R_C = T_{BC}\ \left(P_{BC} + r_{ABC}\ P_{AB,2}\ (1 - \ P_{BC})\right) \qquad [4.27]$$

$$0 \leq r_{ABC}\ P_{AB,2}\ (1 - \ P_{BC}) \leq 1 \qquad [4.28]$$

Equation 4.27 defines the rework duration (R_c) when three activities A, B, and C overlap simultaneously (two simultaneous overlaps). If more than three activities overlap, still the principle of the *union of not mutually exclusive events* should be applied similar to the above. For example, for simultaneous overlapping of four activities (three simultaneous overlaps), the following equation can be used to determine the probability of rework:

$$P(X \cup Y \cup Z) = P(X)+P(Y)+P(Z)-P(X)P(Y)-P(X)P(Z)-P(Y)P(Z)+P(X)P(Y)P(Z) \qquad [4.29]$$

4.6 Overlapping cost impact

The unique advantage of overlapping is the timesaving it generates in the project, which consequently results in a long list of benefits such as earlier operation, earlier income, time to market, increased market share, tax reductions, reduced payback period, increased prestige, etc. Such benefits have their roots in the business objectives of the

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project and are obviously different for owners and contractors (Appendix 2). The main problem lies in extra risks generated, with the risk of rework the greatest. Overlapping can result in more changes, which consequently can result in more rework; more rework can increase expenses and lengthen execution time of the project. Further, sometimes overlapping necessitates utilizing exceptional work procedures, which can adversely affect project quality requirements and even jeopardize safety (Figure 4-12). This means that too much overlapping cannot be applied, because only reasonable levels of risk can be tolerated. If too much overlapping is implemented, then the time saving benefits might be offset and even superseded by the losses originating from rework and cost. Therefore, a trade-off is required between the overlapping timesaving benefits on one hand and its risks and costs on the other hand (Dehghan et al. 2010). Then it is feasible to assess how much overlapping is desirable or which degree of overlapping is optimum.

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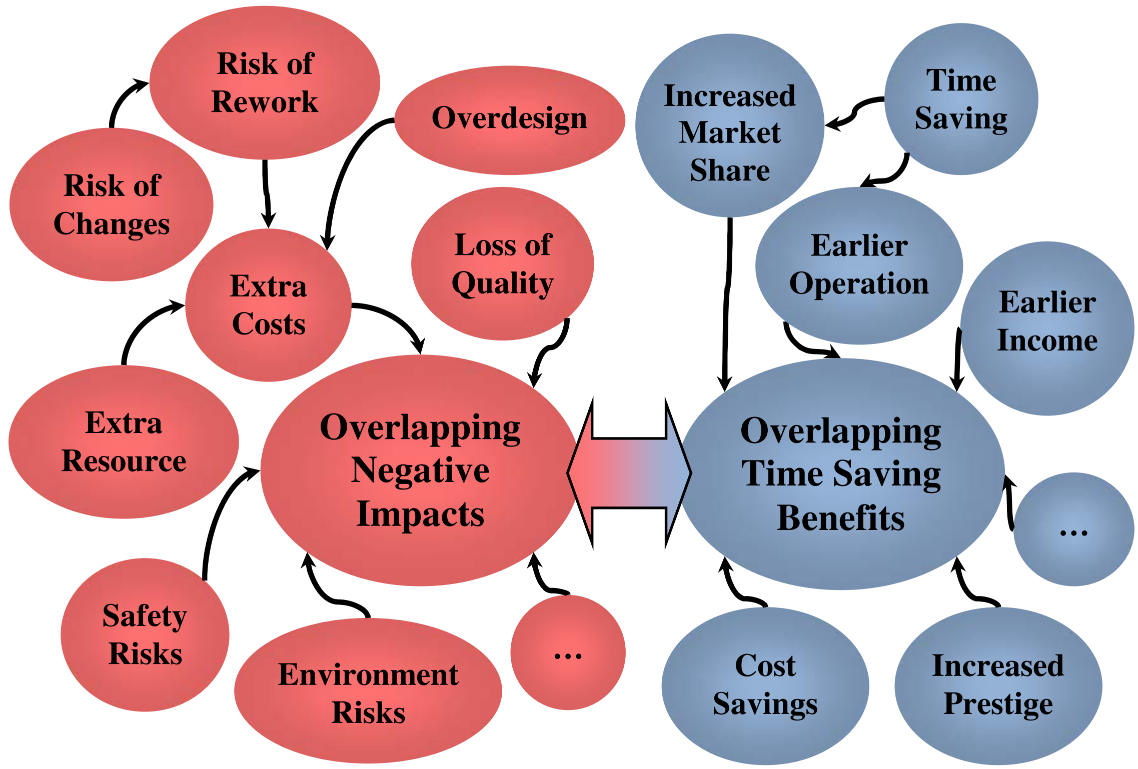

Figure 4-12: Tradeoff between negative consequences and timesaving benefits of overlapping

To facilitate the discussion about overlapping costs, a definition for degree of overlapping is introduced as the percentage of the overlapped fraction duration to the total duration of the shorter activity (Equation 4.30). The shorter activity can be either the predecessor (upstream) or the successor (downstream) activity.

$$A_{ij} = (L_{ij} / min\ (D_i\ and\ D_j)) \times 100 \qquad [4.30]$$

For example in Figure 4-13, the upstream activity (activity A) has a shorter duration compared to the downstream activity (activity B), and the degree of overlapping is $(10 \div 40) \times 100 = 25\%$. According to equation 4.30, 0% overlapping represents the

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time when no overlapping exists between two activities, and 100% overlapping represents the time when two activities are fully overlapped.

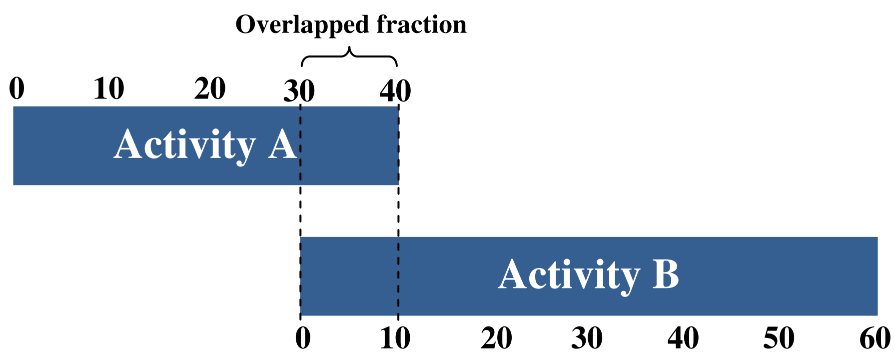

Figure 4-13: Degree of overlapping is 25%

Figure 4-14 shows how the trade-off is implemented on a sample individual overlapping. The sample is not a real example, but is fabricated for better understanding. It envisages four different relative positions of activity B (successor) to activity A (predecessor) in the form of bar charts. In the first position, activity B has no overlapping with activity A, but in the second, third and fourth positions, the degree of overlapping has been increased to 25%, 50% and 75% respectively. Due to the rework, activity B duration is also increased as the overlapping degree increases. Under the bar charts and proportional to their position, a diagram shows loss, benefit and net benefit values of different degrees of overlapping versus timesaving. To get these values, all overlapping risks (such as rework) and opportunities (such as project early finish) are evaluated and converted to their equivalent monetary values (such a conversion is theoretically possible; however, it might be difficult in practice).

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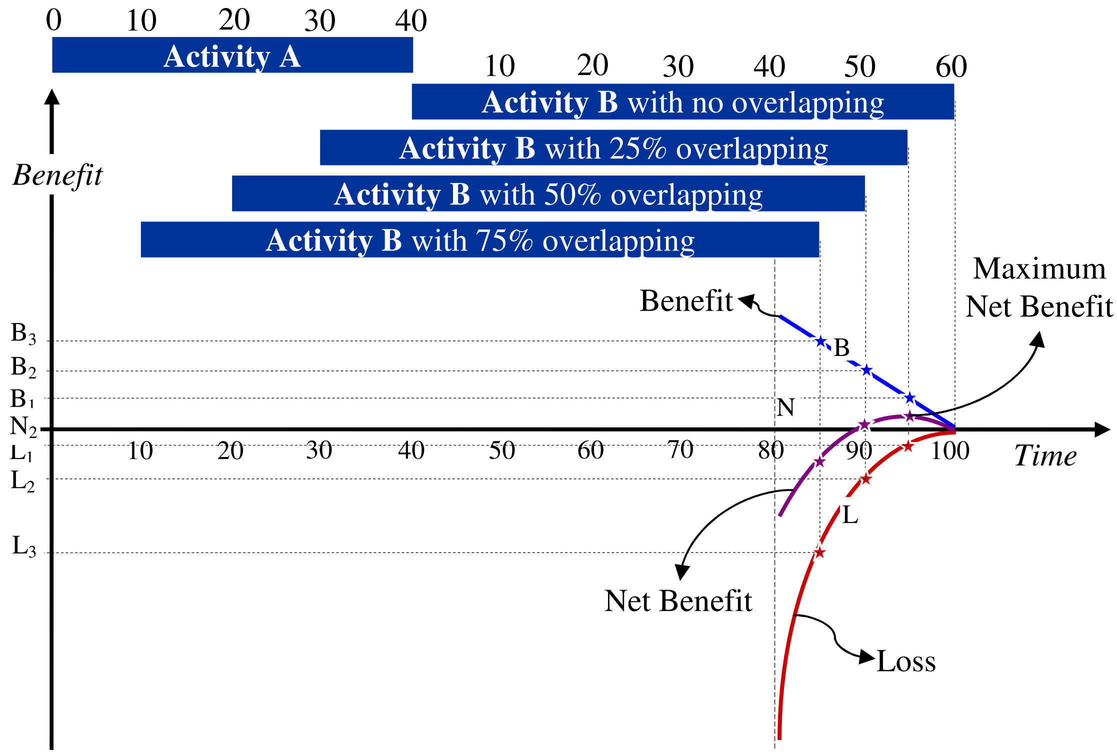

Figure 4-14: Loss-benefit tradeoff for different degrees of overlapping

Although the time unit really does not matter in Figure 4-14, let's assume it is presented in terms of *days* due to the fact that *day* is a very common unit in project scheduling. Therefore, activity A has 40 days duration, activity B has 60 days duration and their total duration is 100 days when no overlapping exists. Naturally, the total duration of both A and B is reduced as the overlapping is increased, e.g. 85 days (which is the same as 15 days timesaving) when the degree of overlapping is 75%. In addition, there is an important assumption in this figure: any change in the total duration of A and B will be directly transferred to the finish time of the project (in that case both A and B must be on the critical path of the project).

When activities A and B are performed sequentially, they generate an added value to the project resulting from the benefits they bring to the project minus the costs of

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implementation. Such costs and benefits (or losses and benefits) are attributed to the sequential or normal execution of A and B, i.e. when no overlapping exists between them. But as soon as overlapping starts, both extra loss and extra benefit are generated on top of the normal execution cost and benefit. The loss/benefit diagram of Figure 4-14 is presenting this extra loss/benefit. For example, when the degree of overlapping is increased to 25%, an additional B_1 benefit and an additional L_1 loss are generated. B_1 is the timesaving benefit because of finishing the project sooner than expected; it reflects gaining any additional financial benefit and tackling any additional business advantage because of reducing project finish time (according to the right hand side of the influence diagram of Figure 4-12). L_1, on the other side, reflects all negative impacts imposed on the project because of the overlapping (refer to left hand side of the influence diagram of Figure 4-12). Examples are losing time and money because of rework and infringement of quality requirements because of work based on incomplete activities. Likewise, when overlapping is increased to 50%, B_2 and L_2 represent the related benefit and loss, and the same is true for 75% overlapping, B_3, and L_3. Normally, with further overlapping, further loss and benefit are generated. In other words, it is expected that $B_3 > B_2 > B_1$ and $L_1 > L_2 > L_3$ (or $|L_1| < |L_2| < |L_3|$).

If a sufficient number of different degrees of overlapping are evaluated the same way as above, then it is possible to plot two curves, one showing the benefits of overlapping versus timesaving and the other showing the losses of overlapping versus timesaving. Such curves have been shown in Figure 4-14 as *benefit* and *loss*. Both curves pass the zero loss/benefit point on day 100.

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Although the benefit is shown as a straight line, it does not mean that other curvatures are not possible. The shape of benefit line depends on the daily value of early project finish and can be of any form; however, according to the interviews typically the benefit is an increasing function and a linear relationship is the most suitable. On the other hand, the loss curve is shown as a convex increasing function (increasing in terms of loss or costs) to represent most real world cases. Other curvatures might be applicable to cost curves, but according to the interviews the cost curves are increasing functions, and usually convex. The literature endorses a similar point as well; for example, Roemer and Ahmadi (2004) state: "... the costs of rework are a convex function of the amount of rework and linear relationships prevail in many applications...". Better information could not be obtained from the interviews about the overlapping cost functions, nor was obtaining the information in the scope of the current research. Separate studies, most likely extensive, are required to reveal more about overlapping cost functions with regard to different types of activities, various conditions, and different types of projects.

Based on the above and in order to resemble the real world, for the experiments with the suggested overlapping tool in Chapter 6 the results of the interviews will be used. In other words, various increasing linear functions will be used for the benefits of early project finish and various increasing functions will be used as overlapping costs.

The net benefit of overlapping is the algebraic summation of its benefit and loss graphically shown in Figure 4-14 as the *net benefit* curve plotted between *benefit* and *loss* curves. This curve determines if a degree of overlapping between two activities is beneficial to the project. For example, in the area between 90 days and 100 days (which represents 50% overlapping to zero overlapping), various degrees of overlapping are

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beneficial to the project, because the net benefit is higher than the default case, i.e. the time no overlapping exists. On the other hand, if the overall timesaving goes beyond 10 days (more than 50% overlapping) the net benefit becomes negative, which means that any degree of overlapping more than 50% is actually a loss to the project. The net benefit curve has a maximum point as well on day 95 (reflecting 25% overlapping or 5 days timesaving), which shows the maximum possible net benefit the project can gain from overlapping activity A with activity B. In other words, in this example 25% overlapping is the optimum degree of overlapping, because it generates the maximum net benefit. Likewise, each individual overlapping has its own characteristics, losses and benefits, which means that each overlapping has its own optimum degree (Dehghan et al. 2010).

The loss curve (which can also be called cost curve) in Figure 4-14 acts as an identification (ID) function for the overlapping. Each individual overlap in the project schedule has its own cost curve or ID (Figure 4-15), which is a function of overlapping risks.

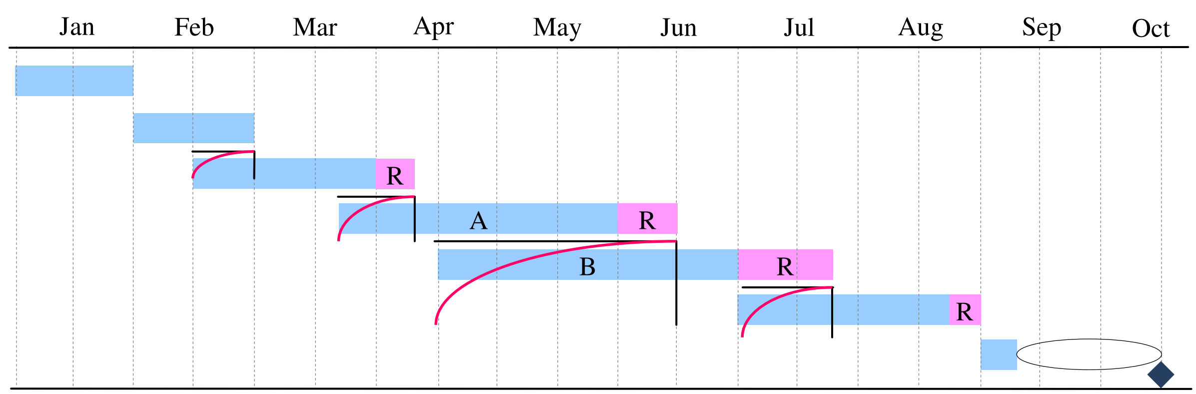

Figure 4-15: Each individual overlap has its own overlapping cost function

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An *Overlapping Strategy* is the collection of individual overlaps and their overlapping degrees arrangement. To evaluate the cost of an overlapping strategy, costs of individual overlaps should be totalled. This matter is further discussed in the next section.

4.7 Formulating the overlapping time-cost trade-off problem

Now that the theoretical mechanism of overlapping and its impact on project schedule is explained, and particularly the overlapping effect on the project costs and benefits are clarified, the time-cost trade-off problem can be formulated. Figure 4-16 shows an overlapping strategy consisting of a number of overlaps in a project schedule. In addition, some examples of benefits and costs generated in the project are given. These benefits and costs are different from contractor to contractor and owner to owner.

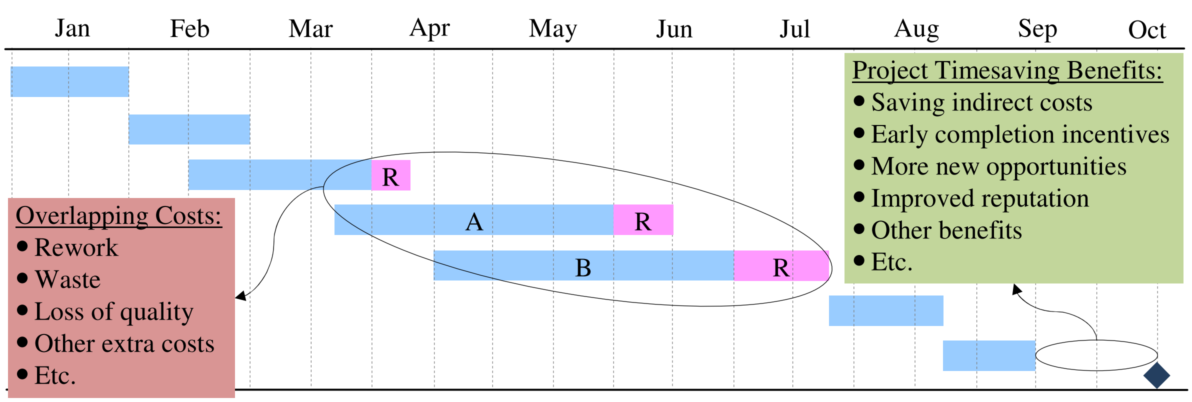

Figure 4-16: Overlapping risks and timesaving benefits

As stated earlier, the net cost/benefit of one individual overlap is the algebraic summation of its costs and benefits. The same is true for an overlapping strategy. If C_{os}

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refers to the costs of an overlapping strategy, and B_{pt} represents the benefits of project timesaving, then the net project cost/benefit of any overlapping strategy will be shown by C and expressed as per equation 4.31:

$$C = C_{os} - B_{pt} \qquad [4.31]$$

If the overlapping strategy results in timesaving, then $B_{pt} > 0$. To formulate C, first C_{os} and B_{pt} should be formulated. However, the following notes and assumptions should be made in advance:

1. The problem is limited to dependent or semi-independent activities and not independent or interdependent activities (because as stated earlier, overlapping independent and interdependent activities does not generate significant risks). In such a condition, the flow of information is unidirectional, from the predecessor activity to the successor activity.
2. To keep the project network logic intact, no activity may commence before its predecessor activities commence. Likewise, no activity may finish before its predecessor activities are terminated.
3. Multiple predecessors or multiple successors are allowed i.e. an activity can have more than one predecessor or successor. Therefore, the network may have a single path or multiple paths; no restrictions apply.
4. Cascade overlapping is allowed, i.e. more than two activities can overlap simultaneously.

Figure 4-17 shows the overlapping of two activities, activity i and activity j. The overlapping interval duration is L_{ij}. As before, if a change in activity i happens and generates rework for activity j, the rework duration is T_{ij} and the probability of such a

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change is P_{ij}. To express i and j overlapping costs, the following variables are also required:

W_j Total daily wage for successor activity j, including daily salaries and daily overheads

E_{ij} Extra costs, other than daily wages and overheads, imposed on successor activity j or on other project areas (design, procurement, construction, etc.) because of the changes made by predecessor activity i during its overlapping with successor activity j

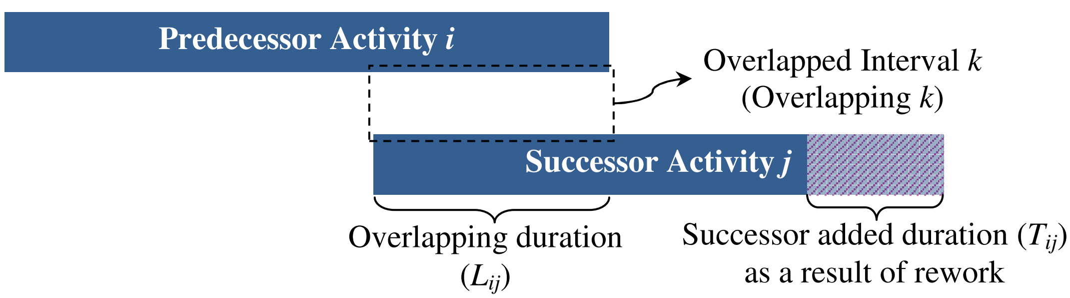

Figure 4-17: Activity overlapping indices with regard to the objective function

If rework happens and T_{ij} is added to the duration of activity j, then $T_{ij} \times W_j$ is the extra money that should be spent to perform this activity. However, this extra expense is not certain. Therefore, taking the probability of rework into account, an *equivalent extra expense* can be defined as $P_{ij} \times T_{ij} \times W_j$. Although for a design activity this cost is typically the predominant cost of rework; to be more comprehensive, E_{ij} is defined to represent any other extra costs which may result from the changes in activity i or rework in activity j. Examples of E_{ij} include wasting design administration and management

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efforts, consequent demolitions and reconstructions in the construction site, and consequent repurchasing materials and equipment. Taking the rework probability into account, the equivalent extra expense becomes $P_{ij} \times E_{ij}$. Therefore, the total costs originated from the rework for activity *j* (or the change in activity *i*) will be $(P_{ij} \times T_{ij} \times W_j) + (P_{ij} \times E_{ij})$ which is simplified to equation 4.32:

$$C_{ij} = P_{ij}\,(T_{ij}W_j + E_{ij}) \qquad [4.32]$$

C_{ij} is the total cost of overlapping *i* with *j* and includes wages, overheads, wastes, damages, and any other extra costs originating from the overlapping risks. Normally, C_{ij} becomes more than zero if *i* and *j* are dependent and inherently sequential, but are overlapped with each other. Otherwise, for any *i* and *j* which are not dependent, C_{ij} is zero, even if *i* and *j* overlap.

In equation 4.32, P_{ij}, T_{ij} and E_{ij} are all functions of L_{ij} and W_j is a constant with regard to L_{ij}. Therefore, C_{ij} is also a function of L_{ij}:

$$C_{ij} = g(L_{ij}) \qquad [4.33]$$

In this research, equation 4.33 (or alternatively equation 4.32) is called "*overlapping cost function*". This function will play the main role in evaluation and optimization of overlapping.

The total cost of an overlapping strategy (C_{os}) is the sum of the individual overlap costs:

$$C_{os} = \sum_{i=1}^{n}\sum_{j=1}^{m} C_{ij} \qquad [4.34]$$

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Therefore:

$$C_{os} = \sum_{i=1}^{n}\sum_{j=1}^{m} P_{ij}\,(T_{ij}W_j + E_{ij}) \qquad [4.35]$$

Now the overlapping cost effect on the project finish time has to be addressed. For this purpose, the following variables are introduced:

B_{ef} Daily benefits of project early finish

C_{lf} Daily costs of project late finish

T Project duration

T_t Project target duration

The interviews in this research showed that B_{ef}, includes but is not limited to the following:

- Daily benefits resulting from saving indirect costs
- Daily incentive amounts for early completion according to the project contract
- Daily benefits of new opportunities obtainable because of early completion
- Daily benefits of gaining reputation for timely completion of the project

Also, the following items were identified in the interviews as contributing factors on C_{lf} :

- Daily indirect costs
- Daily liquidated damages for late completion according to the project contract
- Daily cost of opportunities lost because of late completion
- Daily losses of losing reputation for schedule overrun

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According to the interviews, usually the project indirect cost has the highest contribution to C_{lf} and B_{ef}. Also, C_{lf} and B_{ef} can be generally obtained from project contract terms and conditions, the business department, or the company's senior management. In addition, T_t is the target date of the project which is agreed upon in the project contract or in some cases might be ordered by senior management. T is the duration of the project for any arbitrary overlapping strategy and might be more or less than T_t. Considering the above, the cost effect of any overlapping strategy on the project finish time can be expressed as $C_{lf}\,(T - T_t)$ *if* $T > T_t$ and $B_{ef}\,(T - T_t)$ *if* $T < T_t$. Therefore, the benefit/cost of overlapping timesaving/time-increase is shown as equation 4.36:

$$B_{pt} = \begin{cases} C_{lf}(T_t - T)\ if\ T > T_t\ otherwise\ 0.0 \\ B_{ef}(T_t - T)\ if\ T < T_t\ otherwise\ 0.0 \end{cases} \qquad [4.36]$$

Using equations 4.31, 4.35 and 4.36, the total net project cost is formulated as equation 4.37:

$$C = \sum_{i=1}^{n}\sum_{j=1}^{m} P_{ij}\,(T_{ij}W_j + E_{ij}) + \begin{cases} C_{lf}(T - T_t)\ if\ T > T_t\ otherwise\ 0.0 \\ B_{ef}(T - T_t)\ if\ T < T_t\ otherwise\ 0.0 \end{cases} \qquad [4.37]$$

Subject to:

$L_{ij} < L_{ij,max}$ ensures no overlapping beyond the maximum allowable

$0 < P_{ij} \leq 1$ sets the limit for the rework probability

$C_{lf} \geq 0$ ensures no reward for late finish

$B_{ef} \geq 0$ ensures no penalty for early finish

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$T_t > 0$ maintains the target duration not be negative or zero

$P_{ij} = 0$ if i is not the direct or indirect predecessor to j

Equation 4.37 represents **the overlapping time-cost trade-off objective function** and is central to solve the overlapping optimization problem. Project duration T in equation 4.37 is evaluated using network calculations. For this purpose, the critical path method which includes forward and backward calculations can be used. To calculate T, duration of activities and their dependencies along with overlapping amounts and the resulting rework durations are required. For any project network, the original activity durations and their dependencies are fixed and do not change. Therefore, T varies with variations of overlapping amounts (L_{ij}) and the resulting rework durations (R_{ij}). However, since the rework itself is a function of overlapping duration (equation 4.2: $R_{ij} = f\,(L_{ij})$), project duration is ultimately a function of changes in overlapping durations between predecessor and successor activities in the project schedule:

$$T = h\,(L_{ij}) \qquad [4.38]$$

Considering various possible degrees of overlapping between two activities and the total number of overlaps in a project schedule, an extremely large number of overlapping strategies can be applied to the project schedule. Each strategy results in a net cost/benefit (C) and a total duration (T) for the project. C might be negative or positive depending on the situation. In equation 4.37, if overlapping timesaving benefits exceed overall overlapping costs, then C becomes negative which means net benefit. Otherwise, C becomes positive which means net cost.

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Figure 4-18 presents the locus of project cost/benefit vs. project duration for different overlapping strategies. In the figure, C_{max} is the maximum possible project cost which results from at least one overlapping strategy. Likewise, C_{min} is the minimum possible project cost which results from at least one overlapping strategy. Depending on the overlapping cost functions and early finish incentives and late finish penalties, C_{min} and C_{max} can be less or more than zero. T_{min} is the minimum project duration achieved by an overlapping strategy in which all critical activities are set to their maximum allowable overlapping. Shorter project durations are impossible to achieve with any other overlapping strategy. T_{max} is the longest project duration which is a result of strategies that apply no overlapping onto critical path activities. One such strategy is when no overlapping exists between none of the activities, either critical or non-critical, and results in normal project duration (T_n). Therefore, $T_n = T_{max}$.

The bottom right side of the dotted area is the locus of the overlapping strategies which result in long project durations and high project costs. Naturally such strategies are the least favourable strategies. On the other side, the top left side of the dotted area is the locus of the overlapping strategies with near to minimum project costs and shorter project durations. Such strategies are the most favourable and therefore the preference is to move from the bottom right to the top left side of the dotted area.

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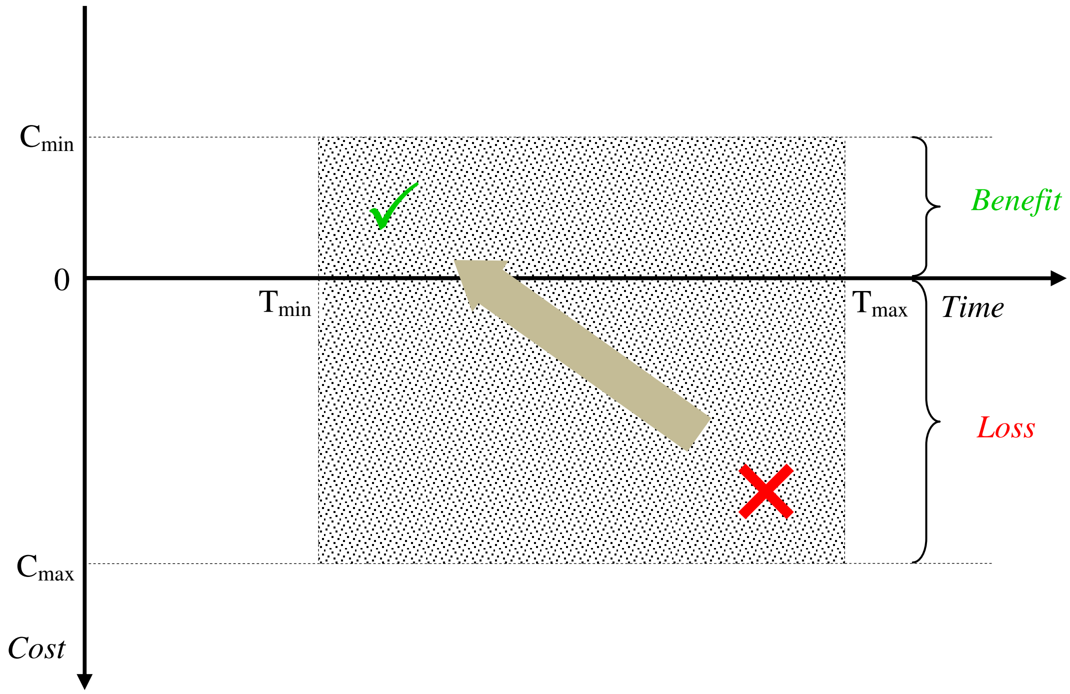

Figure 4-18: Project cost vs. project duration for different overlapping strategies

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4.7.1 Problem variations

Overlapping time-cost trade-off problem has two main variations. The first variation is when the target project duration (T_t) is given, and an overlapping strategy with the minimum cost (maximum profit) is required. As shown in Figure 4-19, the time-cost trade-off problem is finding overlapping strategies that generate the minimum project costs, top side of the dotted area, in the range of T_{min} and T_t.

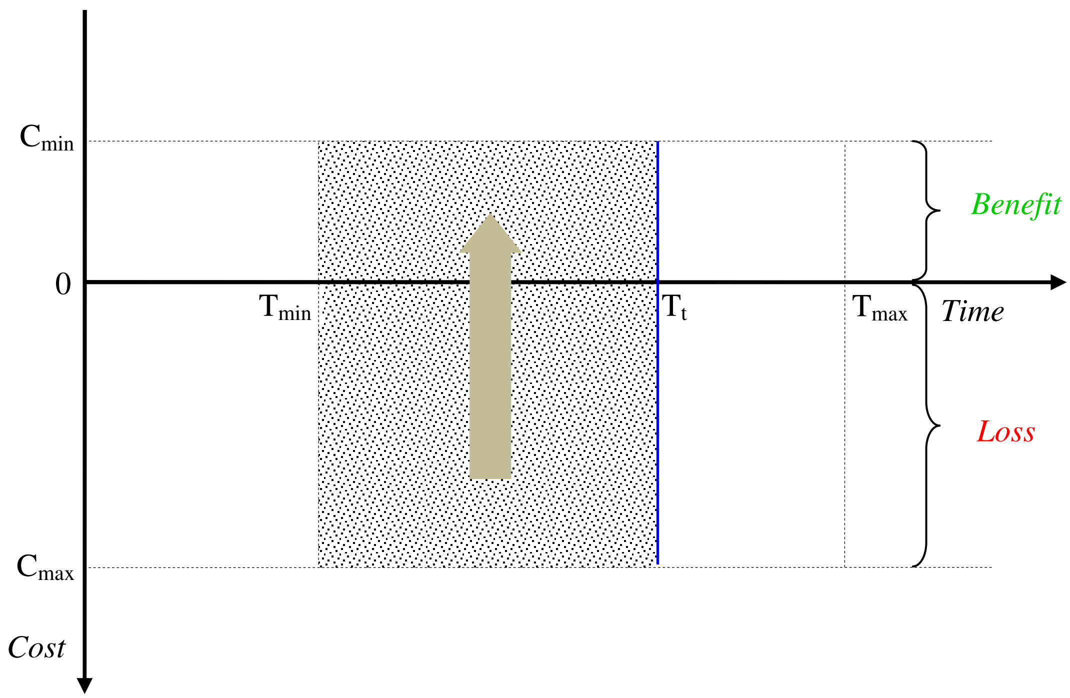

Figure 4-19: Minimizing project cost (maximizing project benefit) within the target project duration T_t

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The second variation is when a target project cost C_t (maximum allowable cost or minimum allowable profit) is given, and an overlapping strategy that results in minimum project duration is asked for. In this case, the time-cost trade-off problem is finding overlapping strategies that minimize project duration (left side of the dotted area) but do not exceed the predetermined project cost limit (C_t) as shown in Figure 4-20.

