THE DECISION-MAKING MODELING FOR CONCURRENT PLANNING OF CONSTRUCTION PROJECTS

A Dissertation

by

EUYSUP SHIM

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2008

Major Subject: Civil Engineering

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ABSTRACT

The Decision-making Modeling for Concurrent Planning of Construction Projects.

(December 2008)

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Concurrent construction, in which multiple construction activities are carried out concurrently or overlapping, is a method developed to reduce time-to-market and increase the value of the project to the owner or user. When overlapping activities, the additional cost for overlap is affected by the interaction between overlapped activities which is affected by the construction work methods used. Thus concurrent planning of construction projects can lead to a benefit for the owner through investigating the interactions between work methods under overlap and finding the best degrees of overlap. However, the determination of the best solution from all the possible combinations of multiple methods and degrees of overlap is affected by the decision-making approach: by a centralized decision-maker (e.g., the project manager) with less accurate information about cost estimates or by a decentralized decision-maker(s) (e.g., subcontractors) with a myopic viewpoint.

The objective of this dissertation is to compare the solutions from the two decision-making approaches and to identify the conditions in which one approach is preferred to the other. Thus project owners can benefit from choosing a better approach for concurrent planning under their own conditions. A Monte Carlo simulation model for each decision-making approach was developed: an algorithm for finding the best solution was developed by heuristic methods. Several parameters were incorporated into the models to reflect different conditions for the decision-making approaches: number of activities, number of methods, the project manager's solution capacity, the uncertainty in the project manager's knowledge and attitudes towards risk.

The comparison of the two approaches was implemented with random cost under different conditions. Furthermore, the model was applied to a hypothetical construction project. From the simulations the major conclusions include: (1) The decentralized approach becomes preferred with more activities; (2) Considering more methods provides more potential for higher benefit to the owner in the decentralized approach; (3) The decentralized approach is recommended under risk-averse attitude and high uncertainty in the project manager's knowledge.

DEDICATION

To my family

ACKNOWLEDGEMENTS

I would like to express sincere gratitude to Professor Kenneth Reinschmidt, my advisor, for his advice, inspiration and support throughout the whole course of this research. His teaching, both formally through courses at Texas A&M University, and, more importantly, through mentoring and discussion has been gratefully appreciated.

I also would like to extend my sincere thanks to my dissertation committee members, Professor Stuart Anderson, Professor David Ford, Professor Julian Kang and Professor John Walewski, for their patience, time commitments and helpful comments.

Finally very special thanks go to my family for their love and support. My parents, Sangki Shim, and Jeongok Jeong, have encouraged and supported me with prayers. Finally I would like to thank my wife, Jennifer Han, for her continuous encouragement and love.

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CHAPTER I

INTRODUCTION

Faster delivery of projects has been one of the critical success factors in almost all industries. In the construction area, fast-tracking (or phased construction), in which activities are executed concurrently, has been argued to be an effective approach to a faster project delivery (Huovila et al. 1994; Williams 1995).

By following the definition of construction work methods, "the way in which construction work is carried out on a construction project" (Froese and Rankin 1998), there are several work methods available to execute a construction activity with regard to amount of resources, sequence, technique, and so on. Since each work method can impose different impacts on other activities, there are certain benefits to selecting the most efficient combination of work methods (Ackerman et al. 1999). For example, the number of tower cranes in high-rise building construction (Howell et al. 1993), the type of forms in concrete work (Tam et al. 2002) and the method for installing windows of a multi-story building (Akinci and Fischer 2000) are among the factors affecting other activities' performance. The need to find cost-effective methods for reducing project duration is the motivation for research on how a project manager may select better combinations of work methods to facilitate overlapping of activities.

This dissertation follows the style and format of the *Journal of Construction Engineering and Management*.

In the centralized decision making approach, the project manager attempts to find the optimal combination of work methods and degree of overlapping based on less reliable information and limited resources. In the decentralized decision making approach, the subcontractors (specialists) select work methods that maximize their profits based on local knowledge, which may often be more reliable than that of the project manager (generalist). This research examines and assesses which approach delivers greater benefits to the owner under different conditions.

Under the decentralized approach, much research has been performed based on the framework in which the subcontractors (or agents) either cooperate or compete in decision making (e.g. resource allocation through competence among agents (Guikema 2003); Distributed Coordination Framework of Project Schedule Change (FDCPSC) (Kim and Paulson 2003); Distributed Planning and Coordination (DPC) (Choo 2003)) However, the current research will be conducted under a different framework where each pair of subcontractors joins to bid for additional time reduction through increased overlapping and the project manager selects the optimal set of bids. This framework is closer to a bidding mechanism in current construction practice.

Some key assumptions are made based on the existing literature on the topics of overlapping, decision making approaches and work methods. With the key assumptions, algorithms are developed to determine the optimal combination of work methods and degree of overlapping for both decision making approaches. In addition, uncertainty and rework are also taken into consideration. Finally, the solutions resulting from the two approaches are compared to identify the advantages of each decision making approach under different conditions.

1.1 Problem Statement

The fact that different decision-making approaches to construction planning produce different solutions has been typically ignored in the development of more efficient methodologies for construction planning. The solutions from the centralized decision making approach and the decentralized decision making approach need to be compared, and the analysis and comparison should be carried out for concurrent construction projects with multiple work methods.

Thus, this research identifies the conditions under which each decision making approach produces greater benefit to the owner for concurrent construction projects with multiple work methods.

1.2 Research Objectives

The main objective of this research is to determine which decision making approach delivers the higher owner profit under different types of conditions. The following sub-objectives will help achieve the main objective:

- To develop an algorithm for each decision making approach in order to determine the best combination of work methods and degree of overlapping

- To develop a framework for the comparisons between the benefits to the owner from both approaches under different conditions
- To identify which decision making approach delivers higher benefits to the owner under each condition

1.3 Scope of the Research

This research focuses on attaining the above objectives by limiting the scope of the research as follows:

- Static Decision Making

This research is based on static planning (or scheduling). While the decision making method for the planning in this research can be applied at any point during construction projects, it is considered in terms of discrete episodes. This is in contrast to dynamic decision making, which is defined as a decision task requiring multiple and interdependent decisions in a changing environment autonomously and in response to a decision maker's action (Brehmer 1990).

- Focus on the Activities in a Critical Path

The current research only deals with the activities on the critical path, and the expansion into multiple parallel paths is left for future research. By overlapping the activities on the critical path, multiple activities on the critical path can be executed concurrently.

- Decentralized Decision Making through a Bidding Process

The current research selects the bidding process as a framework for decentralized decision making, based on its wide use in the construction industry.

- Representation of work methods in terms of different additional costs for time reduction

Because many factors, such as resources, sequence, construction technique and so on affect the activity performance, it is impossible to represent all work methods in terms of different values of these factors. Instead, the current research will focus on different impacts of combinations of different values of these factors on activity performance such as cost and time.

1.4 Hypotheses

The following hypotheses are developed to define certain conditions and attain the main objective of this research;

- **The greater the number of activities, the greater the advantages of decentralized decision making.**

While more resources in planning, such as number of estimators or computers, may be applied to find better solutions for larger and more complex projects, the owner may have some limitations on the amount of resources available. On the contrary, if the number of activities increases, the solution space to be explored to find a set of work methods and degrees of overlapping between activities would increase exponentially.

Thus, in the centralized approach, the solution time required for the optimal solution increases much faster than the number of activities, so, as the number of activities increases, it is more likely that the project manager cannot find the optimal solution. On the other hand, in the decentralized approach, the increase in the number of activities does not affect the solutions determined by each pair of subcontractors. Also, the PM's selection of the optimal set of bids out of what each pair of subcontractors submitted does not require as big a search area as in PM's own solution under the centralized approach. Therefore, as the number of activities increases, there should be some critical number of activities such that, below this value, the centralized method gives better results, but above this critical value, the decentralized method provides a better solution.

- **The project owner benefits from more methods.**
    - *Benefits from more methods in the centralized approach*
    - *Benefits from more methods in the decentralized approach*

More methods for the execution of construction activities can provide the potential for less expensive cost or earlier completion of activities. Without consideration of overlaps between activities, contractors select the method which cost the least for a duration specified by the owner (the base method). However, if the owner wants to benefit from earlier completion of a construction phase with additional cost or from earlier revenues from his project with bigger initial investment, more methods provides the potential for less expensive overlap than the base methods. Some methods which are more expensive than the base method in a sequential execution of construction project may facilitate overlaps and cost less than the overlap by the basic methods. If these methods are found and well negotiated between the owner and subcontractors regarding additional costs required for time reduction by using these methods, then the project performance in terms of RoR may be better.

However, if the number of methods increases, the solution space will increase exponentially and the probability that the project manager cannot find the optimal solution would be diminished accordingly in the centralized approach. Also, if the project manager's knowledge is uncertain, cost estimates for less conventional methods by the project manager would be less accurate and it is more likely that cost estimates are over-estimated or underestimated. Thus some subcontractors may reject the project manager's solution and they are more likely to reject the project manager's solution with more methods. In other words, more methods provide not only more opportunities for overlap but also more likelihood of the rejection of the project manager's solution.

On the other hand, in the decentralized approach the increase in the solution space for a pair of subcontractors would not be as high as that for the project manager and subcontractors are assumed to be able to find their best solution. Therefore, each pair of subcontractors would benefit from more methods in that they can offer cheaper costs for overlap. However, the methods selected by a pair of subcontractors may be incompatible with methods selected by other subcontractors. And the probability of incompatible methods is likely to increase as the number of methods to be considered increases.

Therefore, it is hypothesized whether considering more methods would be beneficial to the project owner both in the centralized approach and in the decentralized approach.

- **The less accurate (or up to date) the knowledge of the project manager, the greater the advantages of decentralized decision making.**

While the project manager's knowledge may be as accurate (or up to date) as the subcontractors, it is usually expected that the subcontractors have more reliable knowledge than the project manager, or are in a better position to formulate new work methods that would be superior in performance when combined with interfacing contractors' work methods. As the project manager's knowledge becomes less accurate than that of the subcontractors', the project manager's cost estimates may be more likely to be different than those of the subcontractors. The project manager's solution based on the possibly different cost estimates from those by subcontractors may not be accepted by the subcontractors under the centralized approach. Thus, less amount of time reduction (or less benefit to the owner) would result.

However, this hypothesis depends on the degree of accuracy in the knowledge of the project manager, interacting with the size of the project. It would be reasonable to expect that the decentralized decision making has more advantage over the centralized decision making with less accuracy in the knowledge of the project manager, if the project size is so large that the project manager might not find the optimal solution. However, if the project size is small, then the centralized approach may give better results because the project manager can solve the optimization problem, if the optimum is not sensitive to variance in the project manager's knowledge. However, if the problem size is small but the project manager's knowledge is unreliable, then the project manager can solve the optimization problem specified, but it is not the right specification of the problem.

- **The centralized solutions have higher variance than the decentralized solutions.**
  - *The variances of the centralized solutions are higher than the decentralized solutions when the project manager's knowledge is as accurate as the subcontractors'.*
  - *The variances of the centralized solutions are higher than the decentralized solutions when the project manager's knowledge is less accurate than the subcontractors'.*

If the project manager's knowledge is less accurate (or up to date) than the subcontractors', then the project manager's estimation of cost, duration, future revenues and economic life of the project would have a high variance or be less reliable. Furthermore, estimated additional costs for overlap would be subject to the accuracy of the project manager's knowledge. Therefore, if the project manager's knowledge is less accurate, then the resulting centralized RoR may be less accurate (or have high variance) also. On the other hand, the accuracy of centralized RoR may not be affected by the uncertainty in the project manager's knowledge, because high variance in the PM's estimates may be reduced through the project manager's optimization process and/or negotiation between the project manager and subcontractors: a method which is estimated to be expensive would not be selected for the project manager's solution and the project manager's own solution which is based on inaccurate knowledge may be rejected by subcontractors. Therefore, it is hypothesized whether the high uncertainty in the project manager's knowledge affects the variance of the centralized RoR, or not. If this hypothesis is accepted by the simulation results, then the accuracy in centralized RoR can be improved by improving the project manager's knowledge. Otherwise, if it is concluded that the uncertainty in the project manager's knowledge does not affect the accuracy in centralized RoR, thus the centralized solutions do not have higher variance than the decentralized solution, it would not be recommended to improve the uncertainty in the project manager's knowledge for a more reliable RoR.

In comparing centralized RoR to decentralized RoR, if the uncertainty in the project manager's knowledge leads to a high variance in the centralized RoR, and if the project manager's knowledge is less accurate than the subcontractors', then the centralized solution would have a higher variance than the decentralized RoR.

- **Risk-averse attitudes by the project manager and subcontractors favor decentralized decision making.**
    - *Decentralized approach is preferred under risk-averseness when the PM's knowledge is as accurate as the subcontractors'.*
    - *Decentralized approach is preferred under risk-averseness when the PM's knowledge is less accurate than the subcontractors'*

Risk-aversion by both the project manager and subcontractors is likely to lead to the selection of more conventional work methods (that is, those with lower variance) and less amount of time reduction, thus producing more conservative (or less aggressive) scheduling. And if the centralized solutions have a higher variance than the decentralized solution as discussed in Hypothesis 4, less utility to the owner (or less amount of time reduction) would result by the centralized approach than by the decentralized approach due to risk-averse attitude.

CHAPTER II

REVIEW OF RELEVANT LITERATURE

2.1 Impacts of Different Work Methods and Overlapping on Project Performance

This research examines two factors which may affect the relationship between two activities; selecting of the optimal combination of work methods and overlapping between activities. According to Howell et al. (1993), the relationship between two activities is affected by the output of the upstream activity and the process required by the downstream activity. This relationship also influences the performance of those activities, especially that of the downstream activity. In order to find ways to manage this relationship more efficiently, much research has been performed with emphasis on the following factors; 1) buffer size between activities (e.g., Howell et al. 1993; Horman and Kenley 1998; Sakamoto et al. 2002); 2) space (e.g., Riley and Sanvido 1995; Riley and Sanvido 1997; Zouein and Tommelein 1999; Guo 2002); 3) subsequence (Echeverry et al. 1991); 4) resources (e.g., Tam et al. 2001; Faniran et al. 1999); and 5) construction technique (Tam et al. 2002). These research results have found that efficient planning of these factors can improve the construction project performance. In this research, the above factors are all combined to represent a work method.

In another area of research, overlapping between activities has been of much interest to reduce the project delivery time (e.g. Takeuchi and Nonaka, 1986; Clark and Fujimoto 1991; Krishnan et al. 1993, 1997). While no previous research has investigated the impact on project performance of different work methods under overlapping, some prior work has provided the basis for this investigation. In their study, Krishnan et al. (1993, 1997) developed two concepts, *upstream evolution* and *downstream sensitivity*, which are inherent to upstream and downstream activities, and argued that the two concepts had an impact on the effectiveness of overlapping. Pena-Mora and Li (2001) added *upstream progress* to the two concepts developed by Krishnan et al. to be the third activity-inherent factor affecting the effectiveness of overlapping. In the area of product development, the internal relationships and the external precedence relationships are described as activity-inherent factors which can influence the activities' progress under overlapping (Ford 1995; Park 2001). Defining these activity-inherent factors may help explain the impact that different work methods under overlapping can have on project performance.

Roemer and Ahmadi (2004) combined overlapping with "crashing" for time reduction as shown in Fig. 2.1, which is a traditional strategy for time reduction, often by allocating more resources. The combination of overlapping and crashing was found to lead to the optimal time reduction. This research also considers both overlapping and crashing as strategies to time reduction. However, while they considered only the amount of resources as a factor which affects an activity's cost and duration, this research considers other factors such as sub-sequence, construction technology or space as well as resource amounts for the decision of time reduction.

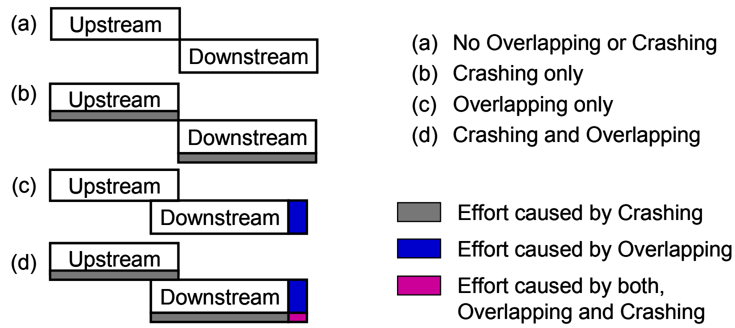


Figure 2.1 Types of Overlapping

The impact of overlapping on cost and rework based on the fixed set of work methods was studied in other research. As for the impact on cost within a project, higher cost due to overlapping was found or agreed with other research (e.g. Roemer et al. 2000; Salazar-Kish 2001; Fazio et al. 1988). The more cost due to overlapping is a key assumption throughout this research.

As for the impact of overlapping on rework, this research emphasizes the rework probability instead of the amount of rework, thus the estimate of the additional cost for time reduction by overlapping should include the effects of induced rework. While no research has empirically proven the impact of overlapping on rework probability, some research has proven that more errors were caused by a higher degree of overlapping between design and construction activities (Salazar-Kish 2001; Fazio et al. 1988). On the other hand, overlapping might have a favorable impact; errors, discrepancies or the need for design changes may be found by the succeeding activity earlier, thus overlapping may reduce rework delays and rework costs. Greater delay in identifying rework was found to lead to greater rework cost in some research (Loch and Terwiesch 1998; Ha and Porteus 1995). More empirical research and more detailed modeling of the rework process are needed to resolve this issue. This research does not address this question; when rework is at issue, it is assumed that increasing overlap increases rework costs.

2.2 Decision Making Approaches to Construction Project Planning

Most of the research on construction project planning (or scheduling) has assumed a centralized and top-down approach where the project manager is the decision-maker who determines the plan and the subcontractors follow that plan. These studies assumed that the project manager obtains all the required information without uncertainty and has no limitation of resources (time or manpower) to determine the best solution.

However, the centralized approach to project planning has been controversial for reasons such as, the complexity and rapid change due to uncertain information (Chang et al. 1993; Veeramani et al. 1993) and the impracticality for one party to hold all required information (Choo 2003; Siwamogsatham and Saygin 2004). Thus, new methodologies have been proposed for a decentralized approach (e.g. Hegazy et al. 2004; Choo 2003; Kim 2001).

However, these two decision making approaches have never been compared on the basis of the benefits to the owner in the area of construction. Some research has been conducted to identify the conditions under which one approach may be advantageous over the other in other areas (e.g. Tan and Harker 1999; Deshmukh et al. 1993; Malone and Smith 1988). Tan and Harker (1999) compared the expected costs between centralized and decentralized work flow organizations under various conditions and showed some conditions for the decentralized approach to be more favorable.

Some advantages and disadvantages of the decentralized decision making approach were addressed in other research. One of the advantages of the decentralized approach applicable in the construction planning environment is the higher reliability of knowledge on local surroundings (Hayek 1945; Siwamogsatham and Saygin 2004). The disadvantages include 1) the myopic viewpoint of decision makers (Choo 2003; Guikema and Paté-Cornell 2001) and 2) information sharing (or communication) cost (Hayek 1945).

In the both decision-making approaches the owner (or the project manager) needs to deal with subcontractors whose additional cost (or cost functions) is not known to the project manager. Under this information asymmetry, the project manager seeks to optimize or maximize the benefit to the owner. This issue is a subject of current research. Cachon and Zhang (2006) discuss how a buyer can procure supply from suppliers with the consideration of factors other than price, such as lead time, and several strategies that the buyer can use are discussed: Late-fee (penalty for late delivery); lead-time (the buyer specifies a delivery time); and scoring-rule (the buyer sets incentives for speed and buyers bid against each other by submitting prices). Beil and Wein (2003) propose mechanisms to optimize the buyer's benefit. They discuss that the buyer learns information about the suppliers' costs in multiple rounds of bidding with the consideration of both price and other attributes such as lead time.

2.3 Algorithm for Solving the Optimization Problem under a Centralized Decision Making Approach

Finding the optimal combination of work methods without considering overlapping in the construction industry has usually been performed in the area of the time-cost trade-off problem (e.g. Zheng et al. 2004; Feng et al. 2000; Feng et al. 1997) using three categories of techniques; heuristics, mathematical programming, and simulation (Feng et al. 2000). However, in the case of considering overlapping activities with multiple work methods, the project manager needs to solve a combinatorial optimization problem requiring a two-level search; to find the best degree of overlapping under a combination of work methods and also the optimal combination of work methods. This two-level search may require substantial computer time. In addition, if the optimization problem must be solved repeatedly in a Monte Carlo simulation, a more efficient algorithm is required.

Therefore, this research develops an algorithm based on heuristic methods that requires less computational effort than mathematical programming (Feng et al. 2000) and also focuses on local search methods. While the constructive approach, which generates solutions from an initially null starting solution by adding components, typically requires the least amount of computer time, its solutions are often poorer than those obtained by a local search approach (Blum and Roli 2003). While the evolutionary approach, such as the genetic algorithm, is robust and able to search a complex space without being trapped in local optima, it requires long computer running time (Hegazy 1999; Li and Love 1997).

2.4 Framework for Decentralized Decision Making

This research establishes a framework for decentralized decision making, under which the project manager makes a final decision based on the subcontractors' inputs. This framework is analogous to a lump-sum bidding mechanism which proposes a monetary incentive to subcontractors for additional reductions in time. The subcontractors bid their own amount of time reduction for the incentive price. However, the project manager may select multiple bids as long as the bids generate net benefit to the project owner.

The framework in this research is similar to a principal-agent game to some degree. In a principal-agent game, the principal (the project manager in the current research) tries to offer incentives to one (or more) agent(s) (subcontractors) to encourage the behavior favorable to the principal's interest (Wellman and Walsh 2001). While each agent in a principal-agent game makes his decision based on both his own and other agents' strategies, this research makes an assumption that subcontractors make decisions based on their own strategy only (amount of time reduction). Therefore, subcontractors aim to bid the amount of time reduction to maximize their profits.

CHAPTER III

SIMULATION MODEL DEVELOPMENT

3.1 Definitions and Assumptions

3.1.1 Environment of construction project planning

The planning in a concurrent construction project with multiple work methods is decided during the contracting phase. After selecting all subcontractors for each activity, the project manager makes plans to reduce the project execution time.

3.1.2 Joint bids between two subcontractors

When two activities are overlapped, it is impossible for a subcontractor to estimate his additional cost due to overlapping without knowing the other subcontractor's selected method. Thus, two subcontractors whose activities are overlapped may have to co-operate to know each other's method and to reach an agreement on work methods, if they are interested in obtaining incentive payments by reducing total project time. To better focus on the comparison between the two approaches, this research will assume that two subcontractors cooperate and agree to a joint bid to maximize their joint profit.

3.1.3 Definition of work methods

A construction work method is determined by several factors, such as resources (crews, equipment), space, sub-sequences, operation and technology. While "crashing" is a different strategy for time reduction from overlapping, allocating more resources is assumed to be a work method, in that the amount of resources deployed creates a different work method by definition. Thus, an activity in which more resources are allocated for direct time reduction can be overlapped with another activity, but it might cost more due to less efficient use of resources and increased congestion. This assumption is based on Ahmadi's (2004) conclusion.

The ***base method*** is defined as the combination of methods requiring the least cost in the normal sequential (non-concurrent) schedule. Thus, the base method is defined as the most conventional (or most frequently used) in this research. In the base method, contractors' work methods are uncoupled, because they are chosen independently of the others.

The following example explains how each method is defined with regard to several factors. This example is for masonry activity for a 3 story building and four factors are considered for defining each work method. Table 3.1 shows four factors and two available methods.

To lay bricks on the exterior of the building, the contractor can choose basic steel scaffoldings or a mast-climbing work platform as shown in Fig. 3.1. It is assumed that using the basic steel scaffolding costs less than using a mast-climbing work platform. Thus using basic steel scaffoldings is named as method I.

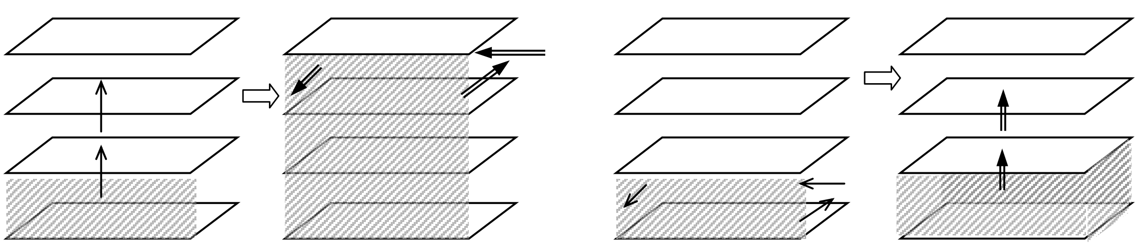
Table 3.1 Examples of different work methods

Factor	Method (I)	Method (II)
Type of equipment	Basic steel scaffolding	Mast-climbing work platform
Sequence	Vertical progress	Lateral progress
Batch size	Whole floor	Half floor
Crew size	2 crews	4 crews

(a) Basic steel scaffolding (b) Mast-climbing work platform

Figure 3.1 Different scaffolding systems

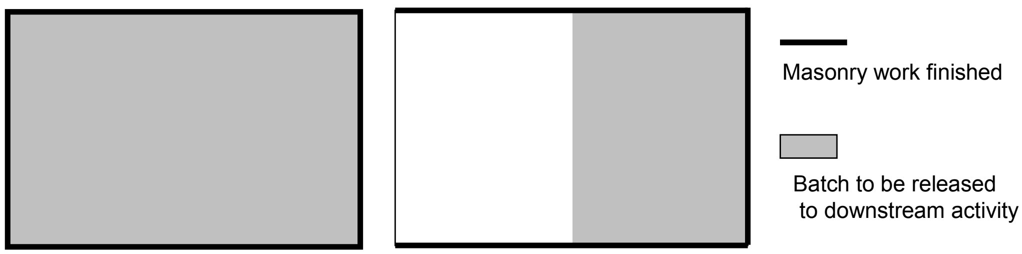
The second factor considered is the sequence of the masonry work. Bricks can be layered in one side of the building at first, and then in another side (vertical progress) as shown in Fig. 3.2.a. Or bricks can be layered for the first floor at first, and for the second floor next (lateral progress) as shown in Fig. 3.2.b.



(a) Vertical progress (b) Lateral progress

Figure 3.2 Different sequences for masonry work

The third factor considered is the batch size of the masonry work to be released to its downstream activity. The downstream activity (e.g., interior finish) can start after the masonry work of each floor is finished (batch size of a whole floor) as shown in Fig. 3.3.a. Alternatively the downstream activity can start when a half of a floor is finished with masonry work (batch size of a half floor) as shown in Fig. 3.3.b.



(a) Batch of a whole floor (b) Batch of a half floor

Figure 3.3 Different batch size for masonry work

Finally, the subcontractor may use different sizes of crews: using 2 crews or 4 crews. Of course, by using 4 crews the activity can be finished earlier, but some additional cost may be required for reasons such as productivity loss due to crowded space. In this example, there are a total 16 methods available (2×2×2×2=16). If the method (I) regarding each factor costs less than the method (II), then the base method would be to use 2 crews and basic steel scaffoldings with a batch size of a floor in vertical progress. Without consideration of overlapping, the subcontractor would use the base method. However, if overlapping between activities is considered, the methods (II) may be chosen. For example, the sequence of lateral progress may be chosen since it can more easily facilitate the overlap with the downstream activity than the sequence of vertical progress.

3.1.4 Impacts of different methods

- *The less conventional a method, the higher the cost.*

  The allocation of more resources (crashing) for time reduction is regarded as a less conventional method, since it costs more for additional resources than the base method.

- *The less conventional a selected method is, the more uncertain the planners' cost estimate becomes.*

  Less conventional methods or innovative methods are the methods which are less frequently used. Thus both the PM and subcontractors may have less reliable knowledge about those methods than the base methods. Therefore, the uncertainty in cost estimates of less conventional methods would be higher than the base methods.

- *The less conventional a method, the higher the rework probability.*

  If a method has not been used frequently, subcontractors (or his employees) may have less experience with that method. Thus, the more errors would be likely to happen.

3.1.5 Impacts of overlapping

- As two activities overlap to a higher degree, the combined cost increases convexly.

For time reduction within an activity, it is generally accepted that cost increases with more time reduction from normal or least-cost point of duration (Reda and Carr, 1989). Additional cost is due to more resources such as more laborers, bigger equipments, or overtime labors (or crashing).

However, when two activities are overlapped, each individual activity's duration may be delayed, but overall duration can be reduced (Roemer et al., 2000). Each individual activity's productivity may be lowered due to several factors such as congestions in the work area, or insufficient work-in-progress. Furthermore, it is researched that more rework is caused by overlapping (Salazar-Kish 2001; Fazio et al. 1988) Thus, when the additional costs of the both activities are accounted for, cost for overlap is expected to increase. This expectation is discussed and supported in several researches.

As for the next issue, how the cost increases due to overlap, it is assumed that the cost increases convexly with more overlap. As more time reduction is achieved by overlapping two activities, it is more likely that more additional cost is required: The unit cost for time reduction (e.g., additional cost for one week's reduction) would become bigger for more time reduction. Construction activity requires the products or the finished work from their immediate predecessor's activity on which it builds its own work. Thus, as the downstream activity starts earlier for overlapping, a lesser amount of finished work from the predecessor is available. If an insufficient amount of work is available (work-in-progress) to an activity, the workers of the activity would be idle and the productivity would decrease. Thus, the unit cost for time reduction is expected to increase with more overlap. Fig. 3.4 shows three typical cost curves versus the amount of time reduction: Linear, concave, and convex cost curve. Out of the three curves, the linear cost curve represents a constant unit cost for time reduction. Moreover, the concave cost curve represents decreasing unit cost for time reduction. Under the concave cost curve the cost converges to a point and no more increase is required for further overlap. If this is the case, then every project owner would overlap activities as much as possible at a constant cost and this is not what happens in the real world. Therefore, it is assumed that the cost for overlapping increases convexly with more overlaps.

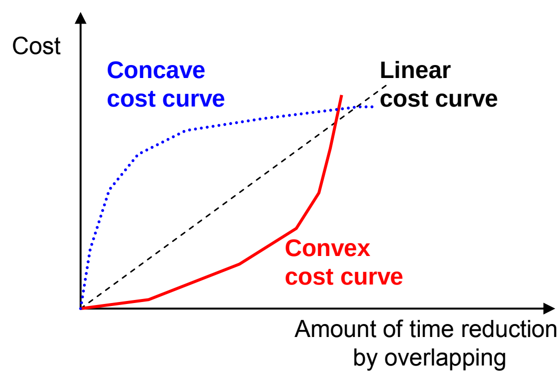


Figure 3.4 Different types of cost curves

- The rates of cost increase due to overlapping are different from each other, depending on the methods selected.

  If two activities are executed by overlap, the additional cost for the two activities is affected by compatibility or interaction between the two activities.
- The more overlapped two activities are, the more uncertain the planner's cost estimation becomes.
- The more overlapped two activities are, the higher the rework probability becomes (Salazar-Kish 2001; Fazio et al. 1988).

- There is a maximum limit of the amount of time reduction by overlap in a project. One of the features of construction activities is that an activity builds its own work (or product) on the work completed by its immediate predecessor's activity. Thus, 100% concurrent execution of activities in a critical path is not possible and it is assumed that there is a maximum limit of the amount of time reduction in a project. The assumed maximum limit of time reduction is 80% of the total duration.

3.2 Model Development: Decision Making Parameters

In the simulation model for this research, five decision-making parameters are developed as control variables to test the hypotheses. These decision-making parameters represent conditions in which the PM and subcontractors find their solutions to the planning of overlapping in a construction project. Therefore, by changing the values of these decision-making parameters the conditions of the decision-makers (the PM and subcontractors) are controlled in the simulation model.

3.2.1 Number of activities

Since each activity is assumed to be executed by a separate subcontractor, the number of activities is a parameter used to control a project size and/or number of subcontractors. As the number of activities increases, if the scope of each activity is constant, the size of a construction project increases. Alternatively, if the scope of each activity is changed and one activity can be split into multiple activities, the number of activities does not change the project size, but increases the number of subcontractors.

The number of activities changes the condition of projects regarding opportunities for overlap. As the number of activities increases, there are more pairs of activities (or subcontractors), thus more opportunities for overlap and time reduction. Moreover, the number of activities affects the number of possible sets of methods (or solution space) to be explored by the PM in the centralized approach.

3.2.2 Number of methods

By the definition of work methods above, there are multiple methods used to execute each construction activity. Each method has a different cost from the other methods without any overlap and any additional cost for overlap between two activities depends on interaction between the methods. While subcontractors may need to invest their resources to develop or invent an innovative method, it is assumed that having more methods available does not require additional cost.

The number of methods affects the number of possible sets of methods (or solution space) to be explored by the PM in the centralized approach and by subcontractors in the decentralized approach.