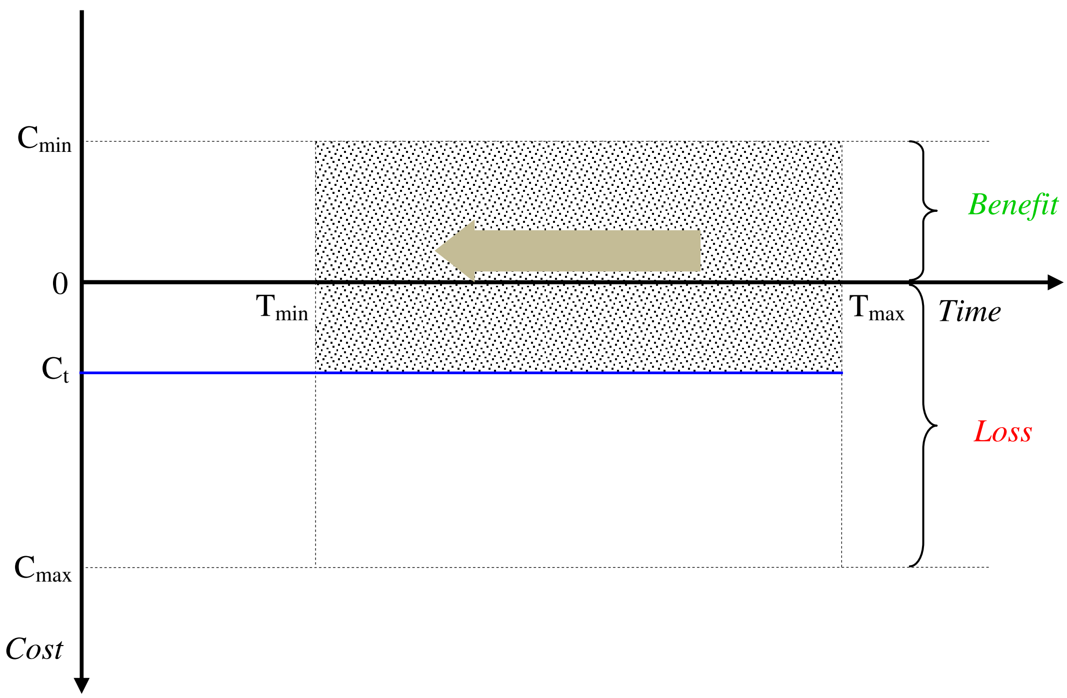

Figure 4-20: Minimizing project duration within the target project cost

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The two variations might be combined and give rise to a hybrid overlapping time-cost trade-off problem in which both project target duration and project target cost are fixed, and still better solutions, i.e. shorter project durations and lower project costs are searched for (Figure 4-21). The overlapping algorithm introduced in Chapter 5 can solve all these variations.

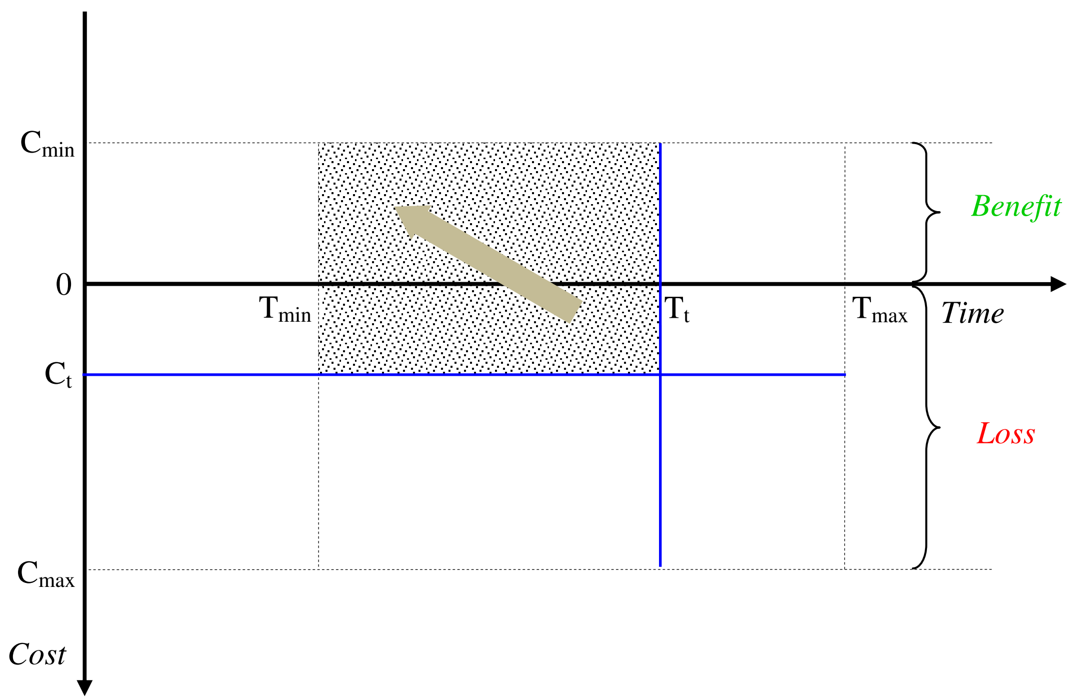

Figure 4-21: Further cost and time improvement within the target project cost and duration

As stated earlier, an extremely large number of overlapping strategies can be applied to the project schedule and each strategy will result in a project duration *T* and project cost *C* as per equation 4.37. Central to solving any variation of the overlapping time-cost trade-off problem is solving equation 4.7. In this equation, T_t, C_{lf}, B_{ef}, and W_j

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(for j= 1 to m) are constant inputs. Also, P_{ij} , T_{ij} and E_{ij} are all functions of L_{ij} and the term $P_{ij}\,(T_{ij}W_j + E_{ij})$ is equal to C_{ij} which can be obtained from overlapping cost functions ($C_{ij} = g(L_{ij})$).

The project duration T is also a challenging parameter to calculate. It should be evaluated from network logic, using forward and backward calculations and the concept of critical path method. However, network calculations are tedious and impossible to be performed manually, even for small networks, if they are supposed to be performed for thousands of times for thousands of overlapping strategies. Further, the resulted project costs and durations of each overlapping strategy should be evaluated and compared with costs and durations of other strategies to find the preferred strategy(s). Therefore, such calculations are practical only when conducted by computer.

Due to the large number of possible overlaps and extremely large number of possible strategies, the optimization process will be complex and extensive. As a result, a robust optimization technique and very likely a computerized one is required to deal with such a complex, multi-objective and parametric problem. Chapter 2 provided an overview on available optimization techniques and introduced Genetic Algorithms as a suitable optimization technique for this purpose. In Chapter 5, an overlapping optimization algorithm which utilizes Genetic Algorithms as its optimization module is developed. Further, the steps to computerize the overlapping optimization algorithm are explained. The computerized overlapping optimization algorithm can solve equation 4.37 and find preferred overlapping strategies.

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4.8 Summary

This Chapter provided insights to the mechanism of overlapping and explained the overlapping model. Types of activity overlapping and the industry practice to apply overlaps in the project schedule were described. Overlapping principle, in which an overlapping may generate rework was explained and the time and cost impacts on the project were highlighted. Also, the effect of multi predecessor activities and cascades of overlaps on the rework duration were formulated. Finally, the overlapping time-cost trade-off problem was formulated and an objective function was developed that have to be optimized using an effective optimization algorithm. The next chapter explains the suggested optimization algorithm.

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Chapter Five: Overlapping Optimization Algorithm and Computer Implementation

The main objective of this research is to develop an activity overlapping model which can determine the best overlapping strategies in projects. This chapter introduces the model which has been developed through the current research and has been founded on the overlapping principles described in previous chapters.

The model uses the genetic algorithms optimization in order to solve overlapping time-cost trade-offs and determine the optimum overlapping strategies. As a result, it encompasses recursive and complex cost and time calculations that cannot be performed manually and which require a computer. This chapter also demonstrates how the model has been computerized by means of two programs: Microsoft Project and Microsoft Excel.

For better and easier understanding, a sample case study has been used all throughout the chapter and different parts of the model are developed using this case study. The sample is a very simple project network with only seven activities and nine relationships. Any particular aspects and specific issues related to the overlapping model performance are also discussed using the same case study. It is emphasized that the purpose of using the case study is to better explain the overlapping algorithm, and is not for verification and validation purposes. Verification and validation will be performed in following chapters using alternate case studies. (Some parts of this chapter have been previously published by the candidate (Dehghan et al. 2011)).

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5.1 Sample Network

The sample network is introduced at the outset to help better understand the mechanism of the overlapping algorithm. Figure 5-1 shows the network which includes seven activities and nine finish-to-start relationships. The original duration of each activity has also been shown in Figure 5-1.

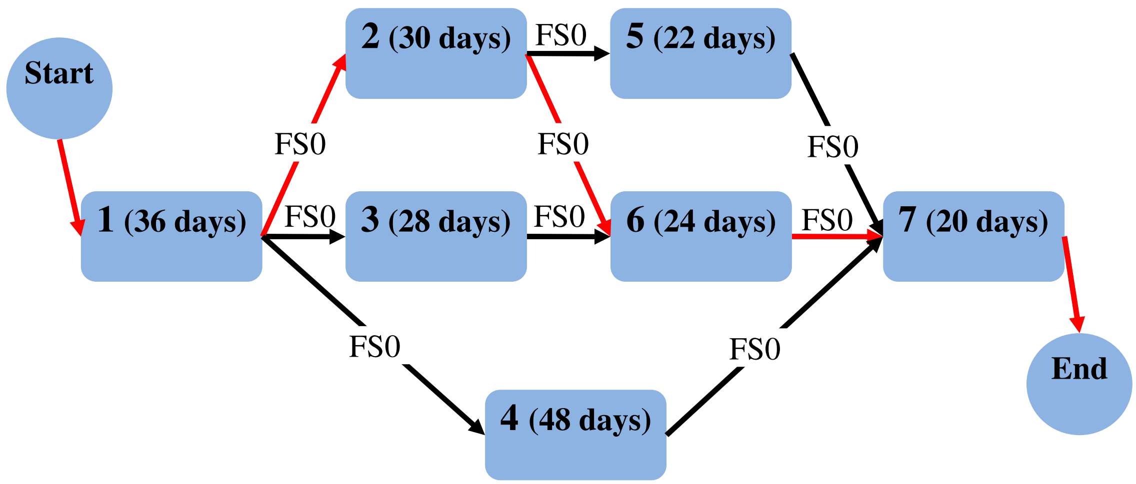

Figure 5-1: The Sample Network

This network encompasses activities with one, two and three predecessors (e.g. activity 2, activity 6 and activity 7 respectively). In addition, activity durations have been defined in a way that all activities may become critical as a result of increasing overlapping between them. The normal duration of this network when there is no overlapping between activities is 110 days and its critical path is:

1 → 2 → 6 → 7

The ultimate goal is to compress the network by applying overlaps between activities. This can be achieved in two different ways: The first is when a finish time is

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given and the least expensive overlapping strategy to meet the finish time is requested. The second is when an additional cost can be given and the overlapping strategy with the shortest duration is searched for. For both cases, some additional information is required. For instance, the maximum allowable overlapping between each pair of activities, the amount of rework generated by each overlap, and the estimated cost of each overlap have to be known. These data as well as other necessary information about the sample case study are presented in Table 5-1.

The table shows activities, their durations, the predecessor(s) for each activity, and the type of relation activities have with each other, before and after overlapping. As stated in Chapter 4, in real world practice, overlapping is applied mainly through finish-to-finish (FF) or start-to-start (SS) relationships with a positive lag and sometimes through finish-to-start (FS) relationship with a negative lag. In the sample case study, a similar strategy is utilized. As shown in Table 5-1, some activities are overlapped by means of FS relationships with negative lags (e.g. activities 1 and 2), some of them are overlapped using SS relationships with positive lags (e.g. activities 1 and 4), and the rest are overlapped through FF relationships with positive lags (e.g. activities 1 and 4). In relation to lag times, table 1 highlights the minimum allowable lag time as well. For example, the minimum allowable lag time for the FS relation between activity 1 and activity 3 is -10, or this amount for the SS relation between activity 2 and activity 5 is 8. With this information, the maximum allowable overlapping can be easily calculated. As explained in Chapter 4, any overlapping beyond the maximum allowable is considered to be technically impossible. Alternatively, any overlapping beyond the minimum lag time is technically impossible (for each of FS , FF, and SS relations the minimum lag indicates

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the maximum overlap. Later in section 5.2.2.1 the relation between the lag time and the overlapping duration will be further detailed).

Table 5-1: General attributes of the sample case study

Act.	Duration	Pred.	Original Relation	Original Lag	Relation after Overlap	Minimum Allowable Lag	Overlapping Rework Function $R_{ij} = f(L_{ij})$	Overlapping Cost Function $C_{ij} = g(R_{ij})$
1	36	-	-	-	-	-	-	-
2	30	1	FS	0	FS	-17	$R_{12}^{\dagger} = 0.2L_{12}^{*}$	$C_{12}^{\ddagger} = 900R_{12}$
3	28	1	FS	0	FS	-10	$R_{13} = 0.1L_{13}$	$C_{13} = 850R_{13}$
4	48	1	FS	0	SS	19	$R_{14} = 0.15L_{14}$	$C_{14} = 1050R_{14}$
5	22	2	FS	0	SS	8	$R_{25} = 0.3L_{25}$	$C_{25} = 800R_{25}$
6	24	2	FS	0	FS	-20	$R_{26} = 0.25L_{26}$	$C_{26} = 1000R_{26}$
6	24	3	FS	0	FF	6	$R_{36} = 0.2L_{36}$	$C_{36} = 1000R_{36}$
7	20	4	FS	0	FF	8	$R_{47} = 0.15L_{47}$	$C_{47} = 950R_{47}$
7	20	5	FS	0	FS	-15	$R_{57} = 0.05L_{57}$	$C_{57} = 950R_{57}$
7	20	6	FS	0	SS	10	$R_{67} = 0.25L_{67}$	$C_{67} = 950R_{67}$

* L_{ij}*: The duration of overlapping between i and j*

† R_{ij}*: The rework duration of the successor activity j as a function of* L_{ij}, $R_{ij} = f(L_{ij})$

‡ C_{ij}*: The cost of overlapping between i and j as a function of* R_{ij}, $C_{ij} = g(R_{ij})$

Overlapping rework durations as a function of overlapped amount and overlapping cost values as a function of rework durations have been also provided in Table 5-1. These functions are required to perform time-cost trade-off computations. As noted in Chapter 4, the cost of overlapping and the rework duration are functions of overlapping degree. In this sample network, various arbitrary types of functions have

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been used to present the overlapping rework and overlapping cost. Although the case study's functions have been selected arbitrarily and do not necessarily reflect any specific real project, they are in compliance with the result of interviews, literature review, and facts and figures extracted from the design phase of oil and gas projects. This means that: 1) The rework ranges are between 5 to 30 percent of overlapping durations. 2) The cost values have a linear relation with rework durations (therefore, cost functions are ultimately a function of overlapping durations).

In addition, we need to know what the daily benefit is for each day of early completion (B_{ef}) and what the daily loss is for each day of late completion (C_{lf}) with regard to project targeted completion date (T_t). For this case study, these values have been shown in Table 5-2.

Table 5-2: Project target duration, early completion benefit, and late completion loss

Project target duration (T_t)	**Project daily benefits for early completion** (B_{ef})	**Project daily losses for late completion** (C_{lf})
105 days	$1000 per day	$1000 per day

Finally, the change transfer ratio (r_{ABC}) is assumed to be zero for all parallel overlaps, which means that changes causing rework only affect the immediate successor activity within a cascade of overlaps.

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5.2 Overlapping Algorithm

The overlapping algorithm developed in this research is based on the overlapping mechanism and fundamentals described in Chapter 4. In this section and its subsections this algorithm is explained in detail. However, it is important to note that the algorithm has two main variations, as the overlapping time-cost trade-off problem has two main variations. As explained in Chapter 4, the first variation is when the project target duration (T_t) is given, and an overlapping strategy with the minimum cost (or maximum profit) is required. Therefore, the time-cost trade-off problem is finding overlapping strategies that generate the minimum project costs. The second variation is when a project target cost C_t (maximum acceptable cost or minimum desirable profit) is given, and an overlapping strategy that results in minimum project duration is asked for. In this case, the time-cost trade-off problem is finding overlapping strategies that minimize project duration but do not exceed the predetermined project cost limit (C_t). It is noteworthy that the first variation is a more common problem in construction industry. In this chapter, the algorithm for the first variation is explained in detail. Then, the algorithm for the second variation, which is slightly different from the first one will be introduced briefly.

Figure 5-2 shows the flowchart of the overlapping algorithm for minimizing the project cost within the project target duration. A part of the algorithm uses the principles of genetic algorithms (GA) optimization in order to solve overlapping time-cost trade-offs. The algorithm encompasses extensive recursive calculations and numerous trial and errors that require computer implementation. Later in this chapter (Section 5.3) it will be shown how the algorithm is computerized. Two major calculation modules exist in the algorithm. One module performs cost calculations and the other performs schedule

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computations and evaluates project time. Furthermore, the algorithm has two main steps. The first step is to generate a collection of random potential solutions (shown as "Generating the initial population" in Figure 5-2) and the second step is to evolve the random solutions to more favourable solutions (shown as "Generating the offspring population" in Figure 5-2). The following subsections further clarify the flowchart (algorithm) of Figure 5-2.

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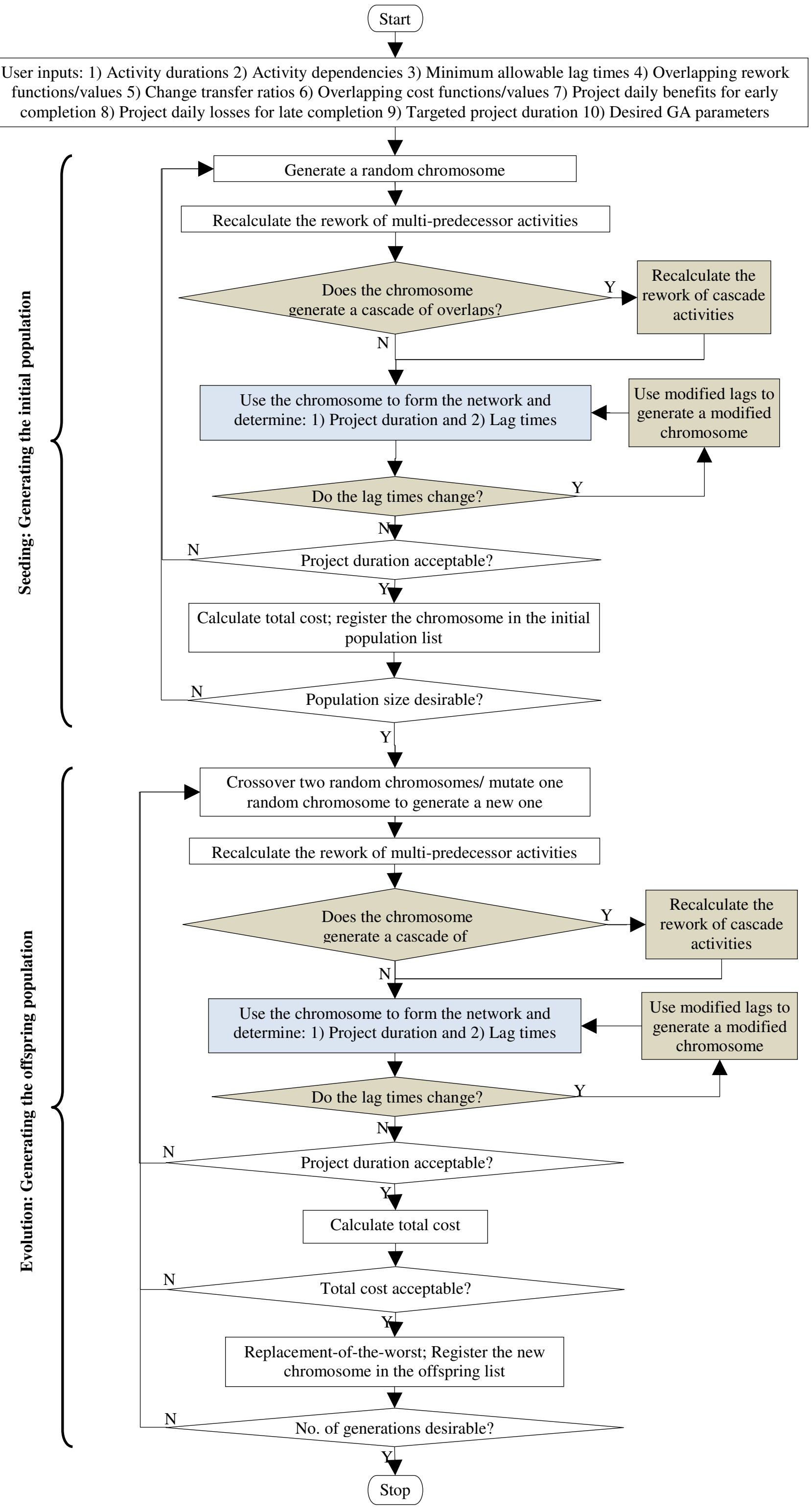

Figure 5-2: The overlapping optimization algorithm for minimizing project cost

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5.2.1 Input Data

The required input data to start the algorithm are:

1. Activity durations
2. Activity dependencies (predecessors and FS, FF, SS relations)
3. Minimum allowable lag times
4. Overlapping rework function (or overlapping rework durations)
5. Change transfer ratios (cascade effect - one ratio per each pair of overlaps)
6. Overlapping cost functions (or cost values for different degrees of overlapping)
7. Project daily benefits for early completion (B_{ef})
8. Project daily losses for late completion (C_{lf})
9. Project target duration (T_t)
10. Desired (user defined) GA parameters

From the above, activity durations and activity dependencies are primary network variables that are required to build the project network. Minimum allowable lag times, rework duration functions, and change transfer ratios are complementary network variables. Overlapping cost functions, project daily benefits for early completion and project daily losses for late completion are cost variables that along with the targeted project duration are used to calculate the total costs/benefits of overlapping. GA parameters are genetic algorithm variables and their variations can change the efficiency of the calculations. Main GA parameters are the desired initial population size, the desired number of offspring reproductions, and the mutation-to-crossover ratio. These parameters will be further clarified through the coming sections.

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5.2.2 Generating Initial Population

An *Overlapping Strategy* is a collection of individual overlaps. Each overlapping strategy is presented by a chromosome and is a potential solution to the problem of reducing the project duration to the targeted time. For the first step, a number of random chromosomes (overlapping strategies) that meet the “time” criterion should be generated.

5.2.2.1 Generating Random Chromosomes

Each chromosome represents an overlapping strategy and encompasses several genes. Each gene represents a relation between two activities and each relation is a potential overlap. Like a real natural gene which holds the information required to build and maintain an organism's cells, the *overlap genes* hold the required information to build the project network and evaluate its duration and cost. Each gene consists of eight pieces of information as follows:

1. Predecessor activity
2. Successor activity
3. Successor activity duration
4. Type of relation between the predecessor and the successor
5. The lag time
6. The overlapping duration between activities
7. The rework duration for the successor activity
8. The cost of overlapping as a result of rework

Figure 5-3 shows a random chromosome from the sample network with the above eight items. The chromosome has 9 genes and each gene has 8 pieces of information. Item 1 indicates which activity is the predecessor and item 2 indicates which activity is

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the successor. Item 3 shows the original duration of the successor activity and item 4 determines what the relation between the two activities will be if they overlap. As shown in Figure 5-3, these four pieces of information are extracted from the original project network, i.e. when the network is at its normal condition. The fifth piece of information is the lag time. The lag time is generated quite randomly because the chromosomes of the initial population must be random chromosomes. Then the overlapping duration (item 6) is calculated using the lag time, the predecessor activity duration and the successor activity duration. Calculating overlapping duration depends on the type of dependency between the two activities. For example, the overlapping duration of Gene no. 4 is 30 – 11 = 19 because for an SS relation:

$$\text{Overlapping duration} = \text{predecessor duration} - \text{SS lag} \qquad [5.1]$$

Also, for an FS relation the overlapping duration is calculated as follows:

$$\text{Overlapping duration} = -\text{ FS lag} \qquad [5.2]$$

And for and FF relation:

$$\text{Overlapping duration} = \text{successor duration} - \text{FF lag} \qquad [5.3]$$

For example, the overlapping duration of Gene no. 5 as per equation 5.2 is - (- 20) = 20 and the overlapping duration of Gene no. 7 is 20 – 12 = 8 as per equation 5.3.

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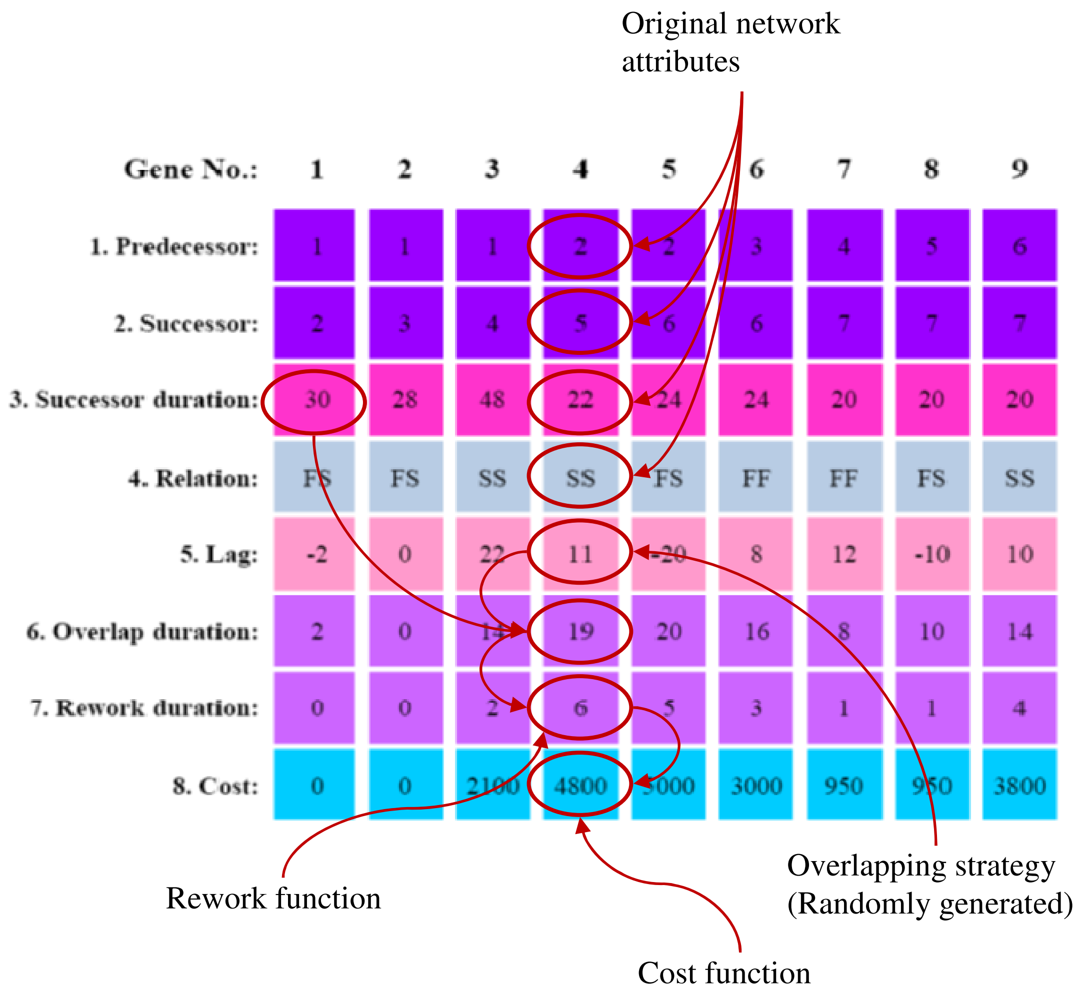

Figure 5-3: A random chromosome

The overlapping duration can be any amount between zero (no overlapping) and the maximum allowable overlapping. As it is the normal practice to express duration in terms of "day" in construction projects, the same time unit is used all through this research. Furthermore, one day is small enough for a construction project so half a day or hours are not used as time units. Therefore, the durations can be expressed as integer

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numbers presenting the number of days. For example, the overlapping duration between activity 1 and activity 2 can be any integer number between 0 and 8. Despite that integer numbers are the preferred way of showing activity durations in this research, the algorithm developed can deal with any type of numbers, both integer and real.

When the amount of overlap is available, its associated rework and cost for the successor activity can be obtained through rework and cost functions (Table 5-1). For example, the overlapping value of gene #4 is 19. According to Table 5-1, the rework function for this gene is $R_{25}= 0.3L_{25}$ which means that the rework for activity 5 should be 6 days:

$R_{25} = 0.3 \times 19 = 5.7$ —roundup→ $R_{25} = 6$

According to Table 5-1, the cost function for this gene is $C_{25}= 800R_{25}$. Therefore, the cost of rework is \$4800:

$C_{25}= 800R_{25} = 800 \times 6 = 4800$.

Similar to lag and overlap durations, the rework durations should be integer numbers. Therefore, the resulted values from rework functions are rounded to the closest integer number.

Note: If two activities have an initial overlap as their normal way of execution, then no rework should be assigned to the overlap as it is a necessary and normal overlap. However, any further overlap may generate rework and the rework should be calculated by considering only the extra overlap.

Therefore, equations 5.1, 5.2 and 5.3 are modified into equations 5.4, 5.5 and 5.6 respectively:

Overlapping duration = predecessor duration - SS lag – original overlap duration [5.4]

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Overlapping duration = - FS lag – original overlap duration [5.5]

Overlapping duration = successor duration - FF lag – original overlap duration [5.6]

5.2.2.1.1 Multi-predecessors effect

With regard to rework duration, genes #5 and #6 have a different story. They reflect a successor activity (activity 6) with two predecessor activities (activity 2 and activity 3). In Figure 5-3, the rework duration of activity 6 in gene 5 is 5 days, while the same rework in gene #6 is 3 days. But activity 6 should only have a unique rework duration. Therefore, its rework should be corrected by calculating the equivalent rework duration. According to equation 4.18, the equivalent rework for activity 6 is calculated as follows:

$$R_1 = \left(\frac{R_{11} + R_{21}}{L_{11}} - \frac{R_{11}R_{21}}{{L_{11}}^2}\right) \times L_{11} \qquad [3.18]$$

$$Rework\ for\ activity\ 6 = \left(\frac{5+3}{20} - \frac{5 \times 3}{20^2}\right) \times 20 = 7.25$$

$$\xrightarrow{\text{rounddown}} \quad Rework\ for\ activity\ 6 = 7$$

Likewise, genes #7, #8 and #9 show that activities 4, 5 and 6 are three predecessors to activity 7. The rework duration of activity 7 should be corrected as well. According to equation 4.21, the equivalent rework for activity 7 is calculated as follows:

$$R_1 = \left(\frac{R_{11} + R_{21} + R_{31}}{L_{11}} - \frac{R_{11}R_{21} + R_{11}R_{31} + R_{21}R_{31}}{{L_{11}}^2} + \frac{R_{11}R_{21}R_{31}}{{L_{11}}^3}\right) \times L_{11} \qquad [3.21]$$

$$R_1 = \left(\frac{4+1+1}{14} - \frac{4 \times 1 + 4 \times 1 + 1 \times 1}{14^2} + \frac{4 \times 1 \times 1}{14^3}\right) \times 14 = 5.38$$

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$$\xrightarrow{\text{rounddown}} \quad \mathit{Rework\ for\ activity\ 7} = 5$$

The above rework corrections are applied on the chromosome and result in the chromosome shown in Figure 5-4. With these corrections, the associated costs will also be changed. Details on how to calculate the total cost of overlaps will be explained in section 5.2.2.4.