3.2.3 PM's solution capacity

The planning of concurrent execution with consideration of multiple methods generates a lot of possible sets of solutions. For example, if *n* activities have *m* methods available, then the number of sets of methods is $m \times m \times ..... \times m = m^n$. And the PM needs to estimate additional costs for each set of method. Therefore, it may be impossible that the PM estimates costs for all possible sets of solutions, since the PM has limited resources such as estimators, computers, allowed time and so on. The PM's solution capacity represents this constraint and the PM's solution capacity affects the quality of his solution (higher RoR or lower RoR).

3.2.4 PM's uncertainty

It is assumed that both the PM and subcontractors don't have certain or 100% perfect knowledge or information about the duration and costs of each method. Furthermore, subcontractors who are specialized in a specific area or activity are assumed to have a better knowledge than the PM. Accuracy of knowledge affects estimates of cost, duration and so on: as knowledge becomes more accurate, estimated cost has less variance. Thus, the PM's uncertainty represents the accuracy (or reliability) of the PM's knowledge relative to the subcontractors' knowledge.

The ratio of uncertainty in the knowledge of the project manager compared to the subcontractors is defined as in following equation.

$$k = \frac{\text{Standard Deviation of PM's Knowledge}}{\text{Standard Deviation of Subcontractors' Knowledge}}$$

The ratio can be equal to or higher than 1.0: if k =1.0, then the project manager has as accurate or reliable knowledge as the subcontractors'. This ratio affects random estimates by the PM. If the uncertainty in the PM's knowledge is as high as 2.0, then his cost estimates would have a high variance.

3.2.5 Attitude to risk (Risk-neutral or Risk-averse)

If there is any uncertainty in knowledge, several different attitudes to risk may exist: risk-averse, risk-neutral, risk-tolerance and risk-seeking (Hillson and Murray-Webster, 2005). In this research two attitudes to risk are considered and the impacts of the attitudes to risk on the solutions from both decision-making approaches are investigated. Hilson and Murray-Webster describe risk-averse attitude as "*to seek security and resolution in the face of risk and to avoid or minimize as many threats as possible*", while risk-neutral attitude is described as "*risk-taking as a price worth pay for future pay-offs*". Thus, under the risk-neutral attitude the solutions would be more aggressive, but risky: a higher expected (mean) value of RoR but a higher variance of RoR. Under the risk-averse attitude the solutions would be more conservative but with a lower variance.

To deal with these two different attitudes, Value at Risk (VaR) is used to measure the profitability on investment (or internal rate of return, RoR). Value at Risk is defined by Schachter (Schachter, 1997):

"A forecast of a given percentile, usually in the lower tail, of the distribution of returns on a portfolio over some period; similar in principle to an estimate of the expected return on a portfolio, which is a forecast of the 50th percentile."

Value at Risk (VaR) can be calculated based on a 95% confidence level in one side as a quartile on a normal distribution as in the following (Reinschmidt, 2004) as shown in Fig. 3.5.

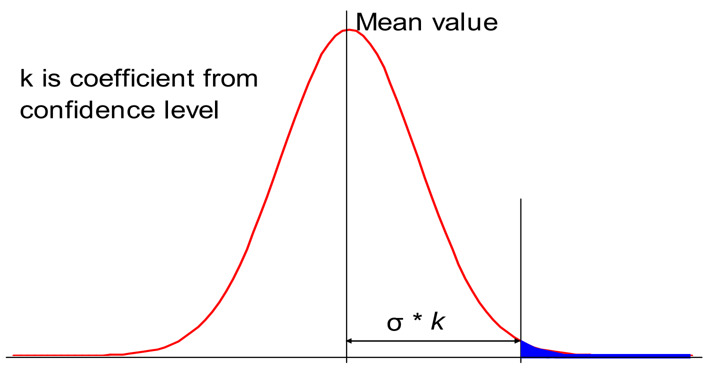


Figure 3.5 Example of VaR

$$P\{\text{cost>x}\}=\int_{x}^{\infty}\xi f(\xi)d\xi$$

Where, $f(\xi)$ is the probability density function of cost.

The inverse of the above approach is required to calculate Value at Risk. If a decision maker has α% level of confidence,

$$F(x)=\int_{x}^{\infty}\xi f(\xi)d\xi$$

$$P\{\text{cost} > \text{x}\}=\int_{x}^{\infty}\xi f(\xi)d\xi = F(\text{x})=1-\alpha$$

$x = F^{-1}(1- \alpha) = \text{VaR}$

This quartile (x) is the Value at Risk.

When additional cost for overlap is estimated under risk-aversion, a quartile of 95% confidence level is selected. Also, when measuring profitability (RoR), VaR is determined from the 5% percentile value from simulated data.

3.3 Calculation of Internal Rate of Return (RoR)

In this research, profitability of investment on construction projects is measured by internal rate of return (RoR). To get the internal rate of return (RoR) from a set of work methods, degrees of overlapping and corresponding duration and additional cost, which may be either from the centralized approach with a knowledgeable PM, or from the centralized approach with an ignorant PM, a simplified owner's financial model is developed.

Earlier completion of the construction phase for a project should justify any additional cost required to reduce the project delivery time in terms of improved RoR value. Otherwise, time reduction is not accepted by the owner, and the baseline schedule without time reduction will be used.

3.3.1 Derivation of an equation for the calculation of RoR

For easier calculation, some assumptions are made:

- All cash flows are made at the end of each time period.

- All cash out-flows during the construction phase have same magnitude.
- Future revenues will start to be obtained one time unit (i.e., month) after the finish of the construction phase.
- Magnitudes of future revenues are the same as each other.

Based on these assumptions, a typical cash flow diagram for a construction project is drawn in Fig. 3.6.

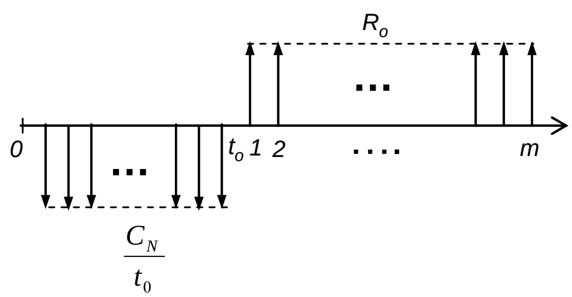


Figure 3.6 Cash flow diagram of simplified construction project

Where, C_N is construction cost

t_0 is duration required to complete the construction phase

m is economic life after the construction phase

R_0 is future revenue

3.3.2 Calculation of RoR for baseline schedule

Based on the above simplified cash flow diagram, an equation for the calculation of RoR is derived based on Reinschmidt's work (Reinschmidt, 2004). Discounted present value of all revenues are expressed in Eq. (3.1)

$$PV_R(r_0,t_0) = \frac{R_0}{(1+r_0)^{t_0+1}} + \frac{R_0}{(1+r_0)^{t_0+2}} + \frac{R_0}{(1+r_0)^{t_0+3}} + ... + \frac{R_0}{(1+r_0)^{t_0+m}}$$

$$= R_0[\frac{1}{(1+r_0)^{t_0+1}} + \frac{1}{(1+r_0)^{t_0+2}} + \frac{1}{(1+r_0)^{t_0+3}} + ... + \frac{1}{(1+r_0)^{t_0+m}}] \quad \text{--- Eq. (3.1)}$$

Where, PV_R is discounted present value of all revenues (or cash-inflows).

r_0 is RoR to be calculated.

By multiplying $(1+r_0)$ on Eq. (3.1)

$$(1+r_0) \times PV_R(r_0,t_0)$$

$$= R_0[\frac{1}{(1+r_0)^{t_0}} + \frac{1}{(1+r_0)^{t_0+1}} + \frac{1}{(1+r_0)^{t_0+2}} + ... + \frac{1}{(1+r_0)^{t_0+m-1}}] \quad \text{--- Eq. (3.2)}$$

By subtracting Eq. (3.1) from Eq. (3.2)

$$r_0 \times PV_R(r_0,t_0) = R_0[\frac{1}{(1+r_0)^{t_0}} - \frac{1}{(1+r_0)^{t_0+m}}] = \frac{R_0}{(1+r_0)^{t_0}}[1-(1+r_0)^{-m}]$$

$$PV_R(r_0,t_0) = \frac{R_0 \times [1-(1+r_0)^{-m}]}{r_0 \times (1+r_0)^{t_0}} \quad \text{--- Eq. (3.3)}$$

Similarly, an equation for discounted present value of all expenses is simplified as following.

$$PV_E(r_0,t_0) = \frac{C_N}{t_0} \times \frac{1}{(1+r_0)^1} + \frac{C_N}{t_0} \times \frac{1}{(1+r_0)^2} + \frac{C_N}{t_0} \times \frac{1}{(1+r_0)^3} + ... + \frac{C_N}{t_0} \times \frac{1}{(1+r_0)^{t_0}}$$

$$= \frac{C_N}{t_0}[\frac{1}{(1+r_0)^1} + \frac{1}{(1+r_0)^2} + \frac{1}{(1+r_0)^3} + ... + \frac{1}{(1+r_0)^{t_0}}] \quad \text{--- Eq. (3.4)}$$

By multiplying $(1+r_0)$ on Eq. (3.4)

$$(1+r_0) \times PV_E(r_0,t_0) = \frac{C_N}{t_0}[1 + \frac{1}{(1+r_0)^1} + \frac{1}{(1+r_0)^2} + ... + \frac{1}{(1+r_0)^{t_0-1}}] \quad \text{--- Eq. (3.5)}$$

By subtracting Eq. (3.4) from Eq. (3.5)

$$r_0 \times PV_E(r_0, t_0) = \frac{C_N}{t_0}[1 - \frac{1}{(1+r_0)^{t_0}}] = \frac{C_N}{t_0}[1 - (1+r_0)^{-t_0}]$$

$$PV_E(r_0, t_0) = \frac{C_N}{t_0} \times \frac{[1-(1+r_0)^{-t_0}]}{r_0} \qquad \text{--- Eq. (3.6)}$$

By setting discounted present value of all revenues, Eq.(3.3) to be equal to discounted present value of all expenses, Eq. (3.6) to calculate RoR,

$$PV_R(r_0, t_0) = PV_E(r_0, t_0)$$

$$\frac{R_0 \times [1-(1+r_0)^{-m}]}{r_0 \times (1+r_0)^{t_0}} = \frac{C_N}{t_0} \times \frac{[1-(1+r_0)^{-t_0}]}{r_0}$$

If the term $(1+r_0)$ is transformed by *X*,

$$\frac{R_0 \times [1 - X^{-m}]}{X^{t_0}} = \frac{C_N}{t_0} \times [1 - X^{-t_0}]$$

$$R_0 \times [1 - X^{-m}] = \frac{C_N}{t_0} \times [X^{t_0} - 1]$$

$$R_0 - R_0 \times X^{-m} = \frac{C_N}{t_0} \times X^{t_0} - \frac{C_N}{t_0}$$

$$\frac{C_N}{t_0} \times X^{t_0} + R_0 \times X^{-m} - \frac{C_N}{t_0} - R_0 = 0 \qquad \text{--- Eq. (3.7)}$$

The Eq. (3.7) is a non-linear equation with unknown *X*. By solving Eq. (3.7) for X (or $1+r_0$), RoR(r_0) can be calculated.

3.3.3 Calculation of RoR for accelerated schedule

In addition to the baseline schedule in which construction activities are carried out sequentially, an equation for RoR for an accelerated schedule is derived based on Reinschmidt's approach (Reinschmidt, 2004).

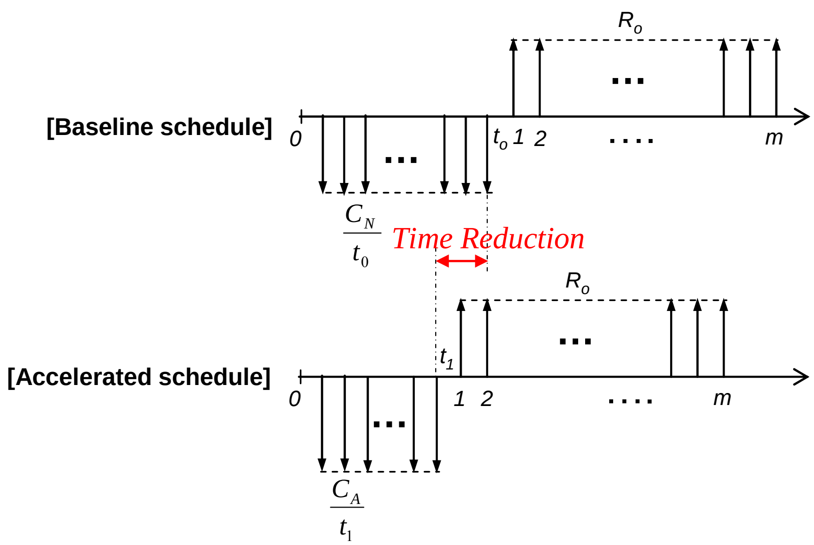


Figure 3.7 Simplified cash flow of accelerated schedule

Where, C_N is construction cost from a baseline schedule.

C_A is the construction cost from an accelerated schedule.

t_0 is the construction duration from a baseline schedule.

t_1 is the construction duration from an accelerated schedule.

m is the economic life after the construction phase.

R_0 is the future revenue

It is assumed that duration can be reduced with additional cost and if new construction cost of an accelerated schedule (C_A) is equally distributed each month, then the cash flow diagram for an accelerated schedule is presented in Fig. 3.7

However, the additional cost for time reduction ($C_A - C_N$) is offered as an incentive for time reduction (offered by the owner) and this incentive may be paid only after the project is completed as an accelerated schedule. Therefore, the construction cost for an accelerated schedule (C_A) is the same as the construction cost for a baseline schedule (C_N) and additional cost for time reduction is the same as the incentive amount (or cost).

Under the decentralized decision-making approach, subcontractors are assumed to be offered the option to submit additional bids for earlier completion. However, it is assumed that the owner pays for the cost of additional bid preparations and the payment is made before the start of the construction phase.

Assumptions:

- Incentive to reduce construction duration is paid to the subcontractors after the project is finished as an accelerated schedule.
- Bid preparation fee for additional rounds of bidding is paid before the start of the construction phase.

Cash flows in a construction project based on the assumptions is shown in Fig. 3.8.

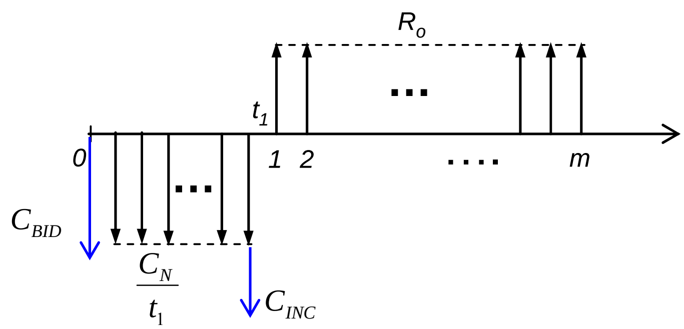


Figure 3.8 Cash flow diagram for an accelerated schedule with bid preparation fee and incentive

Where C_{BID} is the bid preparation fee.

($C_{BID} = 0$ under the centralized decision-making approach)

C_{INC} is incentive paid to subcontractors for time reduction.

$C_N + C_{INC}$ is construction cost for an accelerated schedule.

Discounted present value of revenues from an accelerated schedule can be derived similarly to Eq. (3.3).

$$PV_R(r_1, t_1) = \frac{R_0}{(1+r_1)^{t_1+1}} + \frac{R_0}{(1+r_1)^{t_1+2}} + \frac{R_0}{(1+r_1)^{t_1+3}} + ... + \frac{R_0}{(1+r_1)^{t_1+m}}$$

$$= R_0[\frac{1}{(1+r_1)^{t_1+1}} + \frac{1}{(1+r_1)^{t_1+2}} + \frac{1}{(1+r_1)^{t_1+3}} + ... + \frac{1}{(1+r_1)^{t_1+m}}] \quad \text{--- Eq. (3.8)}$$

Where, PV_R is the discounted present value of all revenues from an accelerated schedule.

r_0 is RoR to be calculated.

By multiplying $(1+r_1)$ on Eq. (3.8)

$$(1+r_1)\times PV_R(r_1,t_1)$$

$$=R_0[\frac{1}{(1+r_1)^{t_1}}+\frac{1}{(1+r_1)^{t_1+1}}+\frac{1}{(1+r_1)^{t_1+2}}+......+\frac{1}{(1+r_1)^{t_1+m-1}}] \quad \text{--- Eq. (3.9)}$$

By subtracting Eq. (3.8) from Eq. (3.9)

$$r_1\times PV_R(r_1,t_1)=R_0[\frac{1}{(1+r_1)^{t_1}}-\frac{1}{(1+r_1)^{t_1+m}}]=\frac{R_0}{(1+r_1)^{t_1}}[1-(1+r_1)^{-m}]$$

$$PV_R(r_1,t_1)=\frac{R_0\times[1-(1+r_1)^{-m}]}{r_1\times(1+r_1)^{t_1}} \quad \text{--- Eq. (3.10)}$$

Where, r_1 is RoR from an accelerated schedule.

t_1 is the construction duration from an accelerated schedule.

And the discounted present value of expenses for an accelerated schedule is

$$PV_E(r_1,t_1)=\frac{C_N}{t_1}\times\frac{1}{(1+r_1)^1}+\frac{C_N}{t_1}\times\frac{1}{(1+r_1)^2}+...+\frac{C_N}{t_1}\times\frac{1}{(1+r_1)^{t_1}}+C_{INC}\times\frac{1}{(1+r_1)^{t_1}}+C_{BID}$$

$$=\frac{C_N}{t_1}[\frac{1}{(1+r_1)^1}+\frac{1}{(1+r_1)^2}+\frac{1}{(1+r_1)^3}+...+\frac{1}{(1+r_1)^{t_1}}]$$

$$+C_{INC}\times\frac{1}{(1+r_1)^{t_1}}+C_{BID} \quad \text{--- Eq. (3.11)}$$

By multiplying $(1+r_1)$ on Eq. (3.11)

$$(1+r_1)\times PV_E(r_1,t_1)$$

$$=\frac{C_N}{t_1}[1+\frac{1}{(1+r_1)^1}+\frac{1}{(1+r_1)^2}+...+\frac{1}{(1+r_1)^{t_1-1}}]+C_{INC}\times\frac{1}{(1+r_1)^{t_1-1}}+C_{BID}\times(1+r_1) \quad \text{--- Eq. (3.12)}$$

By subtracting Eq. (3.11) from Eq. (3.12)

$$r_1 \times PV_E(r_1,t_1) = \frac{C_N}{t_1}[1-\frac{1}{(1+r_1)^{t_1}}] + \frac{C_{INC}}{(1+r_1)^{t_1}} \times [(1+r_1)-1] + C_{BID} \times r_1$$

$$r_1 \times PV_E(r_1,t_1) = \frac{C_N}{t_1}[1-\frac{1}{(1+r_1)^{t_1}}] + C_{INC} \times \frac{r_1}{(1+r_1)^{t_1}} + C_{BID} \times r_1$$

$$PV_E(r_1,t_1) = \frac{C_N}{t_1} \times \frac{1}{r_1} \times [1-\frac{1}{(1+r_1)^{t_1}}] + C_{INC} \times \frac{1}{(1+r_1)^{t_1}} + C_{BID}$$

To calculate RoR, $PV_E(r_1,t_1) = PV_R(r_1,t_1)$

$$\frac{C_N}{t_1} \times \frac{1}{r_1} \times [1-\frac{1}{(1+r_1)^{t_1}}] + C_{INC} \times \frac{1}{(1+r_1)^{t_1}} + C_{BID}$$

$$= \frac{R_0 \times [1-(1+r_1)^{-m}]}{r_1 \times (1+r_1)^{t_1}} \quad \text{--- Eq. (3.13)}$$

If $(1+r_1)$ is substituted by X, Eq. (3.13) is

$$r_1 = X - 1$$

$$\frac{C_N}{t_1} \times \frac{1}{(X-1)} \times [1-\frac{1}{X^{t_1}}] + C_{INC} \times \frac{1}{X^{t_1}} + C_{BID} = \frac{R_0 \times [1-X^{-m}]}{(X-1) \times X^{t_1}}$$

By multiplying (X^{t_1}) on both sides,

$$\frac{C_N}{t_1} \times \frac{1}{(X-1)} \times [X^{t_1} - 1] + C_{INC} + C_{BID} \times X^{t_1} = \frac{R_0 \times [1-X^{-m}]}{(X-1)}$$

By multiplying (X-1) on both sides,

$$\frac{C_N}{t_1} \times [X^{t_1} - 1] + C_{INC} \times (X-1) + C_{BID} \times X^{t_1} \times (X-1) = R_0 \times [1-X^{-m}]$$

The above equation can be re-written into the following equation.

$$C_{BID} \times X^{t_1+1} + (\frac{C_N}{t_1} - C_{BID}) \times X^{t_1} + C_{INC} \times X + R_0 \times X^{-m} - (\frac{C_N}{t_1} + C_{INC} + R_0) = 0 \quad \text{--- Eq. (3.14)}$$

The Eq. (3.14) has only one unknown variable(X) and this equation is solved by using the Newton-Raphson and bisection method (Press et al., 1992).

First derivative of Eq. (3.14) at *X* is

$$(t_1+1)\times C_{BID}\times X^{t_1}+(\frac{C_N}{t_1}-C_{BID})\times t_1\times X^{t_1-1}+C_{INC}+(-m)\times R_0\times X^{-m-1}=0 \quad \text{--- Eq. (3.15)}$$

3.4 Model Development: Centralized Decision Making Approach

To determine the optimal combination of work methods and degree of overlapping (the optimal solution), the project manager is assumed to select a set of work methods and calculate the degree of overlapping and the project's RoR (return on investment) for the set of work methods selected. This process is iterated by an approximate optimization method. However, the value of RoR (or amount of time reduction) depends on the amount of incentive that the owner is willing to pay for additional time reduction and he needs to iterate the above process by changing the amount of incentive for finding the optimal solution. Because he is assumed to have knowledge about cost-duration trade-offs and to be able to estimate the additional cost for time reduction based on his own knowledge, the repeated determination of the optimal solution with different amounts of incentive is continued without limitation. Then, the PM's solution (work methods and degree of overlapping) is offered to subcontractors and each subcontractor will determine if he accepts or rejects the offer. Fig. 3.9 illustrates the procedure in the centralized approach.

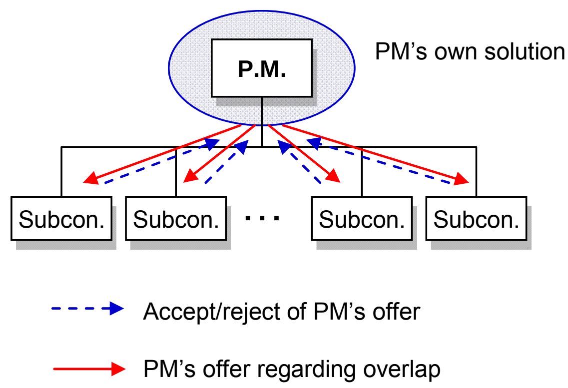


Figure 3.9 The centralized decision-making approach

3.4.1 Determination of amount of overlap for a set of methods

The first step in developing the centralized decision-making approach is to develop a heuristic for the determination of a set of amounts of overlap for a set of methods. The algorithm developed to search for the best amount of overlap is as follows.

1) Select a set of methods for all activities along with an incentive amount
2) Estimate additional costs required for one week's reduction from each pair of activities and select the pair of activities with the least cost
3) Continue searching the best pair of activities for a time reduction of an additional week
4) If the total additional cost for overlap is larger than the incentive amounts (= unit incentive per week * number of weeks for overlap), then this process is stopped and the pairs of activities selected so far are determined for overlap.

This algorithm for determining the best amount of overlap is summarized in Fig. 3.10.

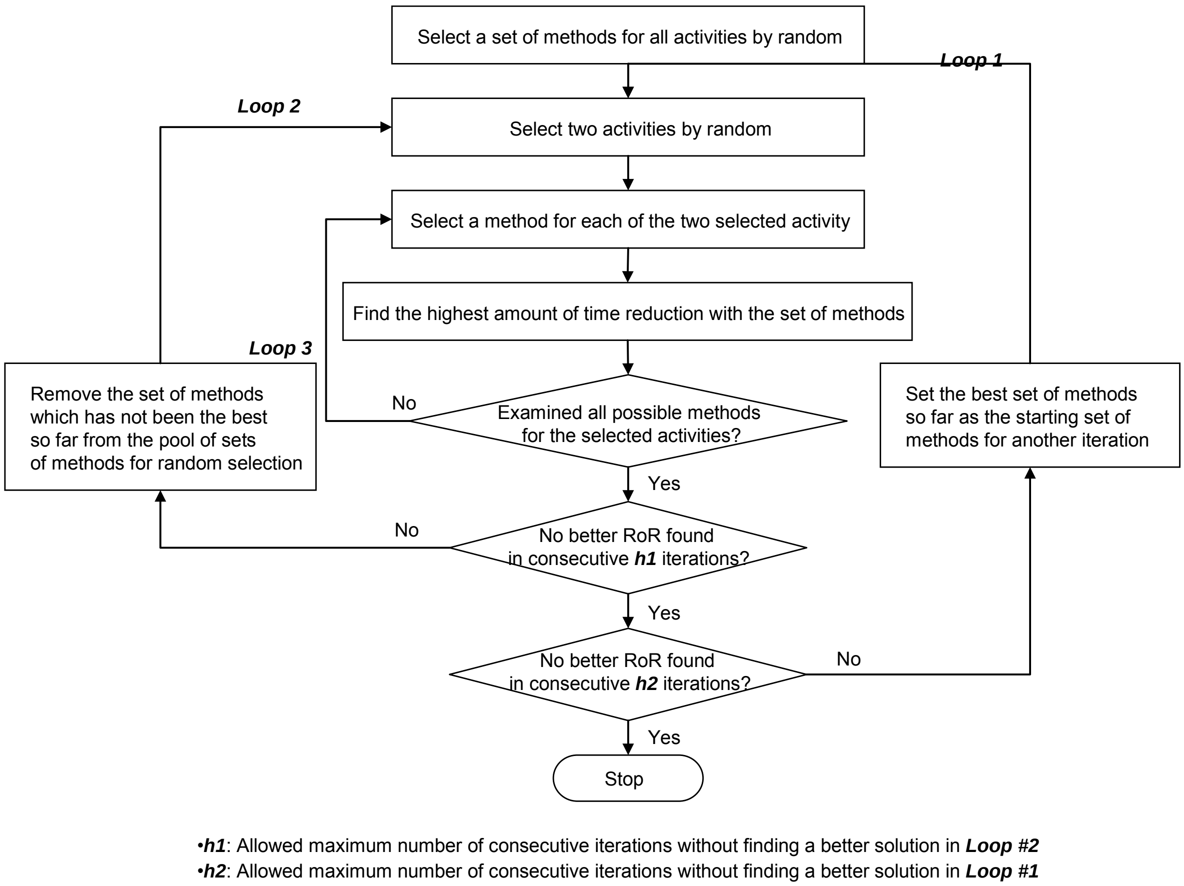


Figure 3.10 Algorithm for the determination of the best overlaps for a set of methods

3.4.2 Determination of the best set of methods

Determination of the optimal set of methods for all the activities for a given incentive amount requires a huge amount of resource capacity. By selecting a set of methods and determining the best amount of time reduction and repeating this process, the PM can find the optimal set of methods. In finding the best solution, three parameters are incorporated to reflect the solution space and the PM's solution capacity: The number of activities, number of methods and the PM's solution capacity. Both the number of activities and number of methods available in each activity affect the solution space to be explored by the PM. In addition, the maximum number of iterations allowed without finding a better solution represents the PM's solution capacity. The PM may not continue selecting another set of methods until he explores all the possible sets of methods. Thus, if he does not find a better set of methods within a number of repetitions of selecting another set of methods, it is assumed that the PM stops his calculation process. The heuristic developed for the determination of the best set of methods with a given incentive amount is as follows.

1) Select a set of methods for all activities
2) Select an activity randomly, to determine the best amount of time reduction, and to calculate RoR
3) Change the method of the randomly selected activity and repeat the second step
4) Save the highest RoR and the related methods for all activities
5) Repeat steps 2 to 4 until the maximum number of iterations (which represents the PM's solution capacity)

By repeating the above steps, the PM's own solution should be improved. When the PM meets the maximum number of iterations, the algorithm is stopped. This algorithm is illustrated in Fig. 3.11.

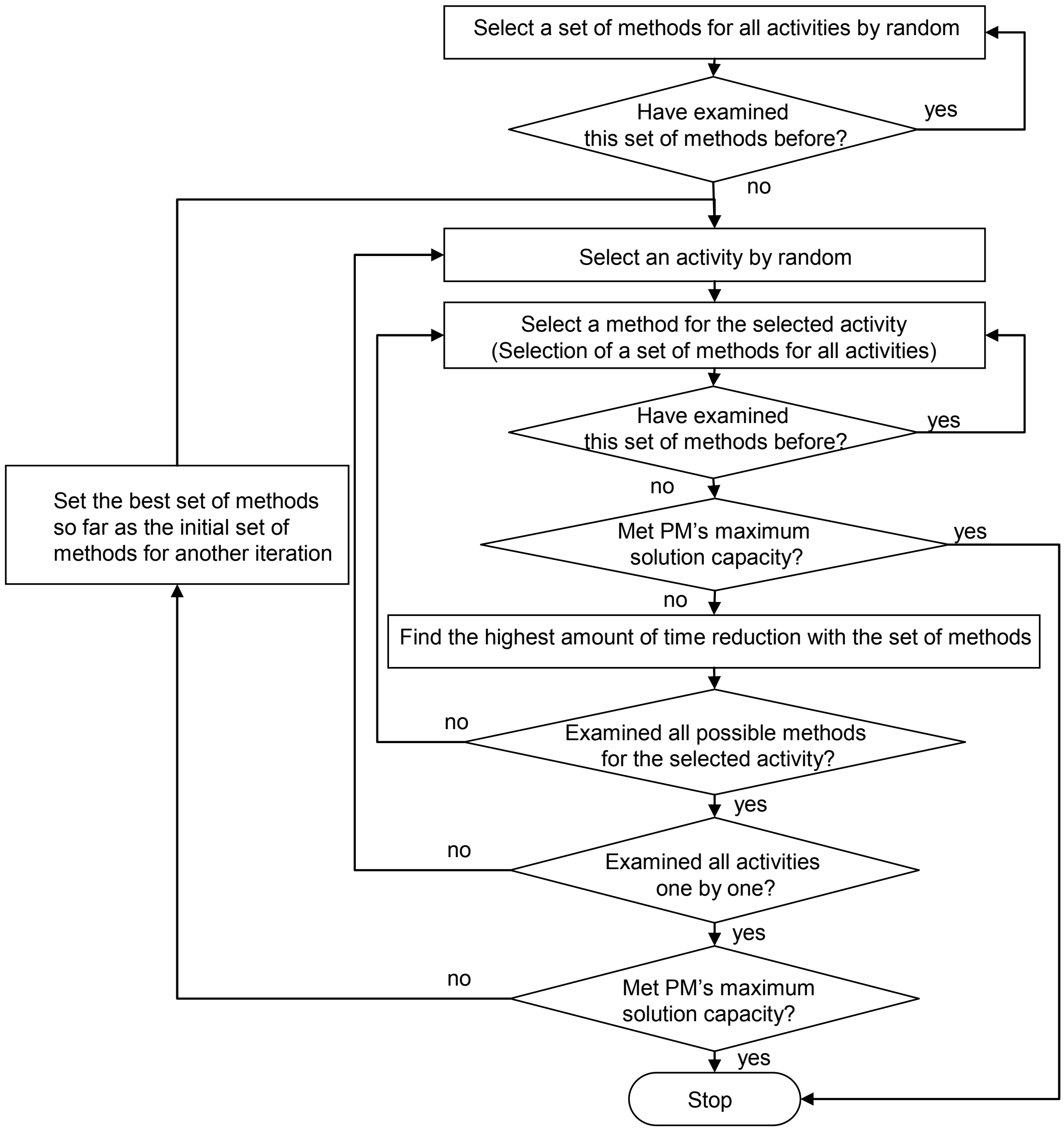


Figure 3.11 Algorithm for the determination of the best set of methods

3.4.3 Determination of the best amount of incentive

To determine the best incentive amount (for example $ per one week's time reduction), an amount of inventive is selected and the two algorithms above are performed for the selection of the best amount of time reduction and additional cost for a give amount of incentive. For more efficient search, Fibonacci Search method is used. Fibonacci Search method is a better method than the binary search method in that that it gives the greatest reduction in the solution band for any given number of iterations (Mathews 2003).

This model for the centralized approach is based on a repetition of calculation or estimations and constrained by the PM's solution capacity. If the PM has a bigger solution capacity (or higher number of maximum iterations allowed), his solution would be improved.

3.4.4 Acceptance or rejection of the PM's offer by subcontractors

Once the PM determines his own solution, he offers the solution (incentive amount, methods and amount of overlap for all the activities) to subcontractors. However, since the PM's own solution is uncertain, it is possible that the estimated cost by the subcontractor could be higher than that by the PM, thus the offer is rejected. If one subcontractor rejects the offer, then he would execute his activity with the base method and without any overlap. Accordingly, another subcontractor whose activity is adjacent to the subcontractor who rejects the offer cannot accept the offer, because he may not use the method which is selected by the PM in the overlap. Therefore, rejection by one subcontractor may cause a ripple effect wherein the amount of time reduction executable may be smaller than the PM's solution. To avoid this adverse effect, it is assumed that the PM will offer additional markup to cover a potential difference in estimated costs to subcontractors. This additional markup would be an additional cost to the owner, but it may improve RoR by facilitating more overlap. The details of the determination of additional markup are discussed below.

3.5 Model Development: Decentralized Decision Making Approach

In the decentralized decision-making approach each pair of subcontractors will determine the work methods and degree of overlapping for an offered amount of incentive and will submit a joint bid for time reduction. The decision by subcontractors will be made by a heuristic-based method. Then, the project manager will have to find the conflicts between work methods from the joint bids, if any, and select the best set of bids which will maximizes the RoR value. The best set of bids will also be selected by a heuristic method. However, to find the optimal solution, the project manager may need to repeat the bidding rounds with different amounts of incentive and he may have to pay additional bid-preparation fees to compensate subcontractors for additional bidding-rounds. Thus, the number of bidding rounds may be limited by these costs.

- Each pair of subcontractors has no resource limitations that prevent them from finding the optimal pair of methods and degree of overlapping.
- A subcontractor may join two separate bids made with two adjacent subcontractors.

  A subcontractor can participate in two joint bids with both of his adjacent subcontractors; upstream and downstream. However, the method for an activity determined with his upstream subcontractor may be different from that with the downstream subcontractor. A subcontractor may join with his immediate adjacent upstream subcontractor or his immediate downstream subcontractor to offer to the project manager a net time reduction for the two activities together, at some increment in price. This requires communication and cooperation between adjacent contractors to determine the best combination of work methods that will achieve a net time reduction for the least marginal cost.

- Subcontractors may be compensated for additional bids to reduce time.

  If the project manager requires additional bid rounds to find a better amount of incentive, he may have to compensate the subcontractors for the additional bidding costs.

The decentralized decision-making approach based on the assumptions is shown in Fig. 3.12.

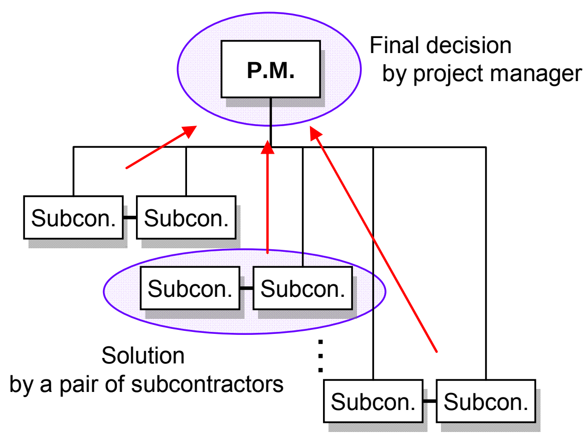


Figure 3.12 The decentralized decision-making approach

3.5.1 Determination of amount of overlap by subcontractors

Based on the assumption that subcontractors have no limits on their solution capacity, each pair of subcontractors can find the best methods and the best amount of time reduction for a given amount of incentive. The algorithm developed for subcontractors is:

1) To select a pair of methods
2) To find the best amount of overlap which maximizes the subcontractors' profit

   The subcontractors' profit would be the difference between the total incentive amount and the estimated cost.

3) To select another pair of methods and repeat step 2 above.

By iterating the above algorithm each pair of subcontractors can find their best solution, but this solution is not to maximize the owner's benefit, but to maximize the subcontractors' profit. This process is like a bid procedure. Once the PM determines the incentive amount, each pair of subcontractors determines the amount of time reduction and methods. The bid price is determined by multiplying the amount of time reduction proposed with the unit incentive amount.

However, one of the problems is that the PM does not know the best incentive amount. Thus, the PM is assumed to repeat the above bid procedures up to a limited number. Since estimating cost and preparing a bid requires the use of resources such as estimators, the PM is assumed to provide a bid preparation fee for each bid round. In the model, selection of the amount of incentive follows the Fibonacci search method, but the number of iterations is limited.

3.5.2 Evaluation of the bids

Once the subcontractors submit their bids, the PM is assumed to evaluate their bids regarding the viability of time reduction in each bid. The PM estimates the additional cost for the amount of time reduction along with the methods proposed in each bid. If the PM's estimated cost is not covered by the incentive amount, the PM regards the bid as risky to complete the activity as proposed and reduce the amount of time reduction according to the incentive amount. This evaluation process by the PM is affected by the uncertainty in the PM's knowledge. If the PM's knowledge is less accurate, it is more likely that the PM finds risky proposals.

3.5.3 Detecting incompatible methods

Based on the evaluated amount of time reduction and bid price in each bid, the PM calculates RoR. However, it is probable that methods proposed by one pair of subcontractors are incompatible with the methods proposed by adjacent subcontractors. The incompatibility between the proposed methods is due to the myopic viewpoint of subcontractors, and this would reduce the amount of time reduction. The PM is assumed to rank all bids based on the bid price proposed and the amount of time reduction evaluated by himself, and to determine compatible methods of all activities by the rank.

3.6 Model Development: Monte Carlo Simulation

In the Monte Carlo simulation, the uncertainty in the decision maker's knowledge is presented by generating two random variables; cost information and the project manager's estimation of the subcontractors' time-cost trade-off functions (additional cost per unit of time reduction). The latter reflects the possibility that the project manager may produce estimates on the additional costs for time reduction that differ from subcontractors' estimates. The models to determine the best combination of work methods and degree of overlapping under conditions of uncertainty runs using the Monte Carlo simulation and the solutions from the models are compared.

This research deals with the uncertainty in the estimation of the additional cost for time reduction and the uncertainty in estimates of the baseline schedule. In estimating the baseline schedule, the estimates of the four input variables are considered uncertain. Due to the uncertainty in the estimates for the baseline schedule, the RoR from the baseline schedule would be uncertain also.

As for the uncertainty in addition cost estimates, even subcontractors may not be able to estimate additional cost for time reduction with certainty, if the work methods selected are unconventional and the amount of time reduction is large. Also, the project manager's estimates for the subcontractors' additional cost for time reduction may have more or less uncertainty. Thus, these uncertainties depend on the decision maker, the work methods available, and the degree of overlapping, and the impact of these uncertainties will be analyzed in the Monte Carlo simulation.

3.6.1 Impact of the uncertainty in the PM's knowledge on random numbers

The uncertainty in the PM's knowledge affects random numbers to be generated in the Monte Carlo simulation. The uncertainty in the PM's knowledge is defined as the ratio of standard deviation of the PM's knowledge to standard deviation of the subcontractors' knowledge as shown below.

$$k = \frac{\text{Standard Deviation of PM's Knowledge}}{\text{Standard Deviation of Subcontractors' Knowledge}}$$

The Coefficient of Variation (CoV) is a measure of dispersion of a probability distribution. Since CoV is a normalized measure by dividing the standard deviation by the mean value, it can provide an easier understating of the dispersion of a probability distribution irrespective of the mean value.

$$CoV_i = \frac{\sigma_i}{\mu_i}, \quad \sigma_i = \mu_i \times CoV_i$$

Where, CoV_i is the coefficient of variation for a random variable (*i*), which is constant.

μ_i is the mean of a random variable (*i*), which is to be fixed.

σ_i is the standard deviation of a random variable (*i*).

In the Monte Carlo simulation model for this research, it is assumed that the CoV and the mean value are constant. Therefore, standard deviation of a random variable is determined both by the mean value and the Coefficient of variation. To set the different reliability of the information (or knowledge), the ratio k is multiplied to the right side of the above equation.

$$\sigma_i = \mu_i \times CoV_i \times k_i$$

If k =1.0 (or the project manager's knowledge is as reliable as the subcontractors') then random variables will be generated with the same standard deviation for both the project manager's estimates and for the subcontractors' estimates. However, if the project manager's knowledge is not as reliable as the subcontractors' (or k>1.0), random variables for the project manager's estimates will be generated with a larger standard deviation value.

3.6.2 RoR calculation with random numbers

Under a risk-neutral attitude, both the PM and subcontractors take a random number for the cost estimate, duration estimates or other estimates for their solutions. However, under a risk-averse attitude, their estimates would be more conservative. Therefore, it is assumed that they know the mean value and standard deviation of the distribution and a VaR at 95% confidence level is selected. Accordingly, the variance of estimates under a risk-averse attitude would be much smaller than that under a risk-neutral attitude.

In the Monte Carlo simulation model for this research, following random variables regarding additional cost and a baseline schedule are generated in each iteration.

- Input variables for a baseline schedule:

The four input variables (cost and duration of each activity, economic life of the project, future revenues) are randomly generated with a constant mean value and CoV. Therefore, under a risk-neutral attitude random variables will be generated and RoR from the baseline schedule will be calculated. However, under risk-averse attitude, based on the assumption of taking VaR, the same estimates will be determined in every iteration. This leads to a deterministic RoR. To avoid this situation, it is assumed that the input variables for the baseline schedule are selected from a random number, not from VaR, even under a risk-averse attitude. This assumption would cause a similar variance of RoR from two different attitudes to risk. And the VaR of resulting RoR distribution will be used for the measurement of profitability.

- Cost estimates for overlap:

  Means of cost estimates for overlap are randomly generated from constant coefficients of exponential functions and a standard deviation which is dependent on the uncertainty in the PM's knowledge.

3.7 Model Development: Baseline Schedule

The baseline schedule is defined in this research as the normal schedule without any overlap with the base methods. This baseline schedule is a base for the comparison of profitability of concurrent execution: RoR from the baseline schedule would be compared to the RoR from either the centralized approach or the decentralized approach. If the RoR from concurrent execution is lower than the baseline RoR, no overlap will be executed. The baseline RoR (or RoR from the baseline schedule) is calculated from four input variables:

- Cost of each activity
- Duration of each activity
- Economic life of the project

  After the completion of the construction phase, the facility or building constructed will be used to make revenues for some years. To get a better benefit to the project owner, longer economic life of the project would be preferred, if he gets future income, there will be not costs.
- Future revenues of the project

  Future revenues of the project are assumed to represent monthly income amount from the operation of the facility. Furthermore, it is assumed that the project owner gets constant income (cash inflow) each month.

3.7.1 Baseline schedule settings and related assumptions

A baseline schedule for a construction project includes four input variables. The mean values and coefficient of variations (CoV) for each variable used for the simulation are summarized in Table 3.2.

Table 3.2 Values of the variables for baseline schedule

	Duration of each activity		Cost of each activity		Economic Project life		Future monthly revenue	
Activity	Mean	CoV	Mean	CoV	Mean	CoV	Mean*	CoV
	Weeks		$		Months		$	
1	14	0.3	350,000	0.3	240	0.2	Target RoR: 20%	0.3
2	20		500,000					
3	22		550,000					
4	24		560,000					
5	22		650,000					
6	20		700,000					
7	16		600,000					
8	13		800,000					
Total	151		4,710,000					

*Mean value of future monthly revenue is determined based on a target RoR of 20% for baseline schedule along with mean values of cost, duration and project life.

The assumptions made regarding the baseline schedule for the model are:

- Estimated costs (or duration) of activities are correlated for each other with the correlation coefficient of 0.9.

It is assumed that estimated durations of activities are correlated each other with the correlation coefficient of 0.9. Also, estimated costs of activities are assumed to be correlated for each other with the correlation coefficient of 0.9. If estimated costs (or durations) are independent each other, then the variances of costs of activities will offset each other so that the variance of total cost of a project will become smaller than the variance of each activity's cost. The impact of assumption of independency is simply proved by using a simple example such as the following (Reinschmidt 2004).

If a project has *n* activities, and the mean value of the estimated cost of each activity is *m*, then the mean of the total cost (*M*) is $m \times n$. Furthermore, let's assume that the standard deviation of the estimated cost for all activities are equal to *s*, and the estimated costs of all activities are independent of each other. Then total variance of all activities (σ^2) is equal to the sum of the variances,

$$\sigma^2 = n \times s^2$$

$$\sigma = \sqrt{n} \times s$$

Then the CoV of total cost is

$$CoV_{total} = \frac{\sigma}{M} = \frac{\sqrt{n} \times s}{m \times n} = \frac{s}{m \times \sqrt{n}} = \frac{1}{\sqrt{n}} \times \frac{s}{m}$$

In the above equation $\frac{s}{m}$ represents the CoV of each activity's cost ($CoV_{activity}$). Then it can be re-written as:

$$CoV_{total} = \frac{1}{\sqrt{n}} \times CoV_{activity}$$

From this equation, the CoV of total cost approaches 0 as the number of activities increases (or project size increases), if the activities' costs are independent of each other. Therefore, it can be concluded that if activities are independent, large and complex projects must have less uncertainty in cost estimates than small projects.

- The estimated cost and duration of an activity for the baseline schedule are independent of each other.

One possible argument about the relation between duration and cost is positively correlated: activity duration greater than average would be associated with greater than average cost, due to indirect cost, overhead, general and administrative costs and so on. On the contrary, one might argue that cost and duration are negatively correlated: activity durations shorter than average can be obtained by and associated with overtime, using additional equipment, and/or crashing. Therefore, construction cost with regard to duration is argued to be U-shaped (Reda and Carr, 1989) and normal duration represents the amount of time to complete an activity with the lowest cost (Hegazy 1999). Any deviation in duration from the normal duration would be associated with a cost increase. And correlation between activity duration and cost could be either positive or negative, but it is hard to tell which is correct. Therefore, it is assumed that the initial cost estimate is at the normal duration for all activities and the correlation between activity duration and cost is assumed to be zero.

- The economic project life and future monthly revenues are independent of each other.

The validation of this assumption is similar to the previous assumption about the correlation between activity duration and cost. One might argue that the economic lifespan of a project becomes longer if revenues become smaller: if revenue from the project is small, then the owner might want to keep the project longer to make sure the invested money (construction cost) is returned. And the economic project life is negatively correlated with future revenues. However, one may argue to the contrary that the correlation is positive, in that the lower the revenues the shorter the economic lifespan. The correlation between the economic project life and future revenues could be either positive or negative, but it is hard to tell which is correct. Therefore, it is assumed that the economic project life and future revenues are independent of each other.

The overall model for the Monte Carlo simulation as well as for the two decision making approaches is shown in Fig. 3.13.

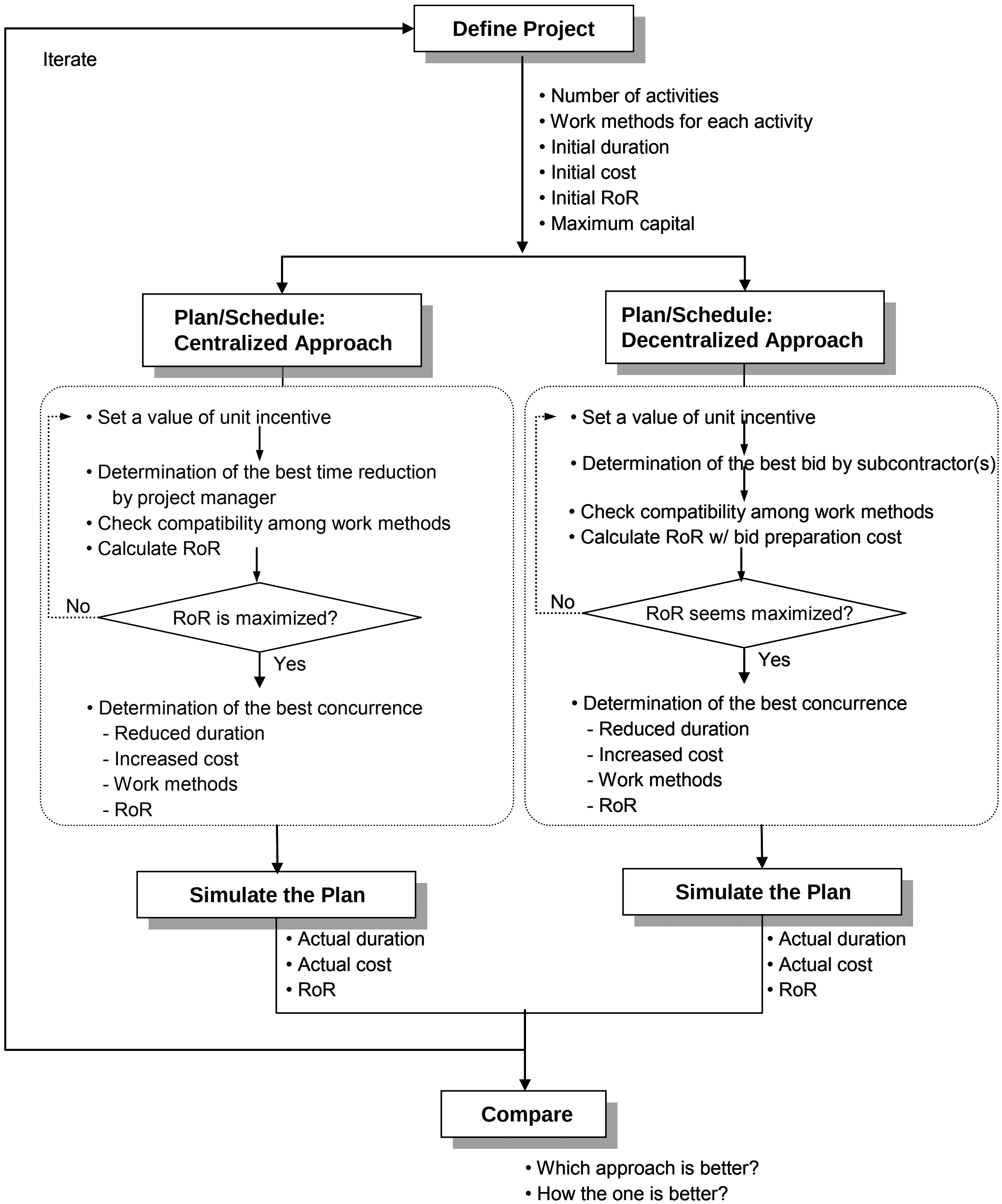


Figure 3.13 The Monte Carlo simulation model

3.8 Model Development: Search for the Optimal Markup

In the centralized decision-making approach the PM's own solution to reduce construction duration (therefore to increase RoR) is offered to each subcontractor with an amount of incentive. However, due to the uncertainties both in PM's estimation and in each subcontractor's estimate, the subcontractor's estimated cost may be higher than the incentive amount. Thus, the subcontractors may reject the PM's offer. If all subcontractors reject the offers, then no time reduction can be implemented and the owner doesn't expect more benefit from an earlier completion of the construction phase. Therefore, the PM may offer additional incentive to attract subcontractors for time reduction, while it is assumed that 10% of the markup is already included in the PM's cost estimates. From the viewpoint of the owner, this additional incentive is a kind of safety factor in that RoR based on the PM's own solution is reduced by decrease in the amount of time reduction due to rejection of the PM's own solution. This additional incentive is offered in a form of multiplier which is larger than 1.0.

By offering this additional markup it is anticipated by the PM that the difference in estimated cost both by the PM and the subcontractors may be covered. However, if this additional markup becomes bigger, then the price offered to the subcontractors will be so high that more subcontractors will accept the PM's own solution. But RoR will be lower due to more cost to the owner. On the contrary, if the markup is small, then the owner will be able to save by reducing any additional markup, but it is more likely that more subcontractors will not accept the PM's offer. Therefore, centralized final RoR is affected by the additional markup value and it is expected that there is a markup value which maximizes the RoR. Optimal markup means the markup value which maximizes the RoR.

Optimal markup may be affected by two decision-making factors. First, if a construction project has more activities (or more subcontractors who are responsible for each activity), the amount of total time reduction to be executed will be affected by the number of subcontractors. If the probability that a subcontractor accepts the PM's offer is ***p*** and there are *n* subcontractors, then the probability that all subcontractors accept the PM's offers will be $(p)^n$. Therefore, as the number of activities (or number of subcontractors) n increases, the probability that the PM can get his solution accepted by all of the subcontractors decreases. This expectation is based on an assumption that all of the subcontractors are completely independent. The next factor which could affect the subcontractors' acceptance (or rejection) is an uncertainty in the PM's knowledge. Since the PM's own solution is based on the PM's knowledge, which may not be as reliable as the subcontractors, the PM's estimated cost required for an amount of time reduction along with a pair of work methods may be lower than the subcontractors' estimated cost. Since subcontractors are assumed to compare additional cost offered by the PM and his (or her) own estimated cost for time reduction, it is expected that the probability that a subcontractor accepts the PM's offer decreases with less reliable knowledge by the PM.

In addition to these two factors, optimal markup value may be affected by whether adjacent subcontractors accept (or reject) the PM's offer. If all subcontractors accept the PM's offer, then the PM's own RoR is expected to be achieved as discussed for the first factor above. However, it is possible that only some of the subcontractors accept the offer, and others don't, due to the uncertainty in cost estimates. If this is the case, the amount of time reduction to be carried out will not be same as the sum of the amounts of time reduction from the subcontractors who accept the offer.

Time reduction through overlapping between two activities with multiple work methods options requires both upstream subcontractor and downstream subcontractor to accept the PM's offer. If an upstream subcontractor accepts the PM's offer, but a downstream subcontractor does not, then the overlapping between the two activities will not be viable. Fig. 3.14 explains how this factor affects the amount of time reduction to be executed. If there are three activities (subcontractors) and all three of the subcontractors accept the PM's offer, then the planned duration will be the same as the PM's solution (Case I). However, if subcontractor 1 who is responsible for the first activity rejects the PM's offer and the other subcontractors accept the PM's offer (Case II), overlapping between activity 1 and 2 will not be viable. But overlapping between activity 2 and 3 can be executable. Therefore, the total amount of time reduction will be shorter than the PM's solution. However, in Case III, if subcontractor 2 rejects the PM's solution and the others accept it, no time reduction either between activity 1 and 2 and activity 2 and 3 will be allowed.

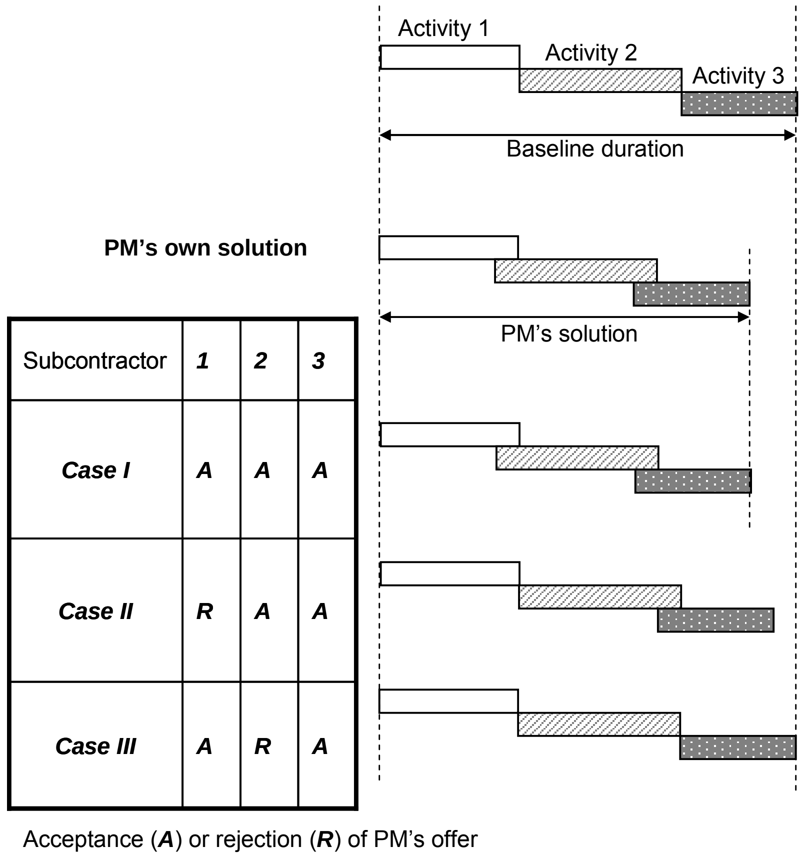


Figure 3.14 Example of the impact of the rejection/acceptance by subcontractors

3.8.1 Preliminary search for the optimal markup

A preliminary approach taken to find the optimal markup in this research was to repeat simulations of the model with a change in values of the markup for two decision-making factors (number of activities and PM's uncertainty). After some repetitions of the simulation, a rough range of the best markup was found.

While it was expected that the optimal markup is affected only by two decision-making factors, it was observed that the degree of variance (or standard deviation) in the baseline schedule affected the search for the optimal markup factor. For example, a search for the optimal markup with the following condition was executed.

- No. of activities: 6
- No. of work methods: 5
- PM' uncertainty: 1.25
- PM's solution capacity: 35
- No. of iterations: 5,000

The degree of variance in the baseline schedule is affected by the values of the input variables as shown in Table 3.3. By changing the coefficient of variation (CoV) of the four input variables, the degree of variance in the baseline schedule is changed. Furthermore, both the centralized RoR and decentralized RoR are also affected.

Table 3.3 Coefficient of variations for different cases

Coefficient of variation for:	***I***	***II***	***III***	***IV***	***V***	***0***
Economic Life of project	0.2	0.1	0.05	0.02	0.01	Fixed
Future Revenues	0.3	0.2	0.1	0.05	0.02	Fixed
Est. Cost of each activity	0.3	0.2	0.1	0.05	0.02	Fixed
Est. Duration of each activity	0.3	0.2	0.1	0.05	0.02	Fixed

Case I in the above table represents a relatively risky project and the case number (***V***) represents the cases which are less risky. And ***Case 0*** represents the case under certainty. As expected and shown in Fig. 3.15, a peak for the mean of the centralized RoR could be clearly defined with certainty (represented as the bottom dotted line). However, as the baseline schedule becomes more variable, it gets more difficult to find a sharp peak point. Instead the peaks become flat between some ranges of markup value (for example, between markup values of 1.4 and 2.2 in ***Case IV***, between 1.6 and 2.2 in ***Case I and II***). These flat peaks can consulate project managers in that the PM does not have to be concerned that small errors in specifying the parameters of the evaluation would have a major effect on the results as long as he (or she) can get into the flat range.

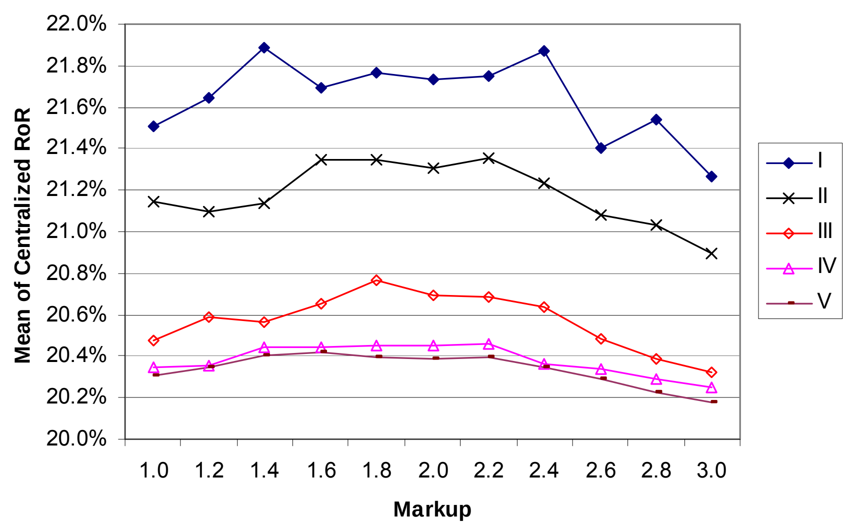


Figure 3.15 Changes of markup factors in different cases

Also, it is observed that the mean of the RoR increases with increasing variability (CoV) at any markup value. If higher variability in the baseline schedule provides more favorable, but less frequent, numbers in cost, duration, economic life and/or future revenues, RoR distribution can have a longer tail to the right. Therefore, the mean value of the RoR can increase with higher variability in the baseline schedule and increasing variability can be an opportunity rather than a risk. However, this approach of repeating simulations by changing the markup factor values requires a huge amount of computer time. Also, if there is some degree of uncertainty in the baseline schedule, it is difficult to define a clear peak. Thus, another approach was taken as discussed in the following chapter.

3.8.2 Approach to search for the optimal markup

The basic assumption used is that the PM can specify a range of optimal markup. For a set of values of decision-making factors, the PM is assumed to know the lower bound of the optimal markup. The lower bound of the optimal markup is based on the preliminary search for the optimal markup as discussed above. In the preliminary search, the optimal markup was sought for by increasing the markup from 1.0 by increments of 0.1. Then the lower bound is reduced from the values found in the preliminary search to make sure the optimal markup is never lower than the lower bound. These lower bounds of optimal markup for specific decision-making factors are obtained from the preliminary search for optimal markup as discussed above and shown in Table 3.4.

Table 3.4 Lower bound of optimal markup

Lower bound of optimal markup		No. of activities		
		4	6	8
PM's uncertainty	1.00	1.0	1.2	1.4
	1.25	1.1	1.3	1.5
	1.50	1.2	1.4	1.6

It may seem rather high that the lower bound of the optimal markup for the case with 8 activities and the PM's uncertainty of 1.50 is 1.6. Since the preliminary search for the optimal markup is based on values for baseline variability and randomly generated cost estimates which may not be applicable in real projects, these lower bounds of optimal markup don't represent an actual number which can be used for a real construction project with 8 activities.

The algorithm to find the optimal markup for the given decision-making factors is, for simplicity, basically a linear search along the markup axis. The procedure is:

1) A lower bound of optimal markup is selected.
2) The markup value selected in step (1) is multiplied with the PM's estimated cost.
3) The subcontractor's acceptance/rejection is determined by a comparison between the PM's offered price and the subcontractor's own estimated cost required for the work method(s) and amount of time reduction determined by the PM.
4) RoR is calculated based on the amount of time reduction and additional cost from the subcontractors' acceptance (or rejection).
5) Markup value is increased by 0.1 (or 10%).
6) Steps (2), (3) and (4) are repeated with a new markup value.
7) Two RoR values are compared.

- If RoR from an increased markup value is higher than or equal to RoR from a low (previous) markup value, the markup is increased by 0.1 and steps (2) to (6) are repeated until RoR from an increased markup value decreases or until 10 repetitions are performed. It is assumed that the PM's knowledge has a limitation in terms of the number of repetitions, and the maximum number of repetitions is set as 10.

- If RoR from an increased markup value is lower than RoR from the low (previous) markup value, then the previous markup value is selected and the algorithm is stopped.

CHAPTER IV

SIMULATION MODEL VALIDATION

4.1 The Heuristic for Finding the Best Solution in the Centralized Approach

In the centralized approach a heuristic is developed to find the best set of methods and the best degrees of overlapping for an incentive amount. In the developed heuristic, three parameters were incorporated to reflect the project manager's solution: number of activities, number of methods and maximum number of iterations. While both the number of activities and number of methods are related to the solution space to be explored by the PM, the maximum number of iterations is related to the PM's solution capacity. Since the objective of this heuristic is to find a solution which is accurate enough in a reasonable time, accuracy of the solution and computer running time of the solution are examined for the validation of the heuristic. The sensitivity of these parameters on both accuracy of the solution and computer time is analyzed.

- **Accuracy of the solution**

To determine the accuracy of the solution, the optimal solutions from a random cost data were calculated from exhaustive enumeration methods and the optimal solution is compared to the solutions from the heuristic. The accuracy of the solution is represented by MAPE (Mean Absolute Percentage Error) as shown in the following equation. Thus, a smaller number of MAPE represents a more accurate solution.

$$MAPE = \frac{(Optimal\ Solution - Solution\ \ from\ Heuristic)}{Optimal\ Solution} * 100$$

This sensitivity analysis is performed with only 500 iterations of the calculations due to the huge amount of computer time required to find the optimal solution through the exhaustive enumeration method. Both the accuracy of the solution and computer time are measured in terms of both mean values and an upper limit based on a 90% confidence level.

4.1.1 Sensitivity of number of activities

As the number of activities increases with other parameters constant, the solution space the PM explores increases exponentially and it is less likely that the PM finds the optimal solution. Thus, it is expected that the accuracy of the solution becomes lower with more activities. Since the maximum number of iterations allowed does not mean the total number of sets of methods to be examined or estimated, the PM is more likely to find a better set of methods in each iteration with more sets of methods. The sensitivity analysis is performed while holding other parameter values constant (3 methods in each activity, 10 maximum iterations allowed without finding a better solution). Fig. 4.1 shows the change in the accuracy of the solution with more activities. As the number of activities increases, the solution becomes slightly worse in terms of the mean value of MAPE (Mean Absolute Percentage Error). The computer running time is observed to increase with more activities as shown in Fig. 4.2. The increase in computer time is faster than the linear increase, because more solution space leads to a higher probability of finding a better solution in a new set of methods.