Gene No.:	1	2	3	4	5	6	7	8	9
1. Predecessor:	1	1	1	2	2	3	4	5	6
2. Successor:	2	3	4	5	6	6	7	7	7
3. Successor duration:	30	28	48	22	24	24	20	20	20
4. Relation:	FS	FS	SS	SS	FS	FF	FF	FS	SS
5. Lag:	-2	0	22	11	-20	8	12	-10	10
6. Overlap duration:	2	0	14	19	20	16	8	10	14
7. Rework duration:	0	0	2	6	7	7	5	5	5
8. Cost:	0	0	2100	4800	7000	7000	4750	4750	4750

Corrected reworks

Figure 5-4: The random chromosome with corrected rework durations

5.2.2.1.2 Cascade effect

The rework durations may still need corrections if any cascades of overlaps exist. The sample network has the potential to generate cascades of overlaps. In fact, any paths

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with 3 or more activities may have a cascade of overlaps. The overlapping algorithm identifies such paths and checks if any cascades of overlaps exist. Potential paths that may generate cascades of overlaps can be identified from the chromosome:

Path 1: 1 → 2 → 5 → 7

Path 2: 1 → 2 → 6 → 7

Path 3: 1 → 3 → 6 → 7

Path 4: 1 → 4 → 7

Cascade of overlaps happen if the duration of an activity is less than its total overlap duration with its predecessor and successor activities. For example, in path 1, if $L_{25} + L_{57} \leq D_5$, then no cascades happen. Otherwise, if $L_{25} + L_{57} > D_5$, a cascade of overlaps happens (Figure 5-5).

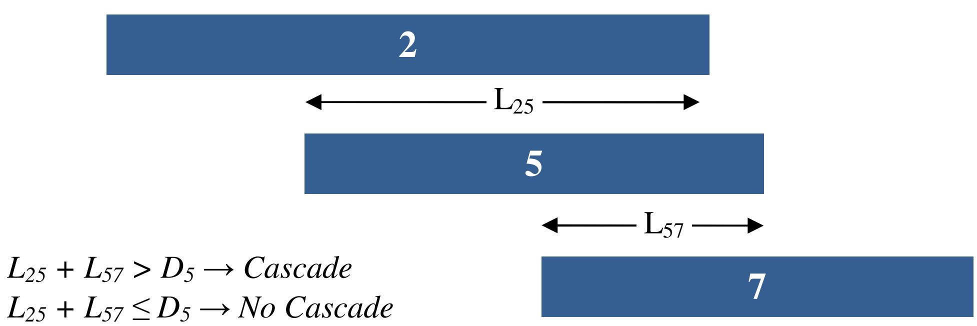

Figure 5-5: Identifying a cascade of 2 overlaps

In this case, L_{25} = 19*,* L_{57} = 10 and D_5= 22. Therefore, a cascade of overlap happens and equation 3.27 should be followed to re-evaluate rework durations. In this example the change transfer ratio was set to zero for all parallel overlaps; therefore, r_{257} =

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0. This means that changes in activity 2 will only affect activity 5. Hence, although cascades of overlaps exist, rework durations remain unchanged. To identify all cascades, every 3 consecutive activities on each path should be checked. For cascades of more than 2 overlaps, a similar approach can be taken. Mathematically, *if the total duration of all overlaps is more than the total duration of all intermediate activities bounded by the first and last activities, a cascade of overlaps happen*. For example, in path 1, If $L_{12} + L_{25} + L_{57} > D_2 + D_5$, then a cascade of 3 overlaps happens (Figure 5-6).

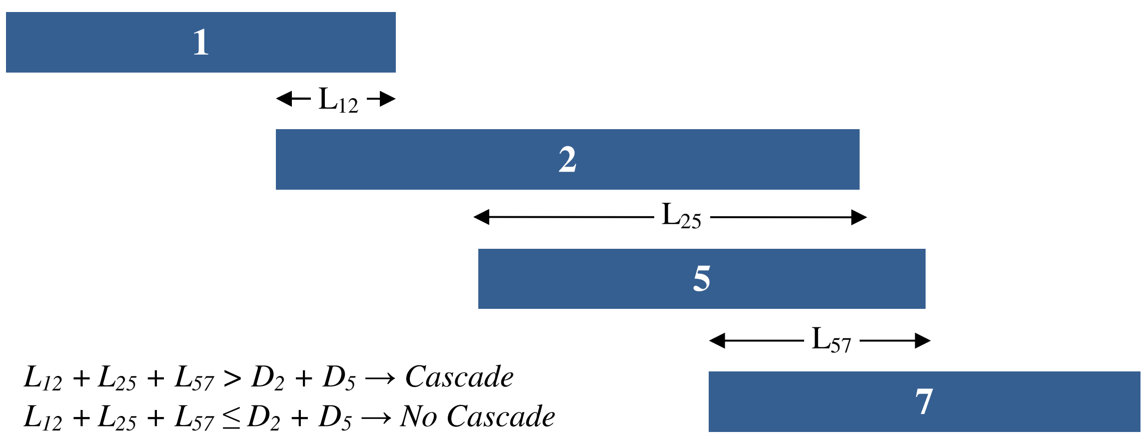

Figure 5-6: Identifying a cascade of 3 overlaps

Missing from the chromosome of Figure 5-4 is the duration of activity 1, which has to be separately taken into account for calculations within the optimization process.

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5.2.2.2 Network (Schedule) Calculations

The next step in the overlapping algorithm (Figure 5-2) is forming the network and performing scheduling calculations. For this purpose, activities original durations, dependencies (FS, SS, FF), lag times, and rework durations are used to form the network.

For example, the sample chromosome from Figure 5-4 contains the required data to form the network of Figure 5-7.

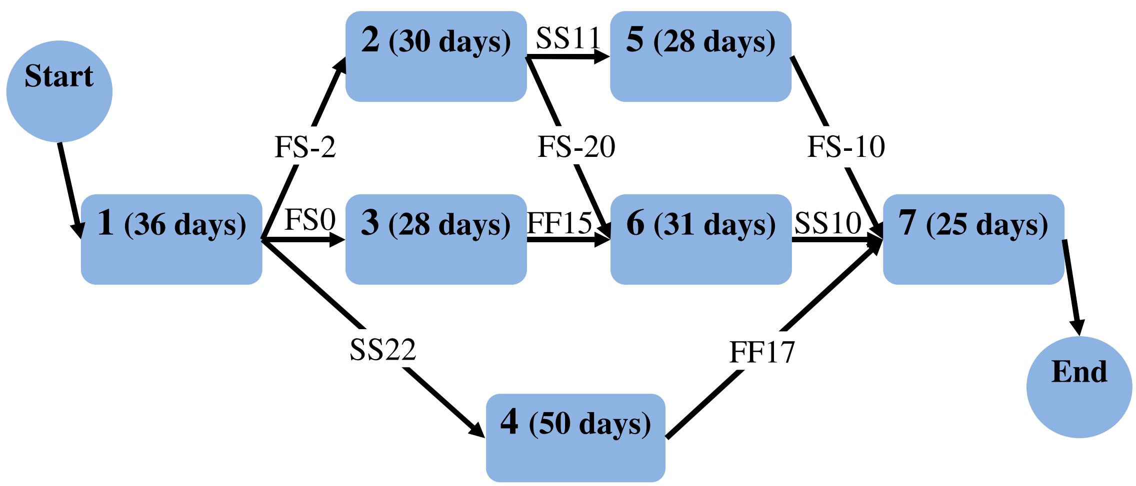

Figure 5-7: The network of the sample chromosome of Figure 5-4

To form the network, activity durations and activity relations should be adjusted according to the data within the genes. The rework duration of each activity must be added to its original duration. As a result, activity durations might be different from their original amounts. For example, the duration of activity 4 is now 50 days instead of 48

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days, as 2 days rework is considered as a result of 14 days overlap between activity 4 and activity 1. Likewise, the durations of activities 5, 6 and 7 are increased.

Rework durations affect the finish-to-finish dependencies as well. Finish-to-finish relations should be adjusted because when the successor activity duration is increased, its FF lag time with the predecessor activity is also increased. As shown in Figure 5-7, the lag time of the FF relation between activity 3 and activity 6 is now 15 days instead of 8 days, as the duration of activity 6 is now 7 days longer due to rework. Consequently, activity 6's FF relation with activity 3 should be 7 days longer as well. Likewise, the lag time of the FF relation between activity 4 and activity 7 is now 12 + 5 = 17.

The rework durations do not affect FS and SS lag times and these lag times remain unchanged.

Network calculations encompass forward and backward calculations in order to determine the earliest and latest start and finish time of each activity, free floats and total floats of each activity, total network duration, and the critical path(s). The sample chromosome leads to a network with 89 days total duration. The critical path is changed from 1 → 2 → 6 → 7 (Figure 5-1) to 1 → 4 → 7 (Figure 5-8). The earliest and latest start and finish time of each activity along with activities free floats and total floats are shown in Figure 5-8.

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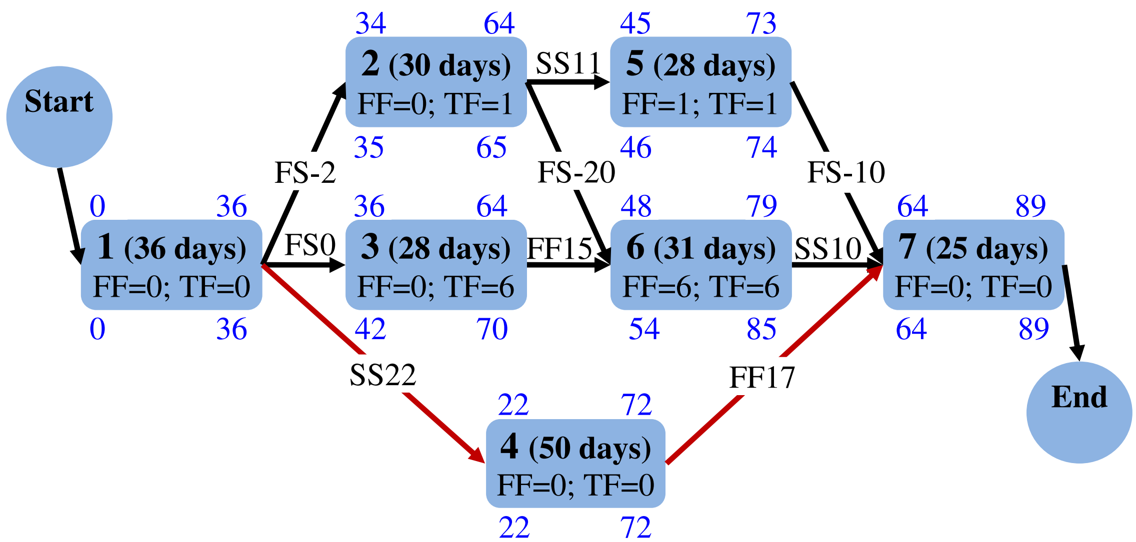

Figure 5-8: The sample network with the earliest start and finish times.

According to the network logic, some of the dependencies are driving dependencies and others are not. For example, activity 6 has two dependencies with its predecessors. The FF15 dependency between activity 3 and activity 6 is a driving dependency, because the start of activity 6 depends on it. But, the FS-20 dependency between activity 2 and activity 6 is not a driving dependency, because it does not trigger the start of activity 6. If the lag time of this dependency is increased to -16, which is equal to reducing the overlap between activity 2 and activity 6 by 4 days, this dependency becomes a driving dependency. Therefore, there are 4 days of unnecessary overlapping between activity 2 and activity 6 that may generate extra cost, but does not affect the start date of activity 6 and consequently the project finish time. To avoid these types of overlaps, the lag times of all non-driving dependencies should be increased until those

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dependencies become driving. by such a relaxation on lag times, unnecessary overlaps, which do not reduce the project finish time but impose extra risks and costs are avoided. Therefore, the lag times modified based on the network logic become different from the original random lag times. Figure 5-9 shows the modified network using modified lag times. Although some of the overlaps have been reduced, the total project duration is still 89 days.

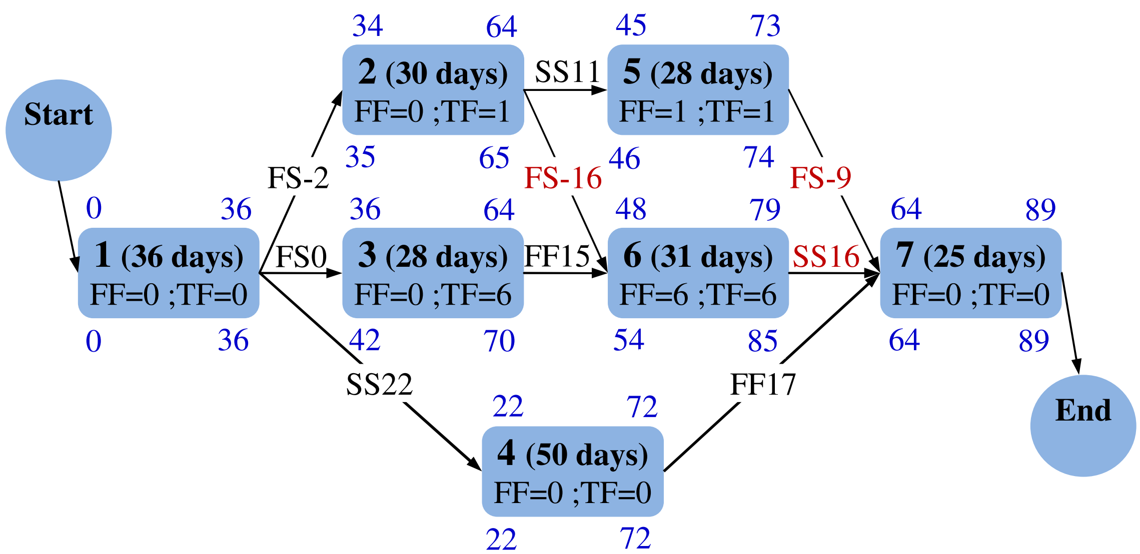

Figure 5-9: The network of Figure 5-8 whose lag times are modified to avoid unnecessary overlaps

Changes in lag times may cause the associated rework durations to change as well. This means that activity durations may also change. For example, when the dependency between activity 2 and 6 is changed from FS-20 to FS-16, the resulting

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rework for activity 6 will be reduced from 5 to 4 as per the relevant rework function from table 1, $R_{26}= 0.25L_{26}$. Consequently, the duration of activity 6 is decreased as well.

Therefore, rework durations and activity durations have to be recalculated and the chromosome should be constructed again. The associated chromosome with the network in Figure 5-9 is reconstructed in Figure 5-10. Multi-predecessor and cascade effects have been incorporated in this chromosome.

Gene No.:	1	2	3	4	5	6	7	8	9
1. Predecessor:	1	1	1	2	2	3	4	5	6
2. Successor:	2	3	4	5	6	6	7	7	7
3. Successor duration:	30	28	48	22	24	24	20	20	20
4. Relation:	FS	FS	SS	SS	FS	FF	FF	FS	SS
5. Lag:	-2	0	22	11	-16	14	15	-9	16
6. Overlap duration:	2	0	14	19	16	16	8	9	8
7. Rework duration:	0	0	2	6	6	6	3	3	3
8. Cost:	0	0	2100	4800	6000	6000	2850	2850	2850

Figure 5-10: The chromosome associated with the network in Figure 5-9

Comparing Figure 5-10 with Figure 5-4 shows that the rework durations, and consequently the cost values are decreased as a result of modifying lag times. This modified chromosome has to go through the same process previously explained, i.e.

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forming the network, recalculating activity durations, recalculating FF dependencies durations, determining the earliest and latest start and finish times of each activity, recalculating activities free floats and total floats, recalculating the total network duration and determining the critical path(s). If necessary, lag times should be relaxed again to prevent unnecessary overlaps. Therefore, the above process might be repeated several times, until all lag times are completely modified and remain unchanged. Then the final network/chromosome is ready for a time check followed by a cost evaluation.

5.2.2.3 Time Check

Each chromosome results in one project duration, which is defined by network calculations. The algorithm can perform a time check if required. For example, the requirement might be only accepting project durations equal to or less than a targeted project duration. If the duration is equal or less than the project target duration ($T \leq T_t$), then the chromosome is acceptable and passes to the next step, otherwise the chromosome is ignored and the previous step to generate a new chromosome is repeated. In the sample case study, the target duration is 105 days which means that project durations more than 105 days are not acceptable ($T \leq 105$).

In order to investigate the total cost for all project durations, the time check can be waived.

5.2.2.4 Cost Calculation

As explained earlier, each chromosome represents a solution which is an overlapping strategy. Each chromosome generates costs because of overlaps and at the same time may generate benefit because of timesaving. The total amount of cost (or benefit) of chromosomes can be calculated using the main objective function, i.e.

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equation 4.37 in chapter 4. Individual costs of overlapping are obtained from the genes (Figure 5-10) and totalled. Also, the cost/benefit of a project late/early finish time is calculated and added to/deducted from overlapping costs.

For the chromosome of Figure 5-10, the total cost is calculated by summing up the cost of rework for all 7 activities. Cost of rework for activity 1 is zero as it does not have any rework (this cost is not reflected in the chromosome). Cost of rework for activities 2, 3, 4, 5, 6, and 7 is 0, 0, 2100, 4800, 6000 and 2850 respectively. Therefore:

Overlapping cost = 0 + 0 + 0 + 2100 + 4800 + 6000 + 2850 = $15750

In which, $4800 is the cost value of genes 5 and 6. Since both genes include the rework cost for activity 6, only one of them is taken into account to calculate the total cost. The same is true for $2850 which is the cost value of genes 7, 8 and 9. Since all of them are the rework cost for activity 7, only one of them should be taken into account to calculate the total cost.

The timesaving benefit for early completion is calculated as follows:

Timesaving benefit = 1000 dollars/day × (105 – 89) days = $16000

Finally, the total net cost is:

Total cost = 15750 – 16000 = -$250

Therefore, the chromosome represents an overlapping strategy which results in $250 net benefit.

5.2.2.5 Initial Population

The generated chromosome, along with the project total duration and project total cost it generates, is recorded. The process of generating random chromosomes is repeated until a suitable number of chromosomes, e.g. 100, are generated. Then random

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chromosomes generation can be stopped. These chromosomes form the initial population of solutions. The population encompasses completely random overlapping strategies with various time and cost attributes. In the next steps, the initial population is used to reproduce offspring population with targeted cost and time attributes.

5.2.3 Generating Offspring Population

The initial population of solutions must evolve to generate better solutions. This is possible by changing the stronger solutions genes with each other (marriage or crossover) to generate new solutions (offspring genes). New solutions are evaluated and, if they are better than the weakest solutions in the population, will replace them. This process of generating better and better solutions is repeated until a satisfactory population is generated. The fittest members of the population are the best solutions.

5.2.3.1 Generating Offspring Chromosomes

Generating offspring chromosomes in genetic algorithms is performed through crossover and mutation, resembling natural evolution. To generate an offspring chromosome via crossover, the algorithm randomly selects two members of the initial population as parent chromosomes, and interchanges their genes. The crossover takes place by randomly selecting some of the genes of one chromosome with the same genes in the other chromosome (Goldberg 1989) (Figure 5-12).

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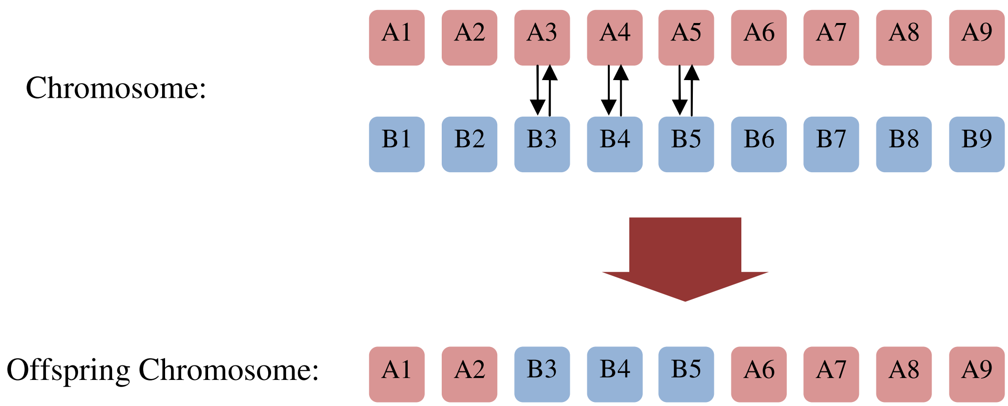

Figure 5-12: Crossover

Unlike crossover, which resembles the common natural way of reproduction (Goldberg 1989), mutation is an odd phenomenon that resembles the process of a sudden generation of an exceptional offspring that may turn out to be a genius. Mutation is performed by randomly selecting one chromosome from the initial population and then arbitrarily changing some of its genes. Essentially, what mutation does is preventing the optimization process from being trapped in local optima (Hegazy 1999) (Figure 5-13).

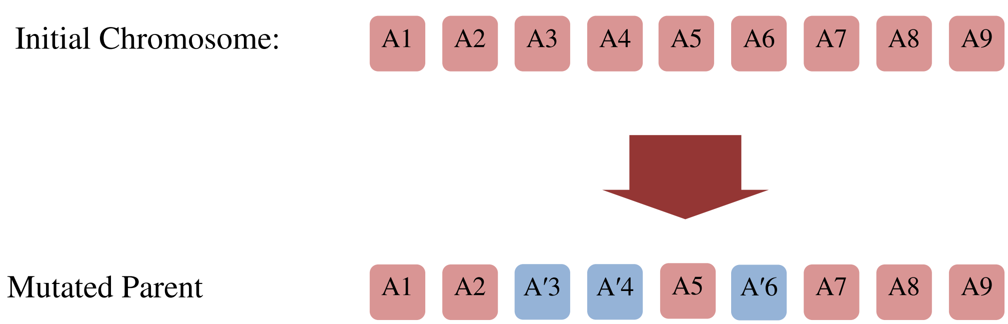

Figure 5-13: Mutation

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Chromosomes generated through crossover or mutation have to undergo the same process as initial random chromosomes.

5.2.3.2 Network (Schedule) Calculations, Time Check, and Cost Calculation

The associated calculations with an offspring chromosome including network calculations, time check, and cost calculations are essentially the same as such calculations for a parent chromosome. Therefore, what was described in sections 5.2.2.2., 5.2.2.3 and 5.2.2.4 are also applicable for offspring chromosomes.

5.2.3.3 Cost Check

When an offspring is generated by crossover or mutation and its cost is calculated, a fitness evaluation should take place to ensure the offspring chromosome is acceptable. This is performed by comparing the cost (benefit) of the offspring chromosome with other chromosomes; if it is better (lower cost or higher benefit) than the worst chromosome in the population, the offspring replaces the old chromosome. Otherwise, the offspring is ignored.

5.2.3.4 Offspring Population

The process of generating offspring chromosomes should be continued until a number of optimum chromosomes that best fit the objective function emerge. Miscellaneous termination criteria exist to stop offspring generation. For instance, one criterion can be the convergence rate of the results. However, in the current algorithm, the number of generations determines when the process should be stopped.

Two points are noteworthy. First, the final offspring population includes a range of solutions and not only one best solution. Second, even the best solution might not be the absolute best solution. Unfortunately, there is no way to ensure if the best

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chromosome in the final offspring population is the absolute optimum or it is only a near-to-optimum solution.

At this point, the first variation of the overlapping optimization algorithm ends. Computer implementation of this algorithm is explained in section 5.3.

5.2.4 Overlapping Algorithm: Second Variation

Figure 5-14 shows the flowchart of the overlapping algorithm for minimizing the project duration within the project targeted cost. This algorithm is only slightly different from the first variation algorithm. Comparing the two algorithms (Figure 5-2 and Figure 5-14) shows that the only visible difference is in the "generating the initial population" step in which a cost check is performed in the second variation instead of a time check in the first variation. The checking ensures that the generated chromosome meets the cost constraint imposed. The rest of the flowcharts are pretty similar to each other. However, the time check and cost check in the "generating the offspring population" step are performed in different ways. In the first variation, the time check is to ensure that the imposed time constraint is met and the cost check is to verify if the generated chromosome is better than the worst chromosome in the population. In the second variation, the cost check is to ensure that the imposed cost constraint is met and the time check is to make sure if the generated chromosome is shorter in duration than the longest duration chromosome in the population.

It is emphasized that both variations of the algorithm are able to handle both continuous and discrete values for activity durations, lag times, rework durations and costs. Therefore, both of them can perform both continuous and discrete optimization.

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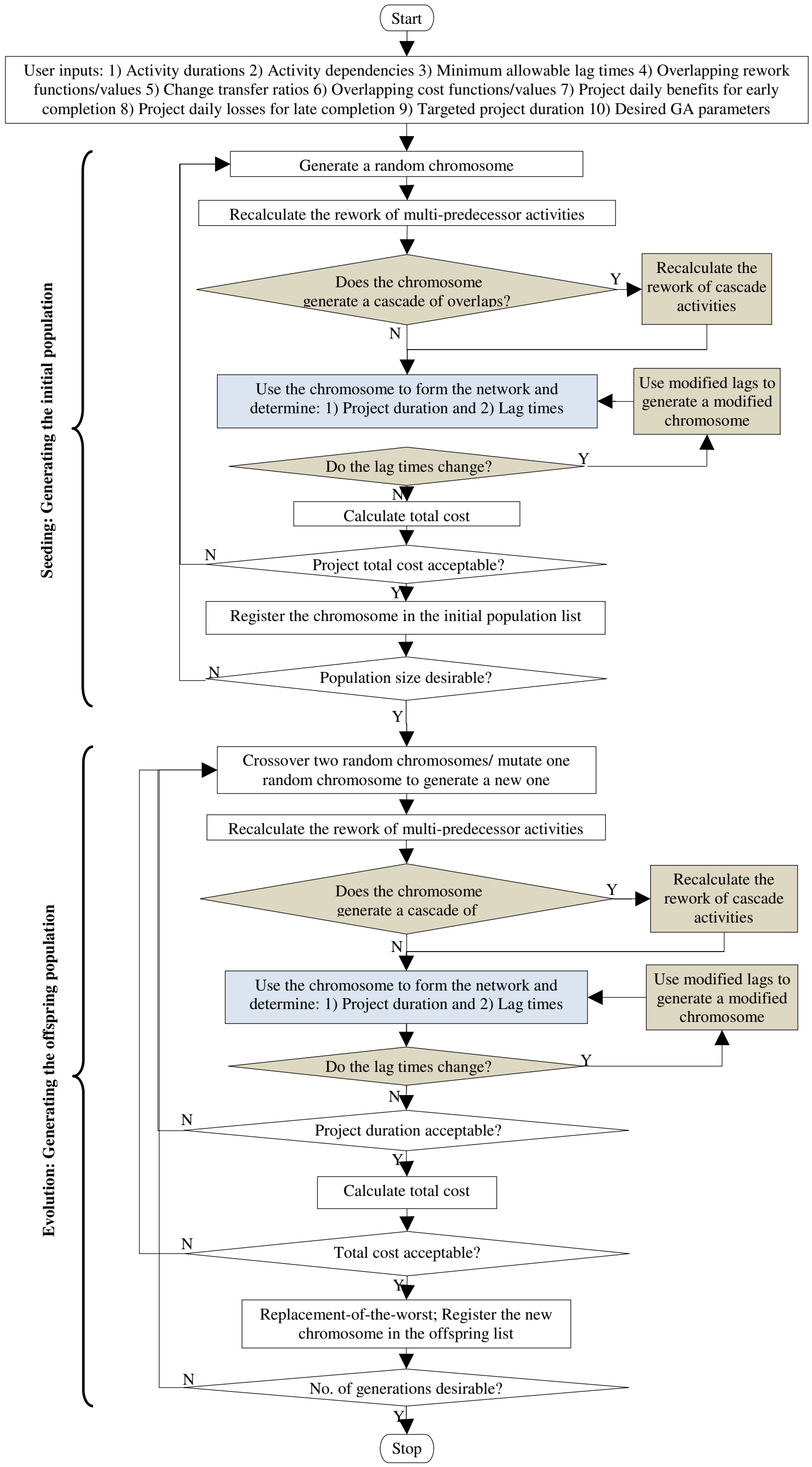

Figure 5-14: The overlapping optimization algorithm for minimizing project duration

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5.3 Computerization

Both variations of overlapping optimization algorithm encompass extensive recursive calculations and numerous trial and errors that require computer implementation. To maximize the benefit, Microsoft Excel (Excel) and Microsoft Project (MSP) were coupled to implement the algorithm. The GA module was generated in Excel as a template, and MSP was used to perform network calculations. This approach highly facilitated the implementation process, as network CPM calculations and other computations such as resource levelling are all included as built-in features in MSP and are not required to be programmed independently. Therefore, practitioners are provided with an automated tool that integrates the current overlapping optimization algorithm into the powerful features of their familiar software. Figure 5-15 presents the flow of information between Excel, MSP and the user.

For several reasons Excel was selected as the GA algorithm platform: First, it is a suitable platform for applying a wide variety of variables and conducting complex and iterative computations. Second, it gives flexibility to the researcher to easily change the variables and review and analyze the results. Third, it is quite compatible with MSP and flow of information can easily take place between them.

Visual Basic for Applications (VBA) has been used for automating the calculations and coding and programming the simulation model. The advantage of VBA is its compatibility with both Microsoft Excel and Microsoft Project applications as well as its flexibility to incorporate changes and perform sensitivity analyses.

In this section, the computer implementation of the first variation of overlapping optimization algorithm is described. The second variation is quite similar to the first one.

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According to Figure 5-15, the following input data (which has also been shown in Figure 5-2) are used to generate a database in Excel:

- Activity durations
- Activity dependencies (predecessors and FS, FF, SS relations)
- Minimum allowable lag times
- Overlapping rework function (or overlapping rework durations)
- Change transfer ratios (cascade effect - one ratio per each pair of overlaps)
- Overlapping cost functions (or cost values for different degrees of overlapping)
- Project daily benefits for early completion (B_{ef})
- Project daily losses for late completion (C_{lf})
- Project target duration (T_t)
- Desired (user defined) GA parameters (initial population size, number of offspring generations, mutation to crossover ratio, etc.)

From the above, activity durations and activity dependencies are primary network variables and are exported to MSP to build the network. Minimum allowable lag times and overlapping rework functions are complementary network variables that are also exported to MSP from Excel. Overlapping cost functions, project daily benefits for early completion and project daily losses for late completion are cost variables and will be used by Excel to calculate the total costs/benefits of overlapping. Project target duration is a constraint defined by the user. The GA parameters are genetic algorithm variables and their variations can change the efficiency of the calculations.

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During optimization process, activity durations, activity dependencies and suggested lag times are sent from Excel to MSP. MSP performs network caluclations. Consequently, project duration and new lag times are returned to Excel. If project duration *(T)* is more than project target duration (T_t), then the chromosome does not meet the time constraint and the above steps should be repeated to generate a new chromosome. But if project duration *(T)* is less than project target duration (T_t), the Excel

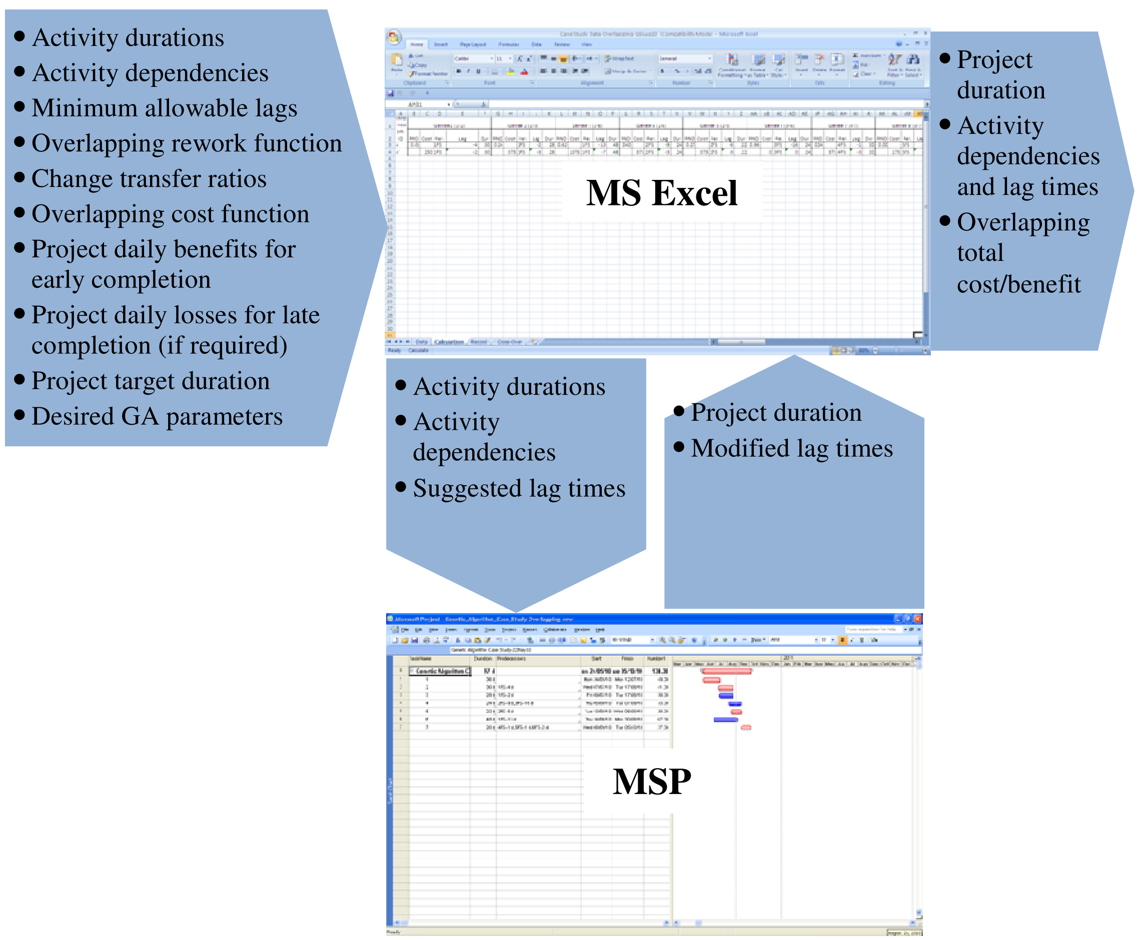

Figure 5-15: Flow of information between MS Excel and MSP

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template uses new lags to form a modified chromosome and recalculate the total cost. This process is repeated until a desirable number of first generation solutions (e.g. 100) are produced.

In the next step, the initial population should evolve to generate better solutions. For this purpose, Excel selects two chromosomes randomly as parent chromosomes and exchanges their genetic information to reproduce an offspring chromosome. Once in a while Excel performs mutation as well, according to mutation to crossover ratio. The offspring chromosome is exported to MSP to perform network calculations and determine project duration, modify lag times, and return the information to Excel. Again, if project duration (T) is less than project target duration (T_t), the Excel template uses the new lags to form a modified offspring chromosome and recalculate the total cost. If the total cost is less than the total cost of a chromosome in the population with the highest total cost, the old chromosome is replaced by the new chromosome. The above process, i.e. crossover-mutation and cost recalculation in Excel and network calculations in MSP is repeated until a satisfactory number of offspring chromosomes are reproduced (e.g. 1000).

The final population is a collection of low cost chromosomes. The chromosome with the lowest total cost is the best solution. However, other chromosomes in the vicinity are alternative solutions depending on the project conditions.

5.3.1 Incorporating constraints

Using MSP for network calculations brings an important advantage to the overlapping optimization algorithm. Any scheduling and even resource constraints that

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can be incorporated in MSP or other commercial scheduling software, can be incorporated into the overlapping optimization algorithm as well.

Resources such as human, machinery, tools, etc. can be allocated to activities in MSP, and in each optimization run MSP levels resources to avoid over-allocations or conflicts.

In addition, very often activities have time constraints. For example, concrete pouring operations must be completed before winter. These time constraints can also be incorporated in MSP. Therefore, MSP performs network calculations while ith taking constraints into account and then exports the results to Excel.

A constraint is a requirement for when a task must start or finish. The following are examples of constraints (note: this information is taken from the MS Project Help File and so is, to a certain degree, specific to that application. It does however show the basic meaning of each type of constraint):

- **As Late As Possible.** With this flexible constraint, Microsoft Project schedules the latest possible start and finish dates for the task, given other scheduling parameters. This is the default constraint for new tasks for a project scheduled from the finish date.
- **As Soon As Possible.** With this flexible constraint, Microsoft Project schedules the earliest possible start and finish dates for the task, given other scheduling parameters. No additional date restrictions are put on the task. This is the default constraint for new tasks for a project scheduled from the start date.

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- **Finish No Earlier Than.** This moderate constraint indicates the earliest possible date that this task can be completed. It cannot finish any time before the specified date.
- **Finish No Later Than.** This moderate constraint indicates the latest possible date that this task can be completed. It can be finished on or before the specified date.
- **Start No Earlier Than.** This moderate constraint indicates the earliest possible date that this task can begin. It cannot start any time before the specified date.
- **Start No Later Than.** This moderate constraint indicates the latest possible date that this task can begin. It can start on or before the specified date.
- **Must Finish On.** This inflexible constraint indicates the exact date on which a task must finish. Other scheduling parameters such as task dependencies, lead or lag time, resource leveling, and delay become secondary to this requirement.
- **Must Start On.** This inflexible constraint indicates the exact date on which a task must begin. Other scheduling parameters such as task dependencies, lead or lag time, resource leveling, and delay become secondary to this requirement.

5.4 Summary

This chapter described the overlapping optimization algorithm suggested by the researcher. Different elements of the algorithm were explained in detail and the implementation was shown on a sample network. Both main variations of the algorithm, i.e. minimizing project duration within a predefined cost and minimizing project cost within a predefined time frame, were highlighted. In addition, the algorithm computerization was described. In the next chapter (Chapter 6), the results of optimizing the above sample network will be presented and discussed. In addition, more experiments

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performed by the computerized overlapping optimization tool on the above sample network and a real world example and the results will be separately analyzed and discussed.

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Chapter Six: Testing the Overlapping Optimization Computer Tool

This chapter highlights some of the experiments performed with the overlapping optimization tool. The objectives of these experiments were:

1. Fine-tuning the tool and setting the performance parameters (GA parameters).
2. Checking and validating the tool performance
3. Obtaining optimization results and analyzing them

Three sets of experiments were performed and the results are presented. The first experiments were conducted on a conceptual case study very similar to the case study explained in Chapter 5. The second experiment aimed at testing and validating the performance of the optimization algorithm and the computer tool. The third experiment was performed on a real project case study.

For all experiments, a personal computer (PC) with the following attributes was used:

- Manufacturer: DELL
- Model: Studio XPS 9100
- Processor: Intel(R) Core(TM) i7 CPU 960 @ 3.2GHz
- Installed memory (RAM): 12.0 GB
- System type: 64-bit Operating System
- Windows: Windows 7 Professional

The PC used is similar to those used in engineering and construction firms. Therefore, the experiments' results, in terms of processing times, are expected to be the same in the real world.

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6.1 Conceptual network (7-activity network)

The first experiment was performed on the conceptual case study explained in Chapter 5. The general attributes of the conceptual case study are shown in Table 6-1 and the network of the case study is shown in Figure 6-1. In addition, the project parameters are as follows:

- Daily benefit for each day of early completion (B_{ef}) = \$1000 per day
- Daily loss for each day of late completion (C_{lf}) = \$1000 per day
- Project targeted completion date (T_t) = 105 days

Cascade effect:

- Change transfer ratio ($\boldsymbol{r}_{ABC}$) = 0.

Objectives: Two main objectives of the first set of experiments are:

1. Fine-tuning the genetic algorithm parameters
2. Testing the performance by random checking different computational elements of the tool

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Table 6-1: General attributes of the sample case study

Act.	Duration	Pred.	Original Relation	Original Lag	Relation after Overlap	Minimum Allowable Lag	Overlapping Rework Function $R_{ij} = f(L_{ij})$	Overlapping Cost Function $C_{ij} = g(R_{ij})$
1	36	-	-	-	-	-	-	-
2	30	1	FS	0	FS	-17	$R_{12}^{\dagger}= 0.2L_{12}^{*}$	$C_{12}^{\ddagger}= 900R_{12}$
3	28	1	FS	0	FS	-10	$R_{13}= 0.1L_{13}$	$C_{13}= 850R_{13}$
4	48	1	FS	0	SS	19	$R_{14}= 0.15L_{14}$	$C_{14}= 1050R_{14}$
5	22	2	FS	0	FS	-22	$R_{25}= 0.3L_{25}$	$C_{25}= 800R_{25}$
6	24	2	FS	0	FS	-20	$R_{26}= 0.25L_{26}$	$C_{26}= 1000R_{26}$
6	24	3	FS	0	FS	-16	$R_{36}= 0.2L_{36}$	$C_{36}= 1000R_{36}$
7	20	4	FS	0	FF	8	$R_{47}= 0.15L_{47}$	$C_{47}= 950R_{47}$
7	20	5	FS	0	FS	-15	$R_{57}= 0.05L_{57}$	$C_{57}= 950R_{57}$
7	20	6	FS	0	FS	-6	$R_{67}= 0.25L_{67}$	$C_{67}= 950R_{67}$

* *L_{ij}: The duration of overlapping between i and j*

† *R_{ij}: The rework duration of the successor activity j as a function of L_{ij}, $R_{ij} = f(L_{ij})$*

‡ *C_{ij}: The cost of overlapping between i and j as a function of R_{ij}, $C_{ij} = g(R_{ij})$*

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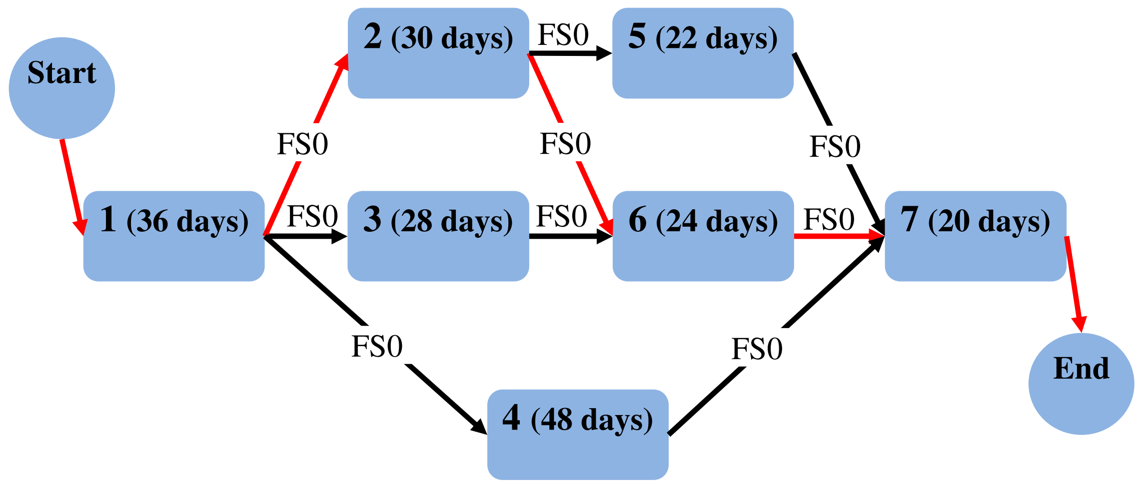

Figure 6-1: The conceptual case study

6.1.1 Experiment 1: Base case study

A base case study was performed to provide a general view of the performance and results. The mutation rate, crossover rate and the population size are the key parameters of a GA. For obtaining good performance, these parameters have to be "tuned" based on results obtained. Typically, a very small mutation rate may lead to stagnation in local optima. A too high mutation rate may lead to loss of good solutions and an essentially random search. No general theory exists to determine good rates. In this case study, several trials were performed and the following GA parameters were found to be suitable:

GA parameters:

- Initial population size: 100
- Crossover-mutation population size: 100
- Crossover rate: 98%

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- Mutation rate: 2%

- Termination criteria: Termination after 100, 200, 300, ... , 2000, 3000, 4000 and 5000 runs.

The results of the optimization are presented in Table 6-2.

Table 6-2: Results of Experiment 1

No.	Population	Max. Benefit ($)	Duration (days)	Calculation Time (Sec.)	Min. Benefit ($)
1	Initial	4700	93	22	-5600
2	1st CO-MU	5400	93	31	-200
3	2nd CO-MU	5400	99	28	850
4	3rd CO-MU	5400	99	29	1850
5	4th CO-MU	5650	94	28	2650
6	5th CO-MU	6500	95	25	3050
7	6th CO-MU	6500	95	27	3400
8	7th CO-MU	6500	95	25	3750
9	8th CO-MU	6500	95	23	3850
10	9th CO-MU	6500	95	24	4350
11	10th CO-MU	7700	93	24	4400
12	11th CO-MU	7700	93	25	4600
13	12th CO-MU	7700	93	22	4650
14	13th CO-MU	7700	93	23	4750
15	14th CO-MU	7700	93	24	5350
16	15th CO-MU	8700	93	23	5400
17	16th CO-MU	8700	93	22	5900
18	17th CO-MU	8700	93	20	6350
19	18th CO-MU	8700	93	19	6350

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20	19th CO-MU	8700	93	19	6500
21	20th CO-MU	8700	93	19	6500
22	30th CO-MU	8700	93	206	6600
23	40th CO-MU	8700	93	198	6700
24	50th CO-MU	8700	93	200	6700

The maximum benefit, the project duration associated with the maximum benefit, and the optimization calculation time are the most important results. The minimum benefit is also presented for further analysis (project duration associated with the minimum benefit is not shown). In any population (or generation), the best chromosome represents the maximum benefit, while the worst chromosome represents the minimum benefit.

According to the table, an initial population with 100 chromosomes was generated. The processing time was 22 seconds. The best chromosome resulted in a project maximum benefit of $4700 and a project duration of 93 days. The worst chromosome in the population generated $5600 cost (-$5600 benefit). Then the initial population was used to generate 100 new chromosomes (1st CO-MU population) by means of crossover and mutation (CO-MU). The calculation time was 31 seconds. In the new generation, the best chromosome had a maximum benefit of $5400 and the worst chromosome generated $200 cost (-$200 benefit). Therefore, both best solution and worst solution improved significantly compared to the initial population solutions. By generating more chromosomes, better solutions were obtained. In the 15th generation, after generating 1500 chromosomes through crossover and mutation, a chromosome emerged that had a maximum benefit of $8700 and 93 days project duration. This

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chromosome was the best solution achievable as even in the 50th generation no better chromosome could be generated. The best solution is shown in Figure 6-2. The worst chromosome in the populations, on the other hand, was improved from $5400 in the 15th generation to $6500 benefit in the 50th generation. Therefore, even though the best solution remains unchanged, later generations encompass better solutions than earlier generations.

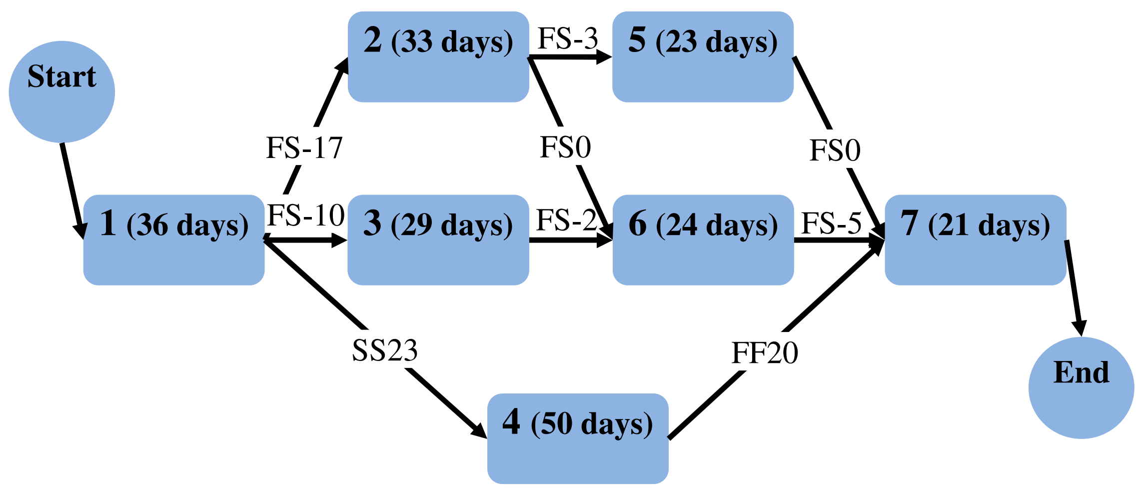

Figure 6-2: The best solution of Experiment 1

Figure 6-3 shows some of the results achieved during Experiment 1. To keep the figure readable, only the results of the initial population and the 1st, 10th and 20th crossover-mutation populations are shown.

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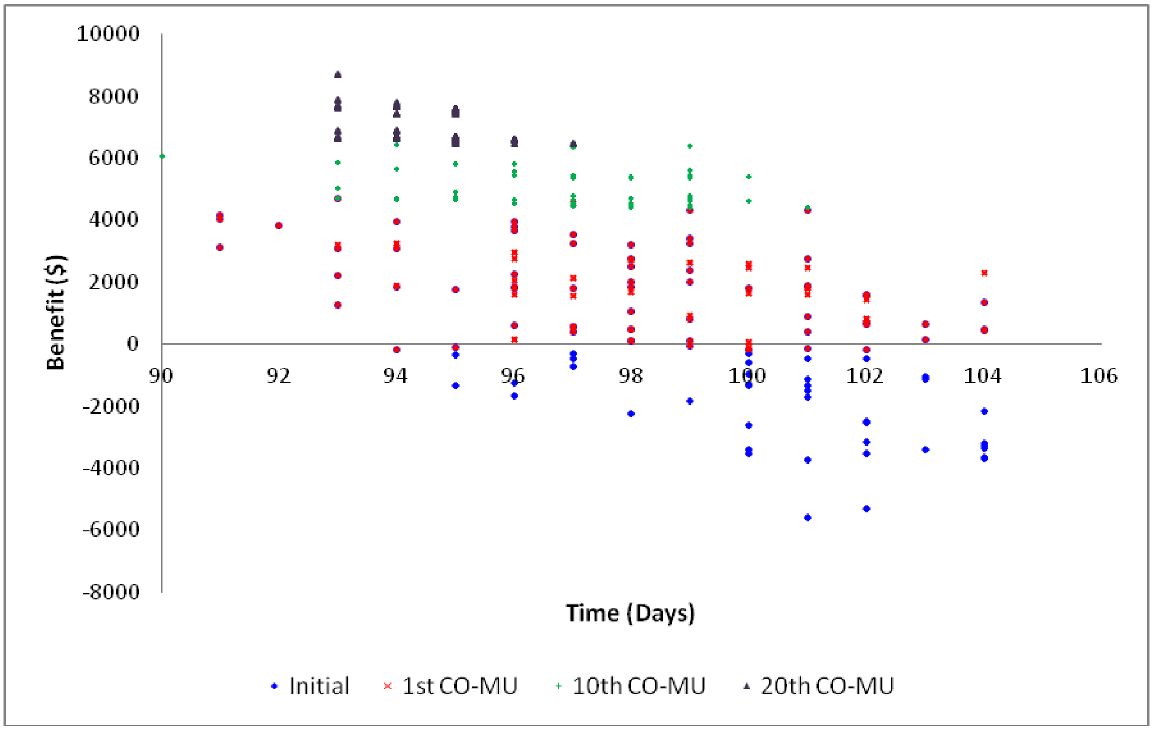

Figure 6-3: The initial population and the 1st, 10th and 20th CO-MU populations of Experiment 1

As shown in the figure, costly solutions happen more with longer project durations such as 101 or 102 days. However, beneficial solutions happen more with shorter project durations such as 93 or 94 days. Therefore, for the current case maximum benefits happen at lowest project durations and the optimization process improves the results from costly long durations to beneficial short durations.

The total optimization calculation time to reach the best solution, which was first obtained in the 15th population, is the sum of previous calculation times of the previous populations. Therefore, the total optimization calculation time is 403 seconds, which is

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less than 7 minutes and a reasonable time to achieve a very good or probably the absolute best solution.

6.2 Validation

The validation targeted the performance of the overlapping optimization algorithm and the associated computer tool. Two approaches were taken. First, various random checks were performed on the conceptual network of Experiment 1 to ensure the different computational components of the overlapping optimization algorithm and overlapping optimization computer tool worked correctly. Second, a simplified network with a limited number of overlapping solutions was generated and all solutions identified. Then the simplified network was optimized using the overlapping optimization tool and the results compared to evaluate the accuracy and efficiency of the tool. The following sections explain these two validation approaches.

6.2.1 Random checks

The computational components of the overlapping optimization computer tool were manually cross-checked to ensure different elements of the tool worked flawlessly. Specifically, random-checks were performed to:

- Check if network calculations and project duration calculations were conducted correctly
- Check if overlapping cost calculations, timesaving benefit calculations and the project total net benefit calculations were conducted correctly
- Examine if crossover and mutation operators work flawlessly
- Trace recursive chromosome modification operations to ensure chromosomes were thoroughly modified

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- Check if rework durations are calculated correctly and the related activity duration were changed accordingly
- Check if rework durations for multi-predecessor situations were calculated properly
- Check if the cost impact of multi-predecessor overlaps on the successor activity were calculated rightly
- Investigate if rounding up/down functions were utilized properly and resulted in right integer activity durations
- Examine if all computational operations were performed in compliance with the sequence predicted in the overlapping optimization algorithm
- Determine if the generated chromosomes' data, i.e. activity durations, activity dependencies and lag times were exported from Excel to MSP correctly.
- Inspect if the network data, i.e. activity durations, activity dependencies, lag times and project duration were exported from MSP to Excel correctly.
- Examine if the timing of calculations in MSP and Excel were synchronized and aligned.

The incorrect operation of any of the above meant that either the computer tool or the algorithm had some errors and mistakes that had to be corrected. Completing the above random checks took a fairly long time (about 1 year); however, the random checks made the overlapping optimization tool very reliable.

6.2.2 Experiment 2: Comparison with a solved example

The objective of this experiment was to compare the overlapping optimization algorithm results with a solved example to show the efficiency of the algorithm. For this purpose,

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the conceptual case study of Experiment 1 was highly simplified. The maximum allowable degrees of overlapping were significantly decreased (minimum lag times increased) so that the total number of possible solutions approached a small and manageable quantity. Then all possible solutions of the simplified network were evaluated to identify the absolute best solution. Thereafter, the simplified network was optimized using the computer tool and the results compared with the absolute best solution.

Table 6-3 shows the general attributes of the case study of Experiment 2. As shown in the table, all lags have been changed in such a way that all overlaps between activities have been limited to maximum 2 days. In other words, each pair of activities can now only have three conditions with regard to each other: 2 days overlapping, 1 day overlapping, and zero overlapping.

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Table 6-3: General attributes of the case study of Experiment 2

Act.	Duration	Pred.	Original Relation	Original Lag	Relation after Overlap	Minimum Allowable Lag	Overlapping Rework Function $R_{ij} = f(L_{ij})$	Overlapping Cost Function $C_{ij} = g(R_{ij})$
1	36	-	-	-	-	-	-	-
2	30	1	FS	0	FS	-2	$R_{12}{}^{\dagger} = 0.2L_{12}{}^{*}$	$C_{12}{}^{\ddagger} = 900R_{12}$
3	28	1	FS	0	FS	-2	$R_{13} = 0.1L_{13}$	$C_{13} = 850R_{13}$
4	48	1	FS	0	SS	34	$R_{14} = 0.15L_{14}$	$C_{14} = 1050R_{14}$
5	22	2	FS	0	FS	-2	$R_{25} = 0.3L_{25}$	$C_{25} = 800R_{25}$
6	24	2	FS	0	FS	-2	$R_{26} = 0.25L_{26}$	$C_{26} = 1000R_{26}$
6	24	3	FS	0	FS	-2	$R_{36} = 0.2L_{36}$	$C_{36} = 1000R_{36}$
7	20	4	FS	0	FF	18	$R_{47} = 0.15L_{47}$	$C_{47} = 950R_{47}$
7	20	5	FS	0	FS	-2	$R_{57} = 0.05L_{57}$	$C_{57} = 950R_{57}$
7	20	6	FS	0	FS	-2	$R_{67} = 0.25L_{67}$	$C_{67} = 950R_{67}$

* L_{ij}: *The duration of overlapping between i and j*

† R_{ij}: *The rework duration of the successor activity j as a function of* L_{ij}, $R_{ij} = f(L_{ij})$

‡ C_{ij}: *The cost of overlapping between i and j as a function of* R_{ij}, $C_{ij} = g(R_{ij})$

Since the network consists of 9 activity dependencies, and each dependency now has 3 different overlapping values, then:

The total number of possible solutions = 3^9 = 19683

Since the total number of possible solutions, 19683, is a small solution space, all possible solutions can be evaluated and the absolute best solution can be identified. This was performed after a minor change in the computer tool. The change is related to

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chromosome generation. Instead of generating and evaluating random chromosomes to make the initial population, the computer tool has to evaluate all 19683 possible chromosomes to find the absolute best solution. To this end, a record of all possible chromosomes was manually generated and given to the computer tool. The computer tool evaluated all possible chromosomes and generated a record of 19683 results. The results were ranked and analysed. The outcome is briefly shown in Table 6-4.

Table 6-4: All possible results of Experiment 2

No.	Total Benefit ($)	Project Duration (days)	Type of result space chromosome	Count of solution space chromosomes
1	1150	107	1	582
2	1100	107	1	108
3	1100	108	1	1254
4	350	106	1	18
5	350	107	1	306
6	300	107	1	36
7	300	107	2	204
8	300	108	1	612
9	250	107	1	324
10	250	108	1	444
11	100	107	1	291
12	50	107	1	54
13	50	108	1	627
14	50	109	1	852
15	0	109	1	1188
16	0	110	1	1848
17	-500	106	1	54
18	-500	107	1	108
19	-550	107	1	108
20	-550	108	1	216
21	-700	106	1	9
22	-700	107	1	153
23	-750	107	1	18
24	-750	107	2	102
25	-750	108	1	198
26	-750	108	2	306
27	-750	109	1	450
28	-800	107	1	162

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29	-800	108	1	222
30	-800	109	1	396
31	-800	109	2	408
32	-800	110	1	900
33	-850	109	1	648
34	-850	110	1	888
35	-1000	109	1	426
36	-1050	109	1	594
37	-1050	110	1	924
38	-1550	106	1	27
39	-1550	107	1	54
40	-1600	107	1	54
41	-1600	108	1	108
42	-1600	108	2	108
43	-1600	109	1	216
44	-1650	109	1	216
45	-1650	110	1	432
46	-1800	108	1	99
47	-1800	109	1	225
48	-1850	109	1	204
49	-1850	109	2	198
50	-1850	110	1	450
51	-1900	109	1	324
52	-1900	110	1	444
53	-2650	108	1	54
54	-2650	109	1	108
55	-2700	109	1	108
56	-2700	110	1	216
	Total number of solution space chromosomes:			19683

As shown in the table, the absolute best solution has $1150 benefit within 107 days. The absolute best solution is shown in Figure 6-4. 582 chromosomes from the initial solution space were converted into one chromosome which is the absolute best chromosome. Similarly, other solution space chromosomes were converted during network calculations into a few chromosomes in the result space. The reason goes back to the network logic that does not accept all suggested chromosomes from the solution space. As a result, the 19683 chromosomes in the possible solutions space are ultimately

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converted into 56 chromosomes in the result space. However, the 56 chromosomes cannot be identified unless all 19683 possible solutions are evaluated.

Table 6-4 shows that the final results ranged from -$2700 to $1150 benefit. Also, project durations ranged from 106 to 110 days. Most of the results come out of a single chromosome. However, 6 of the 56 results are achieved from two different chromosomes. For example, the overlapping strategy with $300 benefit and 107 days resulted from two types of chromosomes. In other words, two types of chromosomes resulted in the same $300 benefit and 107 days duration. Figure 6-5 shows all solutions of the simplified network.

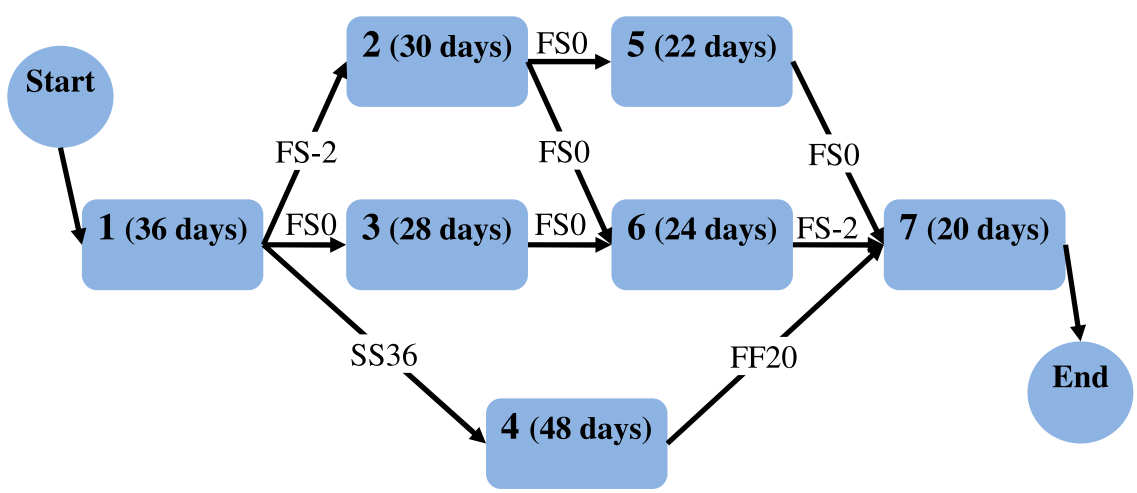

Figure 6-4: The absolute best solution of Experiment 2

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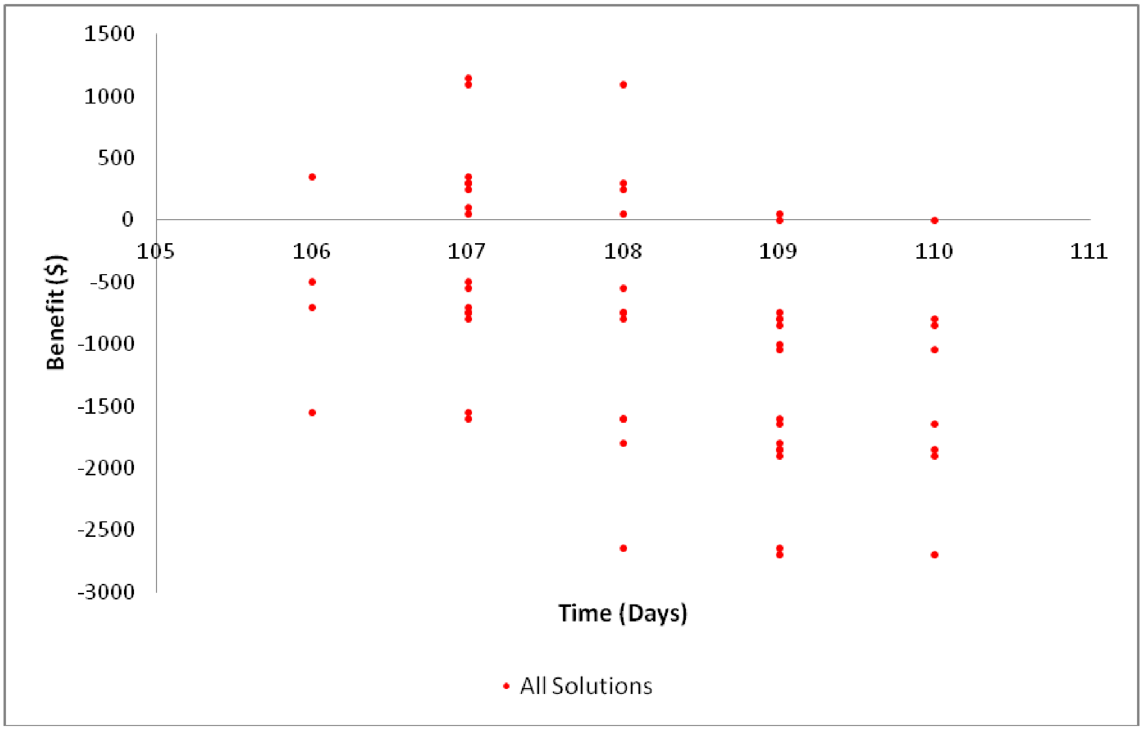

Figure 6-5: All solutions of the simplified network

The total time to evaluate all 19683 chromosomes was 7042 seconds (about two hours).