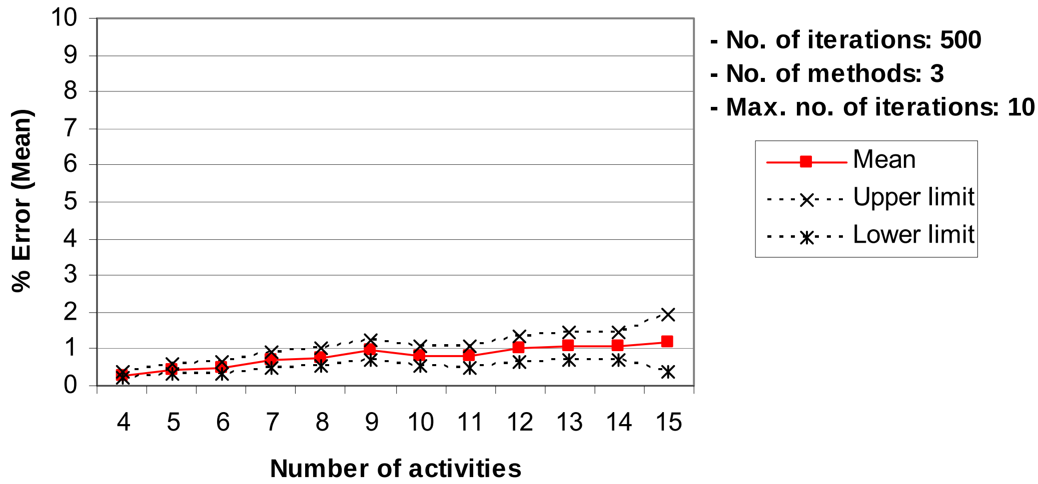


Figure 4.1 Change in the accuracy of the solution with more activities

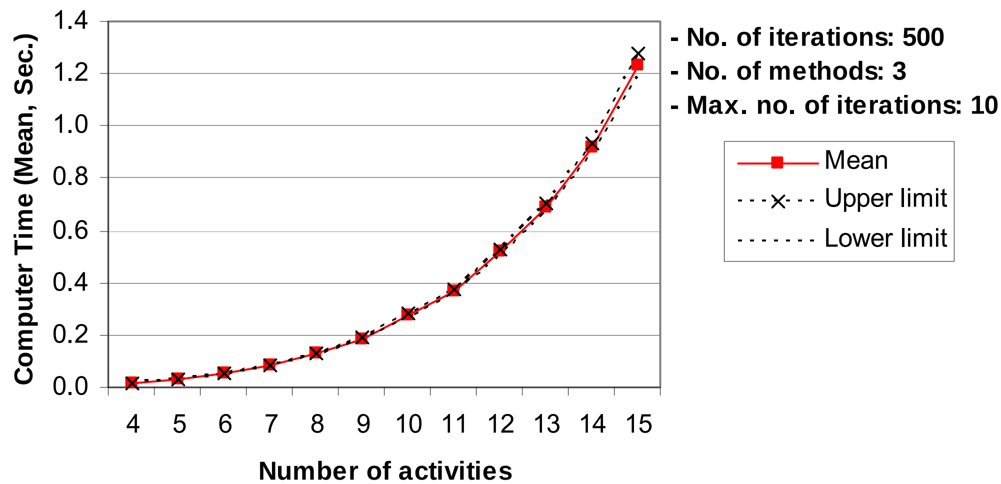


Figure 4.2 Change in computer time with more activities

4.1.2 Sensitivity of number of methods

As the number of methods increases while other parameters remain constant, the solution space the PM explores increases. Thus, it is less likely that the PM finds the optimal solution, as in the case of the increase in the number of activities. Also, more computer time is likely to be required with more methods. Fig. 4.3 and Fig. 4.4 show the change in the accuracy of the solution and change of computer time with more methods respectively. No significant change in the accuracy of the solution by more methods is observed in Fig. 4.3. This is due to the smaller impact of more methods on the solution space than is seen with more activities: The increase in solution space (or all the possible sets of methods) due to the increase of methods from 3 to 6 is 7,533 ($6^5 - 3^5 = 7,776 - 243 = 7,533$), while the increase due to more activities is 14,348,826 ($3^{15} - 3^4 = 14,348,907 - 81 = 14,348,826$). Also, computer time required slightly increases with more methods.

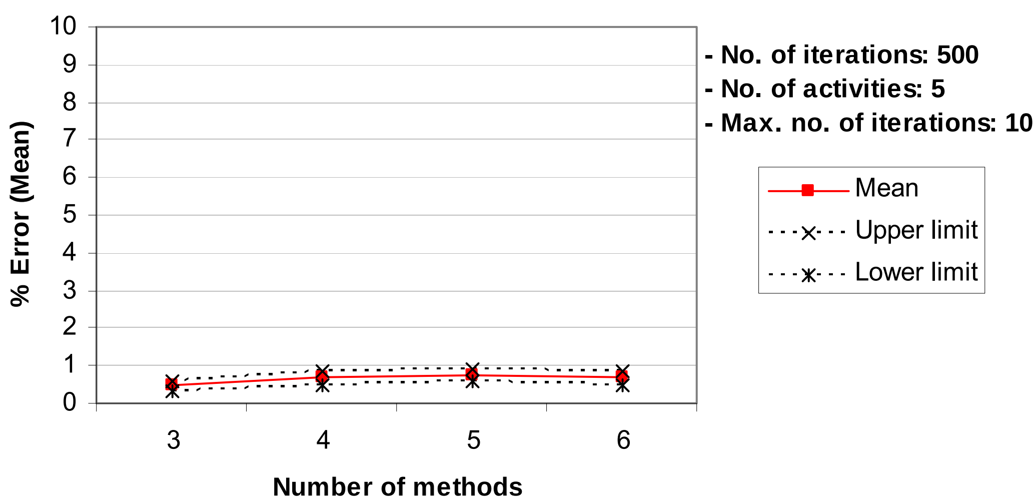


Figure 4.3 Change in the accuracy of the solution with more methods

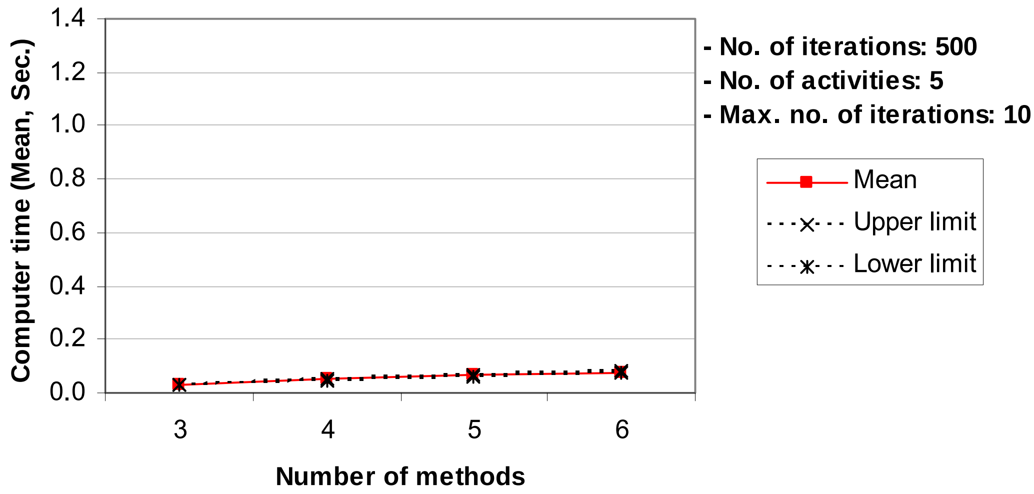


Figure 4.4 Change of computer time with more methods

4.1.3 Sensitivity of maximum number of iterations

As the maximum number of iterations allowed without finding a better solution (or the PM's solution capacity) increases, the PM's solution is expected to be improved and more computer time would be required. Fig. 4.5 and Fig. 4.6 show the results of the impact of more solution capacity by the PM on the accuracy of the solutions and computer time respectively. These results are based on the other fixed parameters: 14 activities and 3 methods for each activity. The PM's solution is observed to improve with more solution capacity by the PM and more computer time is required as expected.

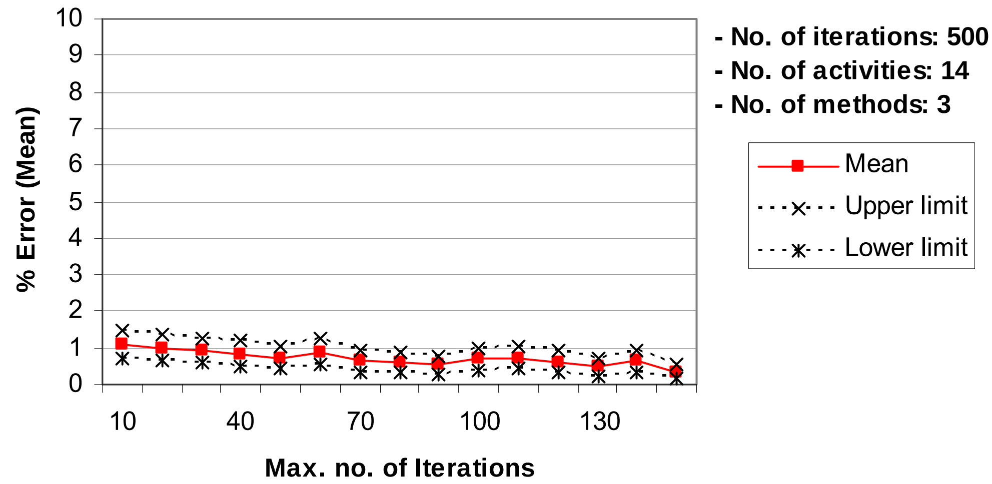


Figure 4.5 Change in the accuracy of the solutions with more PM's solution capacity

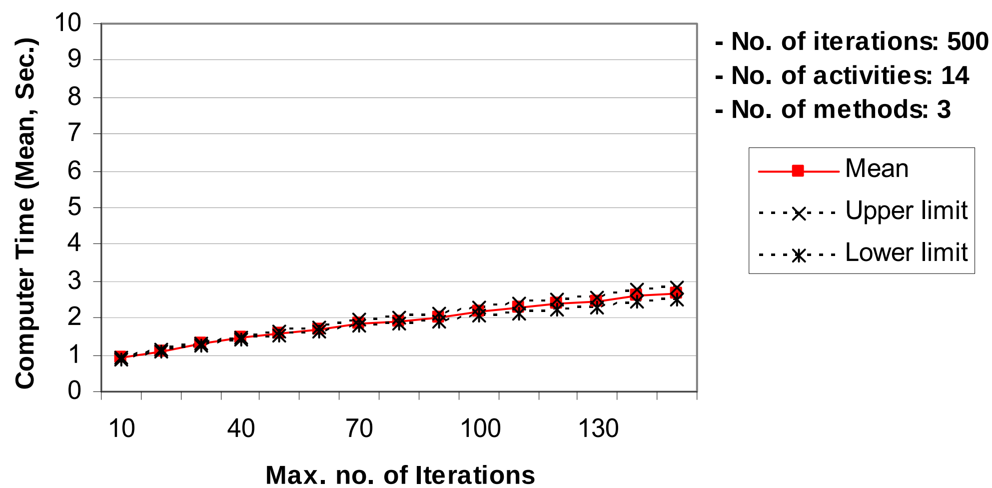


Figure 4.6 Change in the computer time with more PM's solution capacity

4.1.4 Validation for scaling problem

While the sensitivity analysis shows that the heuristic performs as expected, the highest number of activities used in the sensitivity analysis is 15. However, in real construction projects there may be more than 15 activities and the PM's solution from the heuristic would be less accurate and more computer time would be required with more activities. Thus, the viability of the heuristic for bigger construction projects (or more activities) is examined by forecasting the accuracy (or % of error) and required computer time for 100 activities. The forecasting is based on the mean values of MAPE (Mean Absolute Percentage Error) and computer running time.

The accuracy of the solutions for a construction project with 100 activities is forecasted by two methods: linear regression and double exponential smoothing. Fig.4.7 and Fig.4.8 show the forecasting of the accuracy in the solutions by linear regression and by double exponential smoothing respectively. By both methods, the solution for 100 activities is forecasted to be different from the optimal solution by less than 10% and this accuracy may be acceptable for a construction project with 100 activities.

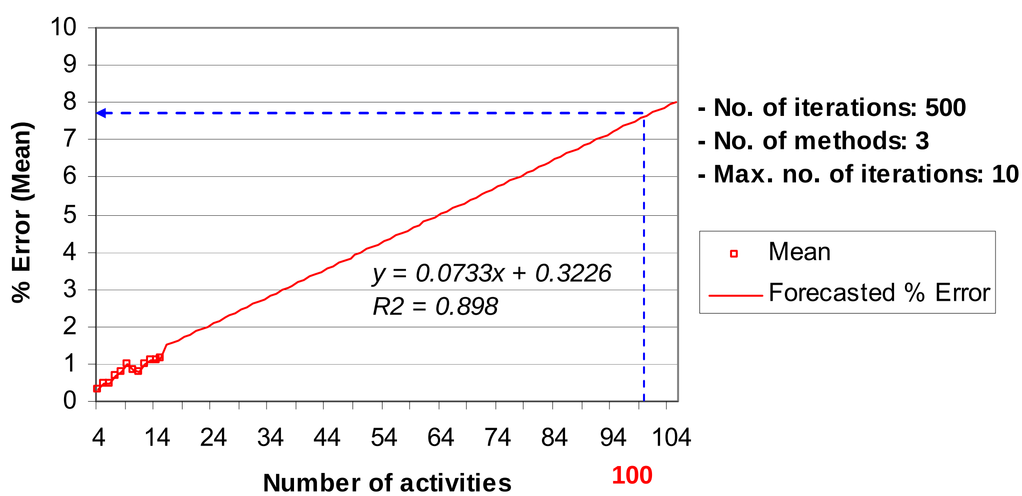


Figure 4.7 Forecast of % error by linear regression

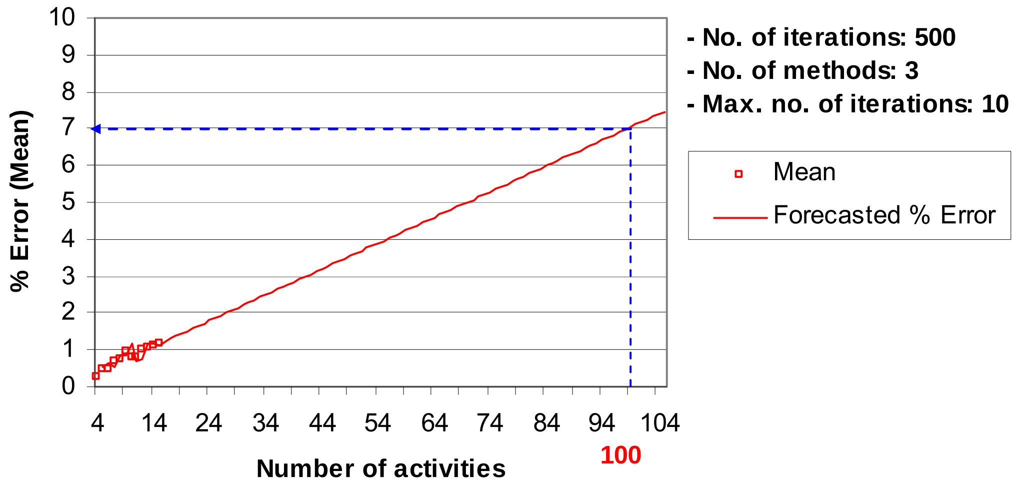


Figure 4.8 Forecast of % error by double exponential smoothing

The computer time required by the heuristic is also forecasted based on a maximum error of 5% in the solution: a mean value of computer time required for the solution with at most a 5% error is used for the forecasting. Since the computer time is observed to increase faster than linearly as shown in Fig.4.2, the computer time required for 100 activities is forecasted both by power regression and by double exponential smoothing as shown in Fig. 4.9 and Fig.4.10. The forecasted computer time required for a solution with a 5% error at most for 100 activities is 41 seconds by power regression, and 27 seconds by double exponential smoothing. 41 seconds for selecting the best set of methods in a big construction project with 100 activities is regarded as reasonable, thus it is concluded that the heuristic develop through this research can be applied to bigger projects.

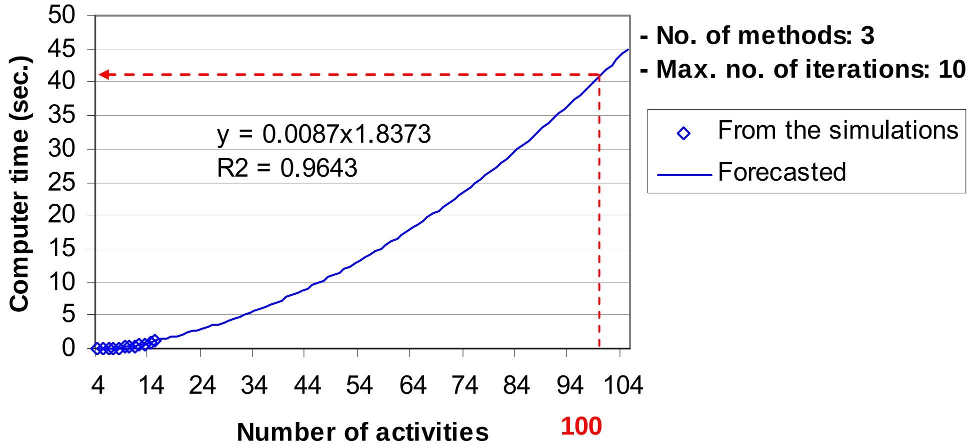


Figure 4.9 Forecast of computer time by power regression

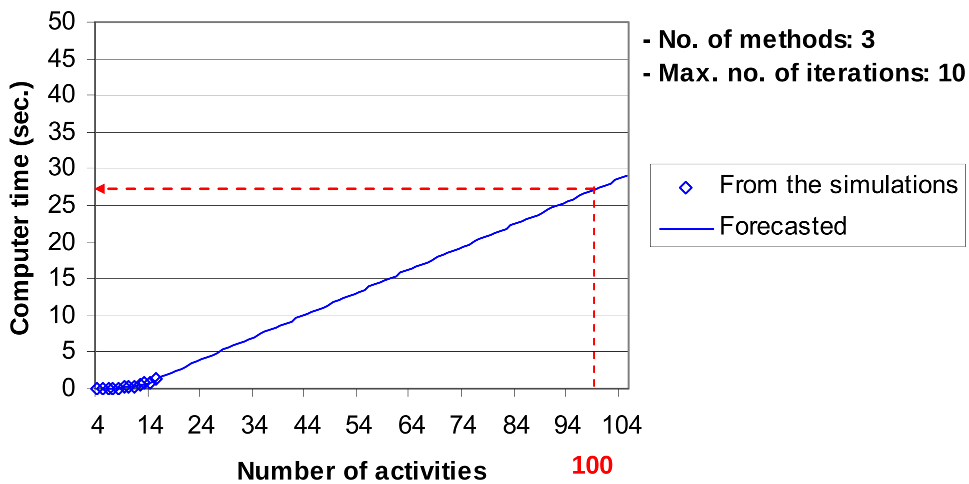


Figure 4.10 Forecast of computer time by double exponential smoothing

4.2 Statistical Tests to be Used

To determine if the change of mean of RoR from a change of a parameter value is statistically significant, ANOVA test for a simple regression is performed. Slope of a linear regression model from change of mean RoR versus change of parameter value is tested if the slope is larger than zero (or equal to zero). For the hypothesis test, the following assumptions are made.

- Distributions of RoR (y values in a linear regression model) are normally distributed.

  While the distributions of RoR are skewed to the right side (Reinschmidt, 2004), the assumption of a normal distribution is made to use a t-test for a linear regression model.
- The error component in the regression model, (ε), is normally and independently distributed with a mean of zero and a variance σ^2 (NID (0, σ^2).
- Confidence level is selected as 90% ($\alpha = 0.10$).

ANOVA test is performed by using a regression function in the Data Analysis tool pack in Microsoft Excel. Through this function, the t-test statistic (t_0) and *P*-value are calculated, and they are compared to the critical value of t-distribution depending on the confidence level and degree of freedom and alpha value.

4.3 Sensitivity Analysis of Baseline Schedule

4.3.1 Basic setting for the sensitivity analysis

The model for the baseline schedule in the simulations is validated by analyzing the sensitivity of each input variable to the baseline RoR. The input variables to be tested for the sensitivity analysis are the estimated cost and duration of each activity, the economic life of the project and future monthly revenues. Furthermore, the sensitivity of the number of activities to the baseline RoR is tested, because the mean of the future revenues are determined based on a target RoR value.

4.3.2 Sensitivity analysis for the input variables

For the sensitivity analysis for the input variables into the baseline schedule the following assumptions are made.

- The number of activities is assumed to be six for the analysis.
- The uncertainty in the PM's knowledge is assumed to be 1.0, which means the PM's knowledge is as accurate as the subcontractors'.

The mean values of costs and durations of activities, types of distribution from which random variables are generated, Coefficient of Variation (CoV) and correlation coefficient between costs (or durations) are set as in Table 4.1.

For the sensitivity analysis, the mean value of future revenues is set as a constant number, \$72,550.10. 10,000 iterations are made in the Monte Carlo simulations in the analysis. In the sensitivity analysis one variable is changed with the others held constant.

Table 4.1 Input variables into baseline schedule

<table>
<tr><td rowspan="2"></td><td colspan="2">Duration of each activity</td><td colspan="2">Cost of each activity</td><td colspan="2">Economic Project life</td><td colspan="2">Future monthly revenue</td></tr>
<tr><td colspan="2">Log-normal distribution</td><td colspan="2">Log-normal distribution</td><td colspan="2">Normal Distribution</td><td colspan="2">Normal Distribution</td></tr>
<tr><td>Activity</td><td>Mean (Weeks)</td><td>CoV</td><td>Mean ($)</td><td>CoV</td><td>Mean (Months)</td><td>CoV</td><td>Mean ($)</td><td>CoV</td></tr>
<tr><td>1</td><td>14</td><td rowspan="6">0.3</td><td>350,000</td><td rowspan="6">0.3</td><td rowspan="6">240</td><td rowspan="6">0.2</td><td rowspan="6">72,550.10</td><td rowspan="6">0.3</td></tr>
<tr><td>2</td><td>20</td><td>500,000</td></tr>
<tr><td>3</td><td>22</td><td>550,000</td></tr>
<tr><td>4</td><td>24</td><td>560,000</td></tr>
<tr><td>5</td><td>22</td><td>650,000</td></tr>
<tr><td>6</td><td>20</td><td>700,000</td></tr>
<tr><td>Total</td><td>122</td><td></td><td>3,310,000</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Correlation coefficient</td><td>0.9</td><td></td><td>0.9</td><td></td><td>0</td><td></td><td>0</td></tr>
</table>

- Correlation of each variable with baseline RoR

  Out of the four input variables entered into the baseline RoR, two variables (economic project life and future revenues) are expected to be positively correlated with the baseline RoR. Larger future revenues mean positive cash in-flows and it leads to a higher RoR. Also, a longer economic life provides more cash in-flows and causes RoR to be larger. To the contrary, RoR is likely to decrease with a higher construction cost which means a bigger initial investment or cash out-flows. And a discounted worth of future revenues decreases with a longer construction duration, thus RoR decreases. These expectations about correlation are observed as shown in Fig. 4.11.

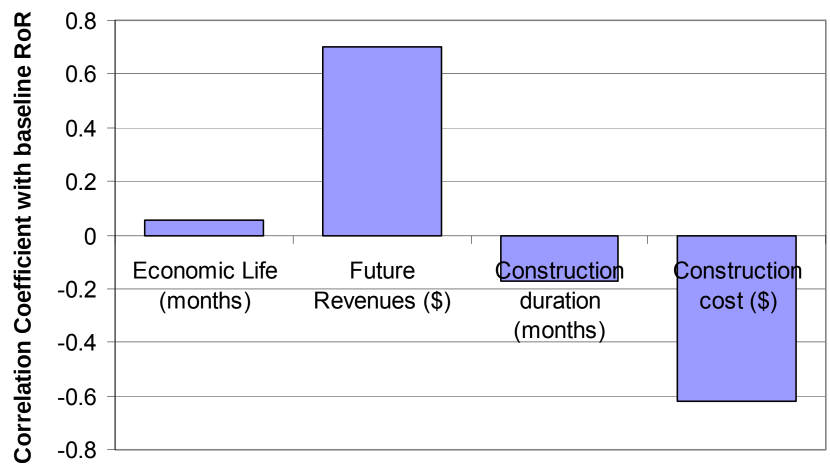


Figure 4.11Correlation coefficient between each input variable and baseline RoR

Furthermore, while economic life and construction duration represent periods of cash in-flows and cash out-flows respectively, future revenues and construction cost represent the amount of cash flows. With regard to the baseline schedule, the variables for the amount of cash flows result in a bigger impact on RoR than the variables for periods of cash flows.

- Sensitivity of Construction cost on Baseline RoR

The sensitivity of construction cost on the baseline RoR is analyzed by increasing the total cost by $100,000. The range of construction cost is the mean value of the total construction multiplied by the assumed subcontractors' markup of 10% plus and minus five increments (decrements) of $100,000.

It is expected that the mean of RoR decreases with more construction cost (or bigger initial cash out-flows) as discussed above regarding a positive correlation.

This expectation is observed as shown in Fig. 4.12 and Fig. 4.13: as the mean of construction cost increases, the mean of the resulting baseline RoR decreases.

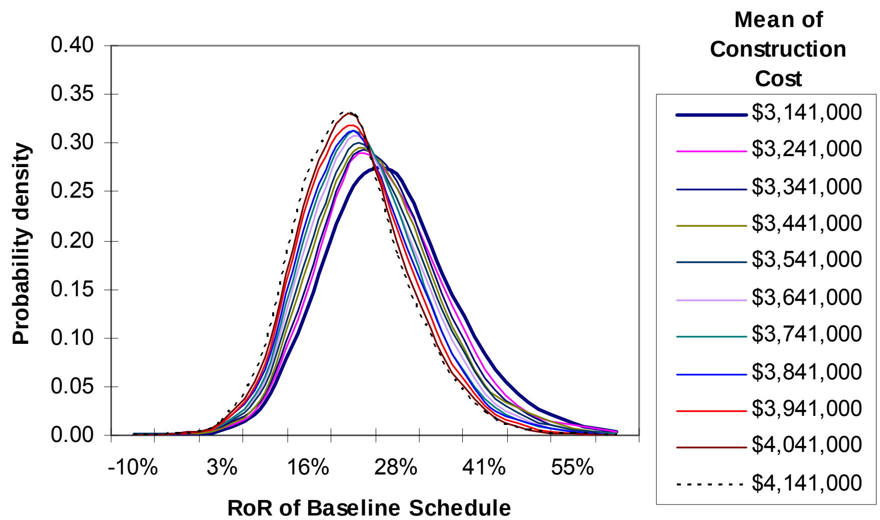


Figure 4.12 Probability distributions of RoR with different mean costs

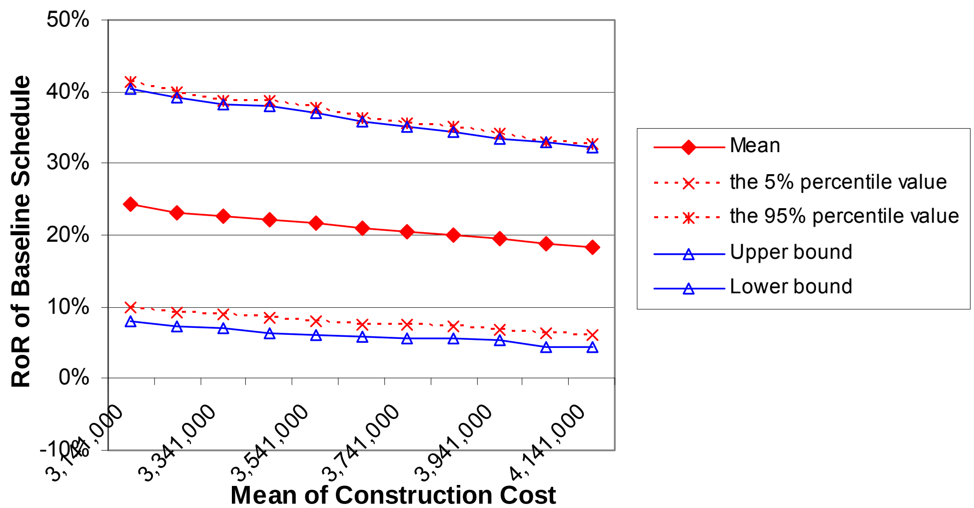


Figure 4.13 Change in mean of RoR with increase in mean cost

Since the rate of decrease in the mean of the baseline RoR depends on the incremental amount of construction cost, ANOVA test was performed to determine whether the slope of the lines representing the mean of RoR versus the mean of construction cost is statistically different from zero. Table 4.2 summarizes the results of ANOVA test.

Table 4.2 Summary of ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.003530767	0.003530767	1348.26617	4.08376E-11
Residual	9	2.35687E-05	2.61875E-06		
Total	10	0.003554336			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.416882961	0.005639007	73.92843918	7.66732E-14	0.404126642	0.42963928
X Variable 1	-5.6655E-08	1.54294E-09	-36.71874412	4.08376E-11	-6.01453E-08	-5.31646E-08

Since it is expected that RoR decreases with larger construction cost, the null hypothesis in this statistical test is if the slope representing a mean RoRs versus a mean construction costs is smaller than 0 is.

$H_0 : \beta_1 < 0$ (β_1 is the slope of the mean RoR versus mean construction cost.)

$H_1 : \beta_1 = 0 \; or \; \beta_1 > 0$

$\alpha = 0.10$

Based on $\alpha = 0.10$ and one-sided test, $t_{0.10,9} = 1.383$ is obtained from the *t*-distribution table. Since $t_0 = -36.72 < -t_{0.10,9} = -1.383$, the null hypothesis is accepted. Also, P-value (4.08376E-11) is much smaller than 0.10. Therefore, it is concluded that the slope of the mean of baseline RoR versus mean of construction cost is statistically smaller than 0.

Furthermore, the probability density functions of the baseline RoR in the two plots above are skewed to the right. And plot above shows two confidence intervals both from the assumption of the Normal Distribution (*Upper bound* and *Lower bound* in the figure) and from the percentile values from the Monte Carlo simulation. Based on the assumption that the resulting baseline RoR is normally distributed, the upper bound of the confidence interval is calculated as $[\mu - n\sigma, \mu + n\sigma]$ and the value of *n* for a 90% confidence level and two-tailed confidence interval is 1.645 (Mathworld, 2008). Another confidence interval is from the 5% and 95% percentile values from the Monte Carlo simulations. While the confidence interval from the assumption of the Normal distribution (Upper bound and Lower bound) should be symmetrical, the other confidence interval is not symmetrical. This difference is due to the characteristics of the probability distribution on rate of return on investment (RoR): the probability distribution on RoR is skewed to the right even without a correlation between cash in-flows (Reinschmidt, 2004). Therefore, the assumption of the Normal distribution underestimates the risk of a lower RoR.

- Sensitivity of Construction Duration on Baseline RoR

The sensitivity of construction duration on a baseline RoR is analyzed by increasing the total construction duration from 23 months to 38 months by 1.5 months.

It is expected that the mean of the baseline RoR decreases with a longer construction duration (negative correlation), because a longer duration delays cash in-flows and the discounted value of cash in-flows after completion of the construction phase becomes smaller. Fig. 4.14 shows the result in the change of the mean RoR with longer construction duration.

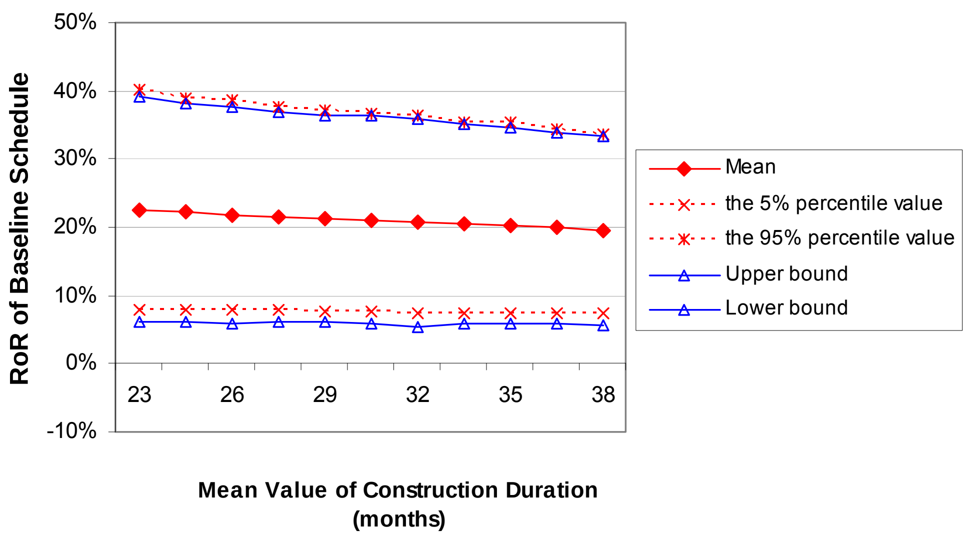


Figure 4.14 Change in mean of RoR with increase in mean duration

The mean of the baseline RoR decreases with a longer construction duration and it is determined that the mean of the baseline RoR significantly decreases from a longer construction duration: the test statistic t_0 (-39.774) is smaller than the t-value at a 10% confidence level on the one-sided test ($-t_{0.10,9} = -1.383$), and the P-value (1.99725E-11) is much smaller than 0.10.

Moreover it is observed that the lower bound of the confidence level for the baseline RoR does not change as much as the upper bound. As construction duration increases with constant construction cost, cash in-flows are delayed and the discounting factor of cash in-flows decreases faster. The rate of decrease in RoR due to a longer construction duration would not be significant. This trend regarding the lower bound is determined to lead to a smaller variance in RoR with a longer duration.

- Sensitivity of Future Revenues on Baseline RoR

  To test the sensitivity of future revenues on the baseline RoR, future (monthly) revenues are varied with plus/minus five increments of $2,000 around the mean value ($72,550). As discussed above regarding the positive correlation between future revenues and RoR, it is expected that the baseline RoR will increase with more future revenues, since more cash in-flows in a constant duration after the construction phase improves RoR. The mean of baseline RoR is observed to increase with higher future revenues as shown in Fig. 4.15 and it is also determined that the impact of the increase in future revenues on the mean of the RoR is statistically significant.

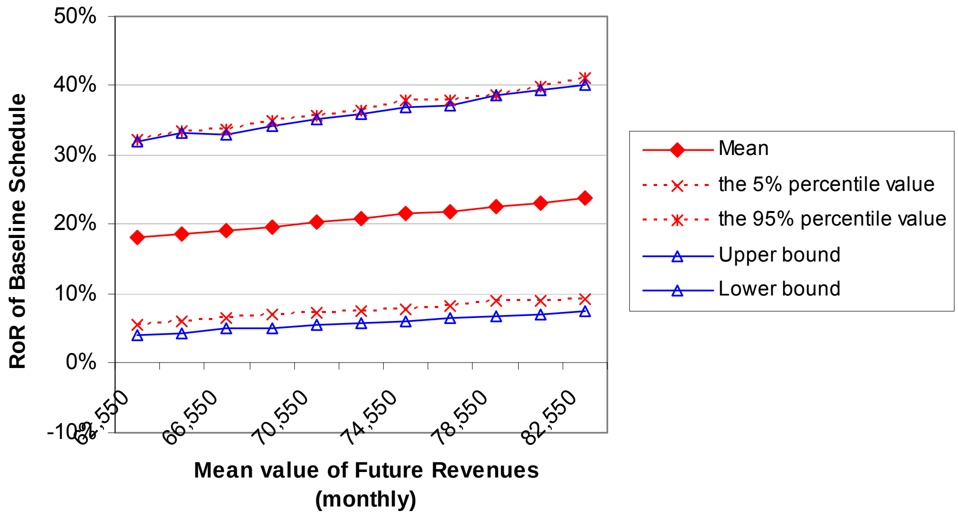


Figure 4.15 Change in mean of RoR with increase in mean future revenues

- Sensitivity of Economic Project Life on Baseline RoR

The economic life of a project is varied over a range of 100 months around the mean value of 240 months for the sensitivity analysis. The mean of the baseline RoR is observed to increase with a longer economic life of the project due to a longer stream of constant cash in-flows, which proves the positive correlation mentioned above. Fig. 4.16 shows the change in the mean of the baseline RoR with a longer economic project life.

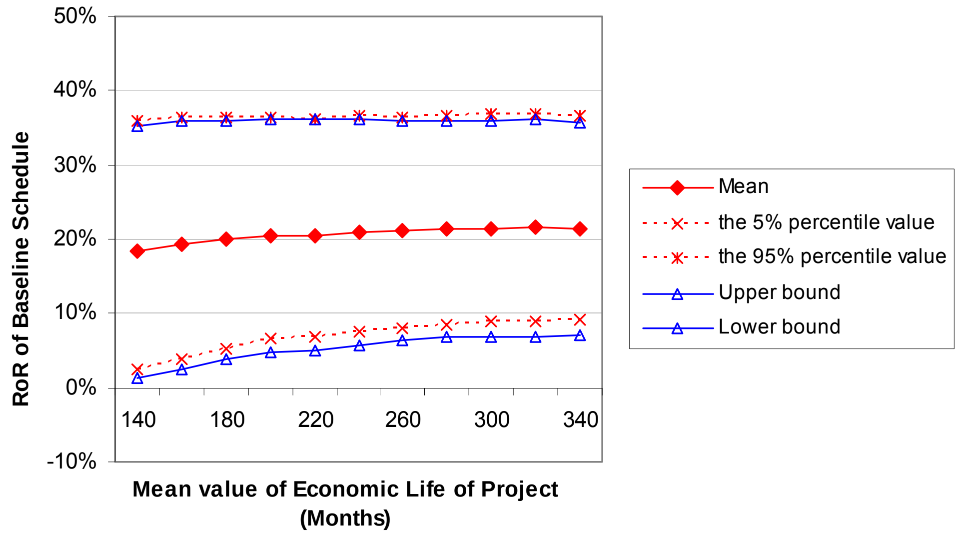


Figure 4.16 Change in mean RoR with increase in mean economic life

It is determined that the mean of the baseline RoR increases significantly by an increase in the economic life of the project. It is observed that the upper bound of the confidence interval is not affected by a longer economic project life. This observation can be explained by the fact that the discounting factor decreases abruptly with a longer discounting period. Thus, the contribution of a very long economic project life would not be significant. To the contrary, the lower bound of the baseline RoR is observed to increase faster than the mean value, because the impact of an increase in a shorter economic project life is more significant than that in a longer project life. Moreover, due to this trend in the upper bound of the confidence interval, the variance of RoR is reduced. Therefore, it is concluded that a longer economic project life can contribute to a better benefit regarding less uncertainty in RoR as well as a higher mean of RoR.

4.3.3 Sensitivity analysis of the number of activities on baseline RoR

In addition to the sensitivity analysis regarding input variables into the baseline schedule, it is tested whether the number of activities (or project size) affects the baseline RoR. Since the internal rate of return (or RoR) does not depend on the size (or scale) of the project, size of the project (or number of activities) should not be a factor which affects the baseline schedule. Therefore, a target RoR is set (as 20%) and the mean value of the future monthly revenues is calculated with a target RoR and the mean values of other input variables (construction cost, duration and economic life of project). It is expected that the mean of the baseline RoR is not affected by the number of activities and the expectation is tested by a sensitivity analysis.

For this sensitivity analysis regarding the number of activities, the mean values of the input variables into the baseline schedule are the same as the previous sensitivity analysis (shown in Table 4.1).

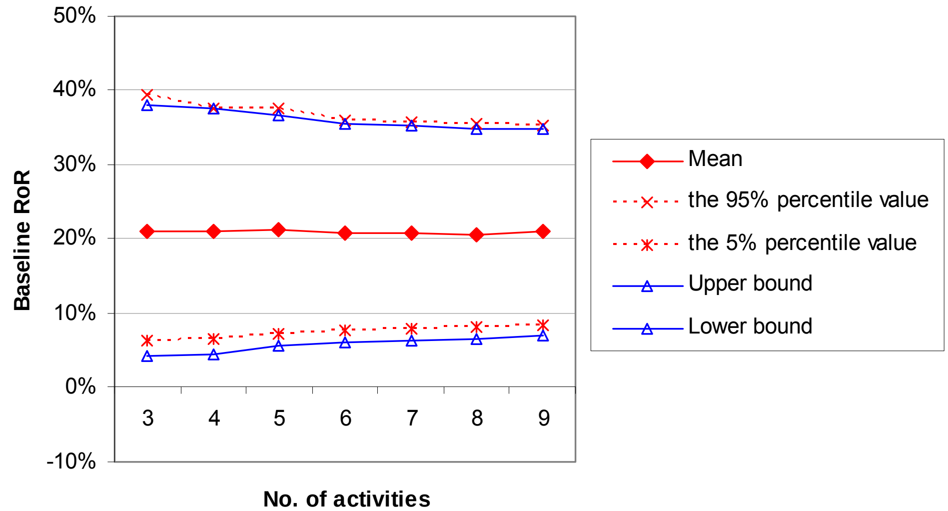


Figure 4.17 Change in mean, upper bound and lower bound of baseline RoR with increase in number of activities

The above Fig. 4.17 shows the change of the mean of the baseline RoR with more activities. While the mean value is observed to slightly fluctuate, it is determined that the mean value of the baseline RoR is not affected by the number of activities.

However, variance of the baseline RoR is observed to be affected by the project size (or number of activities) as shown in the above figure. The decrease in variance of the baseline RoR due to the increase in the number of activities is related to the correlation between the activities' costs (or durations). If it is assumed that the costs (or durations) of activities are independent each other, the variance (or CoV) of the baseline RoR of a project approaches zero. And this result would not be accepted.

Therefore, it is assumed that the activities' costs (or durations) are highly and positively correlated with a coefficient of 0.9. However, even with a high positive correlation of 0.9, variation (or CoV) of the baseline RoR is observed to decrease with more activities. This assumption and corresponding result are explained more fully with Fig. 4.18. Fig. 4.18 shows the change in the CoV of the baseline RoR with more activities and the plot is prepared with a varying correlation coefficient from 0 to 0.99. As the correlation coefficient increases, the rate of decrease in the CoV of the baseline RoR is reduced. And if the correlation coefficient is 0.99, then no decrease is observed. However, this high positive correlation coefficient may not be considered as usual or normal. On the other hand, in the case of a correlation coefficient of 0.8 in the following figure, the decrease in the CoV with four or more activities is not significant. Therefore, the assumption of the correlation coefficient between the activities' costs (or durations) of 0.9 is reasonable in that the impact of the number of activities on the CoV (or variance) of the baseline RoR is not quite significant.

While the variance of the baseline RoR decreases with more activities, no owner (or project manager) would like to increase the number of activities (or divide an activity into smaller multiple activities) only to reduce the variance. Therefore, this counter-intuitive result may not be used as an option by project owners. And this issue requires more research and it may need to be expanded into cross-correlations both between activities' costs (or durations) and between cost and duration. It is intended that this issue be researched in the future.

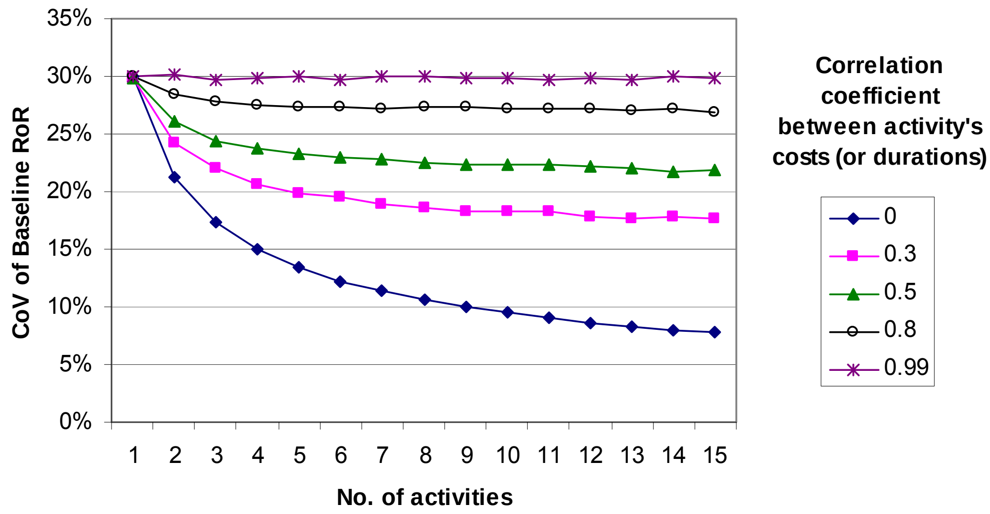


Figure 4.18 Change in CoV of baseline RoR with more activities

4.3.4 Conclusion of the sensitivity analysis on baseline RoR

The sensitivity analysis of input variables on the baseline RoR was conducted to validate the generation of a random baseline RoR in the simulation model. First, the input variables used in the calculation of RoR (construction cost, duration, future revenues and economic project life) are concluded to impact the baseline RoR as follows.

- As construction cost increases, baseline RoR decreases.
- As construction duration increases, baseline RoR decreases. However, the risk of a lower RoR does not decrease, but remains almost constant.
- As future revenues increase, baseline RoR increases and the correlation coefficient of future revenues with baseline RoR is the biggest among the four input variables.

- As economic project life becomes longer, baseline RoR increases. However, as economic project life becomes longer, the rate of increase in RoR decreases.

In addition to the input variables in the baseline RoR, the impact of the number of activities and PM's uncertainty on the baseline RoR are tested. Both factors are determined not to affect the mean of the baseline RoR. However, as the number of activities increases (or the project size becomes larger), the CoV (or variability) in the baseline RoR becomes slightly smaller due to the assumption of the correlation coefficient of 0.9 between the activities' cost (or duration). This topic will be addressed in future research.

CHAPTER V

SIMULATION RESULTS

5.1 Setting for the Main Simulations

5.1.1 Decision-making parameters

This research has five decision-making parameters for the improvement of RoR through overlapping activities and finding a better work method. To examine and answer the hypotheses, the model is simulated with three values for each decision-making parameter (except for attitude to risk). Values of these parameters are summarized in Table 5.1.

Table 5.1 Values of the decision-making parameters

Decision-making parameter	**Values**		
	Low	Medium	High
No. of activities	4	6	8
No. of work methods	3	5	7
PM's uncertainty	1.00	1.25	1.50
PM's solution capacity	5	35	65
Attitude to risk	Risk-neutral		Risk-averse

With the above values of the parameters, a total of 162 (3×3×3×3×2=162) cases are investigated. The model is iterated 20,000 times for each case, giving a total of 3,240.000 simulation runs to generate the final results.

5.2 Results of the Hypotheses Test

5.2.1 Hypothesis #1

The greater the number of activities, the greater the advantages of decentralized decision making.

More activities in a construction project mean more opportunities for overlap between activities. For example, it is a potential for 3 pairs of activities to overlap in a project with 4 activities, while there are 7 potential overlaps with 8 activities. Therefore, more activities in a project lead to a higher potential of a faster completion of the construction phase. And if additional cost for overlap can be justified for the earlier completion that RoR increases, then more activities are likely to provide a higher benefit to the project owner.

However, the question is how good of a solution the PM is able to find regarding work methods and degrees of overlapping for multiple overlaps which will be acceptable by the subcontractors: as the number of activities increases, the solution space to be explored by the PM increases abruptly in the centralized approach. If the resource of the PM's solution capacity such as the number of estimators or computers is limited, but the number of activities increases, then the PM is likely to lose the potential for obtaining a higher RoR.

On the contrary, in the decentralized approach the work methods and degree of overlapping between the two activities are determined by the subcontractors and this decision is not affected by the number of activities. That means that if the solution space to be explored by each pair of subcontractors does not increase with more activities, then their solution is not affected by the number of activities. If each pair of subcontractors are able to find their optimal solution, which is an assumption used in the simulation model, and the number of activities increases, then a faster completion of the construction phase can be obtained and a higher RoR can be achieved if an additional cost for overlap is justified. Therefore, it is expected that the decentralized RoR would be higher than the centralized RoR with more activities. The results of the simulations regarding this hypothesis are discussed as follows.

- Centralized approach

  Centralized RoR becomes improved with more activities if the PM's knowledge is reliable. And an increased PM's solution capacity helps centralize RoR increase further with more activities.

In the centralized approach the mean value of a centralized RoR is observed to increase with more activities, if the PM's knowledge is as reliable as the subcontractors' (PM's uncertainty is 1.0). If the PM's knowledge is less reliable (or accurate) than the subcontractors', then the owner cannot get the potential of overlaps due to more activities. This result is shown in Fig. 5.1 which shows the change of centralized RoR (mean value) with different degrees of the PM's uncertainty from a simulation case.

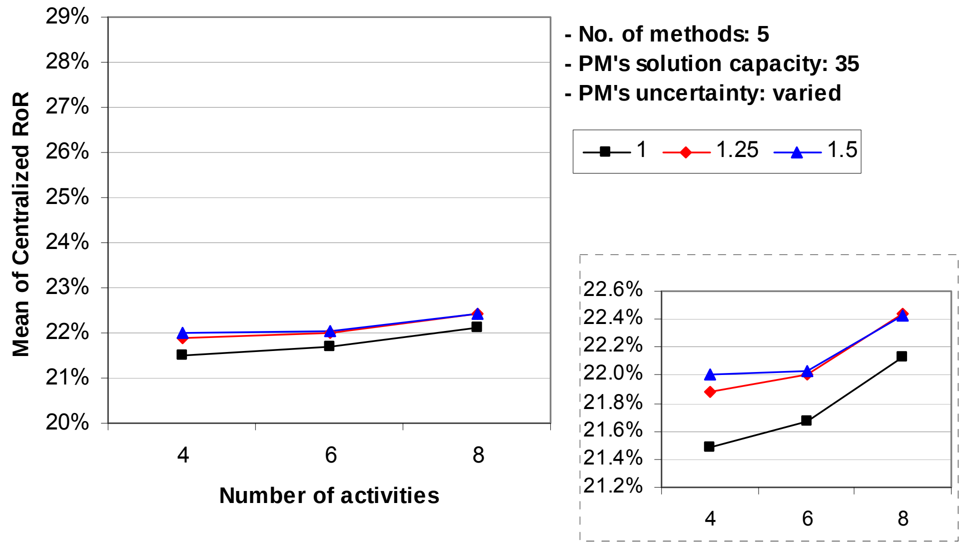


Figure 5.1 Change in mean of centralized RoR with more activities and different uncertainty

In the above figure, while the centralized RoR increases with more activities for all degrees of the PM's uncertainty, the increases of RoR with the PM's uncertainty of 1.25, or 1.5 are determined not to be statistically significant from the hypothetical tests. The impact of different levels of the PM's uncertainty on increase in RoR with more activities can be explained by comparing the centralized RoR to the PM's own RoR.

The PM's own RoR, which is based on the PM's own knowledge, is expected to increase with more activities as discussed above. However, the PM's own RoR may not be acceptable by the subcontractors' due to the uncertainties both in the PM's knowledge and in the subcontractors' knowledge: if the PM's knowledge is less accurate (or reliable) than the subcontractors', then it is more likely that the PM's own solution will be rejected by the subcontractors. The potential of the reduction in RoR due to the uncertainty is expected to be enlarged with more activities: it is less probable that more subcontractors will accept the PM's solution. Therefore, it is expected that the reduction in RoR between the PM's own RoR and the centralized RoR increases with more activities and with a less accurate PM's knowledge. Fig. 5.2 shows a result of the decrease in RoR from a simulation case. The PM's own RoR linearly increases with more activities for all varied values of the PM's uncertainty. However, the benefit of a higher RoR due to more activities is reduced if the PM's knowledge is as reliable as the subcontractors', and lost if the PM's knowledge is less reliable than the subcontractors'. In all the simulation cases it is determined that the mean of centralized RoR is significantly smaller than the mean of the PM's own RoR from hypothetical tests.

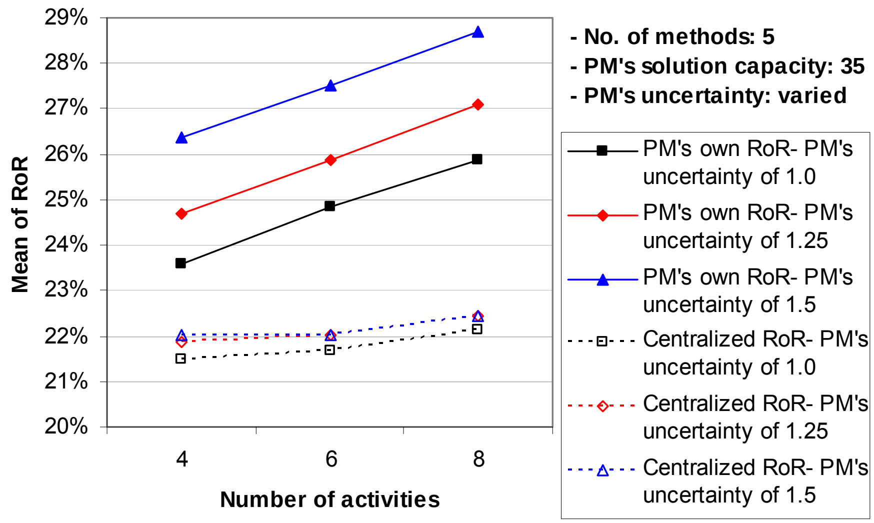


Figure 5.2 Change in means of both centralized and PM's own RoR with more activities

In addition, the improvement in RoR with more activities becomes bigger if the PM's knowledge is as reliable as the subcontractors' and the PM's solution capacity is larger. As the PM comes to have more resources to determine his (or her) solution, a better solution (or higher RoR) is expected. Therefore, the benefit of more activities can be enlarged with more PM's solution capacity. Fig. 5.3 shows an example of the impact of the PM's solution capacity. As more solution capacity is available, the centralized RoR increases faster with more activities.

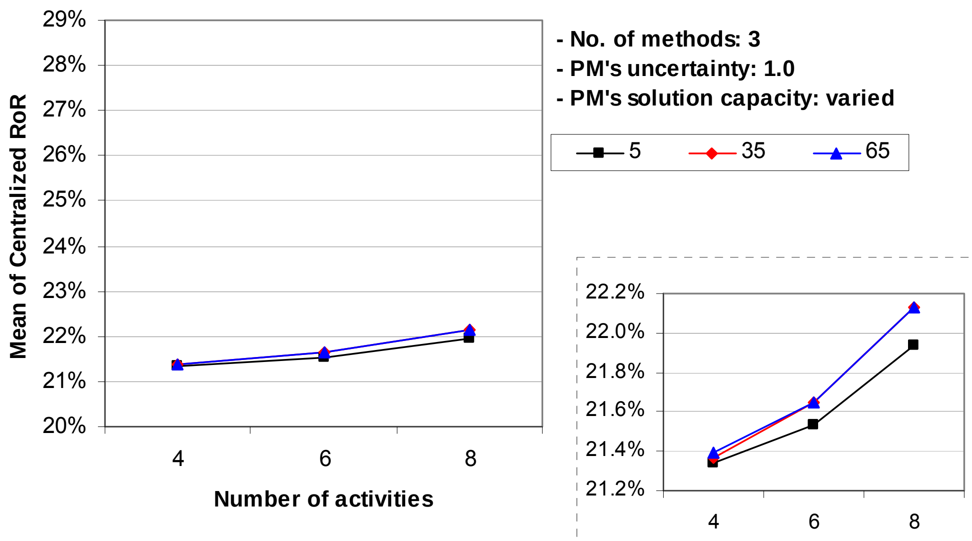


Figure 5.3 Change in mean of centralized RoR with more activities and different solution capacity

Furthermore, the impact of the number of methods on the improvement of the centralized RoR due to more activities is observed not to be statistically significant. While the increase in the centralized RoR is considered as non-significant, the impact of more methods is discussed. Since the consideration of more methods along with more activities expands solution space to be explored, it would be more difficult to find the optimal solution for a constant PM's solution capacity. Fig. 5.4 shows results of a simulation case as an example. In the enlarged plot in the lower-right corner of the following figure, a slightly higher RoR is obtained by considering more methods (increase in number of methods from 3 to 7) when the number of activities is 4. However, when there are more activities the solution space increases and no advantage of considering more methods is found with a constant PM's solution capacity.

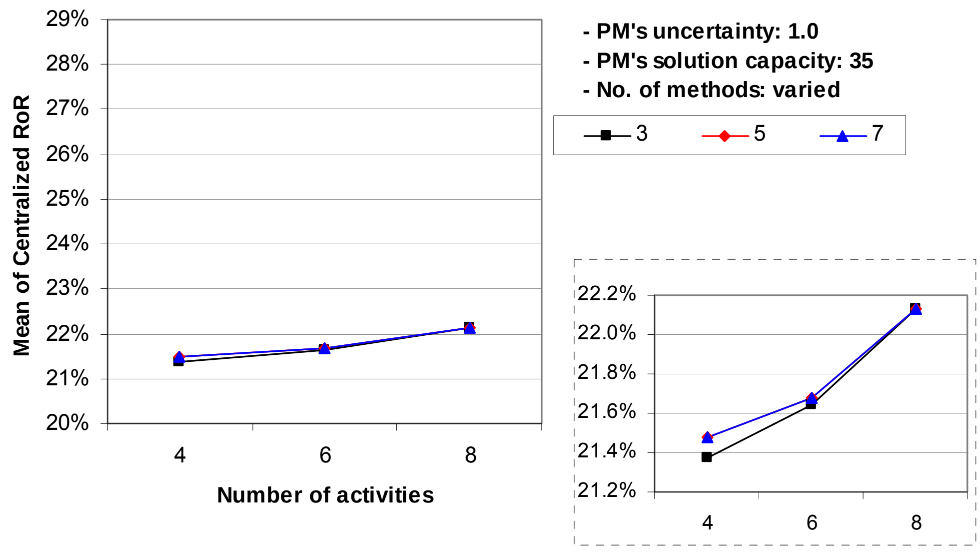


Figure 5.4 Change in mean of centralized RoR with more activities and different number of methods

- Decentralized approach

  Mean of decentralized RoR increases with more activities.

In the decentralized approach the mean of decentralized RoR is observed to always increase with more activities and the slope of the mean of decentralized RoR is determined to be significantly different from 0 in all the simulation cases. Since it is assumed that each pair of subcontractors could find their best solution, the subcontractors' own solutions are not expected to be affected by the number of activities.

This result is interpreted to mean that the project owner can be beneficial by relying on the subcontractors' solutions if the number of activities increases.

Furthermore, it is observed that three other parameters (number of methods, PM's uncertainty, and PM's solution capacity) don't affect the mean of decentralized RoR. The number of methods affects the mean of decentralized RoR slightly: the more methods, the higher the mean of decentralized RoR. However, the rate of increase in the mean of RoR is determined not to be different from 0. In the enlarged plot in the lower-right corner of Fig. 5.5, a slight difference among the mean values of decentralized for a different number of methods with four activities is observed.

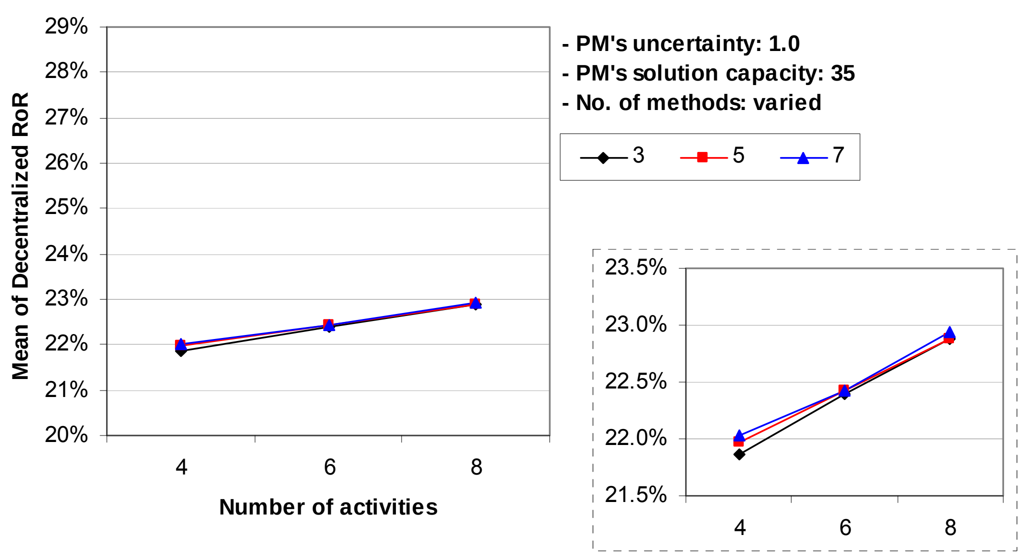


Figure 5.5 Change in mean decentralized RoR with more activities and different number of methods

And Fig. 5.6 shows the impact of the PM's solution capacity on the increase in mean of decentralized RoR with more activities. Decentralized RoR is not affected by the PM's solution capacity.

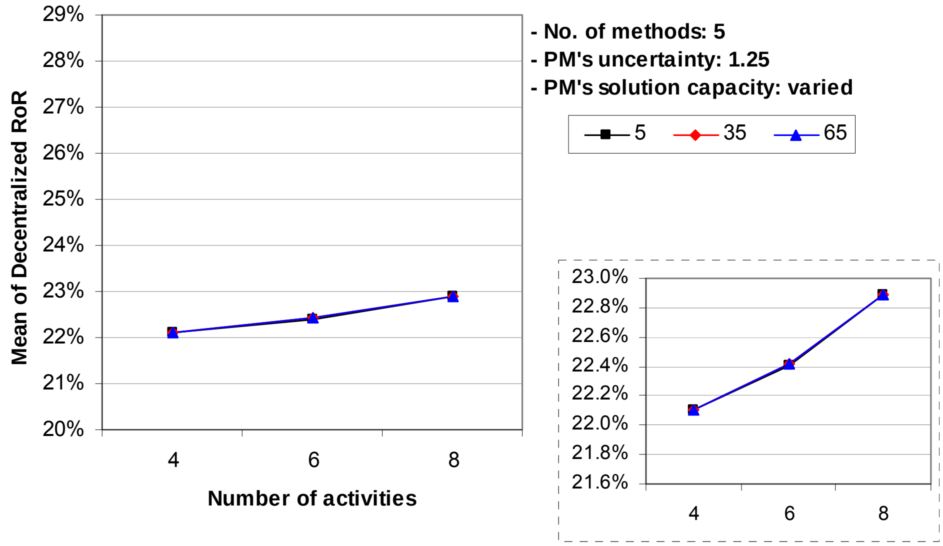


Figure 5.6 Change in mean decentralized RoR with more activities and different solution capacity

When the PM re-evaluates the bids submitted by the subcontractors, he (or she) is assumed to evaluate the risk of late completion of the construction phase: if the estimated cost for the amount of time reduction proposed by the subcontractors is larger than the bid price, the PM is assumed to reduce the amount of time reduction proposed based on his estimated cost. Therefore, if the uncertainty in the PM's knowledge is high, it is more likely that the amount of time reduction proposed is reduced and leads to a lower mean of decentralized RoR. Fig. 5.7 shows the impact of the PM's uncertainty on the increase in the mean of decentralized RoR with more activities. While slightly different mean values are observed with four activities, the difference is determined not to be significant.

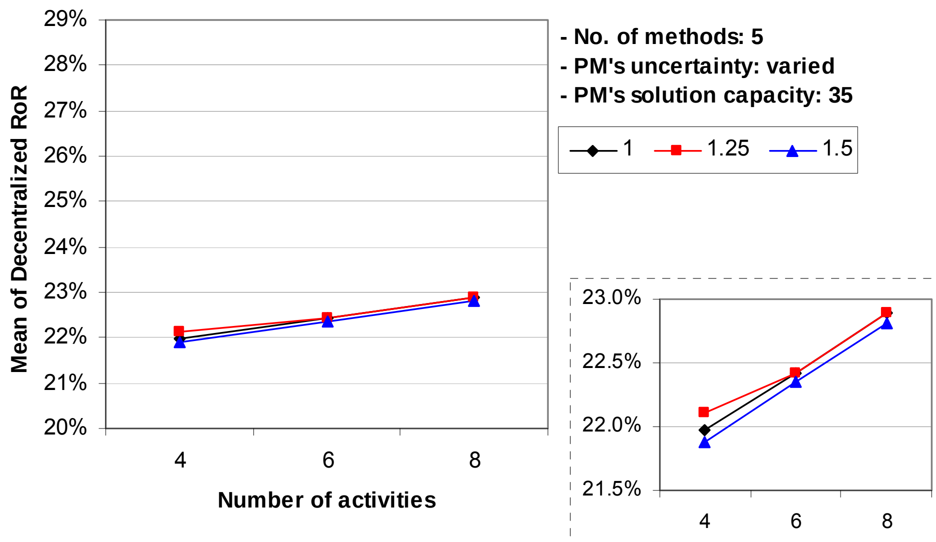


Figure 5.7 Change in mean decentralized RoR with more activities and different uncertainty

- Comparison between centralized RoR and decentralized RoR

  The decentralized approach becomes preferred to the centralized approach as number of activities increases.

The mean of centralized RoR increases with more activities only when the PM's knowledge is as reliable as the subcontractors' (PM's uncertainty is 1.0) and it does not increase or decrease when the PM's knowledge is less reliable than the subcontractors'. Furthermore, the rate of increase in the centralized RoR with more activities becomes bigger when the PM's solution capacity is high and the number of methods is small. On the contrary, the mean of decentralized RoR increases with more activities in all the simulation cases, but the other parameters don't affect the rate of increase in the decentralized RoR.