Once all solutions of the simplified network were achieved, the simplified network was optimized by means of the overlapping optimization computer tool. Since the solution space is very small, the population size for both initial population and crossover-mutation populations were set to 10. Therefore, the initial population encompassed 10 randomly generated chromosomes, and each crossover-mutation population encompassed 10 chromosomes. The results are shown in Table 6-5.

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Table 6-5: Results of Experiment 2

No.	Population	Max. Benefit ($)	Duration (days)	Calculation Time (Sec.)	Min. Benefit ($)
1	Initial	1100	108	2	-1650
2	1st CO-MU	1150	107	3	-750
3	2nd CO-MU	1150	107	3	0
4	3rd CO-MU	1150	107	3	250
5	4th CO-MU	1150	107	2	1100
6	5th CO-MU	1150	107	2	1100

According to Figure 6-5, the best chromosome of the initial population had $1100 benefit and 108 days duration. Compared to Table 6-4, this chromosome is the third best chromosome. However, only one CO-MU generation is sufficient to find the absolute best chromosome.

The optimization processing time to reach the best result is only 5 seconds (2 seconds for initial population and 3 seconds for the first CO-MU population), which is extremely less than the time (7042 seconds) required to check and evaluate all possible solutions (5÷7042 = 0.0007).

In conclusion, the best chromosome was found with 100% accuracy (because the absolute best was obtained) within only 5 seconds processing time. The performance shows the accuracy and efficiency of the overlapping optimization algorithm and the computer tool.

6.3 Real project network

To investigate the applicability of the computer tool in the real world, a real project schedule was examined. For this purpose, a reputable engineering and construction

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company in Calgary, Canada, was approached and this company agreed to support this PhD research. Consequently, the company assigned seven experienced individuals from the planning and scheduling, structure and piping departments to support the research. In addition to participation in focus groups, the experts from the planning and scheduling department provided a real project schedule with 40 activities including the piping design and structural design of an oil-sands plant. The design of the project had just been finished and the construction was under progress at the time. Further, experts from the piping and planning departments helped generate the rework and cost functions.

6.3.1 Rework functions

The researcher suggested and presented four alternatives to estimate the rework duration as a result of overlapping. The experts were asked to decide which suggestion they are more comfortable with or if they have any other suggestions. The suggestions were as follows:

<u>Suggestion 1:</u>

1. Comparing the as-built schedule with the planned schedule to identify activities which are extended.
2. Investigating which part of each activity's extension has been caused by overlapping rework. The discipline engineer in charge can answer.
3. Repeating the above for a suitable number of generic activities to find a possible trend.

Note: This is a time consuming benchmarking, but it is relatively precise; the precision increases when the number of overlaps investigated are increased.

<u>Suggestion 2:</u>

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1. Identifying generic overlaps.
2. Investigating each activity's calculation process to find the fraction of activity duration that should be reworked assuming that rework happens. The discipline engineer in charge can answer.
3. Repeating "2" for a suitable number of generic activities to find a possible trend.
4. Using historical data to determine rework probability (e.g. by comparing the as-built schedule with the planned schedule to determine the frequency of reworks that occured)

Note: This is also a time consuming benchmarking, but it is relatively precise; the precision increases when the number of overlaps investigated are increased.

Suggestion 3:

1. Experts, e.g. discipline engineers and planners/schedulers, generate rough estimates (or range estimates) for the rework probability and duration, or for "equivalent rework".

Note: This method is fast, but might not be very accurate; it is applicable to current projects.

Suggestion 4:

1. Ranking overlaps using expert judgments on the basis of which overlaps are less risky to perform. Pair-wise comparison may be used as well. Planners, schedulers, or discipline engineers in charge may answer.

Note: This method is very fast, but might not be very accurate; it is applicable to current projects.

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The group of experts reviewed and discussed the above suggestions and agreed on the third suggestion. They believed that this suggestion needs reasonable effort and generates results with acceptable accuracy.

Four experts including two piping lead engineers, one structural engineer and one planner helped generate rework functions. The project schedule was reviewed and four pair of activities which could be overlapped were identified. Other activities were either not possible to be overlapped or were so small in duration (less than 3 days) that their overlapping could not generate a tangible timesaving. These four pair of activities are listed in Table 6-6.

Table 6-6: List of activities to be overlapped

Predecessor Activity	Original duration	Successor Activity	Original duration
Plot Plan - Re IFD*	38	Module Key Plan - Re IFD	40
Plot Plan IFC*	20	Equipment Location Plan - IFC	36
60% Model Review Tag Resolution	20	Pipe Rack Module ISOs	148
60% Model Review Tag Resolution	20	Process Module ISOs	48

** IFD = Issued for Design; IFC = Issued for Construction*

For better understanding, a part of the project schedule which includes the above activities and their dependencies with each other is schematically shown in Figure 6-6.

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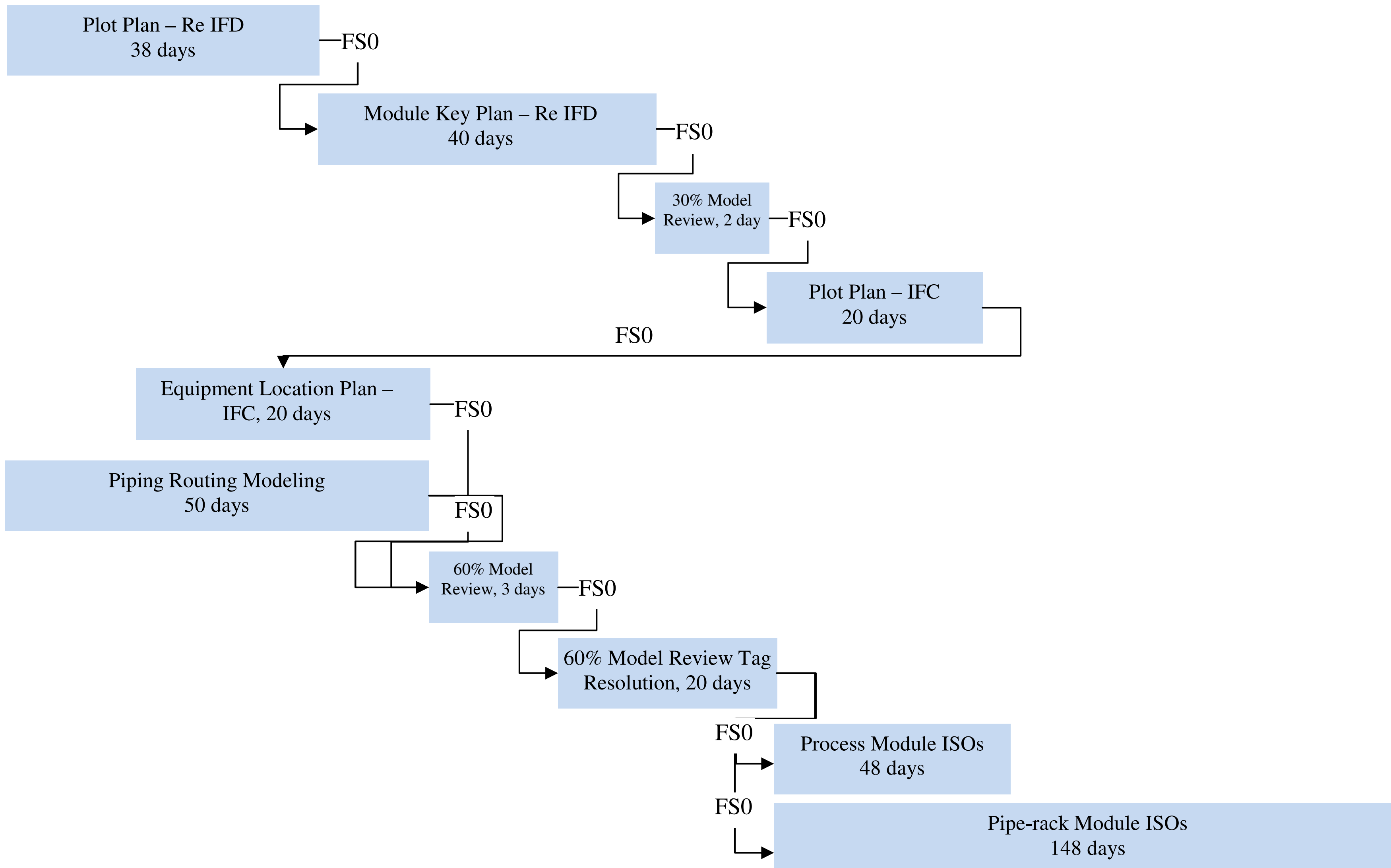

Figure 6-6: Activities to be overlapped and their dependencies with each other

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The group of experts and the researcher formed a focus group to determine equivalent rework durations as a function of overlapping duration. The results are shown in Figure 6-7, Figure 6-8, Figure 6-9 and Figure 6-10.

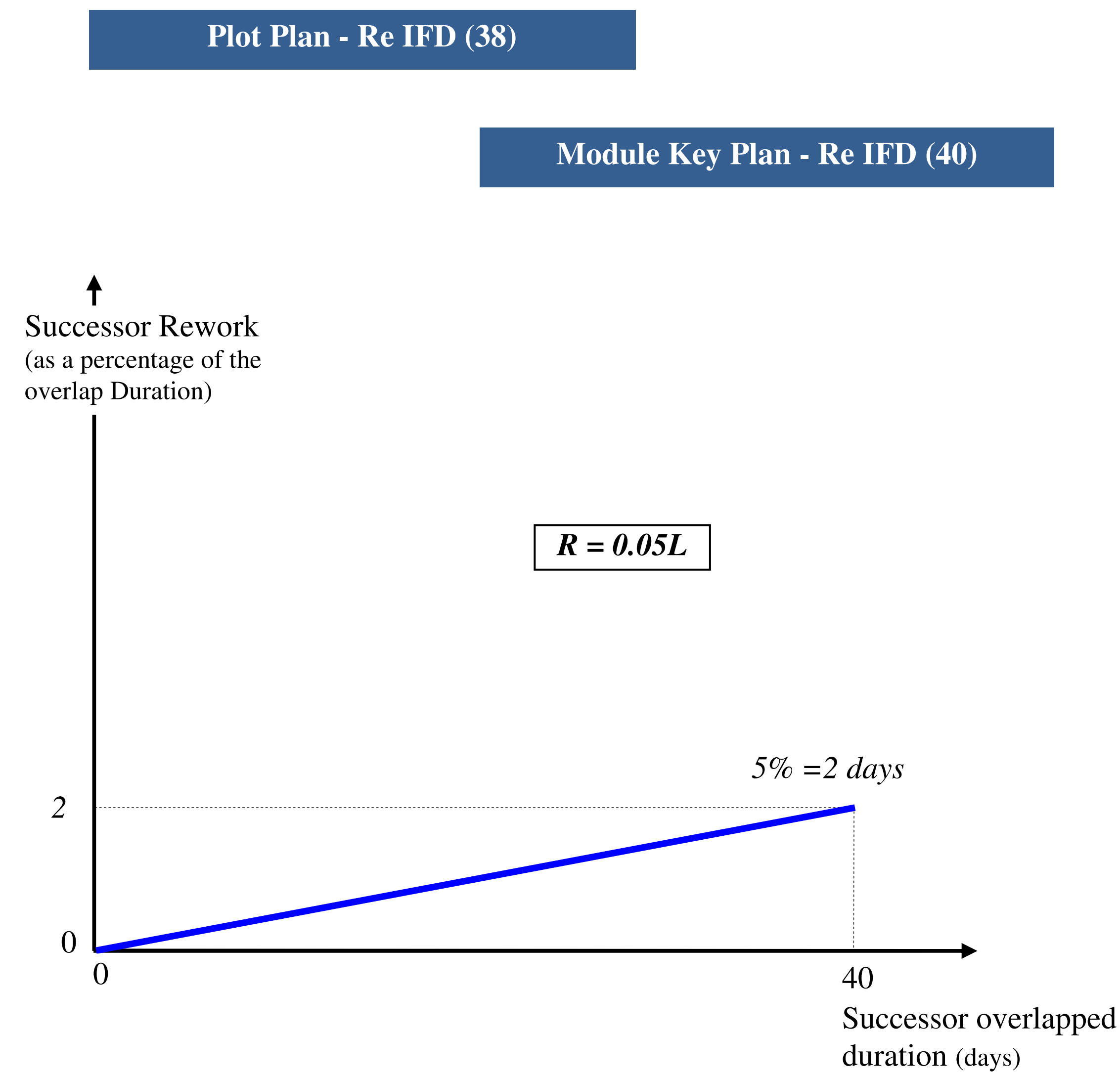

Figure 6-7: Rework function for overlapping "Plot Plan - Re IFD" with "Module Key Plan - Re IFD"

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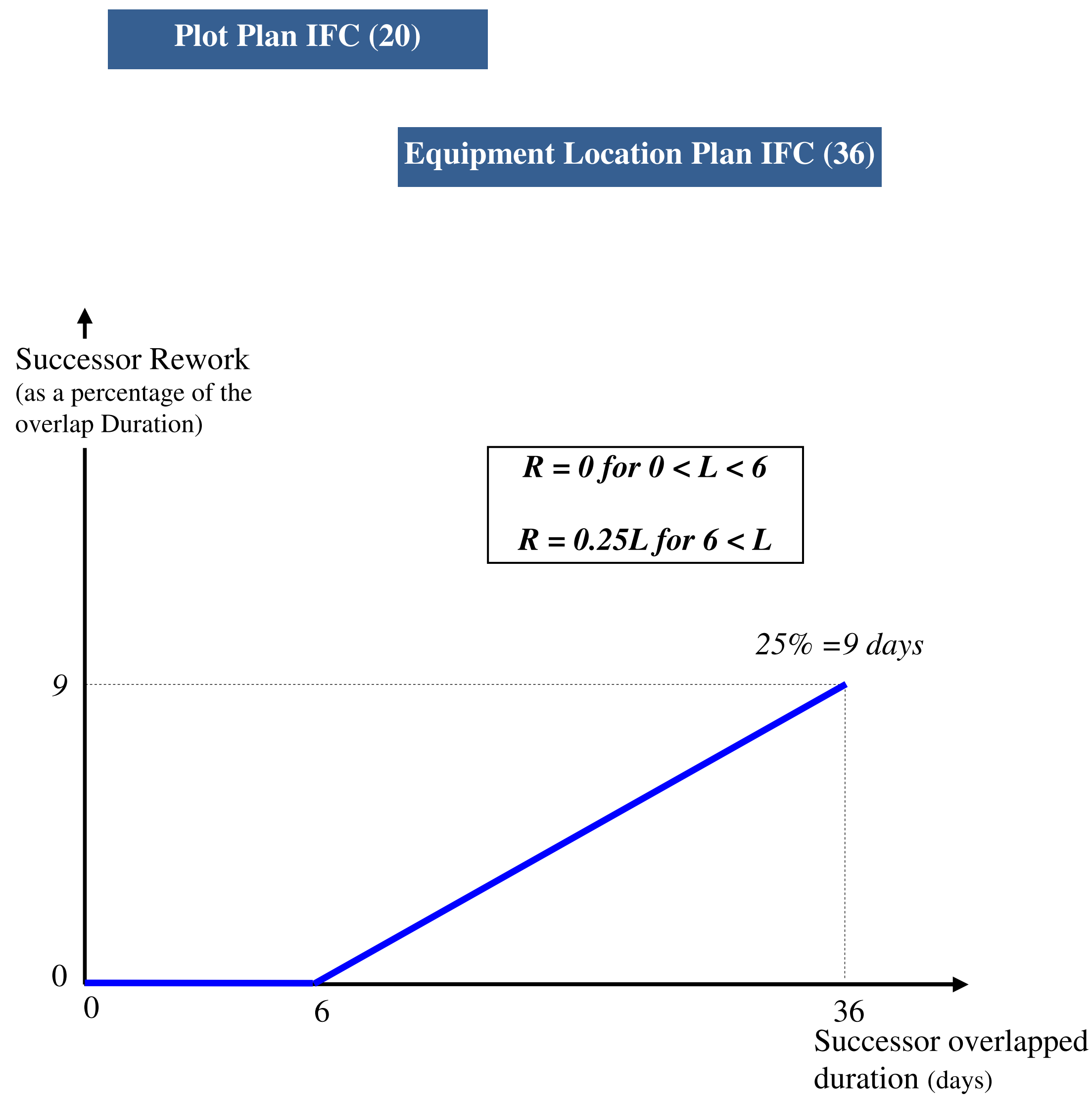

Figure 6-8: Rework function for overlapping "Plot Plan IFC" with "Equipment Location Plan IFC"

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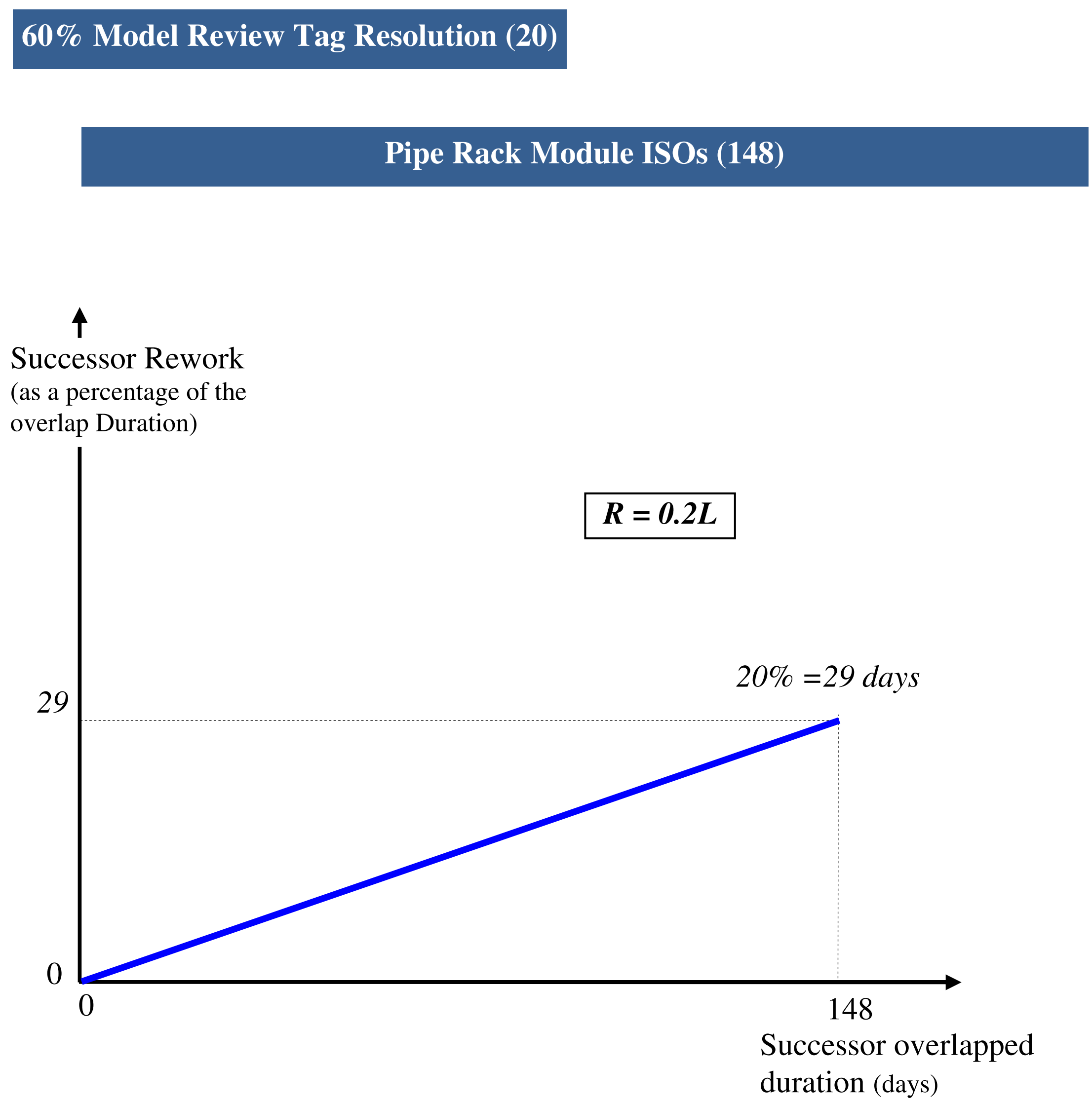

Figure 6-9: Rework function for overlapping "60% Model Review Tag Resolution" with "Pipe Rack Module ISOs"

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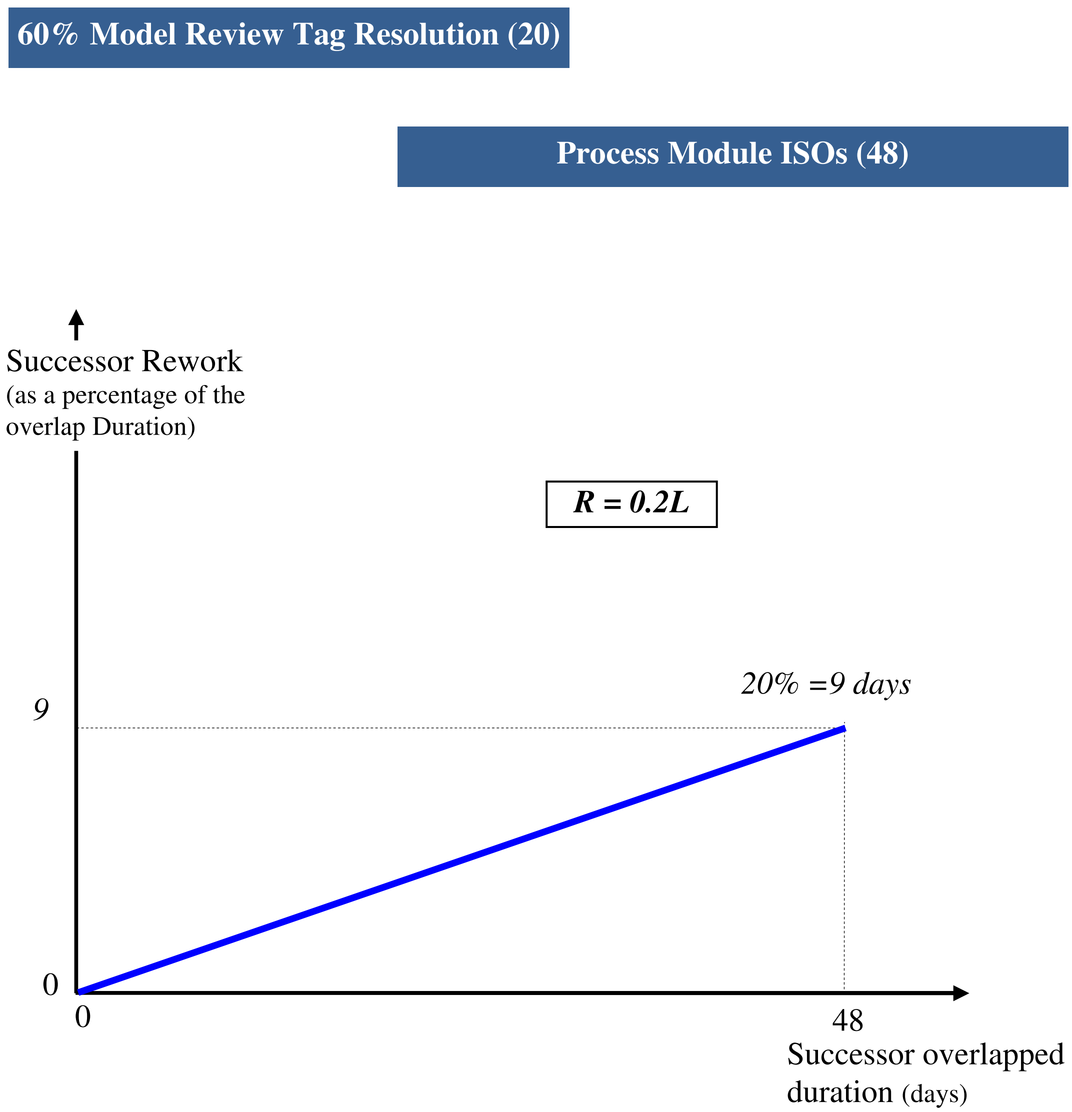

Figure 6-10: Rework function for overlapping "60% Model Review Tag Resolution" with "Process Module ISOs"

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6.3.2 Cost functions

Cost functions were generated by obtaining the direct and indirect costs of performing the successor activities from the company. The cost values (and functions) are reflected in Table 6-7.

Table 6-7: Cost functions

Successor Activity	Cost ($/day)	Cost function
Module Key Plan - Re IFD	1000	C= 1000R
Equipment Location Plan - IFC	1800	C= 1800R
Pipe Rack Module ISOs	2500	C= 2500R
Process Module ISOs	2500	C= 2500R

In addition, the project parameters were set as follows:

- Daily benefit for each day of early completion (B_{ef}) = $1000 per day

- Daily loss for each day of late completion (C_{lf}) = $1000 per day

- Project targeted completion date (T_t) = 730 days

6.3.3 Experiment 3

With the rework functions, cost functions, and other project parameters available, Experiment 3 was performed by running the optimization tool on the real world project schedule. The results are shown in Table 6-8.

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Table 6-8: Results of Experiment 3

No.	Population	Max. Benefit ($)	Duration (days)	Calculation Time (Sec.)	Min. Benefit ($)
1	Initial	9600	713	57	-18000
2	1st CO-MU	17000	711	39	-5500
3	2nd CO-MU	17000	711	40	-500
4	3rd CO-MU	17000	711	39	2300
5	4th CO-MU	17000	711	40	4800
6	10th CO-MU	17000	711	368	8900
7	20th CO-MU	17000	711	355	10200
8	30th CO-MU	17000	711	358	10200
9	40th CO-MU	17000	711	383	10500
10	50th CO-MU	17000	711	379	10700

The maximum benefit, the project duration associated with the maximum benefit, and the optimization calculation time are the most important results. The minimum benefit is also presented in Table 6-8 for further analysis (project duration associated with the minimum benefit is not shown as it does not provide useful information). In any population (or generation), the best chromosome represents the maximum benefit, while the worst chromosome represents the minimum benefit.

According to the table, an initial population with 100 chromosomes was generated. The processing time was 57 seconds. The best chromosome resulted in a project maximum benefit of $9600 and a project duration of 713 days. The worst chromosome in the population generated $18000 cost (-$18000 benefit). In the table, the 1st, 2nd, 3rd, 4th, 10th, 20th, 30th, 40th and 50th CO-MU populations are shown as well.

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In the 1st generation, after generating 100 chromosomes through crossover and mutation, a chromosome emerged that had a maximum benefit of $17000 and 711 days project duration. This chromosome was the best solution achievable as even in the 50th generation no better chromosome could be generated. Therefore, the program finds the best solution very quickly and within 106 seconds (57 + 39), only after generating the initial population and the first crossover-mutation generation.

Figure 6-11 shows some of the results achieved during Experiment 3. To keep the figure readable, only the results of the initial population and the 10th and 50th crossover-mutation populations are shown.

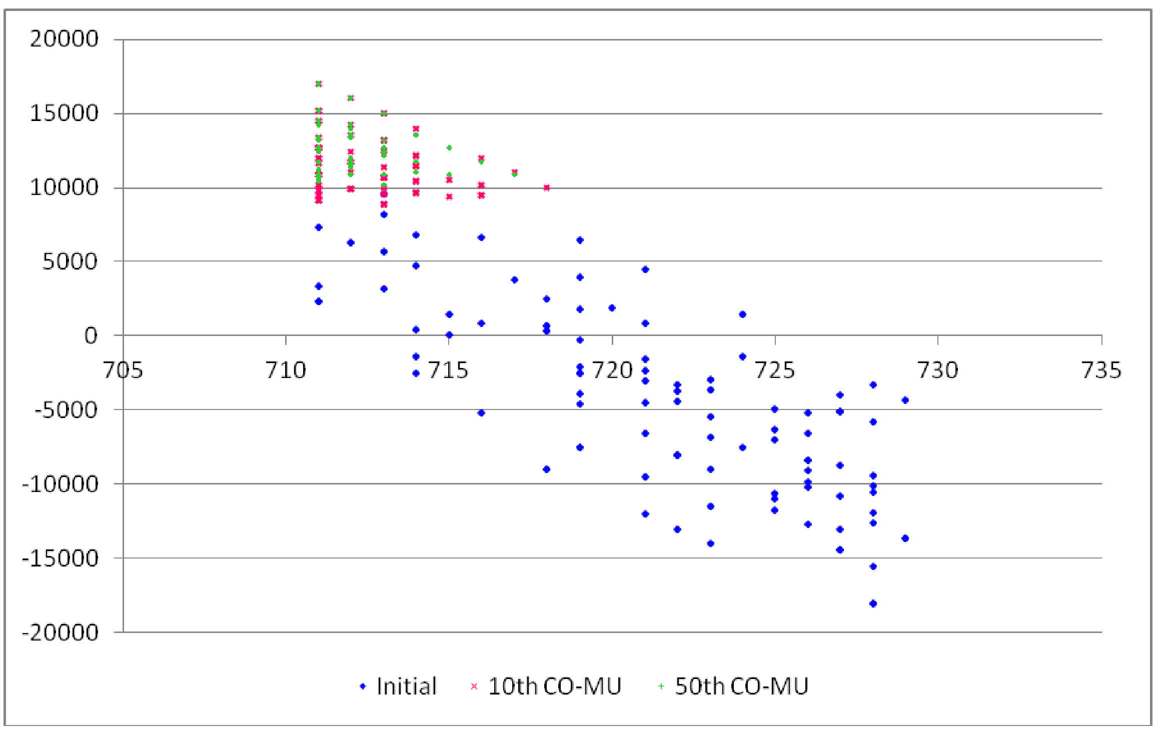

Figure 6-11: The initial population and the 10th and 50th CO-MU populations of Experiment 3

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The final results of this experiment were shown back to the experts in the focus group who had helped generate the rework and cost functions. They admitted that the results make a good sense in terms of practicality. They were also very excited with the processing speed. Moreover, they believed that the results were really optimal as they could not identify any better solution.

To further examine the robustness of the final results, an experiment was arranged with two senior schedulers (+15 years of work experience) from another company. The project schedule and ther required information such as the maximum possible overlaps and overlapping costs and reworks were given to the schedulers and they were asked to generate the maximum timesaving with the minimum costs through overlapping. They had 1 hour time for this exercise and they used Microsoft Project as the scheduling software. The best results each of them could obtain were as follows:

1st scheduler could reduce the duration to 714 days with $12200 benefit.

2nd scheduler could reduce the duration to 713 days with $10700 benefit.

Apparently, the best results the schedulers could reach after 1 hour were worse, from both time and cost standpoint, than the best result obtained by the overlapping computer tool (711 days, $17000 benefit) in less than 2 minutes.

Meanwhile, both schedulers made minor mistakes in calculating the project duration as taking rework durations manually into account was difficult. This shows another superiority of the overlapping computer tool over classic scheduling.

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6.4 Summary

This chapter presented some of the experiments performed with the overlapping optimization tool. These experiments were performed to fine-tune the tool and set the performance parameters (GA parameters), check and validate the tool performance and obtain optimization results and analyze them.

Three sets of experiments were performed and the results were presented. The first set of experiments was conducted on a conceptual case study very similar to the case study explained in Chapter 5. The second experiment aimed at testing and validating the performance of the optimization algorithm and the computer tool. The third experiment was performed on a real project case study.