When comparing the centralized approach and the decentralized approach, the rate of increase in the mean of centralized RoR is smaller than that of the decentralized RoR. Therefore, the decentralized approach becomes preferred to the centralized approach as number of activities increases. Fig. 5.8 shows the comparison of increases in RoR both for the centralized approach and the decentralized approach. As the number of activities increases from 4 to 8, the decentralized RoR increases faster than the centralized RoR. The mean of decentralized RoR (22.88%) is slightly higher than the mean of the centralized RoR (22.13%) for 8 activities, thus the decentralized approach becomes preferred to the centralized approach.

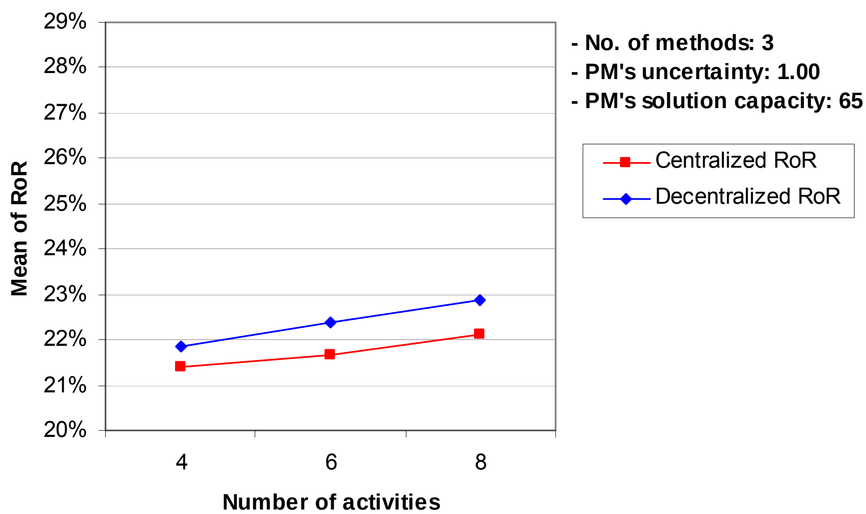


Figure 5.8 Comparison between mean centralized RoR and mean decentralized RoR with more activities

In addition to the above simulation case, the mean of decentralized RoR is observed to increase faster than the mean of centralized RoR. Fig. 5.9 shows the change in the ratio of the mean of centralized RoR to the mean of decentralized RoR with more activities when the centralized RoR increases. Therefore, it is recommended that a faster delivery of the construction project with consideration of multiple methods is planned in the decentralized approach as the number of activities increases.

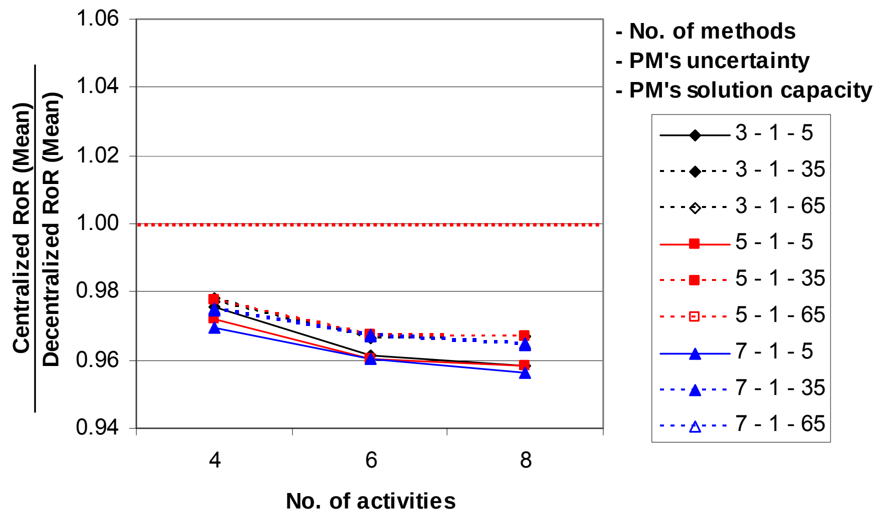


Figure 5.9 Change in the ratio of centralized RoR to decentralized RoR with more activities

Increase in the activities by splitting

As the number of activities increases, the project size increases. However, the project owner may increase the number of activities with the same project scope for example, by splitting one activity into two or multiple activities. Since this research is focused on overlapping between activities, the number of activities may affect the amount of overlap or amount of time reduction. As a construction project adds more activities, there are more opportunities for overlap between activities. Then this approach might lead to a higher RoR, and it might be recommended to split activities into small multiple activities to complete construction faster. Thus, it is tested whether an increase in activities by splitting is beneficial to the project owner in both decision-making approaches.

- **Centralized approach**

In the centralized approach the project owner may split one activity into two small activities to facilitate overlap. However, by splitting activities, the solution space to be explored by the PM would increase exponentially. If the PM has unlimited resources (or a solution capacity such as a number of estimators or number of computers) and he can find the optimal solution, then the project owner can benefit from a higher RoR by splitting activities. However, if the PM has a limited solution capacity, he is more likely not to find the optimal solution with more activities. Another constraint of the increase in the number of activities by splitting is that there is a maximum limit to the amount of time reduction from overlaps in a project. Due to these two constraints, the owner would not always benefit from splitting activities. Fig. 5.10 shows the result of a simple simulation for the impacts of splitting activities in the centralized approach.

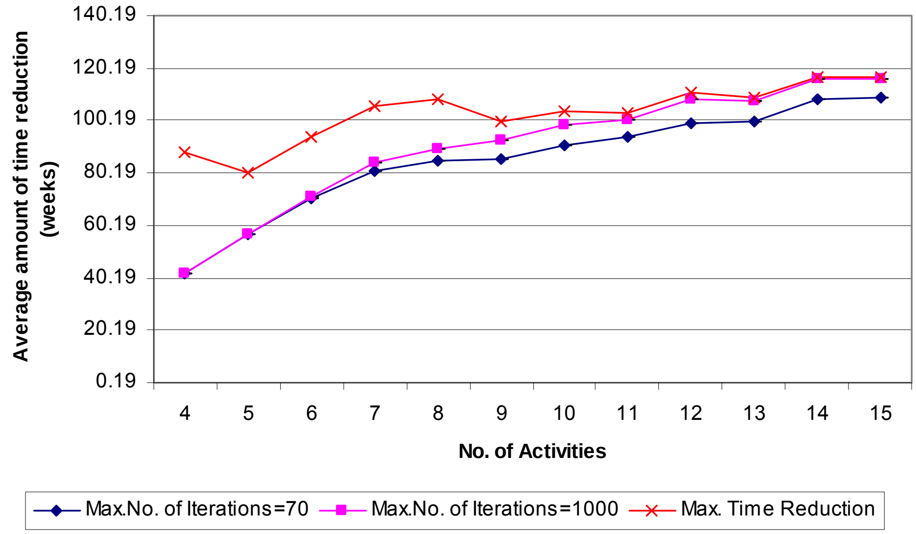


Figure 5.10 Change of mean of time reduction with more splitting activities

In the above figure, *Max. No. of Iterations* represents a limited solution capacity and the number of weeks of time reduction is affected by the solution capacity. And when the number of activities increases up to 14, then overlaps between activities is constrained by the maximum limit of time reduction (*Max. Time Reduction*). Thus, no more time reduction is obtained over 14 activities.

- **Decentralized approach**

In the decentralized approach it is assumed that the subcontractors can find their best solution and they do not have any constraint in solution capacity. Thus, the increase in number of activities by splitting may provide more overlap to the project owner in the decentralized approach.

However, more activities by splitting would cause a problem regarding incompatible methods, if each subcontractor considers multiple methods. Since each subcontractor has a myopic viewpoint, he would choose a method which can maximize his profit. Then as the number of activities increases, the number of activities would affect the frequency of incompatible methods. Furthermore, there is also a maximum limit of time reduction similar to the centralized approach. Fig.5.11 shows the results of a change in RoR with more activities split in the decentralized approach. While the mean of RoR increases up to 7 activities, it does not go up with 8 activities or more.

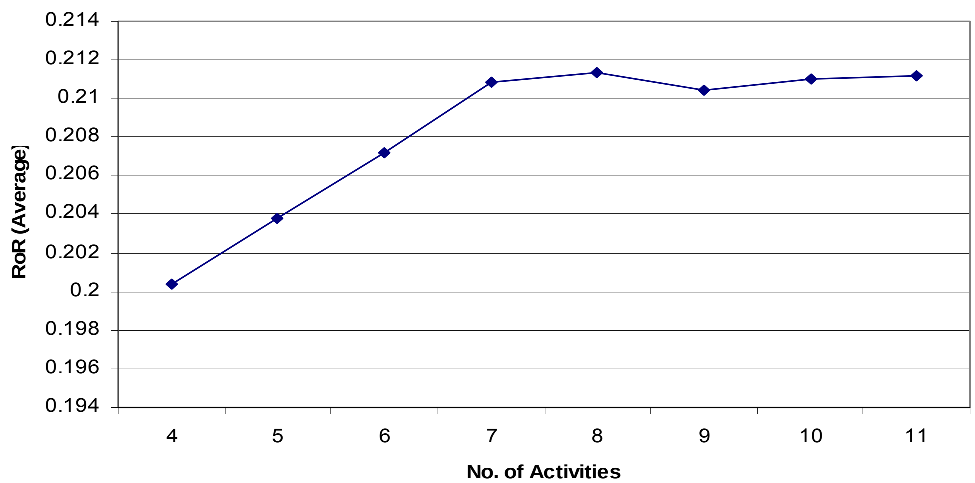


Figure 5.11 Change in mean of decentralized RoR with more split activities

In addition, more activities by splitting would increase the number of subcontractors under the same work scope or total construction cost and it may cause difficulties regarding management, coordination and/or other costs to the owner. Therefore, it is concluded that splitting activities is not always beneficial to the project owner. And now more activities represent bigger projects, not by splitting.

5.2.2 Hypothesis #2

The project owner benefits from more methods.

- *Benefits from more methods in the centralized approach*
- *Benefits from more methods in the decentralized approach*

In construction projects multiple methods are available to carry out each activity, but contractors usually select a method which costs the least. However, if activities are to be overlapped for an earlier completion of the construction phase, other methods which cost more than the least expensive method may cost less for an overlap between activities. Thus it may be possible that less conventional methods require less additional cost for overlap than the usual and base methods. By considering more methods for the potential of a cheaper overlap, project owners may be beneficial in that they pay less cost for an early completion of the construction phase.

In the centralized approach as more methods are considered, the PM should estimate additional costs required for overlap for more methods and the solution space to be explored would increase exponentially. If the PM has fixed resources for estimating and planning, then it is less likely that the PM will find the optimal solution. Furthermore, if the PM's knowledge is uncertain, consideration of more methods, especially more innovative methods, would lead to less accurate cost estimates. Then it is more likely that the PM's cost is over-estimated (or under-estimated) and subcontractors will reject the PM's solution.

On the other hand, in the decentralized approach if each subcontractor considers multiple methods for overlapping his (or her) activity with its predecessor or successor, the solution space would not increase as quickly as the PM's solution space. Thus subcontractors are assumed to be able to find their best (the local optimal) solution. However, the consideration of more methods also increases the probability of incompatible methods due to the subcontractors' myopic viewpoint, thus the mean of decentralized RoR may be reduced.

- Centralized approach

More methods do not improve the centralized RoR.

The first part of this hypothesis with regard to the centralized approach is concluded to be rejected: the mean of centralized RoR is observed to not significantly increase with more methods in all of the simulation cases. While it is observed that the mean of centralized RoR increases slightly with more methods in most simulation cases, the amounts of increase in the mean of centralized RoR are not statistically significant. The following figure shows the change in the mean of centralized RoR due to an increase in the number of methods. As shown in the enlarged plot on the lower-right corner of Fig. 5.12, the mean of centralized RoR slightly increases with more methods if the solution space is large (4 activities) and the PM's solution capacity is constant (65). However, if the number of activities increases into 8 and the solution space is expanded, the mean of centralized RoR does not become improved even with more methods.

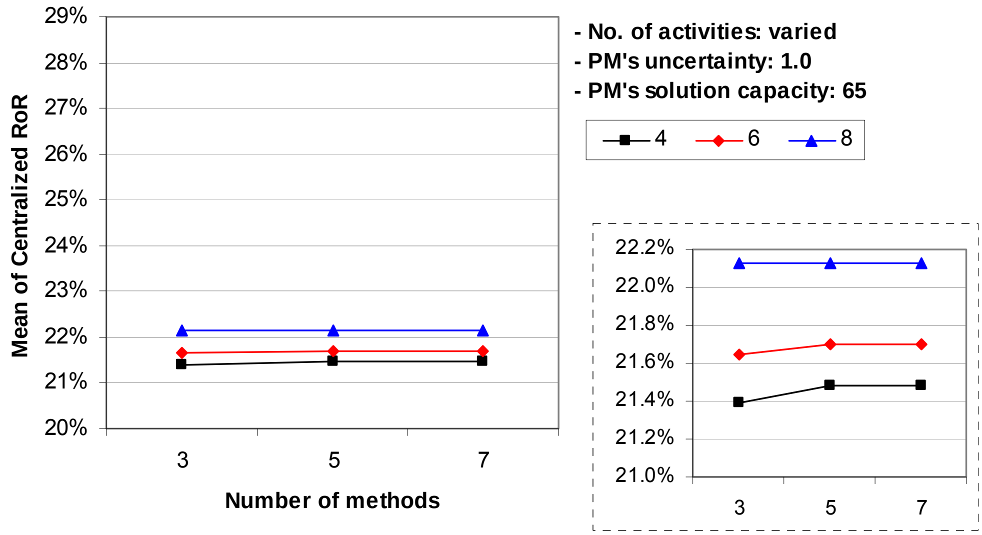


Figure 5.12 Change in mean centralized RoR with more methods and more activities

Also, it is expected that if the PM's solution capacity is high, then the PM can improve RoR by considering more methods. This expectation is proved in Fig. 5.13. As the PM's solution capacity increases, the PM is more likely to find the optimal solution in the expanded solution space. However, the increase in the mean of centralized RoR is determined to be non-significant again.

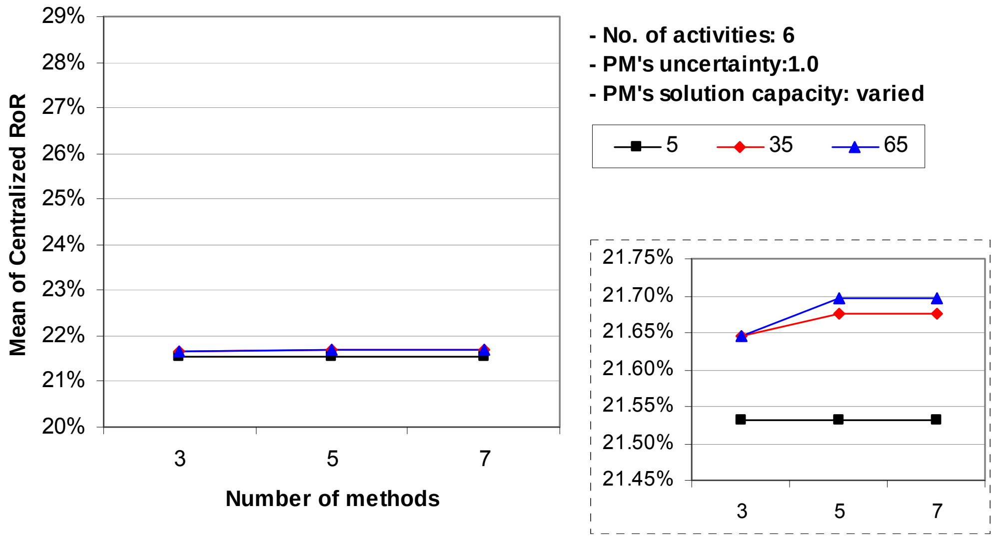


Figure 5.13 Change in mean centralized RoR with more methods and more solution capacity

The non-significant increase of the mean of centralized RoR with more methods can be explained by comparing the PM's own RoR and centralized RoR. In the PM's own solution, the PM can benefit from more methods: cheaper additional cost for overlap from less conventional methods. And this benefit in the PM's own RoR is observed when the number of activities is large and the PM's solution capacity is large: more opportunities for overlap arise with more activities and a better solution (higher RoR) is found with a higher solution capacity. As shown in Fig. 5.14, the improvement in the mean of the PM's own RoR due to more methods increases with more solution capacity and the improvement become larger with more activities.

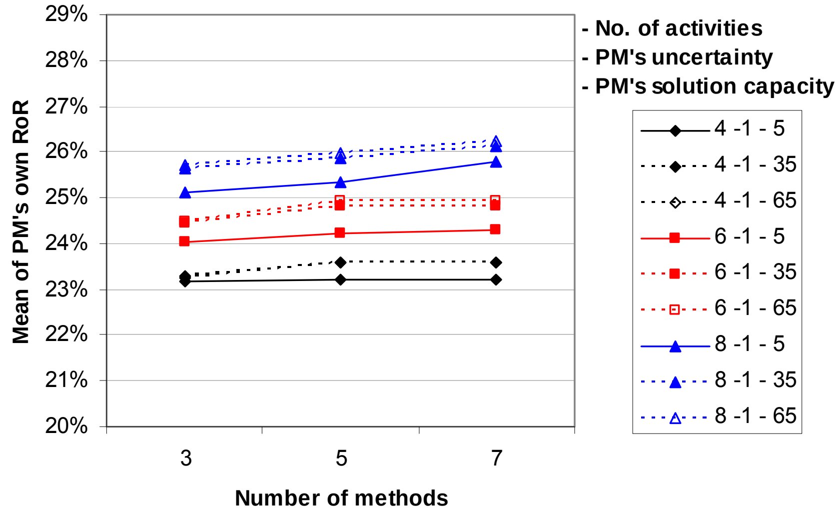


Figure 5.14 Change in mean PM's own RoR with more methods

However, the PM's own solution may not be accepted by subcontractors due to the uncertainty in the PM's knowledge. Therefore, the higher the PM's uncertainty, the bigger the reduction from the PM's own RoR to centralized RoR. Moreover, as the number of activities increases, it would be more difficult if all the subcontractors accept the PM's solution: the more activities, the bigger the reduction from the PM's own RoR to centralized RoR. Fig. 5.15 shows an example case concerning the changes in RoR with more methods between the PM's own RoR and centralized RoR. While the mean of the PM's own RoR increases significantly with more methods, the centralized RoR does not.

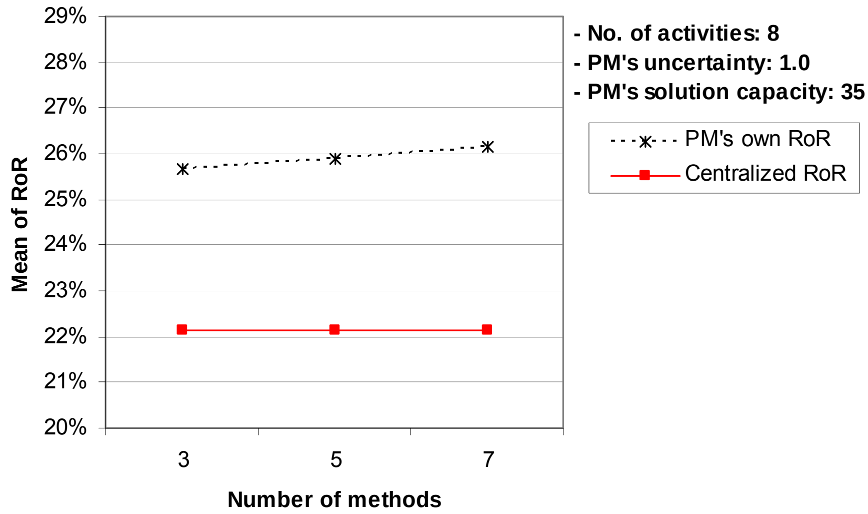


Figure 5.15 Comparison of the changes between mean centralized RoR and mean PM's own RoR

- Decentralized approach

Mean of decentralized RoR does not increase with more methods.

Similarly, as in the centralized approach, it is observed that the mean of the decentralized RoR is not improved by considering more methods and the second part of the hypothesis should be rejected.

Considering more methods improves the subcontractors' solutions: by finding cheaper methods for overlap the amount of time reduction is increased, this leads to a higher RoR. (RoR is calculated based on the amounts of time reduction and bid prices from the bids submitted by subcontractors.) However, when the PM evaluates the bids, the uncertainty in the PM's knowledge may affect RoR. Moreover, the myopic viewpoint of the subcontractors may cause methods to be incompatible with each other. Due to these unfavorable impacts, RoR would be reduced. The following figure shows the comparison between RoR based on the subcontractors' bids and a decentralized RoR with regard to an increase in the number of methods. First, the subcontractors' solution increases with more methods and the increase becomes bigger with the number of activities. Since more activities provide more opportunity for overlap, the amount of time reduction for more activities would be bigger than small activities. The dotted curves in Fig. 5.16 represent the RoR based on the subcontractors' bids. Then there are reductions in RoR between the subcontractors' bids and the decentralized RoR (the dotted curves versus the solid curves). This reduction increases with more methods, since more methods are likely to lead to more frequently incompatible methods. And the bigger reduction in RoR with more methods becomes more significant as the number of activities increases. As a result, the mean of decentralized RoR does not significantly increase with more methods.

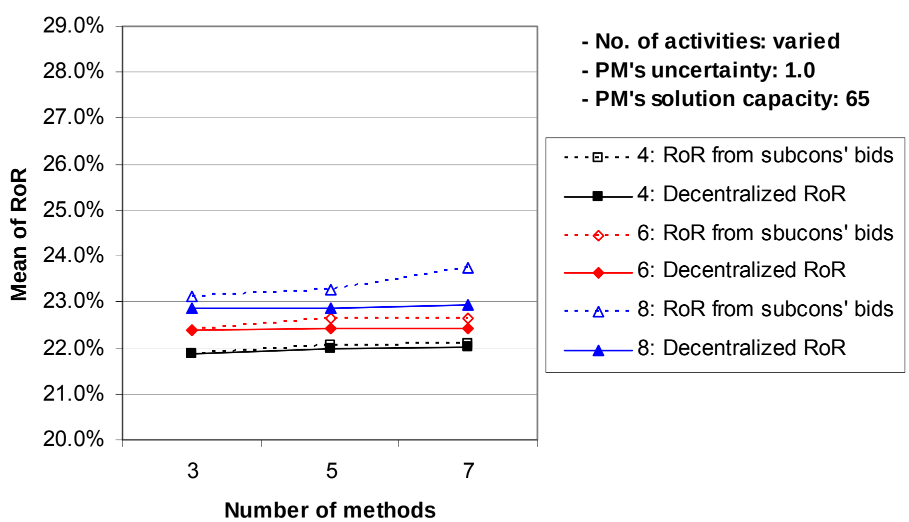


Figure 5.16 Comparison between the changes in mean decentralized RoR and mean RoR from subcontractors' bids

The uncertainty in the PM's knowledge plays a role in the PM's evaluation process in the decentralized approach. But it is observed that the PM's uncertainty does not significantly affect the mean of decentralized RoR as shown in Fig. 5.17.

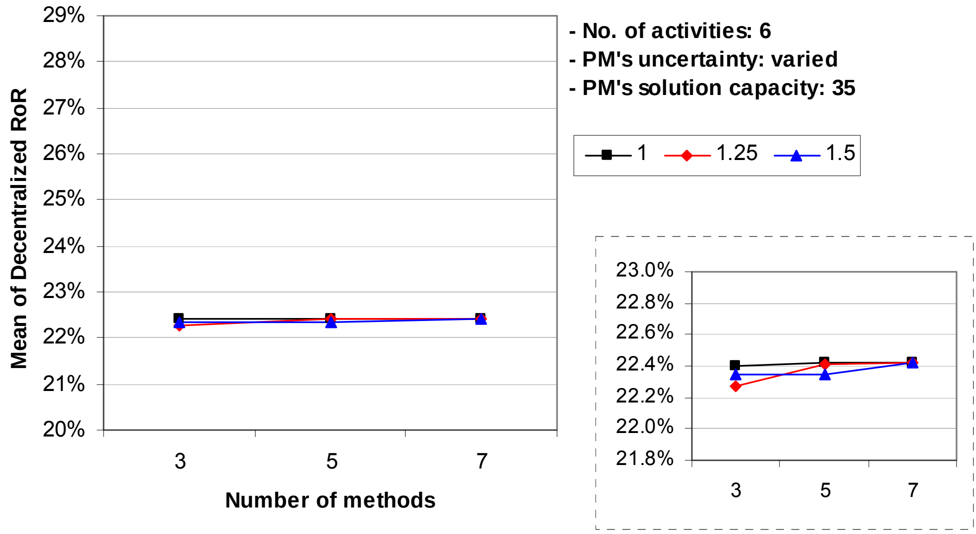


Figure 5.17 Change in mean decentralized RoR with more activities (Different PM's uncertainty)

In addition, the PM's solution capacity is not expected to affect decentralized RoR. Fig. 5.18 shows the result of the impact of the PM's solution capacity on the decentralized RoR.

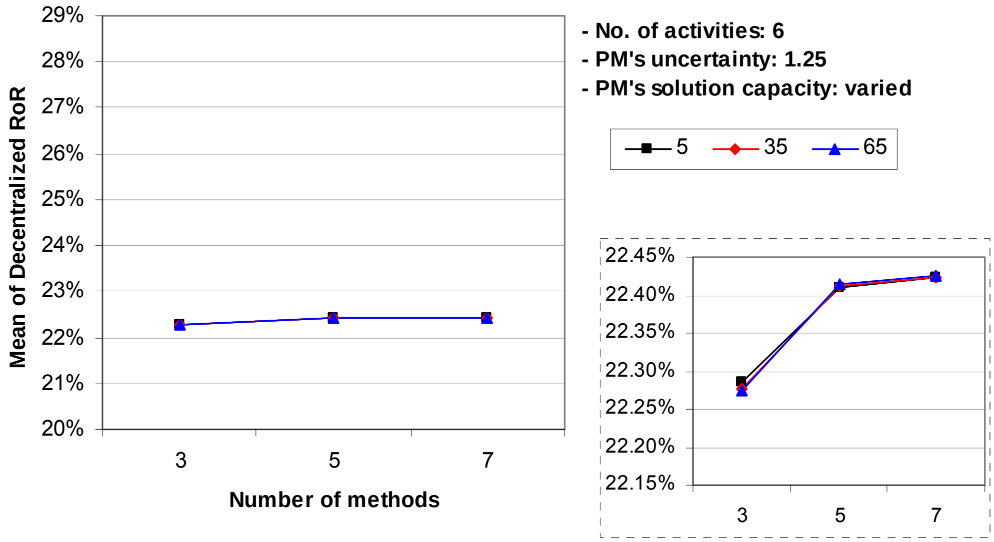


Figure 5.18 Impact of PM's solution capacity on the change in mean decentralized RoR with more methods

5.2.3 Hypothesis #3

The less accurate (or up to date) the knowledge of the project manager, the greater the advantages of decentralized decision making.

While it is assumed that both the PM's knowledge and the subcontractors' knowledge are uncertain with regard to the estimate of additional cost for overlap, the subcontractors' knowledge may be more accurate (or up to date) than the PM's knowledge. Subcontractors are usually specialized in a certain type of activities and they may know better the interaction with their upstream activity or downstream activity. If the PM's knowledge is less accurate than the subcontractors', the PM's own solution in the centralized approach may be improved, but may not be reliable or accepted by the subcontractors. Therefore, the centralized RoR would be reduced from the PM's own

RoR and the centralized RoR may become lower with a higher uncertainty in the PM's knowledge. If a higher uncertainty in the PM's knowledge leads to a lower RoR, then it would be recommended to invest more resources to reduce the uncertainty in knowledge.

On the other hand, a decentralized RoR is expected to not be affected by the PM's uncertainty, because the methods and the degree of overlap are mainly determined by the subcontractors. Therefore, as the uncertainty in the PM's knowledge becomes bigger, it is expected that the decentralized approach becomes preferred to the centralized approach.

- Centralized approach

The uncertainty in the PM's knowledge does not affect the mean of centralized RoR.

While a less accurate PM's uncertainty lowers the mean of centralized RoR, it is concluded that the PM's uncertainty does not affect the mean of centralized RoR. Thus the hypothesis should be rejected.

However, the PM's own RoR is observed to increase as his knowledge becomes less accurate. As the uncertainty increases, the PM's estimated cost will have more variability and estimated cheaper methods will contribute to a higher RoR. This impact of higher uncertainty is shown in Fig. 5.19. The probability distribution of the PM's own RoR is positively skewed and the degree of skewness increases with higher uncertainty. Due to the greater skewness, the mean of the PM's own RoR increases and increases in the PM's own RoR in all the simulation cases are determined to be statistically significant.

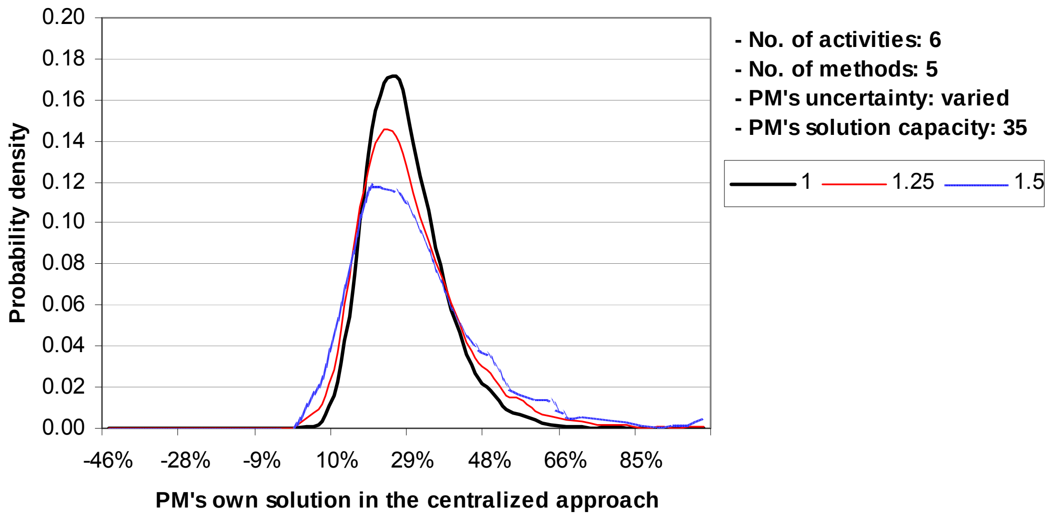


Figure 5.19 Comparison of probability distributions of the PM's own RoR with different PM' uncertainty

However, the PM's solution, which is based on less accurate knowledge, needs a bigger reduction in RoR. If the PM's knowledge is less reliable, then the subcontractors may not accept the PM's solution, or the PM may need to offer a higher markup to make an overlap more attractive. Therefore, the reduction of RoR becomes bigger as the uncertainty in the PM's knowledge increases. This result is shown in Fig. 5.20. While the increase in the PM's own RoR is statistically significant, the centralized RoR does not increase significantly.

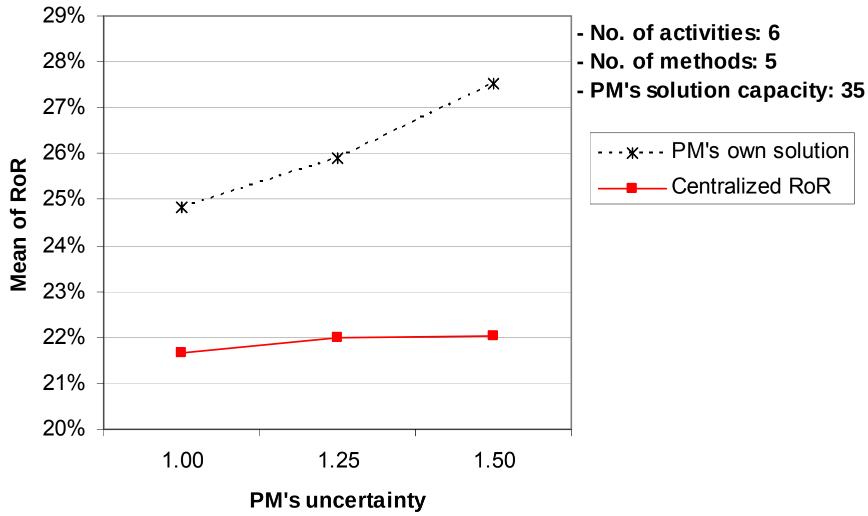


Figure 5.20 Comparison of the changes in the mean PM's own RoR and the mean centralized RoR with a different PM's uncertainty

Fig. 5.21 shows the distributions of the centralized RoR for the same simulation case. While they are slightly skewed to the right, the skewness is less than those of the PM's own RoR. And the mean of the centralized RoR increases slightly with a higher PM's uncertainty, but the increase is not significant.