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Chapter Seven: Conclusion

This study investigated the activity overlapping in the design phase of construction projects. During the literature review, it was revealed that overlapping is the most popular method to compress project schedules. Also, a gap on how to optimize activity overlapping to achieve the maximum timesaving at the minimum price was found in the previous literature. The gap led to the research question: Which activities have to be overlapped and to which extent to reduce the project duration at the minimum cost? Therefore, the main objective of this research was to develop a systematic and practical approach to assessing and determining the optimal overlapping in construction projects. Accordingly, three deliverables were generated in the research: An overlapping model, an overlapping optimization algorithm, and an overlapping optimization computer tool. The deliverables were the results of a research methodology with two parts. First, a qualitative research approach through interviews and focus groups was taken to generate the overlapping model. Second, an analytical approach was taken to create and develop the overlapping optimization algorithm and the computer tool. In total, 43 experienced experts from 11 international owner and contractor companies mainly active in oil and gas projects contributed to this research.

7.1 Contribution to research

Three main deliverables of this research were inherently different in nature and one single research methodology could not help generate all deliverables. Therefore, a combinatory research methodology, a combination of qualitative and analytical approaches, was customized to conduct the research. Furthermore, various validation

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methods including respondent validation, feedback from others, real world test, and computational crosschecks were used to validate the results (Figure 3.1).

The overlapping model was generated in a unique way, in which the fundamental information were gathered through interviews and then the development and validation of the overlapping model was performed concurrently through focus groups (Figure 3.2). This process is very similar to the process of generating requisite models introduced by Phillips (1984). The process worked very well for this research, because generating the overlapping model required regular interactions between the researcher and experts to gradually and simultaneously build-up, fine-tune and validate the model. It is noteworthy that the questions provided and used in interviews and focus groups are the research instruments and can be used by other researchers to replicate the research.

7.2 Contribution to theory

The gap in the literature is related to the inability or weakness of available models and frameworks to determine the activities to be overlapped and the extent of overlapping. A group of researchers modeled each overlap separately and isolated from other overlaps in the project. Second group of researchers took a more comprehensive approach than the first group by trying to model overlaps in relation to all overlaps in the project. A problem existed in the research of the second group: They assumed that either the project had only one chain (path) of activities which naturally is the critical path (Roemer and Ahamdi 2004), or at least the overlaps under study were on the critical path of the project (Gerk and Qassim 2008). However, construction projects have several paths, one or some of the paths are critical, and new critical paths emerge when different overlapping strategies are applied. In addition, previous research studies do not address schedule

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constraints, resource constraints, and activity dependencies other than finish-to-start. The current PhD research attempted to circumvent the above criticisms and shortcomings by providing a comprehensive answer to the research question: **Which activities have to be overlapped and to which extent to reduce the project duration at the minimum cost**? The research resulted in three deliverables, overlapping model, overlapping optimization algorithm and overlapping optimization computer tool which all together could answer the research question. The deliverables have the following abilities:

- Handle multi-path networks
- Take all activities, critical and non-critical, into account and follow the critical path if the critical path changes or new critical paths emerge
- Take resource limitations into account
- Take schedule constraints into account
- Handle all types of activity dependencies (FS, SS, FF, SF)

It is noteworthy that using genetic algorithms for the purpose of overlapping optimization is a new idea first implemented by this research.

7.2.1 Handling multi-path networks

The ability to handle multi-path networks goes back to the fact that two special situations, effect of multi-predecessor overlaps on rework and effect of cascades of overlaps on rework, have been addressed in the overlapping model and considered in the overlapping optimization algorithm. By addressing these two situations, the overlapping optimization algorithm is able to handle all types of project networks. In particular, project networks with multiple paths can be optimized. This is an advantage of the current research compared to previous studies.

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7.2.2 Critical path control

During overlapping optimization process, critical paths may change and new critical paths may emerge. The overlapping optimization computer tool has the ability to follow the critical path(s). In addition, a feature exists in the overlapping optimization algorithm that let the computer tool apply overlaps only on critical activities and relax noncritical overlaps through a recursive process. This is another step ahead of other overlapping optimization methods developed by previous researchers.

7.2.3 Handling resource and schedule constraints

The overlapping optimization computer tool has the ability of taking resource and schedule constraints into account. It performs resource levelling and handles schedule constraints such as "start no later than" a pre-specified date or "must finish" on a pre-specified date.

7.2.4 Handling various activity dependencies

The overlapping optimization tool handles different types of activity dependency, i.e. finish-to-start, start-to-start and finish-to-finish. The necessary activity duration adjustments and rework duration calculations related to each type of activity dependency have been predicted in the overlapping optimization algorithm.

7.3 Contribution to practice

The overlapping optimization computer tool is unique; as of today no similar tool exists in industry or academia. In spite of the novelty, practitioners, i.e. project planners, schedulers, engineers, and managers, can easily use the computer tool and apply overlapping on activities in project schedules. Specifically, MS Excel and MS Project which were coupled for the tool are familiar to practitioners.

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Using MS Project as the network calculator has other advantages as well. Project time calculations are an important part of the overlapping optimization algorithm. Using MS Project for this purpose makes the optimization tool very powerful because MS Project can perform network calculations very quickly and efficiently. However, plugging MS Project to the optimization module in the MS Excel platform was a difficult task that had to be performed carefully.

The main reason for utilizing MS Project as the scheduling module in the suggested overlapping optimization algorithm was to avoid reinventing the wheel as MS Project is an available powerful scheduling software.

7.3.1 Optimizing large project schedules quickly

The overlapping optimization algorithm and computer tool can deal with complex and large project networks which can be seen in real world practice. Such strength is a result of utilizing a genetic algorithm as the optimization module. Therefore, the overlapping optimization algorithm developed in this research is inherently a genetic algorithm, which is capable of handling numerous cost evaluations quickly and effectively and is suitable for solving complex problems with several variables. In a typical network with hundreds of activities, billions of overlapping strategies are possible. The genetic algorithm optimization finds the best solution or near-to-best solutions by only examining a very small portion of possible overlapping strategies. This process drastically saves optimization time. As shown in one experiment, the optimization processing time was 0.0007 of the time required to check all possible solutions. Therefore, the optimization process (time minimization or cost minimization) is performed efficiently and within fairly short processing times.

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7.3.2 Ability to perform partial optimization

Another important advantage of the suggested optimization algorithm is that if all of the information about all overlaps is not available, the algorithm is still able to find the best arrangement for those overlaps whose information is available. This is a partial optimization due to lack of some of the overlaps' rework or cost functions.

7.3.3 Different optimization variations

The overlapping optimization algorithm and the associated tool have the flexibility to deal with different optimization variations. The algorithm can find Pareto optimal solutions, in which solutions with both minimum cost and minimum time are searched for. Also, the algorithm can find the least expensive overlapping strategy within a pre-specified project duration or the shortest project duration cheaper than a pre-specified project cost.

7.4 Future research

Future potential research studies sorted in descending order in terms of proximity to the current research are as follows:

1. Increasing the optimization speed
2. Generating a database for the optimization tool
3. Enabling the algorithm to perform stochastic optimization
4. Extending the results to other project phases, i.e. procurement and construction
5. Developing a combined crashing-overlapping optimization algorithm
6. Customizing the algorithm to apply Primavera as the scheduling module instead of MS Project
7. Extending the research results to industries other than construction

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7.4.1 Increasing the optimization speed

The current research tried to maximize the performance, effectiveness, quality of results, and success factor of the Genetic Algorithms optimization tool as much as possible. However, further improvement is always possible and a part of the future research can be allocated to speeding-up the whole process and obtaining better results. Improvements can be conducted in two ways. First, further adjustments and fine-tunings can be applied on the current optimization (Genetic) algorithm. Second, other meta-heuristic optimization algorithms or a combination of them (hybrid algorithms) can be investigated. Other optimization algorithms might generate better quality results in shorter processing times.

7.4.2 Overlapping optimization database

The final result of this research is an overlapping optimization tool which requires reliable input data to run properly and provide reliable outputs. These data are mainly overlapping rework functions which represent the rework amount as a function of overlapping degree. In this research, a few of the functions were provided to perform a real world test. However, the research was not designed to determine overlapping rework functions for all activities. As such, separate studies are required to determine the rework functions for the full spectrum of activities in construction projects. The results of the studies will be a database that provides reliable input data to the overlapping optimization tool developed in this research.

7.4.3 Stochastic overlapping optimization

Equation 4.1, $R_{ij} = P_{ij} \times T_{ij}$, is a deterministic equation and the whole overlapping optimization algorithm is based on deterministic rework and cost functions. However,

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overlapping analysis is more realistic if stochastic rework and cost functions are used. A stochastic approach is much more complex and requires numerous data. Future research can be constructed on the foundations of the current research to optimize activity overlapping using stochastic rework functions.

7.4.4 Overlapping optimization for all project phases

The focus of this research was the design phase of construction projects. However, overlapping is also practiced in other project phases, i.e. procurement of materials, installation of equipment and construction of the plant. In other words, this research addresses design-design activity overlapping; however, other types of overlaps such as design-construction, design-procurement, and construction-construction exist. Therefore, future research should extend the overlapping optimization to procurement and construction phases. However, the overlapping mechanism for these phases is different from the design phase. One difference is the amount of rework which might be significantly more for construction activities than design activities. For example, if a constructed structure is to be reworked, first it should be demolished. The demolition is time-consuming and costly. A similar situation does not exist for the design activities.

7.4.5 Hybrid crashing-overlapping optimization

A comprehensive and robust schedule reduction strategy is one that includes both overlapping and crashing. Crashing, sometimes called acceleration, refers to reducing an activity duration by adding more resources to the activity; therefore, the cost increases. A very important step forward to this research is to develop an algorithm and a computer tool that can identify the best combined crashing-overlapping strategy for project schedule reduction.

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7.4.6 Utilizing Primavera as the scheduling module

The current research utilizes MS Project as the scheduling module in the overlapping optimization computer tool. MS Project is a well-known commercial scheduling software with a wide range of strengths and capabilities. However, the majority of engineering and construction firms use Primavera (by Oracle) as the scheduling software because Primavera is the most powerful scheduling software in the market as of today. Therefore, customizing the overlapping optimization algorithm with Primavera promotes the practicality of the overlapping optimization computer tool. However, software incompatibility issues have to be overcome first.

7.4.7 Overlapping optimization in other industries

The potential of using the results of this research in other industries, e.g. automotive industry, software development, military projects and electronic device manufacturing can be investigated in future research.

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Appendix 1

Ethics approval and ethics extension approvals

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CONJOINT FACULTIES RESEARCH ETHICS BOARD

APPLICATION FOR ETHICS REVIEW

Research Services, ERRB Building, Research Park

Be sure to consult the “Instructions to Applicants” when completing this form

Copies: Faculty (and students from those Faculties/Departments which do not have their own Ethics Committees*): Submit 1 original and 1 photocopy including all supporting documentation to Research Services, ERRB Building, Research Park

Copies: Students – Variable*: Submit the original and the number of copies required by your Faculty/Department Ethics Committee

*** See Ethics website for list of Committee Chairs and specific locations for submission of applications**

CFREB Ethics Certification extends only to those individuals who have a current University of Calgary affiliation (student, faculty, staff). For the purposes of this application, “applicant and co-applicant” refer to those individuals who are applying for ethical clearance from the University of Calgary. This may be different from the person who is listed as the Principal Investigator /Co-investigator on the project.

1.1 Applicant:	
Family Name Dehghan	Given Name and Initial Reza
Department/Faculty Civil Engineering/ Schulich School of Engineering	
Mailing Address (complete only if different from Department/Faculty)	E-mail Address: RDEHGHAN@UCALGARY.CA Telephone (local) (403) 891 5797

Title/Position (Check One)

[ ] Full-time Faculty Member

[ ] Adjunct Faculty Member

[ ] Postdoctoral Fellow

[ ] Sessional Instructor

[ ] Professor Emeritus

[ ] Staff Member

[x] Graduate Student: [ ] Master's [x] Ph. D [ ] Other (please specify):

[ ] Undergraduate Student

[ ] Other (please specify):

1.2 Supervisor, if applicable:	
Family Name Ruwanpura	Given Name and Initial Janaka
Department/Faculty Civil Engineering/ Schulich School of Engineering	
Mailing Address (complete only if different from Department/Faculty)	E-mail Address Janaka@ucalgary.ca Telephone (local) (403) 870 7503

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Title/Position (Check One)
[x] Full-time Faculty Member
[ ] Adjunct Faculty Member
[ ] Sessional Instructor
[ ] Professor Emeritus
[ ] Other (please specify):

1.3 Co-Applicant, if applicable: Not Applicable

Family Name	Given Name and Initial
Not Applicable	Not Applicable

Department/Faculty

Mailing Address (complete only if different from Department/Faculty)	E-mail Address
	Telephone (local)

Title/Position (Check One)
[ ] Full-time Faculty Member
[ ] Adjunct Faculty Member
[ ] Postdoctoral Fellow
[ ] Staff Member
[ ] Sessional Instructor
[ ] Professor Emeritus
[ ] Graduate Student: [ ] Master's [ ] Ph. D [ ] Other (please specify):
[ ] Undergraduate Student
[ ] Other (please specify):

1.4 Additional Research Team Members: Provide as an attachment.

If other person or persons is/are involved in the project, but not affiliated with the University of Calgary, please provide his or her name, organization/employer, affiliation and other details to identify them.

2. Project Details:

2.1 Exact Title of the Project

A Framework for Activity Overlapping Assessment in Construction Projects

2.2 Is this an amendment/modification to a previously approved protocol? [x] No [ ] Yes (Note: see Information to Help Applicants for more details. Separate procedures apply when modifications do not involve significant changes to the original protocol. Please contact the CFREB office [220-3782] if you are unsure whether the changes to an existing protocol constitute a modification/amendment, or are significant enough to warrant a new application.)

2.3 Status of funding/support for the project - please choose one:
[ ] Unfunded project [ ] Funding pending [x] Funding received
Sponsor(s)/funding agency(s): [ ] SSHRC [x] NSERC [ ] CIHR Other (please specify):

Name of investigator(s) applying for or receiving funding: Dr. Janaka Ruwanpura
Project title as submitted to funding agency (if different than title of ethics submission):

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2.4 Anticipated start date of work involving human participants (mm/yy) **10/09**	Anticipated completion date of research activity; for graduate thesis or dissertation, please list anticipated date of defense (mm/yy) 12/10
2.5 List the location(s) where the data will be collected Engineering and construction companies, oil & gas companies and construction firms in Canada	
2.6 Are other approvals/permissions required where this research will occur? [x] No [ ] Yes If yes, provide a copy of the approval: [ ] Attached [ ] To follow (Specify where from):	

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2.7 Provide a succinct summary of the purpose, objectives, and aims of the research. Describe your methodology, and what will be required of the human participants. Please use language that can be understood by a non-specialist. Up to 1 additional page may be added, if required. (Note: Project descriptions exceeding the two-page limit will not be considered.) **REMINDER:** Be sure to include a copy of any questionnaire(s) or test instrument(s).

There are several reasons such as financial, social, legal and even political reasons to reduce the execution time of construction projects, and one of the most effective ways to reduce overall project delivery time is to *fast track* the project. The term *fast track* is generally used to describe something that takes place more quickly than normal, and that is indeed the essence of a fast track project.

The practice of overlapping dependent activities or phases, normally done in sequence, is an example of the application of fast tracking. Overlapping, also called executed concurrent engineering, means that activities that normally would be done in sequence are performed in parallel, in such a way that the work on the downstream activity starts before the work on the upstream activity is finished.

This technique, however, exposes significant additional risks to the project. Such risks include but are not limited to a greater number of design changes, more reworks, cost overrun, and quality loss. As a result, overlapping should be approached in a systematic manner to reduce the risks. In this regard, the primary goal of this research is to develop a systematic approach and a conceptual framework, to assess the overlapping and determine the optimized degree of overlapping and therefore help project managers and planners to successfully deliver their fast track projects.

Sub-Objectives:

1. Develop criteria to identify activities with higher priority for overlapping
2. Identify, analyze and quantify the risks of overlapping
3. Develop a model to determine the optimum degree of overlapping
4. Identify the best strategies to overlap activities

Research Methodology:

1. A literature review
2. Interviews with planning and scheduling experts, constuction experts, project managers and other project key personnel.
3. Case studies and workshops

What will be required by human participants:

In this research, I will look for expert ideas and opinions. The questions that will be asked are quite general questions to seek different opinions of planning, scheduling and project experts about the best ways of overlapping activities inside the construction projects. No personal question will be asked.

In addition I will conduct workshops and ask practitioners to attend the workshops.

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3. Recruitment of Participants

3.1 Describe the "types" of participants (e.g. city planners, environmental specialists, minor age children, University students) to be involved in the research. Be very specific about your method(s) for recruiting them, and comment on who will do the recruiting. Describe how and where you will advertise your project. **Include a copy of your recruitment notice, advertisement, information sheet, as well as that used by a sponsor or supportive organization, if applicable.** If actively seeking participation by speaking to specific groups, include the text used for verbal presentations. If remuneration/compensation is offered, provide details, including amount and confirm the budget provisions to meet these obligations. Describe any provisions that have been made to accommodate the participants' language.

Construction projects experts including project managers, planners, schedulers, senior engineers, construction supervisors are the targeted participants in this research. I have a good network so I know some of these people and I can ask them to participate in the research. The others are asked to participate by my supervisor, Dr. Janaka Ruwanpura. I will not advertise my project. No remuneration or compensation will be offered.

4. Informed Consent

4.1 Described the informed consent process. **Provide a copy of your consent form.** If there is no written consent form, please provide an explanation for this and details about your alternative procedures. If obtaining verbal consent, a script containing the same points normally covered by written consent is required. Are participants minors or, for other reasons, not able to provide fully informed consent? Explain and justify, and describe alternative procedures (e.g. parental consent).

The consent form is attached.

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4.2 When and how will people be informed of the right to withdraw from the study? What procedures will be followed for people who wish to withdraw at any point during the study? What happens to the information contributed to this point? Please note that the CFREB does not require that researchers withdraw/destroy partial data in cases of participant withdrawal, provided that it is made clear on the informed consent form that data collected to the point of withdrawal will be retained/used.

Participation is completely voluntary. Participants are free to discontinue participation at any time during the study. If this happens, partial data collected to the point of withdrawal will be retained and used, unless otherwise asked by the participants.

4.3 Do you plan follow-up procedures with participants? [x] No [ ] Yes, if yes, what are they? Does your research design require formal debriefing? [x] No [ ] Yes, if yes, please provide details about the procedures you will use.

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5. Privacy: Confidentiality and Anonymity:

5.1 Check all that apply: **Participant contributions will be: [X] public and cited; [ ] anonymous; [ ] confidential.** Explain the steps you propose to respect an individual's privacy. Describe these precautions in terms of access to raw data, as well as in terms of the write-up of the results. For example, will data be reported in aggregate? Will participants select a pseudonym? Will participants be asked to review their contribution before inclusion? (Please note that the CFREB does not require that participants be given the option of reviewing their data, provided they are aware that this opportunity will not be offered to them. Should you wish to provide participants with a chance to review material attributed to them, it is recommended that you set a specific time limit [e.g. within two weeks of receiving the material] by which participants must contact you with any suggested changes to material attributed to them, with a lack of response within that time indicating that the participant approves of the material as is, in order to avoid delays to your research. This timeline should be made clear in the consent protocol.) Who gets the data and in what form?

I will acknowledge the participants in the final thesis. Before each interview or workshop, I will tell them that they are acknowledged in the beginning of the final thesis. If they prefer not to do this, I simply can keep their names confidential. The final data will be reported in aggregate. The participants are not asked to review their contribution before inclusion.

5.2 Provide specific details about the security procedures for the data as well as plans for the ultimate disposal of records/data. Who will have access to confidential data now or in the future? Specify the length of time the data will be retained and the plans for disposal of records/data. (Note: The CFREB does not have specific data retention or destruction requirements. Researchers are free to retain data for long periods of time, or archive data indefinitely, provided this is made clear to participants in the informed consent protocol, and continued/future use of the data is consistent with what is described by the researcher[s] within this application.)

There will be no confidential data in my research. Data retention period is unlimited. Data will be archived indefinitely and an anonymous dataset may be made available to other researchers who have first gained the proper ethics clearance

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6. **Estimation of Risks**: Will this study involve the following? Please check Y **When responding, see also Section 3– Information to Help Applicants**	None	Minimal Risk	More than Minimal risk
6.1 Psychological or emotional manipulations – might a participant feel demeaned, embarrassed, worried or upset? Could subjects feel fatigued or stressed?	X		
6.2 Are there questions that may be upsetting to the respondent?	X		
6.3 Does your study have the potential for identifying distressed individuals?	X		
6.4 Is there any physical risk or physiological manipulation?	X		
6.5 Is any deception involved? Withholding of information from, or misinforming, participants?	X		
6.6 Is there any social risk - possible loss of status, privacy and/or reputation?	X		
6.7 Do you see any chance that subjects might be harmed in any way?	X		
6.8 Is there any potential for the perception of coercion? That is, might prospective participants feel pressured to participate in the research (due to, for instance, actual or perceived power relationships between those involved in recruiting and those being recruited, e.g. manager/employee or teacher/student)?	X		
6.9 Are the risks similar to those encountered by the subjects in everyday life?	[X] Yes [ ] No if "no" , elaborate		

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- If you answered, "more than minimal risk" to any of the above, describe the manipulations and/or potential risks as well as the safeguards or procedures you have in place. Please provide justification for any risks involved and explain why alternative approaches involving less risk cannot be used. Use additional pages, as required.
- If your study has the potential to upset or distress individuals, arrangements must be made to mitigate such effects. Describe the arrangements you have made. Have participants been informed of any costs to be incurred by them for services? **See "Provision for Rescue – Guidelines for Applicants"**
- If your study has the potential to identify upset or distressed individuals, you must describe the arrangements you have made (if any) to assist these individuals. If you do not make any arrangements, please explain why. Have participants been informed of any costs to be incurred by them for services?
- If, prior to the start of the research session, participants will not be fully informed of everything that will be required of them or deliberately misinformed about some aspect of the study, explain why. Please describe the procedures in detail and justify why deception is necessary to conduct the research.
- If the potential for any perception of coercion exists, please explain what measures have been put in place to minimize the possibility that individuals will feel pressured to participate.

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7. Benefits

What are the likely benefits of the research to the researcher, the participants, the research community and society, at large, that would justify asking people to participate?

- Student researcher: increase understanding of research methods and increase project management knowledge;
- Participants: no direct benefit; the outcome of the research benefit will benefit them in the long run
- Scientific community: the study introduces a new method for assessing the overlapping;
- Industry: the study may provide insights into better practices to deliver the projects successfully;

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8. Signatures

I/We, the undersigned, certify that (a) the information contained in this application is accurate; (b) conduct of the proposed research will not commence until ethical certification has been granted; (c) the Board will be advised of any revisions to the protocol arising before or after ethical certification is granted; (d) an annual renewal report will be filed 12 months from the date that ethics approval is issued, and a final report will be filed immediately upon completion of research activity. Failure to submit renewal or final reports in a timely manner will be considered a breach of University and Tri-Council policy, and may result in the suspension of research funding and/or the research being rendered academically invalid; students who fail to submit reports may be barred from graduating. Conduct of research using human subjects that has not received ethics certification is a breach of University policy on integrity in scholarly activity.

Applicant's signature: ____ Date: ____________________________

Co-applicant's signature: ____________________________________ Date: ____________________________

Supervisor's Signature: I have been involved in the preparation of this application, and agree with the information it contains.

Supervisor's Signature: ____ Date: ___________________________

PROTOCOL CHECKLIST – required	N/A	Attached
Copy of the verbal or written explanation that will be provided to participants before they are asked for consent to participate	X	
Copy of the informed consent(s) that will be distributed to each participant.		X
If written consent is not used, a detailed explanation of alternative procedures is <u>required in Section 4 of this application, along with one or more of the following:</u>	X	
• If verbal consent is to be obtained, (e.g. telephone surveys), a script containing the equivalent points covered by written consent is required.	X	
• Totally anonymous online or mail out questionnaires: Signed consent is not necessary. A covering letter, containing the equivalent points covered by written consent, is required.	X	
Copies of questionnaire(s), sample questions or thematic overview, interview guide		X
Recruitment: Your recruitment notice, advertisement, and/or information sheet <u>as well as</u> that used by a sponsor or supportive organization, as may be applicable		X
Documents or information specific to or requested by the potential sponsor.	X	
Completed and signed application for review with the required number of copies.		X

Revised: 03/07

Note: The information contained in this application is collected under the authority of the Freedom of Information and Protection of Privacy (FOIP) Act. It will be used to evaluate your application for ethics certification. Anonymized data will also be used to fulfill reporting obligations.

If you have any questions about the collection or use of this information, please contact the Ethics Resource Officer (Research Services, ERRB Building, Research Park) at (403)220-3782.

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UNIVERSITY OF CALGARY

Name of Researcher, Faculty, Department, Telephone & Email:

Reza Dehghan, Shulich School of Engineering, Civil Engineering Department, (403) 891 5797, rdehghan@ucalgary.ca

Supervisor:

Dr. Janaka Ruwanpura, Civil Engineering Department

Title of Project:

A Framework for Activity Overlapping Assessment in Construction Projects

Sponsor:

NSERC

This consent form, a copy of which has been given to you, is only part of the process of informed consent. If you want more details about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

The University of Calgary Conjoint Faculties Research Ethics Board has approved this research study.

Purpose of the Study:

The purpose of this research is to develop a systematic approach and a conceptual framework, to assess the overlapping and determine the optimized degree of overlapping and therefore help project managers and planners to successfully deliver their fast track projects.

What Will I Be Asked To Do?

In this research, you'll be asked for discussing your own opinions about the best practices of overlapping activities in the project schedule. This can take about half an hour of your time.

You may also be asked for attending a 3.5-hour workshop to do a risk analysis on several overlappings inside the project schedule.

There will be no follow up sessions in addition to the above sessions.

Your participation in this research is voluntary and you may refuse to participate altogether, may refuse to participate in parts of the study, or may withdraw from the study at any time without penalty or loss of benefits to which you are otherwise entitled.

What Type of Personal Information Will Be Collected?

No personal identifying information will be collected in this study.

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Please put a check mark on the following option that grants me your permission to:

I grant permission to be audio taped: Yes: ___ No: ___

Are there Risks or Benefits if I Participate?

This research brings no risks or benefits to you.

What Happens to the Information I Provide?

Participation is completely voluntary. Participants are free to discontinue participation at any time during the study. If this happens, partial data collected to the point of withdrawal will be retained and used, unless otherwise asked by the participants. The researcher and his supervisor will be allowed to see or hear any of the answers to the interview tape, but data will be archived indefinitely and an anonymous dataset may be made available to other researchers who have first gained the proper ethics clearance. In the workshop, participants are asked to reply orally to a few general questions regarding planning and scheduling, and then they are asked to perform an assessment over several activity overlapping in the project schedule. They first select overlappings, then assess them through the suggested method by the researchers, and finally give their evaluation on the quality of the workshop and the suggested method. The collected data will be used to inform the researchers' Doctoral project. The raw data are only accessed by the researcher and his supervisor, but the processed data will be published in journals in form of statistics and analytical reviews. Data retention period is unlimited. There will be no confidential data in the research.

Signatures (written consent)

Your signature on this form indicates that you 1) understand to your satisfaction the information provided to you about your participation in this research project, and 2) agree to participate as a research subject.

In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) ____

Participant's Signature ____Date: _______________

Researcher's Name: (please print) ____

Researcher's Signature: ____Date: ________________

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Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

Mr. Reza Dehghan, Department of Civil Engineering, UoC, (403) 891 5797, rdehghan@ucalgary.ca

Dr. Janaka Ruwanpura, Department of Civil Engineering, UoC, (403) 220 6892, Janaka@ucalgary.ca

If you have any concerns about the way you've been treated as a participant, please contact the Senior Ethics Resource Officer, Research Services Office, University of Calgary at (403) 220-3782; email rburrows@ucalgary.ca.

A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

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Appendix 2

List of questions used in interviews (and focus groups)

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Please carefully study figure 1 and the following description regarding *the mechanism of activity overlapping* and then answer the questions on the next pages.

Normally, when the start of a *design activity* depends on the finish of another *design activity* (a finish to start dependency), the second activity (also known as the *successor* activity) can only be started if the first activity (also known as the *predecessor* activity) is finished completely. This is because the successor needs the information generated by the predecessor. However, to compress the schedule, the successor activity may be intentionally started before the completion of its predecessor activity. This becomes possible if the predecessor activity releases some preliminary information before its completion to the successor activity. Therefore, the successor can start sooner, using the preliminary information and making the necessary assumptions and predictions. The two activities can proceed in parallel for a while and, during this period, some intermediate information may be transferred, until the predecessor is completed; then, the predecessor may release its final information to the successor. At this point, it is likely that the final information is different from the preliminary information and therefore, changes and adjustments should be made to the successor to make it compatible with the final information. The changes and adjustments will take some additional work (rework) in form of extra person-hours (i.e. extra cost and time), which means an increase in the duration of the successor activity compared to its normal duration.

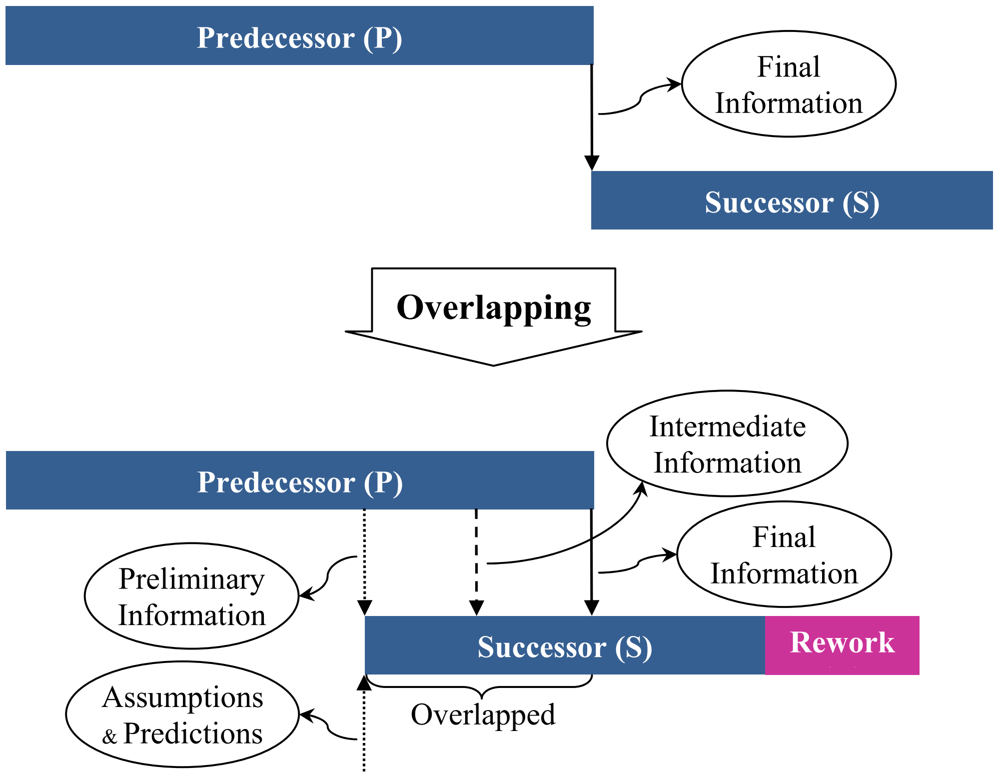

Figure 1: The mechanism of activity overlapping

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1. Considering your professional experience, to which extent do you agree that the above overlapping mechanism (or the mechanism presented in PowerPoint slides) reflects real world practice?

   Strongly agree. The logic is quite sound. However, in practice, schedulers overlap activities by converting finish-to-start dependencies to finish-to-finish and start-to-start dependencies.

2. Please provide any comments (if any) you feel important on *the mechanism of activity overlapping* stated in page 2 (or presented in PowerPoint slides) and your answers to the questions up to this stage:

   If a change happens in the predecessor activity that results in rework for the successor activity, the same change may result in rework for the predecessor activity as well.

3. Why schedulers do not overlap by applying a negative lag to FS dependencies rather than converting them to FF and SS dependencies?

   Easier understanding and judgment by engineers. A finish-to-start dependency with a negative lag makes less sense to people than finish-to-finish or start-to-start dependencies.

4. The probability that the rework happens, is a function of:

   a. *Overlapping duration*
   b. *Complexity, type and nature of overlapping activities*
   c. *The position of the overlapping in the project schedule which depends on the relation the overlapping activities have with other activities*

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5. If rework happens, the amount of rework is a function of:

   a. *Overlapping duration*

   b. *the strength of the successor activity dependency to the predecessor activity*

   c. *The intensity of nonconformity between final and preliminary information*

6. Can the rework period be longer than the overlapping duration?

   For design activities, no. For construction and procurement activities, yes.