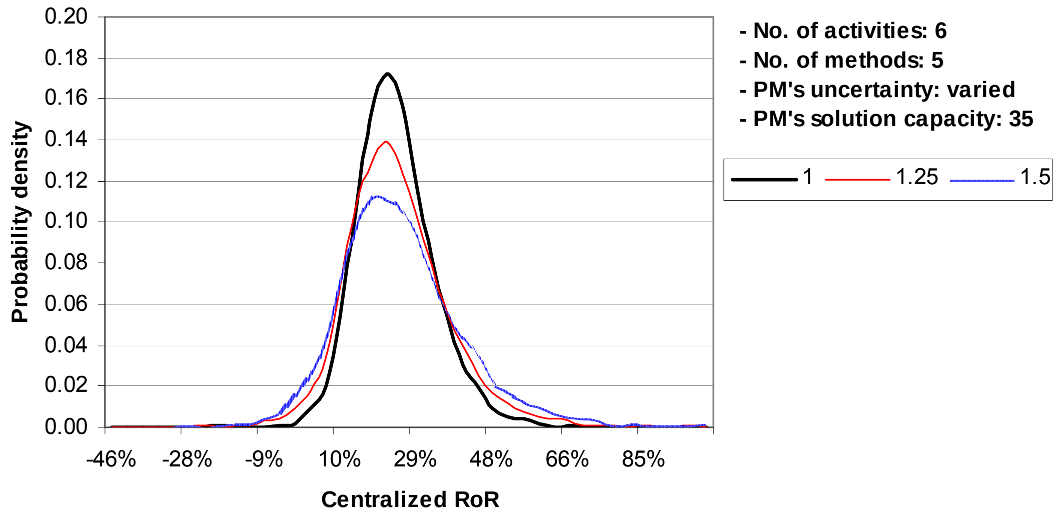


Figure 5.21 Comparison of the probability distributions of a centralized RoR with a different PM's uncertainty

In other simulation cases, the change of the mean centralized RoR due to a less accurate PM’s knowledge are observed as inconsistent. As shown in Fig. 5.22, the change of the mean centralized RoR is not significant and its behavior is not consistent.

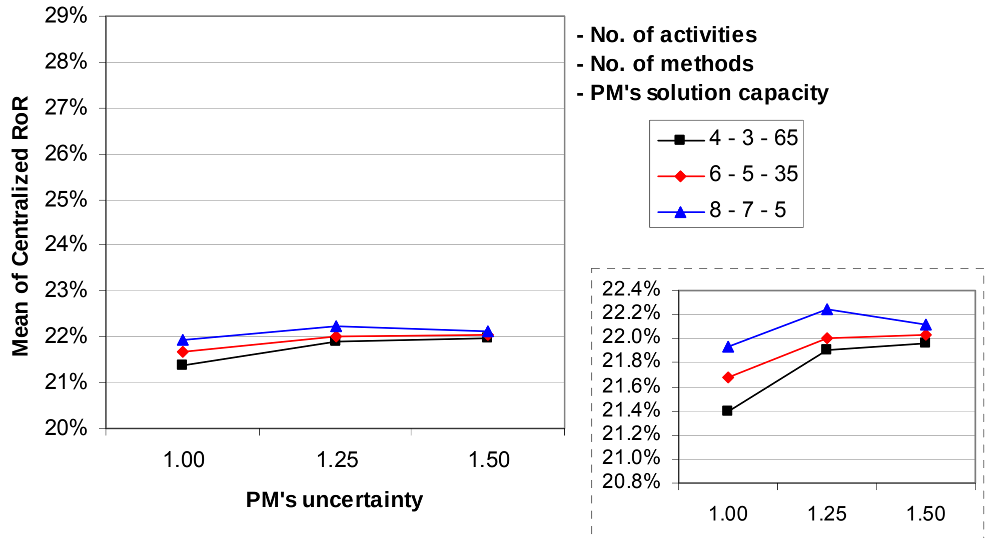


Figure 5.22 Change in mean centralized RoR with different PM's uncertainty

- Decentralized approach

The uncertainty in the PM's knowledge does not affect the mean of decentralized RoR.

A decentralized RoR is observed not to be affected by the PM's uncertainty. While a very slight decrease with a higher PM's uncertainty is observed, the amount of decrease is not significant.

When the PM evaluates the subcontractors' bids, if the PM's uncertainty is high, then it is more likely that the estimated cost will be much higher or lower than the bid price. If the PM's estimated cost is bigger than the bid price, he accepts their bids and the amount of time reduction is reduced and a re-calculated RoR would be lower than he thought. However, this impact through the PM's evaluation may be smaller than the impact of the difference in estimated costs in the centralized approach. In the centralized approach a lower estimated cost by the PM than the subcontractors' estimated cost may reject an overlap. But in the decentralized RoR, an overlap is not canceled through the PM's evaluation process and only the amount of time reduction is reduced.

Fig. 5.23 shows the change of the mean of decentralized RoR with an increase in the PM's uncertainty. The changes are not consistent, nor significant.

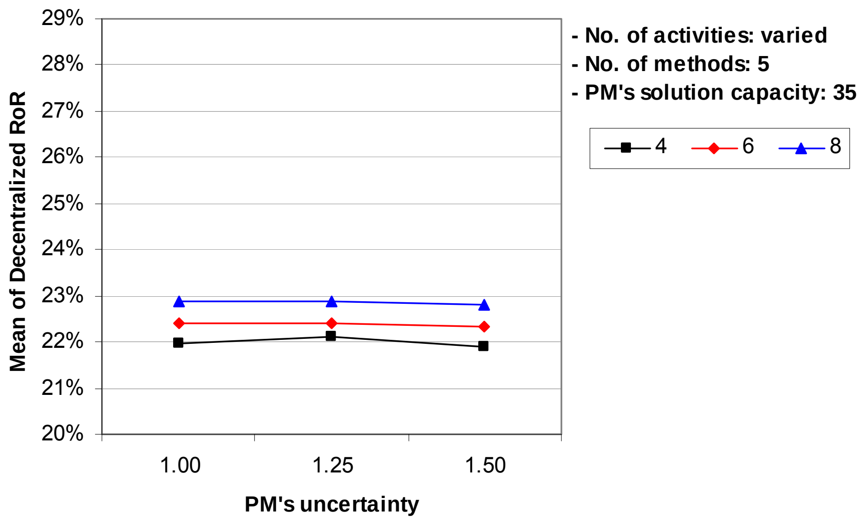


Figure 5.23 Changes in the mean decentralized RoR with different PM's uncertainty

- Comparison between centralized RoR and decentralized RoR

Since both the mean of centralized RoR and the mean of decentralized RoR are not affected by the PM's uncertainty, the hypothesis is rejected. However, from the comparison between the centralized mean of RoR and the decentralized mean of RoR, it can be concluded that the decentralized RoR is preferred to the centralized approach. In the simulation cases in which the mean of decentralized RoR is bigger than that of the centralized RoR, the differences are significant. However, in the simulation cases in which the mean of centralized RoR is bigger, the difference is very slight. When considering no significant impact of the PM's uncertainty, it can be concluded that the mean of decentralized RoR is bigger than the mean of centralized RoR. Fig. 5.24 and Fig. 5.25 show two example simulation cases regarding the difference between a centralized RoR and a decentralized RoR.

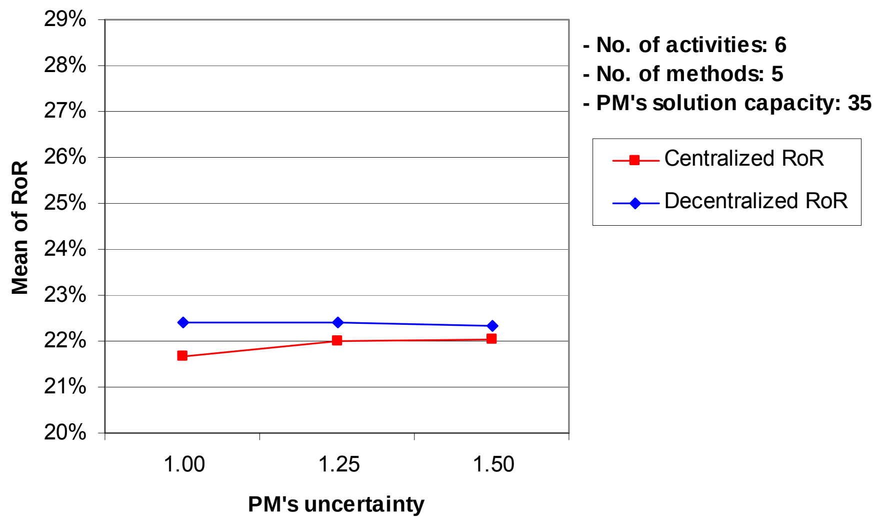


Figure 5.24 Comparison of the impacts of PM's uncertainty on centralized RoR and decentralized RoR

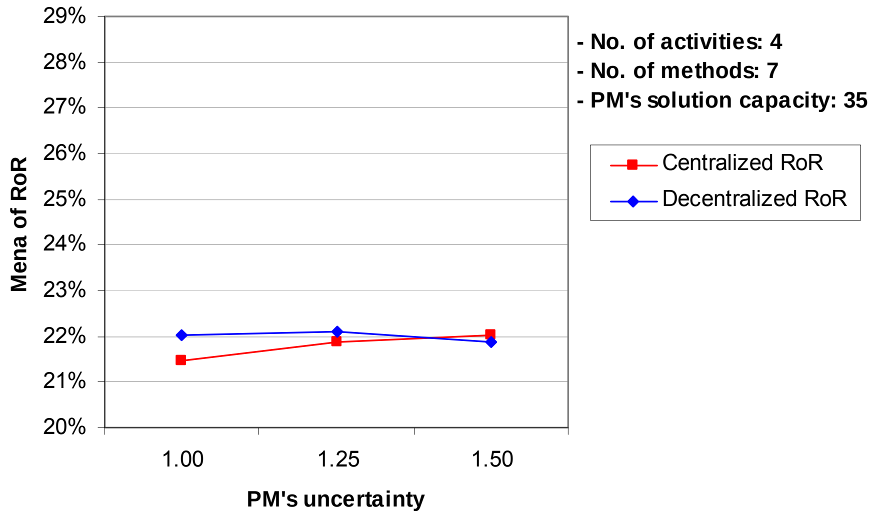


Figure 5.25 Comparison of the impacts of PM's uncertainty on centralized RoR and decentralized RoR

5.2.4 Hypothesis #4

The centralized solutions have a higher variance than the decentralized solutions.

- *The variances of the centralized solutions are higher than the decentralized solutions when the project manager's knowledge is as accurate as the subcontractors'.*
- *The variances of the centralized solutions are higher than the decentralized solutions when the project manager's knowledge is less accurate than the subcontractors'.*

In the centralized approach, the accuracy of the PM's estimates for cost, duration, future revenues of the project and economic life of the project would be affected by the uncertainty in the project manager's knowledge. If the project manager's knowledge is less accurate (or up to date) than the subcontractors, his estimated cost, for example, would have a wider range than the subcontractors'. However, the high variance in the project manager's estimates may be reduced through the project manager's decision-making process and through the subcontractors' rejection (or acceptance) of the project manager's solution. If this is the case, the project manager may not need to reduce the uncertainty in his knowledge. On the other hand, high uncertainty in the project manager's knowledge may lead to a high variance in the centralized RoR. If RoR has a high variance, it may not be favored by the project owner who is more interested in the risk of a lower RoR.

Furthermore, the impact of the uncertainty in the project manager's knowledge on the variance in the centralized RoR would change the risk-averse owner's preference between the centralized approach and the decentralized approach.

- Centralized approach

Variance of centralized RoR increases with higher uncertainty in the PM's knowledge.

In the centralized approach it is observed that a higher uncertainty in the PM's knowledge leads to a higher variance in the centralized RoR. As the uncertainty in the PM's knowledge increases, the variance of the PM's own RoR significantly increases. That means the uncertainty in the PM's estimates affects the PM's own RoR even through his optimization process. Fig. 5.26 shows the increase in the standard deviation of the PM's own RoR with higher PM's uncertainty. Also, it is observed that the variance of the PM's own RoR slightly increases with a larger PM's solution capacity. While it is determined that the increase in variance of the PM's own RoR is not significant, more solution capacity does not reduce the variance of the solution.

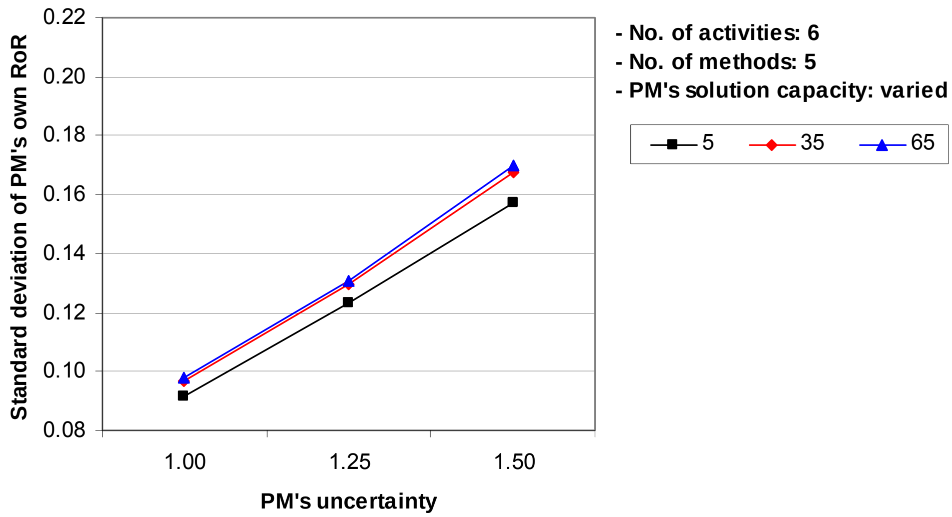


Figure 5.26 Change in standard deviation of PM's own RoR with different PM's uncertainty

Fig.5.27 shows the significant increase in variance of the centralized RoR with a higher PM's uncertainty. Variance of the centralized RoR still increases with a higher PM's uncertainty even after negotiation between the PM and subcontractors.

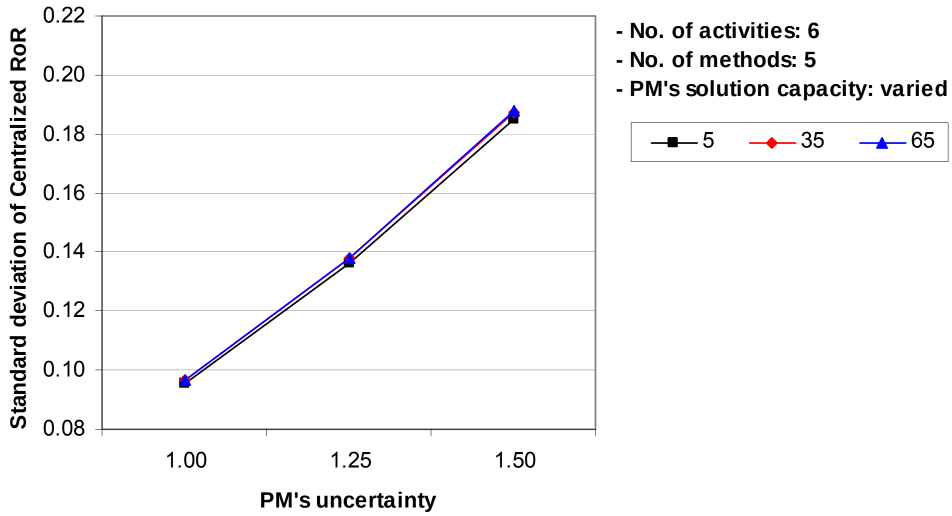


Figure 5.27 Change in standard deviation of centralized RoR with different PM's uncertainty

However, when variances (or standard deviations) both of the PM's own RoR and the centralized RoR are compared, the centralized RoR always has a higher variance than the PM's own RoR. When subcontractors and the PM negotiate, the PM would add more markup to make an overlap more attractive and the subcontractors may accept or reject the PM's offer for an overlap. This negotiation process increases the variance. Fig. 5.28 compares the probability distribution of the PM's own RoR to that of the centralized RoR as an example. It is obvious that high positive skewness (long tail to the right) of the RoR is reduced, but the variance increases.

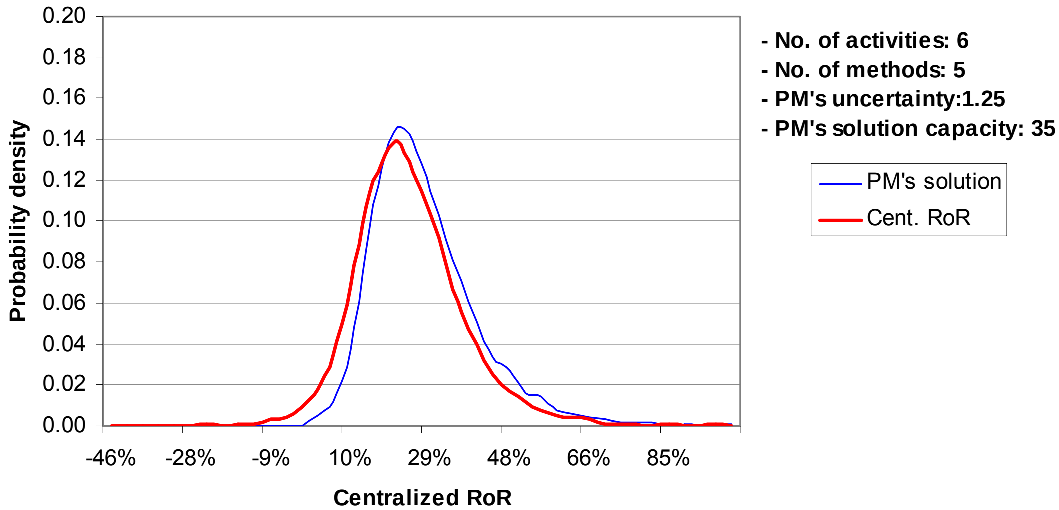


Figure 5.28 Comparison of the distributions of PM's own RoR and centralized RoR

In addition to the impact of the PM's uncertainty, the impacts of other parameters on the variance of the centralized RoR are examined. All of the other parameters, number of activities, number of methods, and the PM's solution capacity have no effect or negligible effect on the variance of centralized RoR. Fig. 5.29, Fig.5.30 and Fig.5.31 show example results of the impacts of other parameters.

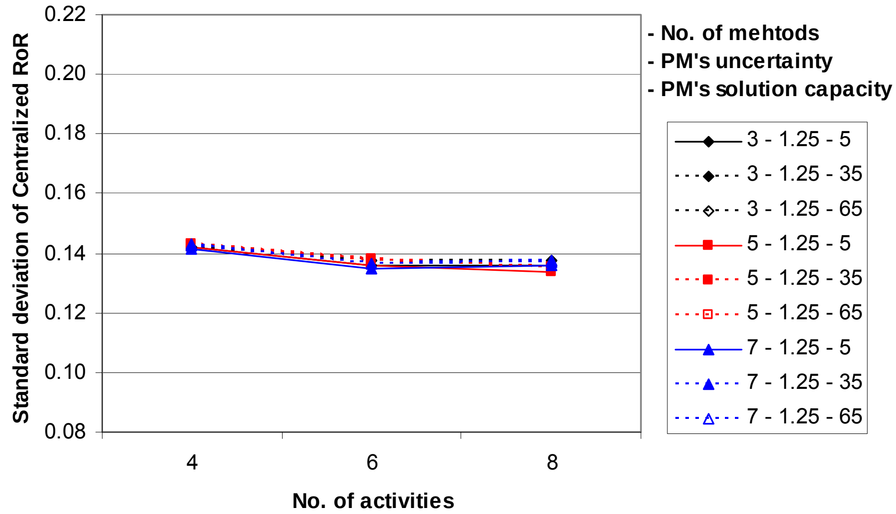


Figure 5.29 Changes in standard deviations of centralized RoR with more activities

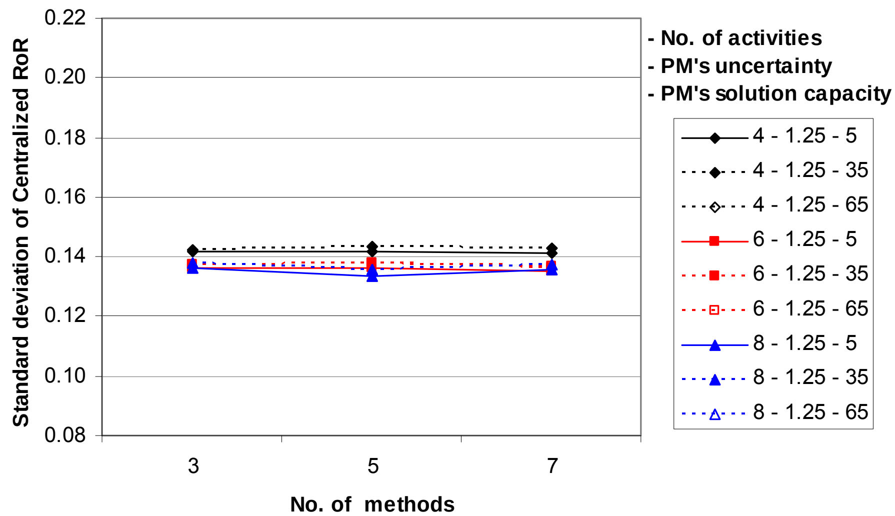


Figure 5.30 Changes in standard deviations of centralized RoR with more methods

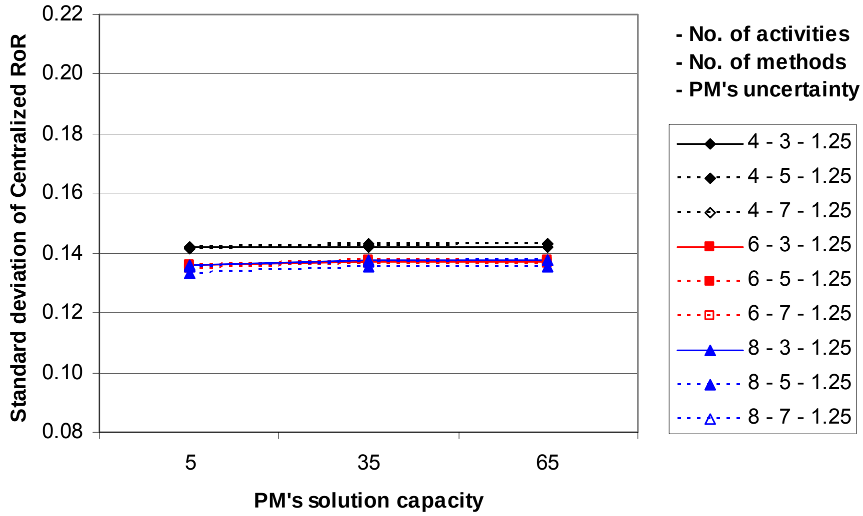


Figure 5.31 Changes in standard deviations of centralized RoR with more PM's solution capacity

- Decentralized approach

  Variance of the decentralized RoR is not affected by the uncertainty in the PM's knowledge.

Since it is expected and observed that the uncertainty in the PM's knowledge does not affect the decentralized RoR, the variance of decentralized RoR is not affected by a higher uncertainty in the PM's knowledge. Fig. 5.32 shows no impact of the PM's uncertainty in the variance of decentralized RoR.

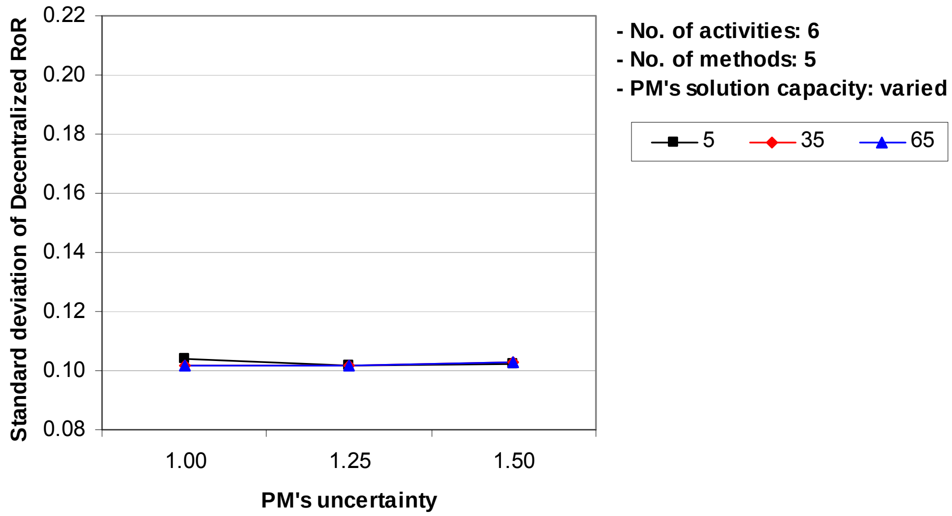


Figure 5.32 Change in standard deviations of decentralized RoR with different PM's uncertainty

- Comparison between the centralized RoR and decentralized RoR

Centralized RoR proves to have a higher variance than the decentralized RoR, as the uncertainty in the PM's knowledge increases.

Since the variance of centralized RoR significantly increases with a higher PM's uncertainty and the variance of decentralized RoR is not affected by the PM's uncertainty, it is concluded that the variance of centralized RoR increases with a higher PM's uncertainty than the decentralized RoR. Fig. 5.33 shows the ratio of standard deviation of a centralized RoR to that of a decentralized RoR. The ratio, which is bigger than 1.0, represents a bigger variance of centralized RoR than the decentralized RoR.

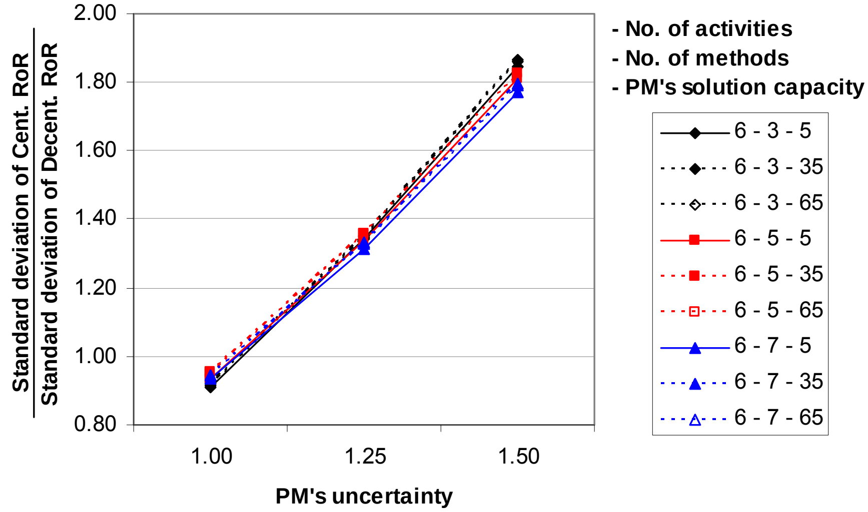


Figure 5.33 The impact of PM's uncertainty on the ratio of standard deviation of centralized RoR to standard deviation of decentralized RoR

While the centralized RoR has a bigger variance than the decentralized RoR, if the PM's knowledge is less accurate than the subcontractors', the centralized solutions have a slightly smaller variance than the decentralized solutions if the PM's knowledge is as accurate as the subcontractors'. This result is observed in all of the simulation cases, thus it is concluded that the centralized approach provides a slightly more reliable solution than the decentralized approach if the PM's knowledge is improved as much as the subcontractors'.

5.2.5 Hypothesis #5

Risk-averse attitudes by the project manager and subcontractors favor decentralized decision making.

- The decentralized approach is preferred under risk-averseness when the PM's knowledge is as accurate as the subcontractors'.
- The decentralized approach is preferred under risk-averseness when the PM's knowledge is less accurate than the subcontractors'.

If both the project manager and subcontractors are risk-averse, then their estimated cost would be over-estimated based on their confidence level to avoid the risk of cost overrun. This attitude will result in the selection of more conservative methods, because less conventional methods are assumed to have a higher variance than conventional methods. Also, it would lead to less overlap than under a risk-neutral attitude, because estimated costs under a risk-averse attitude would be more expensive.

Moreover, it is assumed that a risk-averse project manager (or the project owner) measures the monetary performance of his project by a VaR under 95% confidence levels. Thus the measurement (VaR) under a risk-averse attitude is related with the variance of RoR as well as the mean of RoR. If the centralized solutions have a higher variance than the decentralized solutions, then the VaR of the centralized solution would be lower than that of the decentralized solution.

- ***The decentralized approach is always preferred to the centralized approach under a risk-averse attitude if the PM's knowledge is less accurate than the subcontractors.***
- ***The centralized approach may be slightly preferred to the decentralized approach under a risk-averse attitude if the PM's knowledge is as accurate as the subcontractors'.***

Since it is concluded that variance of centralized RoR based on a higher uncertainty in the PM's knowledge is bigger than that of the decentralized RoR in hypothesis #4, the decentralized approach becomes more preferred with a higher PM's uncertainty under a risk-averse attitude. And when the PM's knowledge is as reliable as the subcontractors', it is concluded as in the previous hypothesis that the variance of centralized RoR is smaller than the decentralized RoR. Therefore, the decentralized approach may be preferred depending on the mean values as well as variance. Fig. 5.34 shows the probability distributions of a centralized RoR and decentralized RoR under a risk-averse attitude.

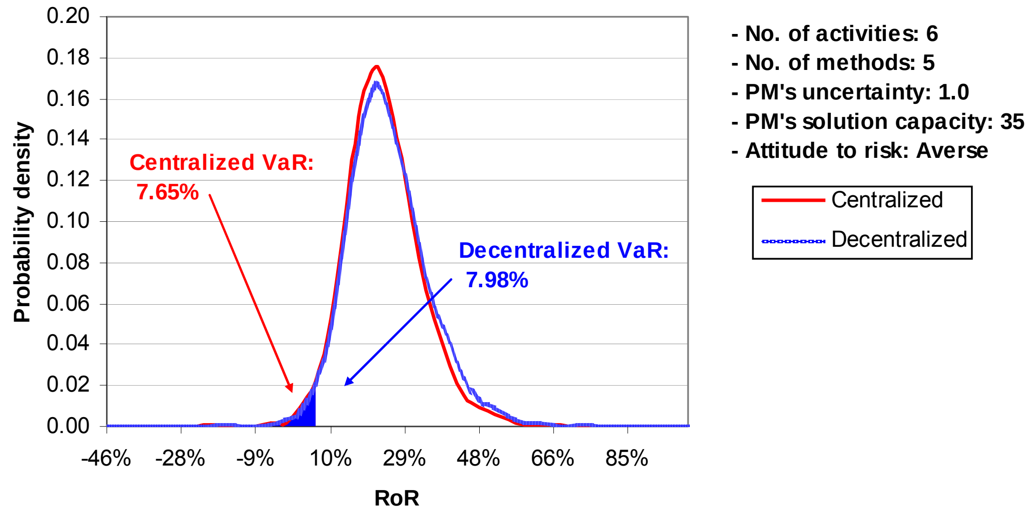


Figure 5.34 VaRs of centralized RoR and decentralized RoR when PM's uncertainty is 1.0

When the PM's knowledge is as accurate as the subcontractors as shown in Fig. 5.34, the variance of the centralized RoR (0.0958) is slightly smaller than that of the decentralized RoR (0.1037). But the mean of the decentralized RoR (22.67%) is slightly higher than that of the centralized RoR (21.50%). Therefore, VaR of the decentralized RoR is slightly higher than that of the centralized RoR.

As the uncertainty in the PM's knowledge increases into 1.25, then VaR of the centralized RoR becomes lower (3.66%). And in this case, the decentralized approach should be recommended. Moreover, higher PM's uncertainty (1.5) leads to a stronger preference of the decentralized approach as opposed to the centralized approach. Fig. 5.35 and Fig. 5.36 show the preference of the decentralized approach under a risk-averse attitude and a high PM's uncertainty.