7. Is it possible to define a pattern for the probability of rework?

   A specific pattern or function does not exist as so many variables affect.

8. Is it possible to define a pattern for the amount of rework?

   a. *A specific pattern or function does not exist as so many variables affect.*

   b. *Proposing a unique relation or a set of relations to show the variations of rework duration as a function of the variations of overlapping duration is extremely difficult, if not impossible.*

   c. *As a general rule and except for very odd cases, the more overlapping, the more rework and consequently the more increase in the successor duration.*

   d. *The amount of rework generally should be between 5 to 30 percent of the overlapping period.*

9. What is the probability of rework, if the successor overlaps with more than one predecessor?

   a. *There is a higher probability that rework happens.*

   b. *The more predecessors, the more probability.*

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10. What is the duration of rework period, if the successor overlaps with more than one predecessor?

   a. *Regardless of the number of predecessors, the rework duration cannot be more than the longest individual overlapping duration*
   b. *The rework duration should not be less than the longest individual rework duration.*
   c. *The more predecessors, the more rework*

11. What are the risks and costs of overlapping design activities?

   a. *Cost of rework*
   b. *Cost of extra communication*
   c. *Cost of heavier project coordination workload*
   d. *Cost of waste*

12. What are the benefits of overlapping design activities?

   To owners:

   a. *Earlier income generation from the new asset*
   b. *Ability to deliver against commitments/ contractual obligations*
   c. *Earlier completion of urgent works*
   d. *Earlier availability of cheaper production from up-dated assets*
   e. *Earlier closure of old and less efficient plants*
   f. *Alignment to fixed date of plant shut-down*
   g. *Shorter investment payback time, especially in times of high inflation*
   h. *New product to market ahead of competition*
   i. *Increased market share*

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j. Benefiting from changes in the tax regime

k. Earlier start to other projects following release of resources

To contractors:

l. Saving indirect costs

m. Earlier income from the job due to the shorter overall duration

n. Earlier deployment of resources to other jobs

o. Ability to tackle more jobs with the same level of resources

p. Possible opportunity to earn incentives

q. Possible opportunity for longer term relationship with Owner through an alliance

r. Enhanced reputation leading to opportunities with other Owners

s. Reduction in risk of late completion against contractual target by working to even tighter schedule

13. In the current scheduling practice, do the schedulers reevaluate the duration of the successor activity when they overlap it with its predecessor activity? (□Yes / □No)

No. However, a few companies do a risk analysis on overlaps. Risk analysts may consider up to 30% of the overlapping duration as rework duration during risk analysis.

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Appendix 3

PowerPoint slides used in focus groups

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University of Calgary

Department of Civil Engineering

Project Management Specialization

Activity Overlapping Optimization

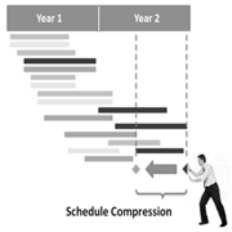
Researcher: Reza Dehghan

Supervisor: Dr. Janaka Ruwanpura

1

Introduction

Time is money



Shorter Project Duration ➡ More Business Benefits

2

Introduction

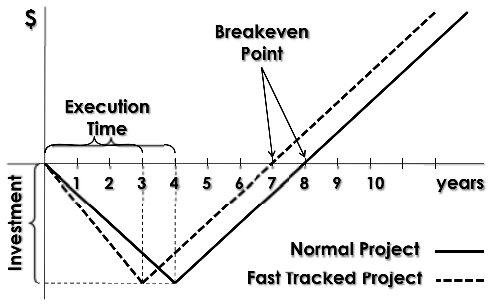
Time is money

1- Earlier income
2- Reduced payback period
3- Increased market share
4- Earlier start to other projects
5- Earlier release of resources
6- etc.

3

Introduction

Return on Investment



4

Fast Tracking

Normal Execution

ENGINEERING

PROCUREMENT

CONSTRUCTION

Minimum Overlaps

Fast Tracking

Fast Track Execution

ENGINEERING

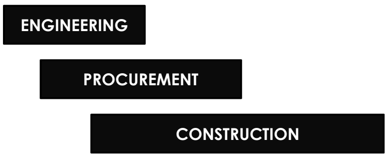
PROCUREMENT

CONSTRUCTION

Significant Overlaps

Fast Tracking

Extreme Fast Track Execution

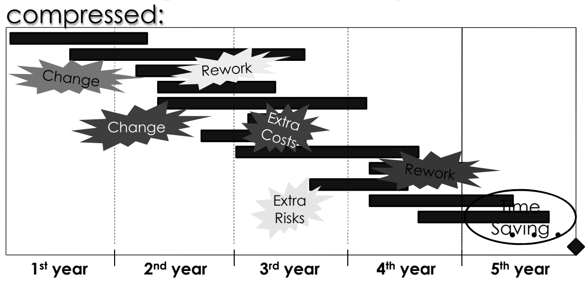


Maximum Overlaps

Problem Statement

Fast Tracked Schedule

Fast tracking makes the project schedule compressed:



Research Objectives

Main Objective

- Determine activity overlaps in the project schedule to generate the maximum timesaving with keeping costs at minimum

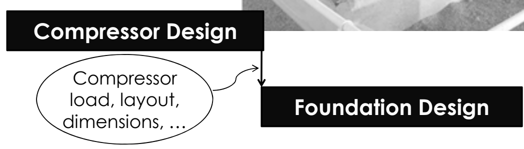
Overlapping

Example:

Compressor design

A: Compressor design

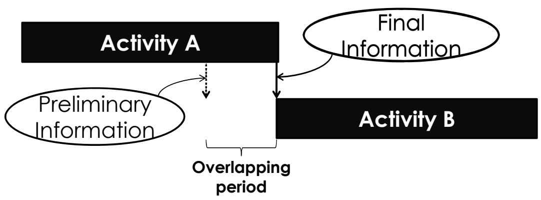
B: Foundation design



Overlapping

Overlapping Principle

- The basis of overlapping design activities is *the early release of preliminary information* by the predecessor to the successor activity.

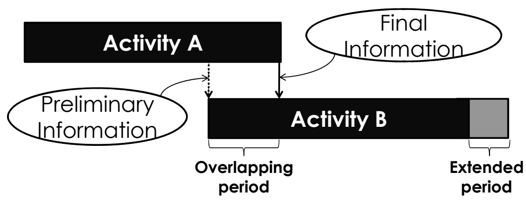


Overlapping

Overlapping Principle

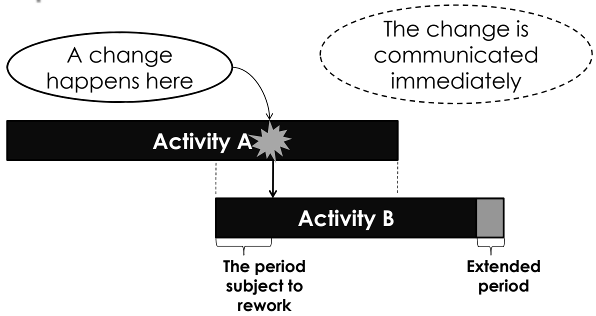
Changes in Activity A

→ Rework Activity B



Overlapping

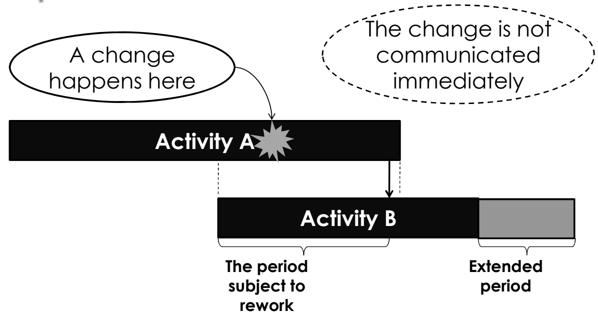
Importance of Communication



Reza Dehghan

Overlapping

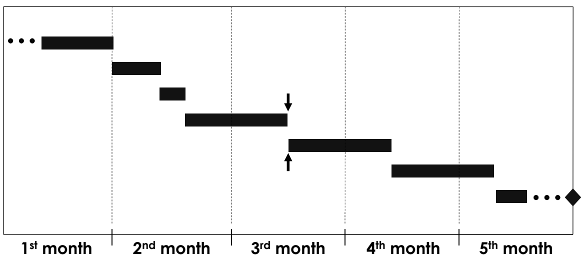
Importance of Communication



Reza Dehghan

Overlapping

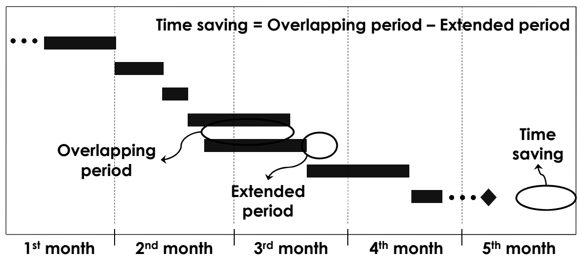
Overlapping Time Impact



15

Overlapping

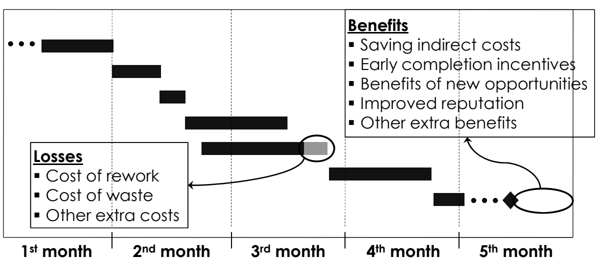
Overlapping Time Impact



16

Overlapping

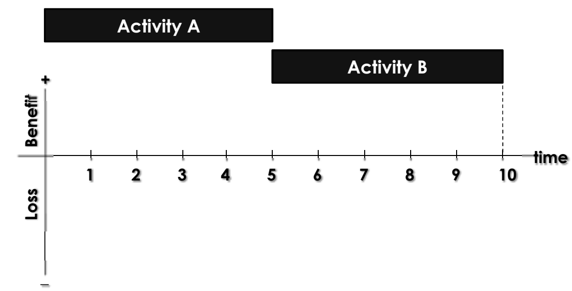
Overlapping Cost Impact



17

Overlapping

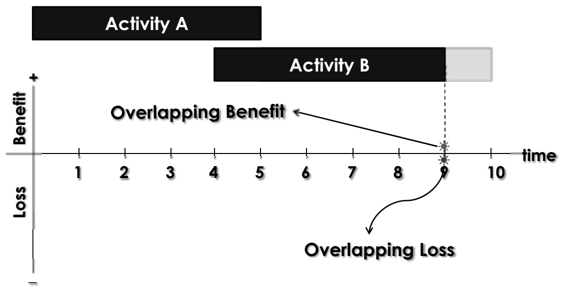
Overlapping Tradeoff



18

Overlapping

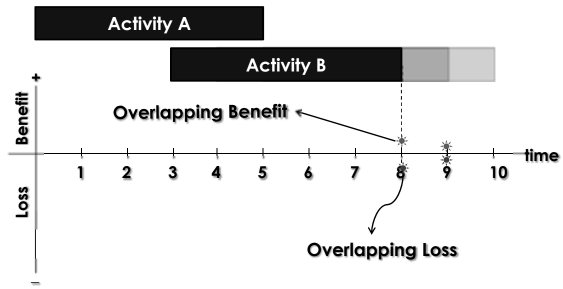
Overlapping Tradeoff



19

Overlapping

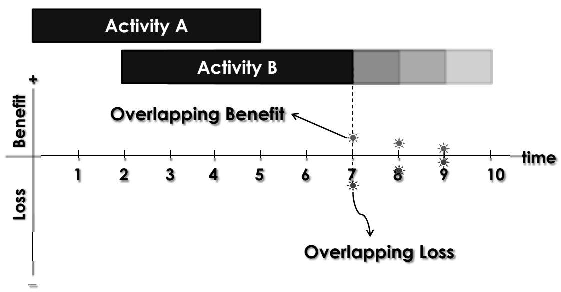
Overlapping Tradeoff



20

Overlapping

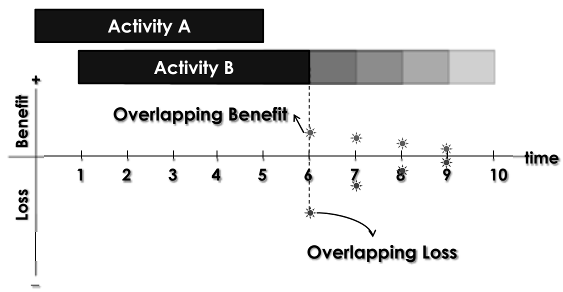
Overlapping Tradeoff



21

Overlapping

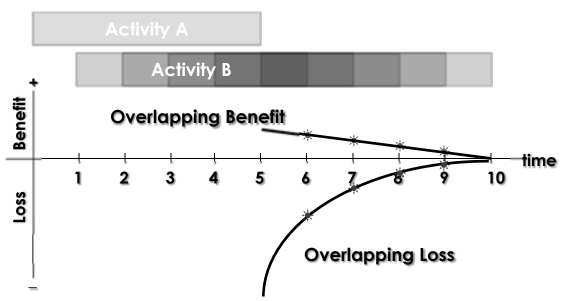
Overlapping Tradeoff



22

Overlapping

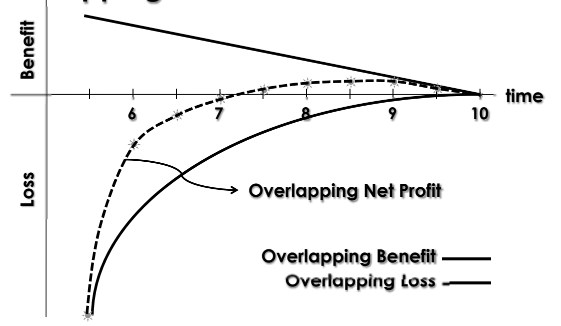
Overlapping Tradeoff



23

Overlapping

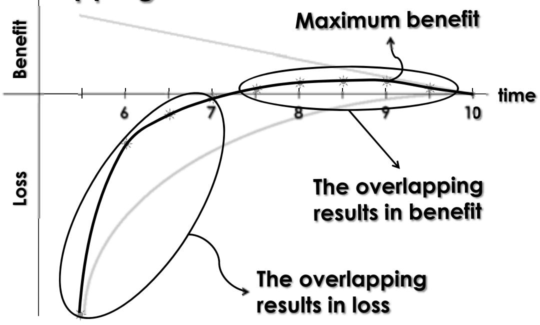
Overlapping Tradeoff



24

Overlapping

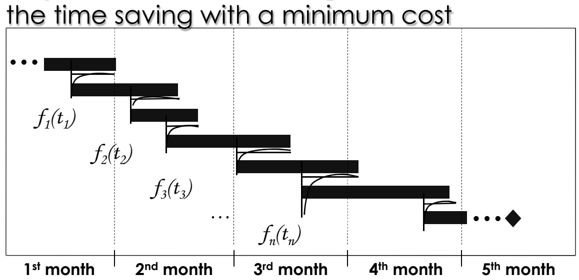
Overlapping Function



Overlapping

Overlapping Functions

Objective: The best arrangement to maximize the time saving with a minimum cost



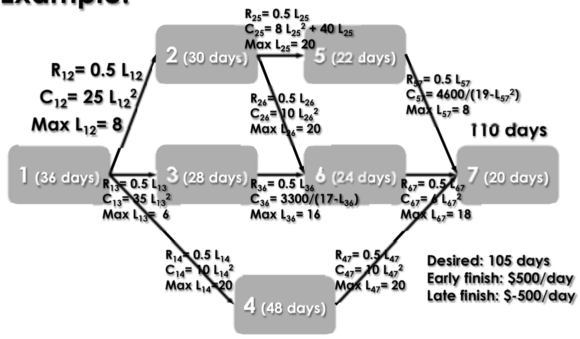
Optimization Tool

Optimization Model

- The *genetic algorithm* module is plugged into the scheduling software

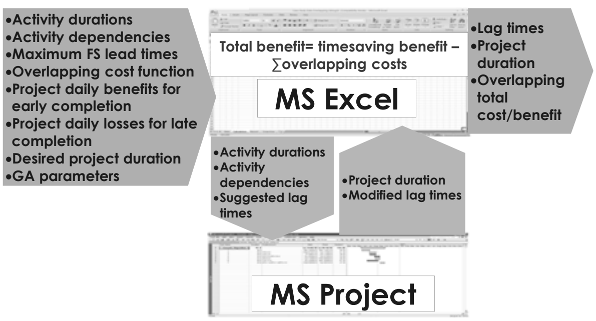
Optimization Tool

Example:



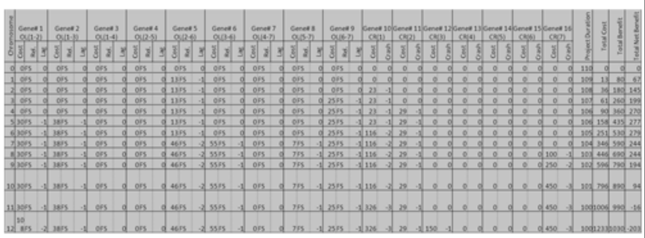
Optimization Tool

Computer Tool



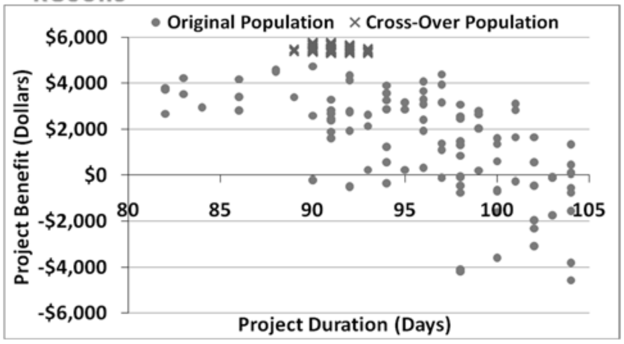
Optimization Tool

Computer Tool



Optimization Tool

Results



Optimization Tool

Results

Gene #	Succ.	Pred.	Overlapping Cost ($)	Lead Time
1	2	1	1225	7
2	3	1	35	1
3	4	1	640	8
4	5	2	1008	9
5	6	2	40	2
6	6	3	300	6
7	7	4	360	6
8	7	5	48	2
9	7	6	575	11
Total Cost of Overlapping			4231	

Appendix 4

Questions for validating through feedback from the others + results

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1. To what extent do you agree that the presented overlapping model is logically sound?
    - Strongly agree
    - Agree
    - Neither agree nor disagree
    - Disagree
    - Strongly disagree
2. To what extent do you agree that the presented overlapping model reflects the real world practice?
    - Strongly agree
    - Agree
    - Neither agree nor disagree
    - Disagree
    - Strongly disagree
3. To what extent do you agree that the presented overlapping model is comprehensive? In other words, To what extent do you agree that all essential elements have been addressed in the model?
    - Strongly agree
    - Agree
    - Neither agree nor disagree
    - Disagree
    - Strongly disagree

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4. To what extent do you agree that the presented overlapping model is too complicated?
    - Strongly agree
    - Agree
    - Neither agree nor disagree
    - Disagree
    - Strongly disagree
5. To what extent do you agree that the presented overlapping model is too simple?
    - Strongly agree
    - Agree
    - Neither agree nor disagree
    - Disagree
    - Strongly disagree

Results (for the total of 6 participants):

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
Q1	4	2			
Q2	2	4			
Q3	1	5			
Q4			1	3	2
Q5			1	4	1

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Appendix 5

List of contributors in the research with pseudonyms, professions and years of experience

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No.	Name	Company	Position - Specialty	Work Exp. (yr)
1	BM[1]	BL	Risk Manager	25^{+}
2	RJP[2]	BL	Manager, Project Controls	25^{+}
3	BNS[2]	BL	Planning and Scheduling Manager	25^{+}
4	AA[2]	BL	Senior Planning Specialist	25^{+}
5	GG[2]	BL	Senior Scheduling Specialist	20^{+}
6	DLW[2]	BL	Piping Senior Lead Engineer	30^{+}
7	DEB[2]	BL	Piping Senior Lead Engineer	25^{+}
8	MT[1]	BL	President of Bantrel Constructors Co.	30^{+}
9	GM[2]	BL	Vice President, Manager of Operations	25^{+}
10	JPL[2]	BL	Manager of Engineering, Project Manager	25^{+}
11	TA[1]	BL	Cost Control Specialist	15^{+}
12	KD[2]	BL	Senior Structural Engineer	15^{+}
13	JH[2]	FR	Vice President, Project Director	30^{+}
14	PRH[2]	FR	General Manager, Engineering	25^{+}
15	AG[2]	FR	Contracts and Materials Management	20^{+}
16	FH[2]	FR	Senior Director, Design Engineering	25^{+}
17	MD[2]	FR	Senior Project Control Specialist	25^{+}
18	TDG[1]	FR	Senior Project Control Specialist	25^{+}
19	MT[2]	NN	Project Controls Manager	20^{+}
20	AJ[2]	NN	Schedule and Module Planning Manager	25^{+}
21	IWH[2]	NN	Vice President, Yemen Strategic Initiatives	25^{+}
22	JH[2]	NN	Manager, Project Services	20^{+}

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No.	Name	Company	Position - Specialty	Work Exp. (yr)
23	EJC[2]	NN	Project Manager	25+
24	LM[3]	AC	Vice President, Project Management Oil Sands	30+
25	LJ[3]	AC	Director, Delivery Assurance Oil Sands	20+
26	DC[3]	AC	Director of Construction, Oil Sands	20+
27	JDM[3]	AC	Engineering Director, Oil Sands	20+
28	YK[2]	AC	Lead Planner	15+
29	AM[1]	AC	Project Engineer	15+
30	DP[2]	SR		25+
31	JMC[2]	SR	Director Project Controls	20+
32	JC[2]	SR	Manager, Planning and Scheduling	20+
33	AZ[2]	SR		20+
34	SB[3]	HH	Project Controls Hub Lead	25+
35	KS[1]	HH	Structural Engineer	15+
36	BA[1]	HH	Hydrotechnical Engineer	15+
37	JMK[2]	OE	Senior Vice President, General Manager, Primavera Global Business Unit	20+
38	KTN[2]	OE	Vice President, Product Strategy, Primavera Global Business Unit	15+
39	RES[2]	OE	Engineering & Construction, Primavera Global Business Unit	15+
40	BM[2]	TA	Senior Planner	15+
41	MF[1]	JS	Piping Engineer	15+
42	RV[1]	SN	Electrical Designer	15+
43	QY[3]	WS	Project Control Specialist	15+

[1] *Interviewed (9 individuals)*
[2] *Participated in focus groups for both model development and validation (28 individuals)*
[3] *Participated in focus groups for validation (6 individuals)*

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Appendix 6: Overlapping optimization tool snapshots and macros

Appendix 6

Overlapping optimization tool snapshots and macros

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Appendix 6: Overlapping optimization tool snapshots and macros

Activity	Original Duration	Predecessors	Relation Type	Relationship	Min. Lead Time	Max. Lead Time	Rework Function	Overlapping Cost Function
1	36	-	-	-	-	-	-	-
2	30	1	FS	1FS	0	17	$R_{12}= 0.2L_{12}$	$C_{12}= 900R_{12}$
3	28	1	FS	1FS	0	10	$R_{13}= 0.1L_{13}$	$C_{13}= 850R_{13}$
4	48	1	SS	1SS	19	36	$R_{14}= 0.15L_{14}$	$C_{14}= 1050R_{14}$
5	22	2	FS	2FS	0	22	$R_{25}= 0.3L_{25}$	$C_{25}= 800R_{25}$
6	24	2	FS	2FS	0	20	$R_{26}= 0.25L_{26}$	$C_{26}= 1000R_{26}$
6	24	3	FS	3FS	0	16	$R_{36}= 0.2L_{36}$	$C_{36}= 1000R_{36}$
7	20	4	FF	4FF	8	20	$R_{47}= 0.15L_{47}$	$C_{47}= 950R_{47}$
7	20	5	FS	5FS	0	15	$R_{57}= 0.05L_{57}$	$C_{57}= 950R_{57}$
7	20	6	FS	6FS	0	6	$R_{67}= 0.25L_{67}$	$C_{67}= 950R_{67}$

Genetic Algorithm Data Sheet

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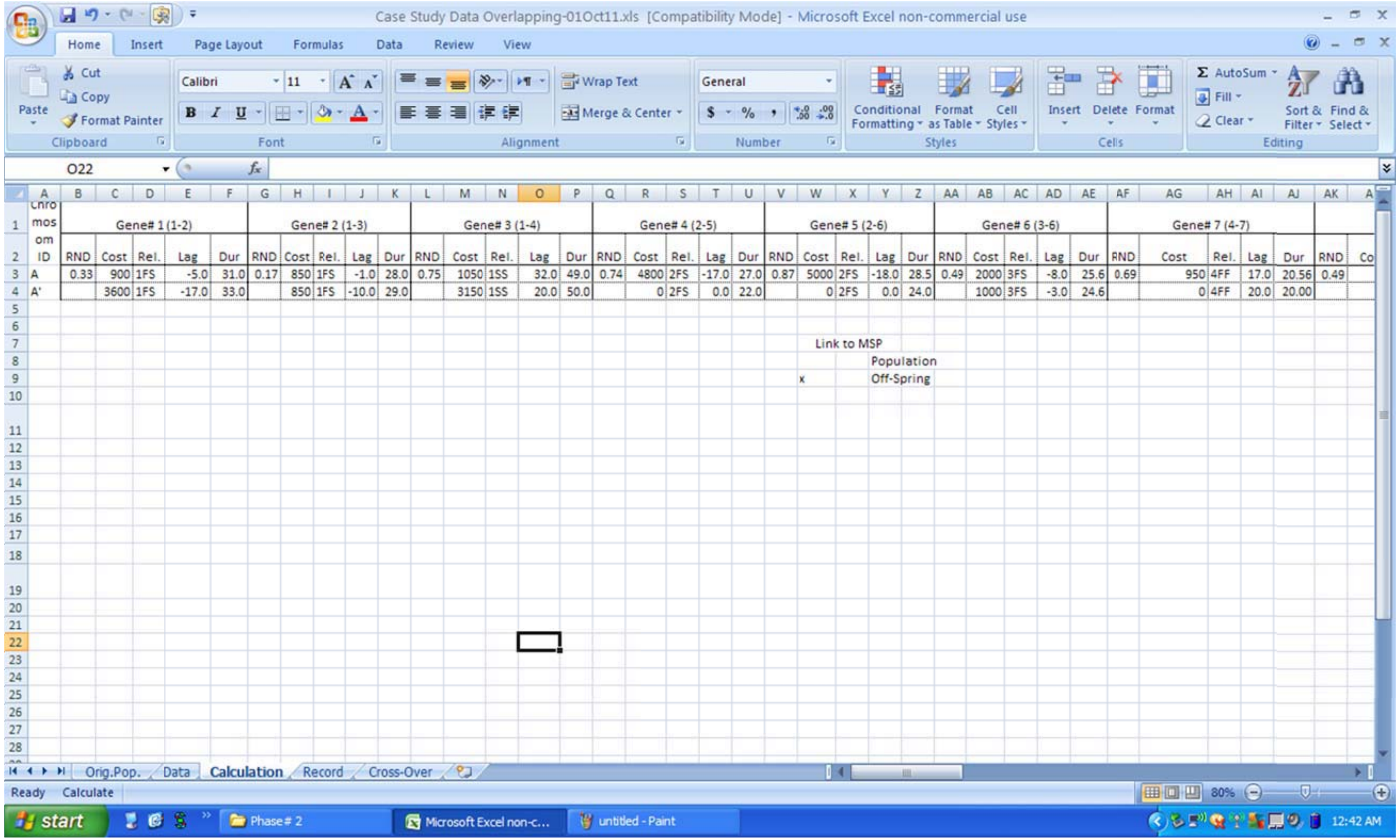
Appendix 6: Overlapping optimization tool snapshots and macros



Genetic Algorithm Original Population Sheet 1

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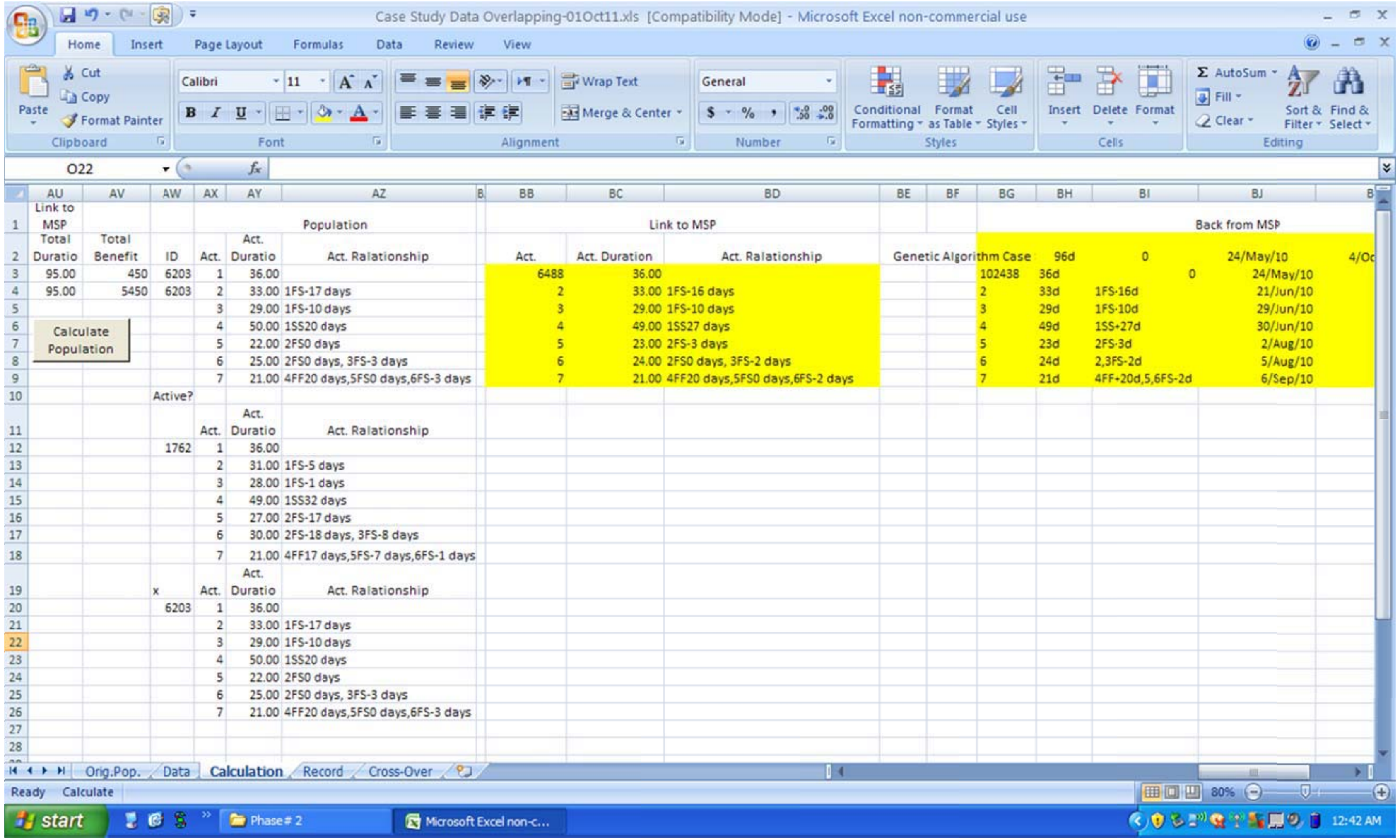
Appendix 6: Overlapping optimization tool snapshots and macros



Genetic Algorithm Original Population Sheet 2

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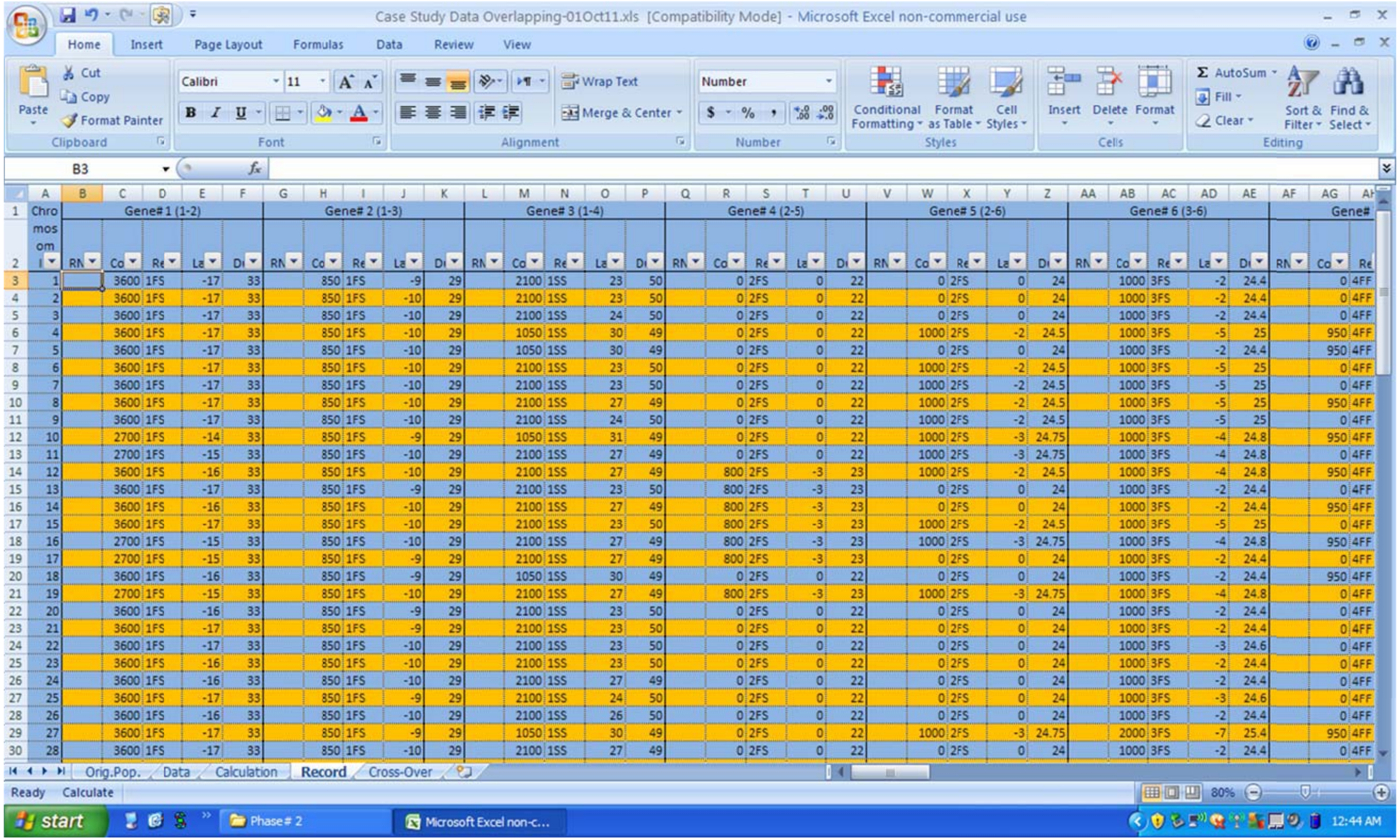
Appendix 6: Overlapping optimization tool snapshots and macros



Chromosome	Gene# 1 (1-2)					Gene# 2 (1-3)					Gene# 3 (1-4)					Gene# 4 (2-5)					Gene# 5 (2-6)					Gene# 6 (3-6)					Gene#		
	RN	Co	Re	La	Di	RN	Co	Re	La	Di	RN	Co	Re	La	Di	RN	Co	Re	La	Di	RN	Co	Re	La	Di	RN	Co	Re	La	Di	RN	Co	Re
1		3600	1FS	-17	33		850	1FS	-9	29		2100	1SS	23	50		0	2FS	0	22		0	2FS	0	24		1000	3FS	-2	24.4		0	4FF
2		3600	1FS	-17	33		850	1FS	-10	29		2100	1SS	23	50		0	2FS	0	22		0	2FS	0	24		1000	3FS	-2	24.4		0	4FF
3		3600	1FS	-17	33		850	1FS	-10	29		2100	1SS	24	50		0	2FS	0	22		0	2FS	0	24		1000	3FS	-2	24.4		0	4FF
4		3600	1FS	-17	33		850	1FS	-10	29		1050	1SS	30	49		0	2FS	0	22		1000	2FS	-2	24.5		1000	3FS	-5	25		950	4FF
5		3600	1FS	-17	33		850	1FS	-10	29		1050	1SS	30	49		0	2FS	0	22		0	2FS	0	24		1000	3FS	-2	24.4		950	4FF
6		3600	1FS	-17	33		850	1FS	-10	29		2100	1SS	23	50		0	2FS	0	22		1000	2FS	-2	24.5		1000	3FS	-5	25		0	4FF
7		3600	1FS	-17	33		850	1FS	-10	29		2100	1SS	23	50		0	2FS	0	22		1000	2FS	-2	24.5		1000	3FS	-5	25		0	4FF
8		3600	1FS	-17	33		850	1FS	-10	29		2100	1SS	27	49		0	2FS	0	22		1000	2FS	-2	24.5		1000	3FS	-5	25		950	4FF
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28		3600	1FS	-17	33		850	1FS	-10	29		2100	1SS	27	49		0	2FS	0	22		0	2FS	0	24		1000	3FS	-2	24.4		0	4FF

Genetic Algorithm Record Sheet

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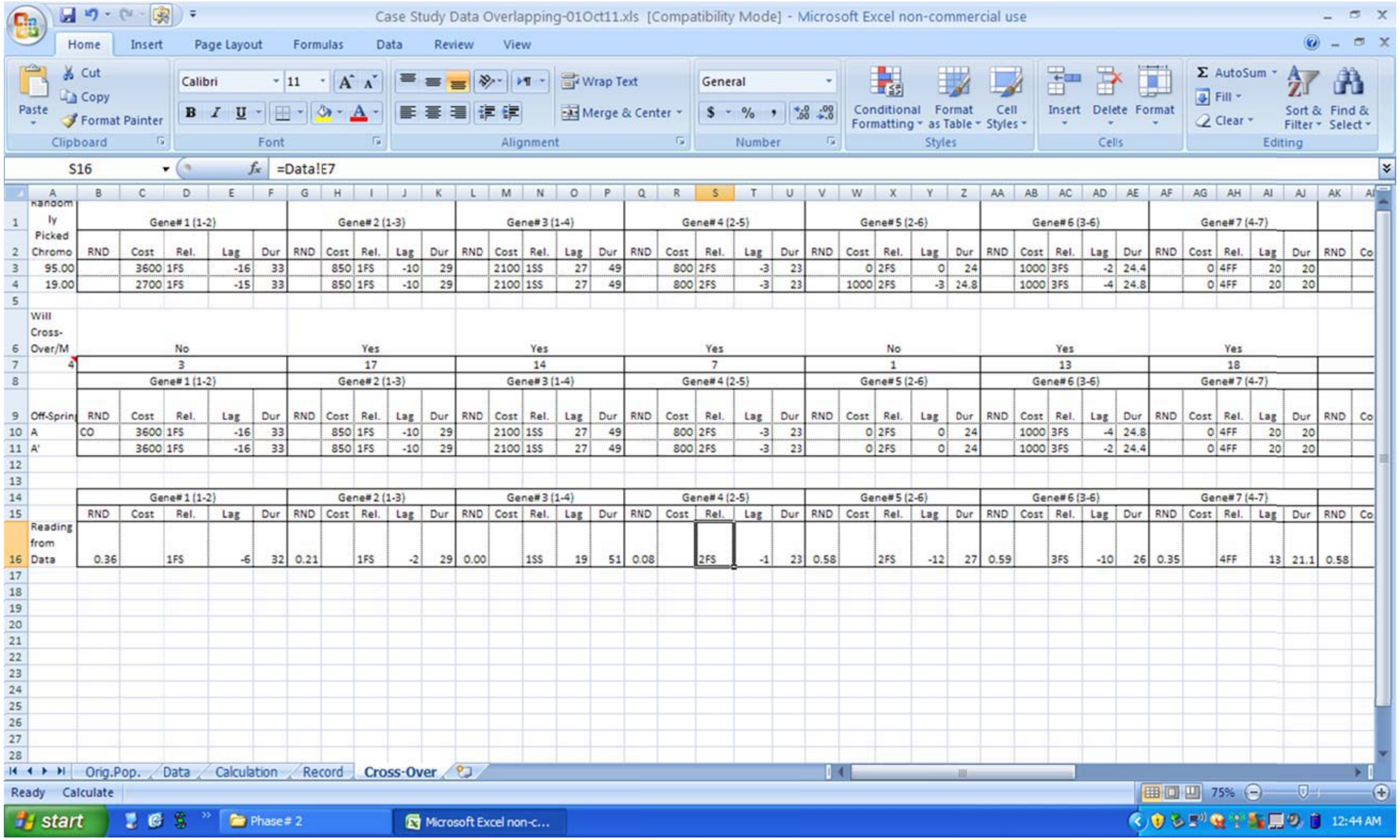
Appendix 6: Overlapping optimization tool snapshots and macros



Genetic Algorithm Cross-Over Sheet 1

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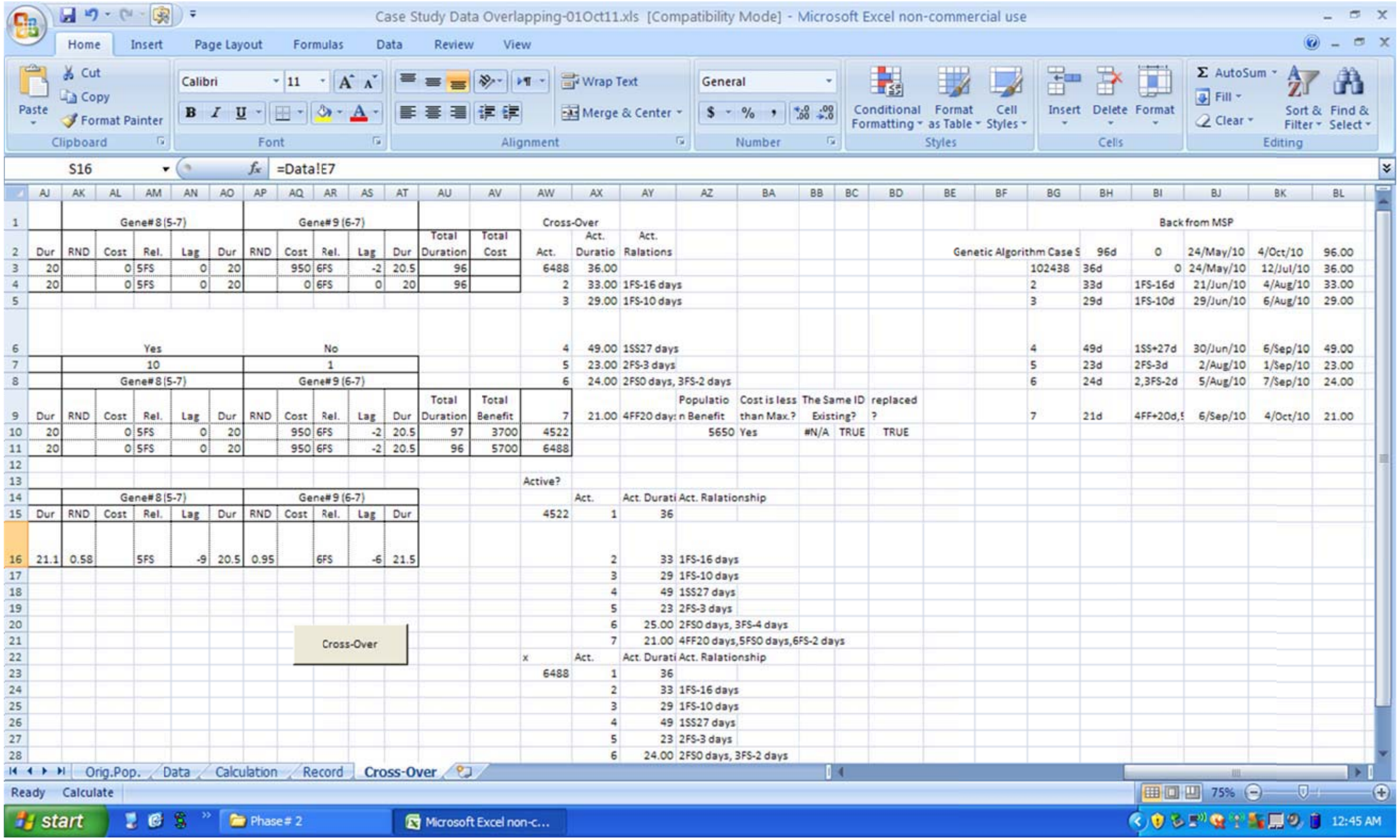
Appendix 6: Overlapping optimization tool snapshots and macros



Genetic Algorithm Cross-Over Sheet 2

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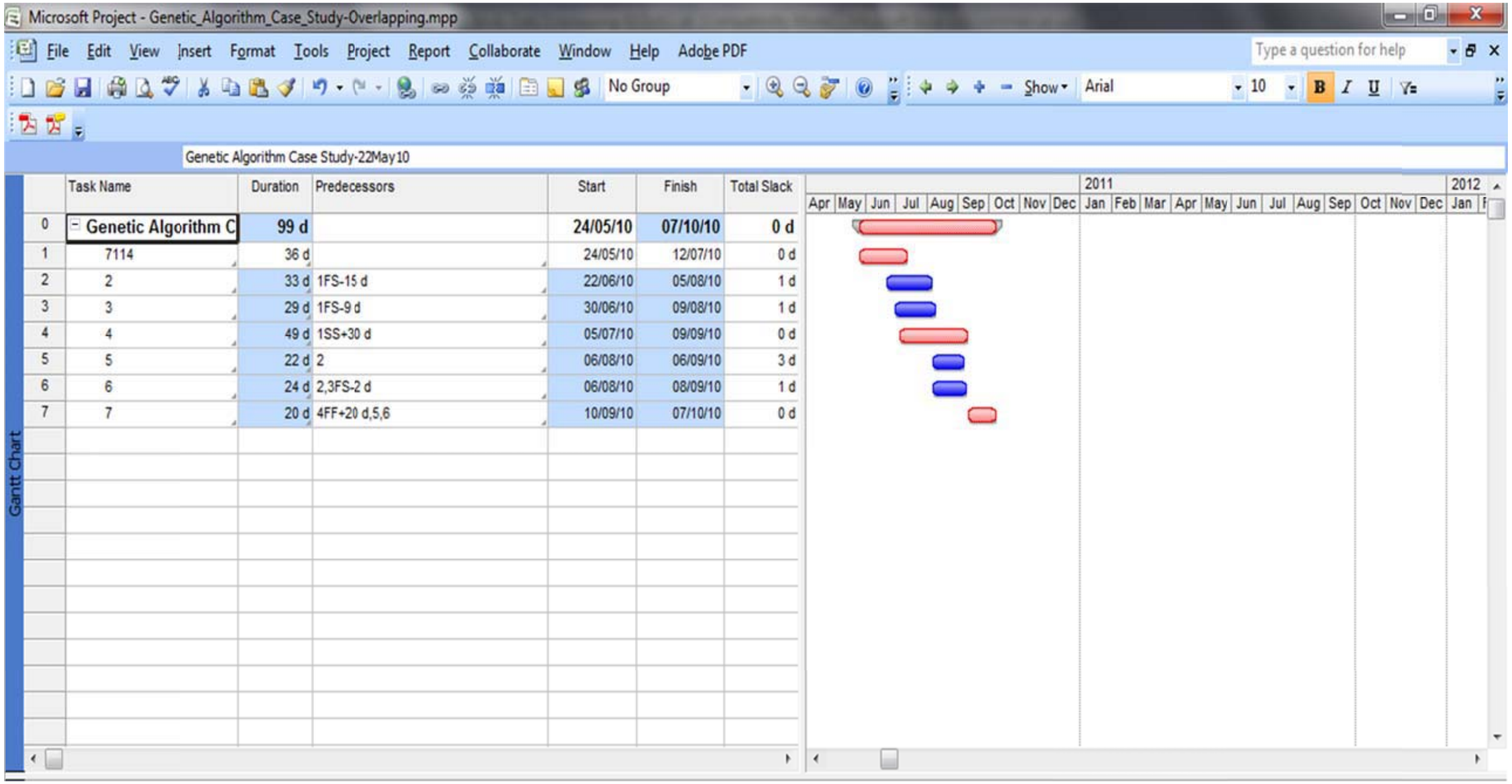
Appendix 6: Overlapping optimization tool snapshots and macros



	Task Name	Duration	Predecessors	Start	Finish	Total Slack
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1	7114	36 d		24/05/10	12/07/10	0 d
2	2	33 d	1FS-15 d	22/06/10	05/08/10	1 d
3	3	29 d	1FS-9 d	30/06/10	09/08/10	1 d
4	4	49 d	1SS+30 d	05/07/10	09/09/10	0 d
5	5	22 d	2	06/08/10	06/09/10	3 d
6	6	24 d	2,3FS-2 d	06/08/10	08/09/10	1 d
7	7	20 d	4FF+20 d,5,6	10/09/10	07/10/10	0 d

Microsoft Project

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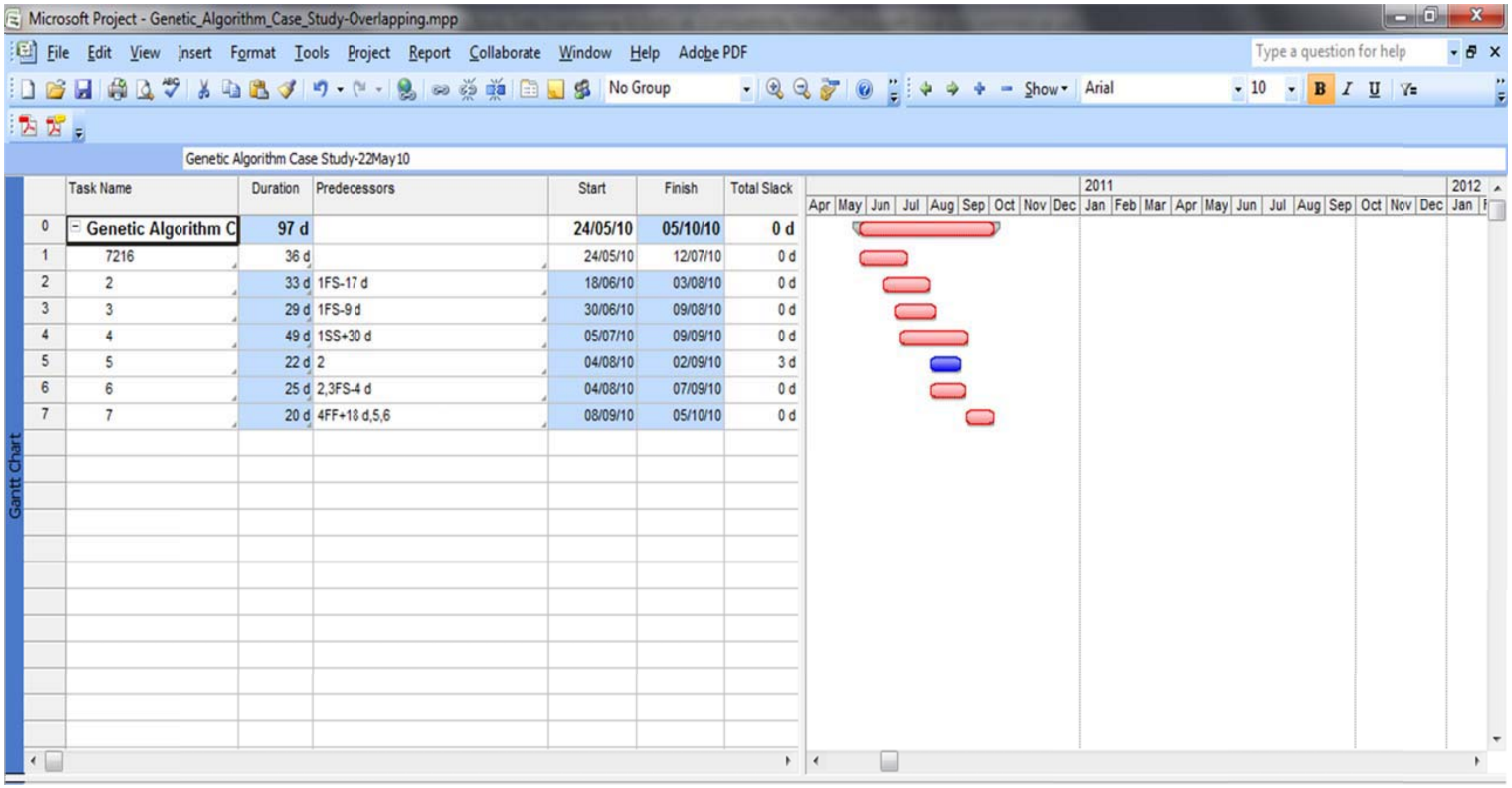
Appendix 6: Overlapping optimization tool snapshots and macros



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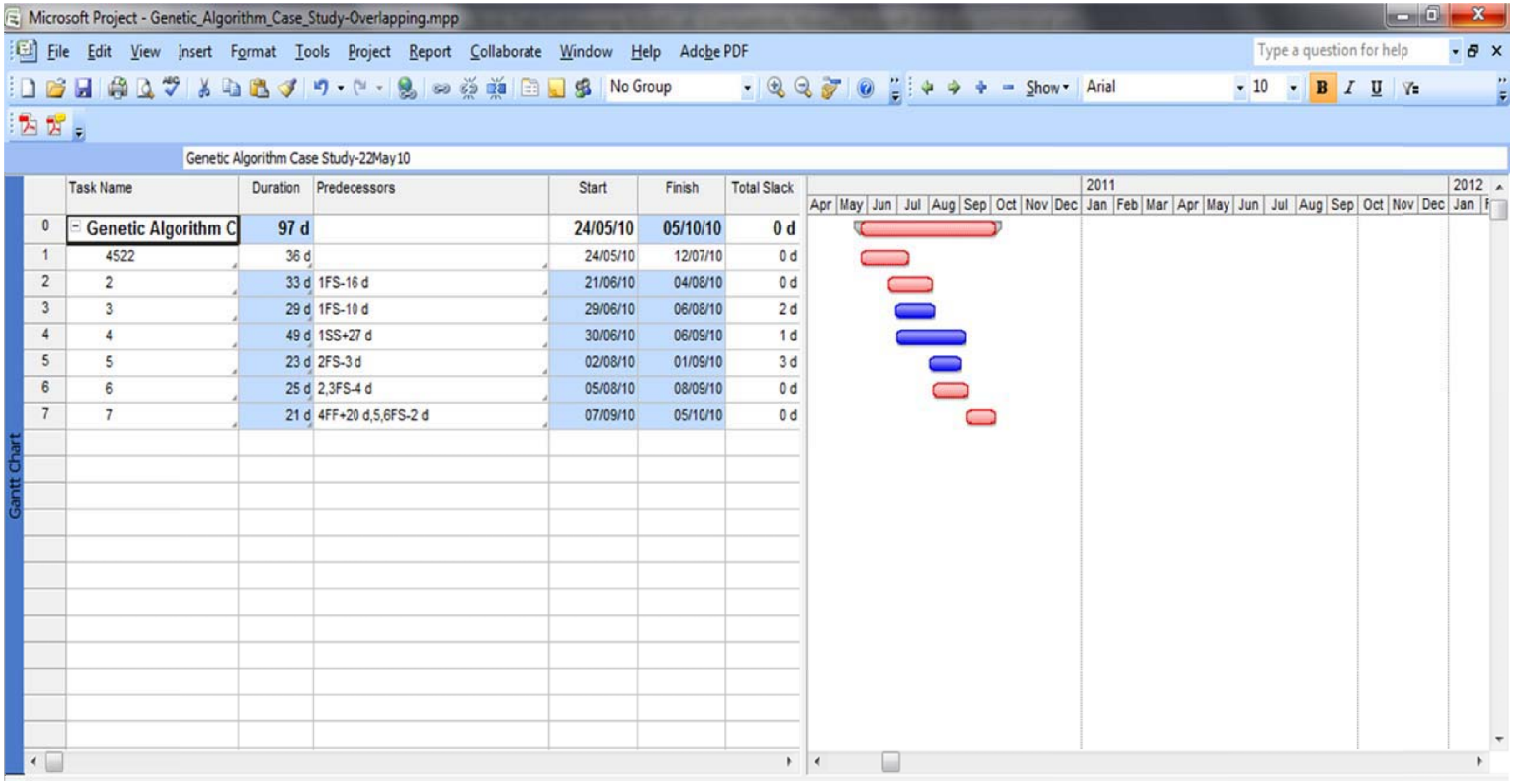

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Appendix 6: Overlapping optimization tool snapshots and macros

Population Generation Macro

```
Sub Population_Generation()
'
' Population_Generation Macro

Dim d(20) As Integer

i = 3: r = 1
Application.Calculation = xlManual
Application.CalculateBeforeSave = False
Application.AutoRecover.Enabled = False
Application.ErrorCheckingOptions.BackgroundChecking = False
ActiveWorkbook.UpdateLinks = xlUpdateLinksNever
ActiveWorkbook.UpdateRemoteReferences = False
ActiveWorkbook.SaveLinkValues = False

Sheets("calculation").Range("w8").FormulaR1C1 = "x": Sheets("calculation").Range("w9").FormulaR1C1 = ""

filename = Application.GetOpenFilename("Microsoft Project Files (*.mpp), *.mpp")
Start = Timer 'to calculate the run time, sets the start time

20 Sheets("calculation").Range("aw11").FormulaR1C1 = "x": Sheets("calculation").Range("aw19").FormulaR1C1 = ""

Sheets("Calculation").Calculate

30 Link_update

Sheets("calculation").Range("bg2:bl9").Calculate
'If Sheets("calculation").Range("aw11").FormulaR1C1 = "x" Then
Sheets("calculation").Range("au3:av3").Calculate

' check if MSP is calculated the overall duraiton
```

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Appendix 6: Overlapping optimization tool snapshots and macros

```
' -----------------------------------------------
yy = Sheets("calculation").Range("aw3").Value
xx = Sheets("calculation").Range("bg3").Value
If Int(yy) <> Int(xx) Then GoTo 30
' -----------------------------------------------

Sheets("calculation").Range("b4:aw4").Calculate

d(r) = Sheets("calculation").Range("au4").Value

If r > 1 And d(r) = d(r - 1) Then GoTo 100

Sheets("calculation").Range("aw11").FormulaR1C1 = "": Sheets("calculation").Range("aw19").FormulaR1C1 = "x"

Sheets("calculation").Range("aw11:az26").Calculate: Sheets("calculation").Range("aw3:az9").Calculate

Sheets("calculation").Range("bb3:bd9").Calculate

r = r + 1
GoTo 30

100 If d(r) < 105 Then 'chromosome meets the duration criteria so can be copied to Population


Range(Sheet3.Cells(i, 2), Sheet3.Cells(i, 49)).Value = Range(Sheet2.Cells(4, 2), Sheet2.Cells(4, 49)).Value

Range(Sheet3.Cells(i, 50), Sheet3.Cells(i, 97)).Value = Range(Sheet2.Cells(3, 2), Sheet2.Cells(3, 49)).Value

i = i + 1

End If

r = 1

If i = 103 Then GoTo 200 'do we have enough population size?
```

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```
GoTo 20

200 Sheets("record").Select 'sorting the population with cost
    Range("B2:cs102").Select
    Selection.Sort Key1:=Range("av3"), Order1:=xlDescending, Header:=xlGuess, _
        OrderCustom:=1, MatchCase:=False, Orientation:=xlTopToBottom, _
        DataOption1:=xlSortNormal

Finish = Timer    ' Set end time.
    TotalTime = Finish - Start    ' Calculate total time.
    MsgBox "Total Run-Time was " & TotalTime & " seconds"

1000 End Sub
```

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Appendix 6: Overlapping optimization tool snapshots and macros

Cross-over Macro

```
Public filename As String

Sub Link_update()
ActiveWorkbook.UpdateLink Name:="MSProject.Project.9|" & filename & "!!LINK_220", Type:=xlOLELinks
'ActiveWorkbook.UpdateLink Name:= _
        "MSProject.Project.9|E:\GA-27Jul11\Phase# 2\Genetic_Algorithm_Case_Study-Overlapping.mpp!!LINK_208" _
        , Type:=xlOLELinks


End Sub

Sub Cross_Over()
'
' Cross_Over Macro
'
'Application.ScreenUpdating = False

Dim d(35) As Integer

r = 1
Application.Calculation = xlManual
Application.CalculateBeforeSave = False
Application.AutoRecover.Enabled = False
Application.ErrorCheckingOptions.BackgroundChecking = False
ActiveWorkbook.UpdateLinks = xlUpdateLinksNever
ActiveWorkbook.UpdateRemoteReferences = False
ActiveWorkbook.SaveLinkValues = False

i = 0 'total runs
j = 0 'counter for mutation
```

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Appendix 6: Overlapping optimization tool snapshots and macros

```
filename = Application.GetOpenFilename("Microsoft Project Files (*.mpp), *.mpp")
Start = Timer 'to calculate the run time, sets the start time

Sheets("calculation").Range("w8").FormulaR1C1 = "": Sheets("calculation").Range("w9").FormulaR1C1 = "x"

20 Sheets("cross-over").Range("aw14").FormulaR1C1 = "x": Sheets("cross-over").Range("aw22").FormulaR1C1 = ""

If j = 50 Then Sheets("cross-over").Range("a15").Value = "x": j = 0 'mutation every 50 run

Sheets("cross-over").Calculate

Sheets("calculation").Range("bb3:bd9").Calculate

25 Link_update

Sheets("calculation").Range("bg2:bl9").Calculate: Sheets("cross-over").Range("bg2:bl9").Calculate

' check if MSP is calculated the overall duraiton
' -----------------------------------------------
yy = Sheets("cross-over").Range("aw3").Value
xx = Sheets("cross-over").Range("bg3").Value
If Int(yy) <> Int(xx) Then GoTo 25
' -----------------------------------------------

If Sheets("cross-over").Range("aw14").FormulaR1C1 = "x" Then Sheets("cross-over").Range("au10:av10").Calculate

30 Sheets("cross-over").Range("b11:aw11").Calculate

Sheets("cross-over").Range("aw14").FormulaR1C1 = "": Sheets("cross-over").Range("aw22").FormulaR1C1 = "x"

Sheets("cross-over").Range("aw14:az29").Calculate: Sheets("cross-over").Range("aw3:az9").Calculate

Sheets("calculation").Range("bb3:bd9").Calculate

40 Link_update
```

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Appendix 6: Overlapping optimization tool snapshots and macros

```
Sheets("calculation").Range("bg2:bl9").Calculate: Sheets("cross-over").Range("bg2:bl9").Calculate

' check if MSP is calculated the overall duraiton
' ----------------------------------------------
yy = Sheets("cross-over").Range("aw3").Value
xx = Sheets("cross-over").Range("bg3").Value
If Int(yy) <> Int(xx) Then GoTo 40
' ----------------------------------------------

Sheets("cross-over").Range("au11:av11").Calculate

d(r) = Sheets("cross-over").Range("au11").Value

If r > 1 And d(r) = d(r - 1) Then GoTo 100

r = r + 1

GoTo 30

100 Sheets("cross-over").Range("az10:bd10").Calculate

If d(r) < 105 And Sheets("cross-over").Range("bd10") = True Then 'chromosome meets the duration and cost criteria so can be copied to
Population

Sheets("record").Range("b102:Aw102").Value = Sheets("cross-over").Range("b11:Aw11").Value

Sheets("record").Range("ax102:cs102").Value = Sheets("cross-over").Range("b10:Aw10").Value

' sort the population
  Sheets("record").Select
  Range("B3:cs102").Select
   Selection.Sort Key1:=Range("AV3"), Order1:=xlDescending, Header:=xlNo, _
      OrderCustom:=1, MatchCase:=False, Orientation:=xlTopToBottom, _
      DataOption1:=xlSortNormal
```

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Appendix 6: Overlapping optimization tool snapshots and macros

```
Sheets("Cross-Over").Select

End If

r = 1
Sheets("cross-over").Range("a15").Value = ""
    i = i + 1: j = j + 1

    If i < 5000 Then GoTo 20

    Finish = Timer    ' Set end time.
    TotalTime = Finish - Start    ' Calculate total time.
    MsgBox "Total Run-Time was " & TotalTime & " seconds"

'Application.ScreenUpdating = True
End Sub
```

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