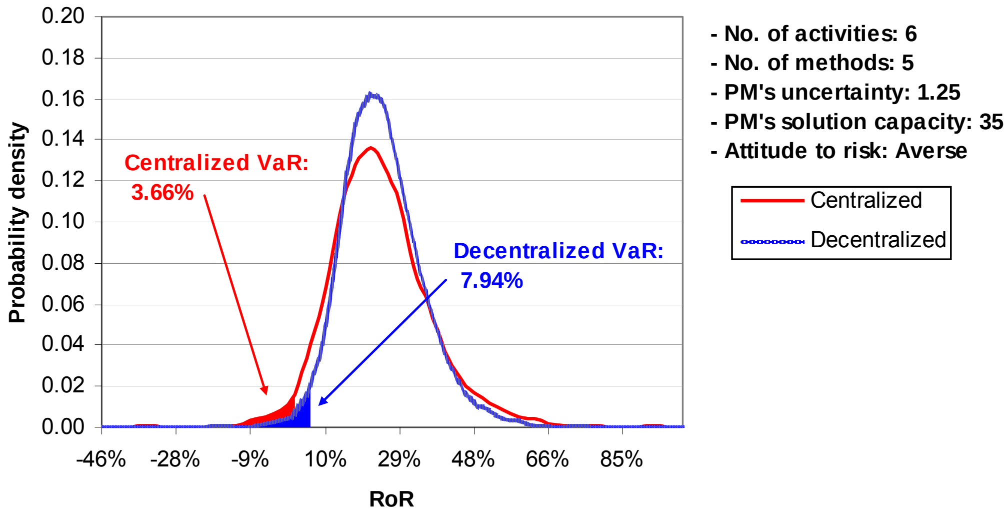


Figure 5.35 Comparison of VaRs under risk-averse attitude when PM's uncertainty is 1.25

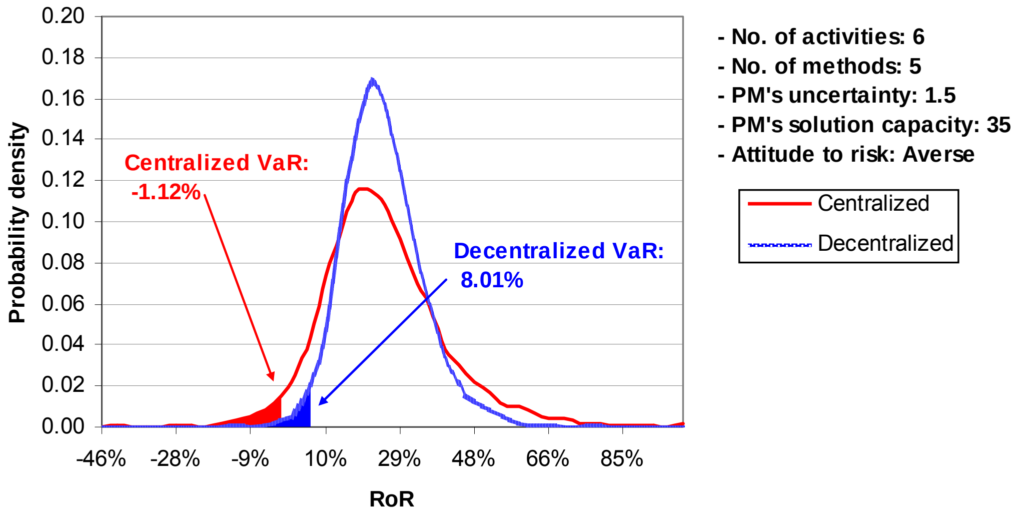


Figure 5.36 Comparison of VaRs under risk-averse attitude when PM's uncertainty is 1.50

5.3 Conclusion of Results of Simulations

The hypotheses are tested based on the simulated results, and the results of the hypothesis test are:

- **The greater the number of activities, the greater the advantages of decentralized decision making.**

While the mean of decentralized RoR increases with more activities, the mean of centralized RoR increases only in some conditions, and does not increase in other conditions. And the rate of increase in the mean of decentralized RoR due to more activities is higher than that in the centralized approach. Thus this hypothesis is accepted.

- **The project owner benefits from more methods.**

- Benefits from more methods in the centralized approach.

While the project manager's own solution benefits from more methods under some conditions, more methods are not beneficial to a centralized RoR. Thus, this hypothesis is rejected.

- Benefit from more methods in the decentralized approach.

While subcontractors possibly benefit from more methods under some conditions, RoR does not increase by considering more methods.

This hypothesis (both sub-hypotheses) is rejected under the given parameter values and it is concluded that fewer methods are just as good as more methods, thus subcontractors are justified in not proposing more innovative work methods.

- **The less accurate (or up to date) the knowledge of the project manager, the greater the advantages of decentralized decision making.**

The centralized solutions are not affected by the uncertainty in the PM's knowledge, while the PM's own solutions benefit from the higher uncertainty in the PM's knowledge. The uncertainty in the PM's knowledge does not affect the decentralized RoR. Thus this hypothesis is rejected.

- **The centralized solutions have a higher variance than the decentralized solutions.**

- **The variances of the centralized solutions are higher than the decentralized solutions when the project manager's knowledge is as accurate as the subcontractors'.**

If the PM's knowledge is as accurate as the subcontractors', variance of the centralized RoR are very close to that of the decentralized RoR and may be slightly lower than the decentralized RoR depending on the given set of parameters.

- **The variances of the centralized solutions are higher than the decentralized solutions when the project manager's knowledge is less accurate than the subcontractors'.**

When the PM's knowledge is less accurate than the subcontractors', the centralized RoR has a higher variance than the decentralized RoR. As the PM's knowledge becomes less reliable, the centralized RoR has a higher variance than the decentralized RoR.

- **Risk-averse attitudes by the project manager and subcontractors favor decentralized decision making.**

- **The decentralized approach is preferred under risk-averseness when the PM's knowledge is as accurate as the subcontractors'.**

Since the centralized RoR has a variance very close to or even smaller than the decentralized RoR under low uncertainty in the PM's knowledge, VaRs both of a centralized RoR and a decentralized RoR are very close to one another. Thus there is no strong preference of one approach to the other, when the PM's knowledge has low uncertainty.

- **The decentralized approach is preferred under risk-averseness when the PM's knowledge is less accurate than the subcontractors'.**

When the PM's knowledge has a higher variance than the subcontractors', then the centralized RoR has a higher variance and lower VaR than the decentralized RoR. Therefore, the decentralized approach is preferred to the centralized approach when the PM's knowledge is less reliable than the subcontractors'.

CHAPTER VI

CASE STUDY

6.1 Introduction

The case study applies the developed decision-making models (the centralized approach and the decentralized approach) into a hypothetical construction project for one decision-making approach that can be recommended to the owner of the project. In addition to the determination of the decision-making approach which provides higher benefits to the owner, required change in the condition of the project will be examined for the other decision-making approach to be recommended. The identification of the required change for the use of the other decision-making approach can provide insight to the owner about the selection of the decision-making approach so that the owner can select a better decision-making approach more flexibly with the required change.

6.2 Objectives of the Case Study

The objectives of the case study include

- To show how the two decision-making approaches can be applied to a hypothetical construction project and how a better approach is selected.
- To show what should be advised to the owner if a non-optimal decision-making approach needs to be chosen.

Under specific conditions of the case project, the decision-making processes by the project manager and subcontractors in each of the two approaches are shown and one approach is selected as a better method which can lead to a higher RoR value.

6.3 Methodology of the Case Study

To achieve the objectives of the case study, a hypothetical construction project is developed. For each activity in the hypothetical construction project, several work methods are developed based on RS Means cost data and the related costs and schedules are estimated based on RS Means cost data. Then additional costs required for time reduction through overlap are developed by some assumptions.

To determine the optimal decision-making approach for the case project, specific conditions which represent the values of key parameters are selected by some assumptions. These specific conditions (or values of the key parameters) represent the base case of the project.

Then the simulation model is applied to the base case of the case project and the optimal decision-making approach for this case project is determined. Sensitivity analysis is used to identify the required change in each parameter value, if the optimal approach under the given scenario needs to be changed to the other.

6.4 Development of the Case Project

6.4.1 Description of case project

Case project - 3 story department store with a 16' story height and 95,000 square feet of floor area (Exterior perimeter: 715 linear feet)

Structural features of the case project:

- Building structure: Steel frame and concrete slab, metal deck and beams
- Exterior wall: Face brick with concrete block backup
- Interior: Wall finishes of paint (70%), vinyl wall covering (20%), and ceramic tile (10%) on partitioned with gypsum board on metal studs
    - Floor finishes of carpet tile (50%), marble tile (40%) and terrazzo (10%)
    - Ceiling finishes of mineral fiber tile on concealed zee bars
- Two elevators (one hydraulic for passenger, and one hydraulic for freight)
- Four escalators

This case project is composed of nine phases (or activities) in the upper level: excavation, substructure, superstructure, exterior enclosure, interior construction, interior finishes, fire protection, mechanical (including plumbing and HVAC) and electrical. A critical path network for the case project is presented in Fig. 6.1.

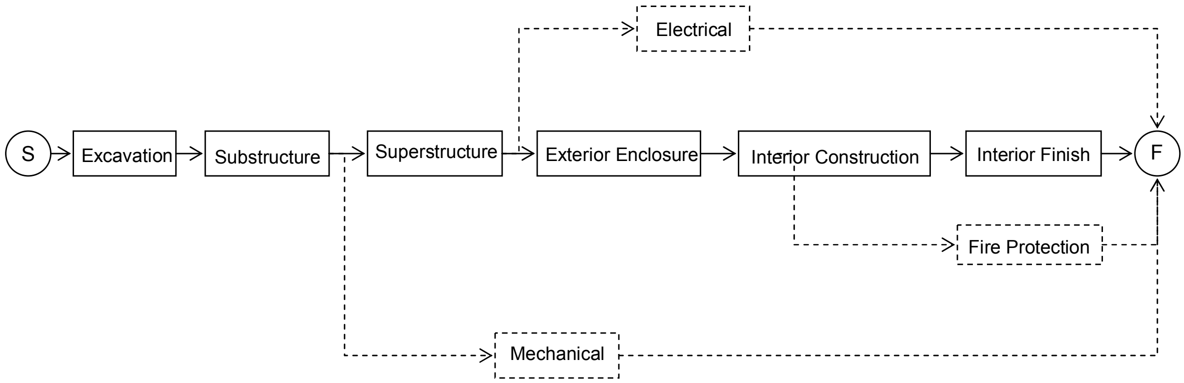


Figure 6.1 The critical path network of the case project

While all of the nine activities compose this case project, the critical path is assumed to be made up of excavation, substructure, superstructure, exterior enclosure, interior construction and interior finish as shown in Fig. 6.1, only the activities on the critical path are taken into consideration and tested for time reduction through overlapping between activities.

This case project is based on a sample of the calculation of square foot cost (RS Means 2004), and the summary of the project cost estimates is as follows. Detailed cost estimates are presented in Appendix1.

- Total project cost: $7,483,625
- Cost of the activities on the critical path: $5,029,870

(67.21% of total project cost)

The duration of this case project is estimated based on the unit cost estimation (RS Means 2003) without the consideration of any time reduction in each activity. A detailed estimate of duration is presented in Appendix 2, and Fig. 6.2 shows the duration of this case project.

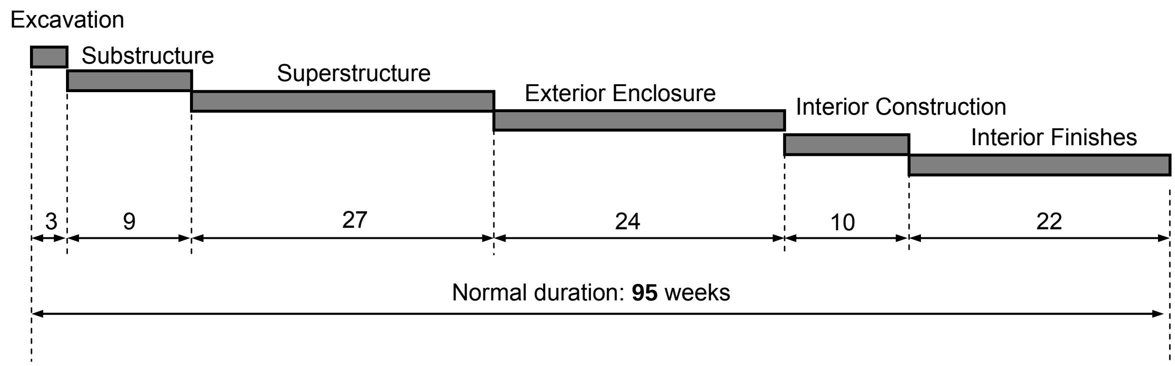


Figure 6.2 The baseline schedule of the case project

6.4.2 Work methods in each activity

The estimates of cost and duration for this case project are based on normal work methods in each activity. This normal work method in each activity is assumed to be the base method in that it requires the least cost without time reduction. However, if a pair of activities are overlapped for time reduction, this base method may not be the best method due to additional cost required for a time reduction. Another pair of work methods which require more cost than the base method on normal schedule may facilitate the overlapping; requiring less additional cost for time reduction.

Thus, this case study exemplifies multiple work methods in each activity, each of which requires a different crew size, type of equipment, and subsequence or batch size based on some assumptions. While these work methods may not be realistic, the multiple work methods are examples of multiple work methods in a construction project and to show how overlapping between activities can be affected by a different set of work methods.

This case study develops six work methods, including the base method in each activity, based on the following assumptions:

- **Excavation**

The sub-activities in this activity include site preparation for the slab and trenching for the foundation wall and footings (strip and spread). A plan of the substructure for this case project was made-up as shown in Fig. 6.3 based on the general description of this project and sub-activities used in the estimation of square foot cost in Appendix 1.

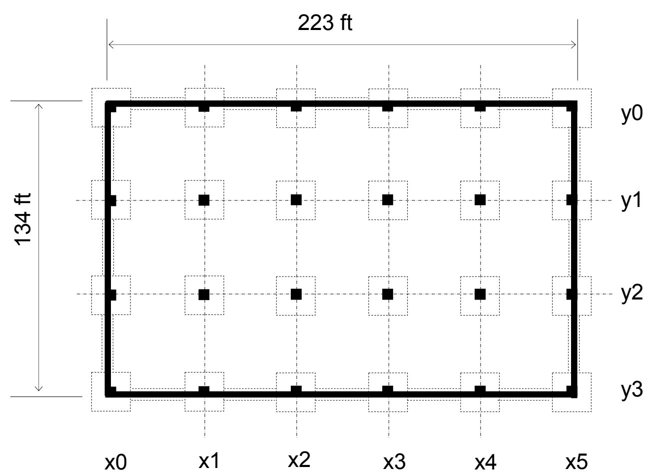


Figure 6.3 Sub-structure of the building for the case project

The subcontractor for excavation is assumed to prefer excavating footings in a row consecutively and going down to the footings in the next row as shown in Fig.

6.4.(a). The sub-sequence of excavating footings (spread or strip footings) is x0y0→ x1y0→ x2y0→ x3y0→ x4y0→ x5y0→ x5y1→ x4y1→ ….→ x0y3. In addition, the subcontractor for the excavation is assumed not to allocate additional resources (equipment and operators). That sub-sequence with one crew is assumed to require the least cost if no time reduction is considered, thus this work method is set as the base work method. Alternately, excavation for footings in a column and moving to the next column with one crew can be another work method in that excavation is carried out in a different sequence with different cost. However, this sub-sequence is assumed to incur the loss in productivity, thus, requires more cost than the base work method.

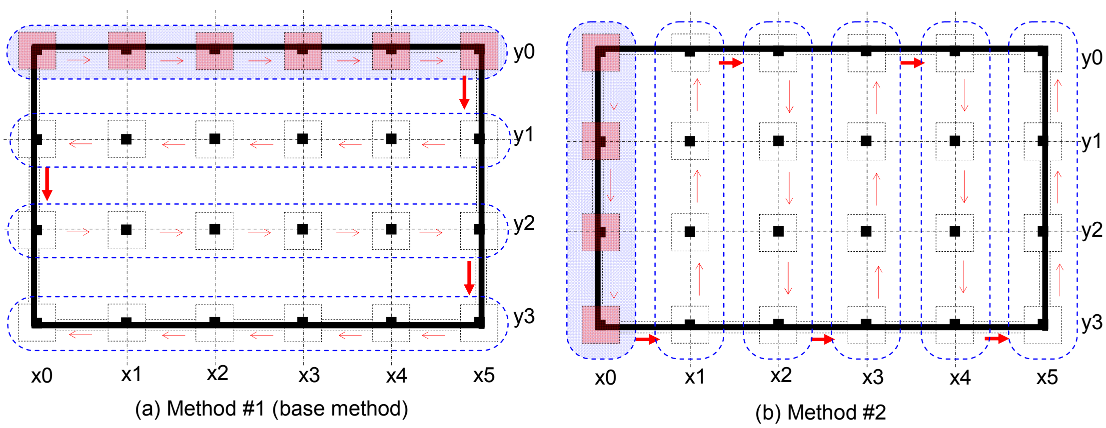


Figure 6.4 Work method #1 and work method #2 for excavation

Another sequence under which the subcontractor may carry out excavation is to excavate some footings which are adjacent in both the x and y-axis directions at a time and to move to the next set of footings as shown in Fig. 6.5.(a). Or he may excavate for the outer footing (both strip and spread footings) first, then excavate for the inner spread footings as shown in Fig. 6.5.(b).

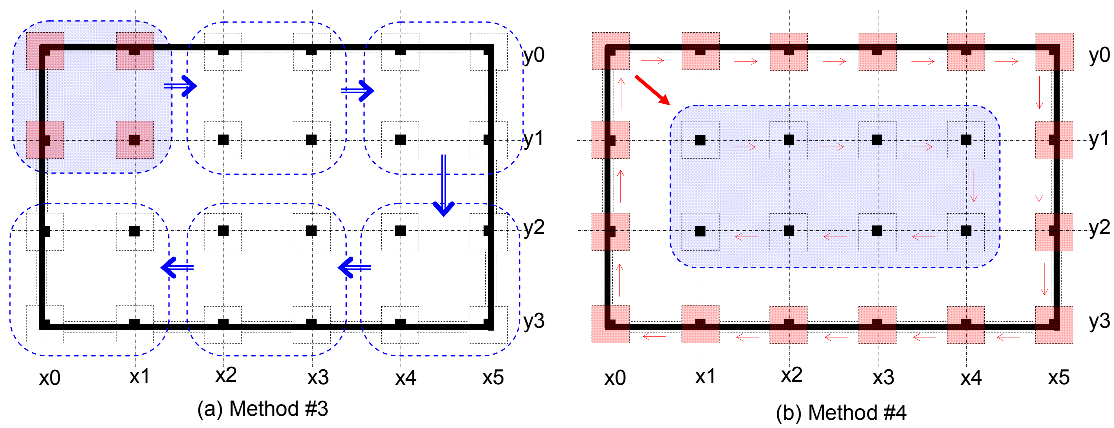


Figure 6.5 Work method #3 and work method #4 for excavation

Alternatively, the subcontractor may excavate the inner spread footings first, then excavate the outer strip and spread footings later as shown in Fig. 6.6.(a). These five sub-sequences for excavation are assumed to be executed by one crew of one excavator and the operator. The subcontractor may execute the job with two crews (two excavators) to finish the job earlier: one crew for the inner spread footings, and the other crew for the outer strip and spread footings simultaneously as shown in Fig. 6.6.(b). While using more resources can lead to the earlier completion of the job, it may cause lower productivity due to overcrowding on the site. Thus, it is assumed that simultaneous excavation of both outer strip and spread footing and inner spread footing can reduce excavation earlier, but the productivity is lost to some degree.

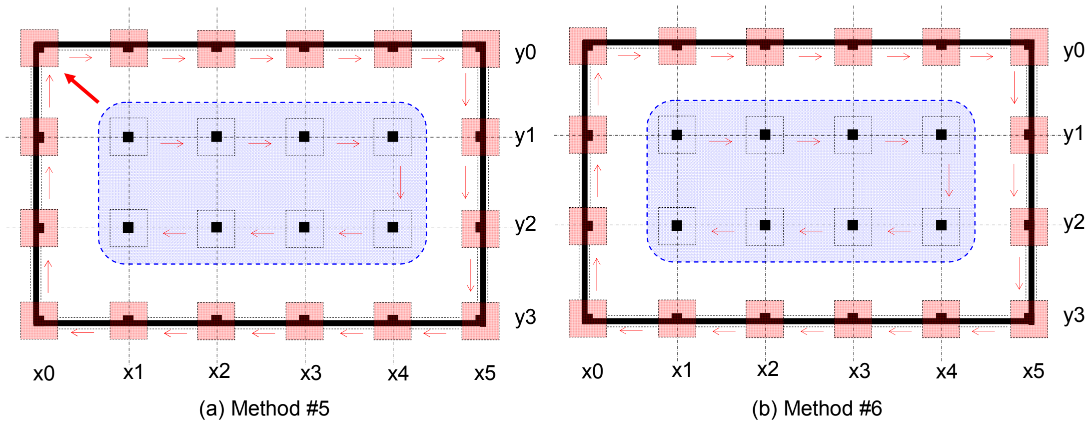


Figure 6.6 Work method #5 and work method #6 for excavation

Depending on the sub-sequence and amount of resources (crew size), six work methods for excavation are developed as follows:

a) Method #1: Excavation for footings in a row and moving to the next row with one crew (the base method)

b) Method #2: Excavation for footings in a column and moving to the next column with one crew

c) Method #3: Excavation for a group of footings adjacent to each other, then moving to the next group of footings with one crew

d) Method #4: Excavation for the outer strip and spread footings followed by excavation for the inner spread footings with one crew

e) Method #5: Excavation for the inner spread footings followed by excavation for the outer strip and spread footings with one crew

f) Method #6: Simultaneous excavation for both the inner spread footings and outer strip and spread footings with two crews

The base work method (Method #1) is assumed to require the least cost when no time reduction is required and the other work methods (Method #2 ~ Method #6) are assumed to require more cost due to the loss in productivity.

- **Substructure**

The sub-activities in this activity include the construction of the footings, foundation wall and slab on grade. As for this activity, several work methods are developed depending on the sub-sequence and the amount of resources similar to the activity of excavation.

The normal sequence for the substructure may be to construct (formwork, rebar and concrete work) footings and foundation walls (or columns), then to backfill and to place concrete for the slab on grade. That is, after placing and curing concrete for the footings and backfilling, forming and installing rebar for the slab on grade would start. However, to facilitate overlapping with the downstream activity, all areas of the slab on grade may not be constructed at one time. Instead, the slab can be subdivided and constructed sequentially. The division of the slab into smaller areas can allow downstream activity to start earlier, thus two activities (substructure and superstructure) can be executed simultaneously by some degree. Also, the construction of the footing will be affected by the compatibility with the work methods developed for excavation.

The base method is assumed to construct footings in a row and to move to the next row and start constructing the slab on grade only after all the footings are constructed and the backfill is finished with one crew as shown in Fig. 6.7.(a). With this base method, it is assumed that the sub-sequence of constructing footings followed by constructing footings in the next row incurs the least cost and the best productivity. Another method can be to construct footings in a column and to move to the next column, then to construct the slab on grade as shown in Fig. 6.7.(b). This subsequence is assumed to lead to a lower productivity than the base method. Thus, more cost is required than the base method.

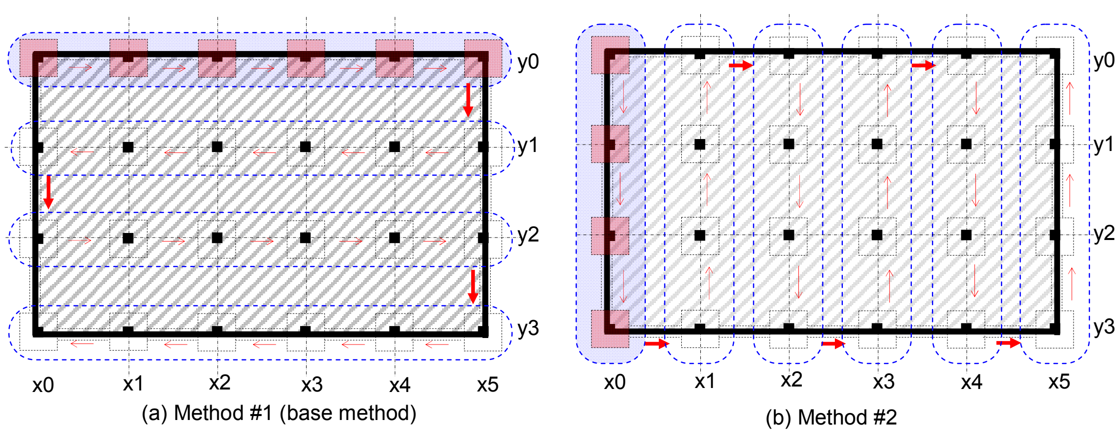


Figure 6.7 Method #1 (base method) and method #2 for substructure

The next method is to start the construction of the slab only after 50% of the footings are constructed with the subsequence of constructing footings in a row and moving to the next row as shown in Fig. 6.8.(a). Alternatively, the sub-sequence of constructing footings in a y-axis and moving to the next footings with a batch size of 50% of the slab is available as shown in Fig. 6.8.(b). These two methods are assumed to incur a loss in productivity due to the smaller work amount for concrete pouring than in the base method.

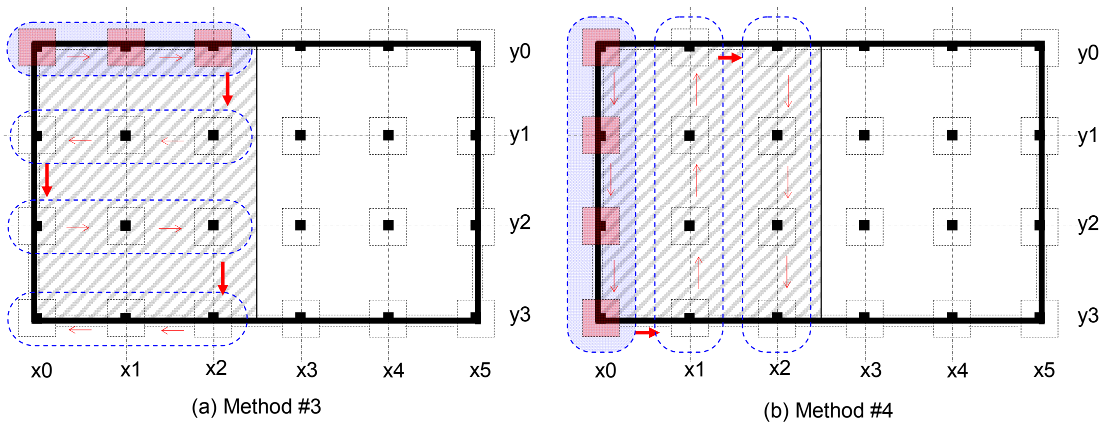


Figure 6.8 Method #3 and method #4 for substructure

Moreover, the size of the slab on grade to be constructed at one time can be reduced to a quarter of the whole slab. A smaller batch size of slab on grade can allow for an earlier release of work to downstream activity. However, the small amount of work with a fixed sized crew may make the resources idle by some degree. Thus it is assumed that a smaller batch size leads to lower productivity. This method, #5, is shown in Fig. 6.9.(a). Instead of using one crew for the construction of the footings, foundation walls and slab on grade, using two crews constitutes another method (#6). As shown in Fig. 6.9.(b), the batch size of half of the slab can allow some substructure activity to be completed earlier, but it can deteriorate productivity due to overcrowding. Thus, it is assumed that the substructure activity can be completed earlier by two weeks with two crews, but productivity gets lowered.

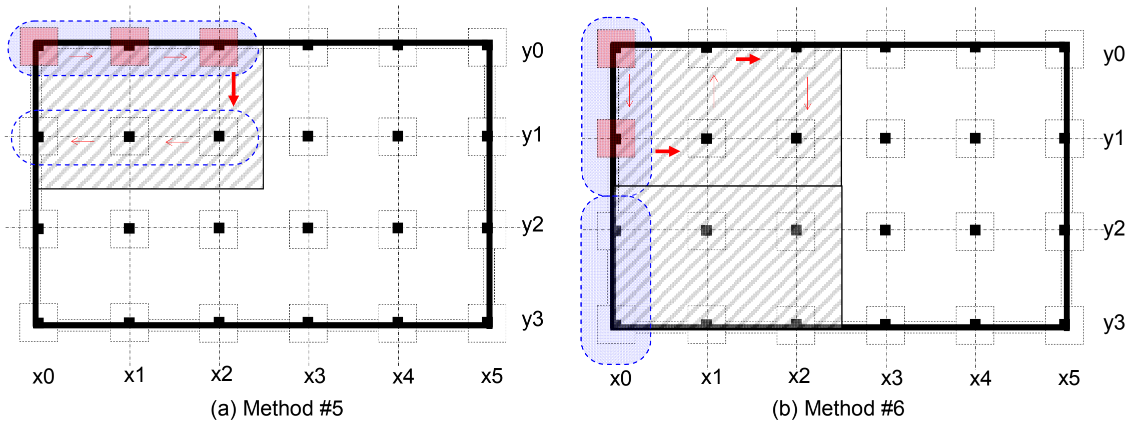


Figure 6.9 Method #5 and method #6 for substructure

The six methods mentioned above are developed and summarized as follows:

a) Method #1: Construction of footings in a row followed by the construction of the footings in the next row and construction of the slab on grade in batch size of a whole slab with one crew (the base method)

b) Method #2: Construction of footings in a column followed by the construction of the footings in the next column and construction of the slab on grade in batch size of a whole slab with one crew

c) Method #3: Construction of the footings in a row followed by the construction of the footings in the next row within a half of the slab and construction of the slab on grade in batch size of a half slab with one crew

d) Method #4: Construction of footings in a column followed by the construction of the footings in the next column within a half of the slab and construction of the slab on grade in batch size of a half slab with one crew

e) Method #5: Construction of footings in a row followed by the construction of the footings in the next row within a quarter of the slab and construction of the slab on grade in batch size of a quarter slab with one crew

f) Method #6: Simultaneous construction of footings in a row followed by the construction of the footings in the next row within a quarter of the slab and construction of the slab on grade in batch size of a quarter slab with two crews

- **Superstructure**

The superstructure of this case study building is composed of a concrete slab with metal deck and beams, plus steel columns. The construction of the superstructure in this case project can be executed in many ways depending on the sub-sequence, and the placement of materials such as the metal deck, steel, and concrete in the required positions, or batch size. Different batch sizes and the way in which concrete is poured over the metal deck were considered in the development of the six work methods.

To pour concrete for the construction of a multi-story building, pumped concrete pouring may be the most efficient and economical way in terms of productivity. Alternatively, concrete can be poured through a crane and a bucket. Also, a tower crane can be used for concrete pouring. However, since the number of stories in the case project is only three, it is assumed that pumped concrete pouring requires the least cost based on the cost estimates from RS Means cost data (RS Means 2004). Thus, concrete pouring with a crane and a bucket is assumed to lead to lower productivity, and to require more cost than pumped concrete pouring due to a higher rental cost for equipment. While a tower crane may not be used for the construction of three-story buildings in real projects, a tower crane is considered as another method. The method using a tower crane is assumed to require much more cost and less productivity. In addition to the way in which the concrete is poured, two different batch sizes are assumed to be appropriate for the superstructure of this case study: a half of floor and a quarter of floor. These two different batch sizes are shown in Fig. 6.10.

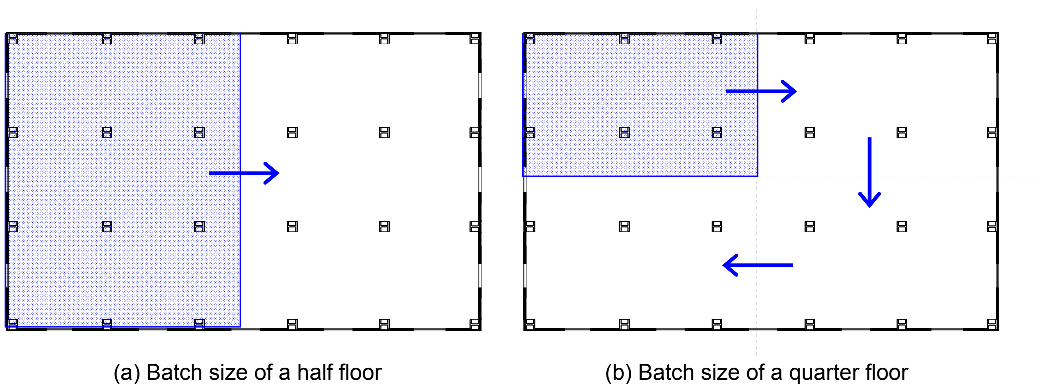


Figure 6.10 Two different batch sizes for the construction of the superstructure

Depending on the combination of these two factors, six work methods for the construction of the superstructure are developed as follow:

a) Method #1: Pumped concrete placement with a batch size of a half floor area (the base method)
b) Method #2: Pumped concrete placement with a batch size of a quarter floor area
c) Method #3: Concrete placement by one hydraulic crane and one bucket with a batch size of a half floor area

d) Method #4: Concrete placement by one hydraulic crane and one bucket with a batch size of a quarter floor area

e) Method #5: Concrete placement by a tower crane with a batch size of a half floor area

f) Method #6: Concrete placement by a tower crane with a batch size of a quarter floor area

- **Exterior enclosure**

The activities involved in the construction of the exterior enclosure include the components of the exterior wall (face brick with concrete block backup), exterior windows and exterior doors. Since masonry work is estimated to hold the highest portion of the cost for this activity, work methods are developed with respect to different methods for the construction of the exterior wall for this case activity.

With the design of two-layer walls (exterior face brick and interior concrete block) as shown in Fig. 6.11, it is assumed that the simultaneous laying of both brick and block is the least expensive method, since sequential laying of both brick and block may require additional work to cope with connectors, such as wire-mesh, between the two layers.

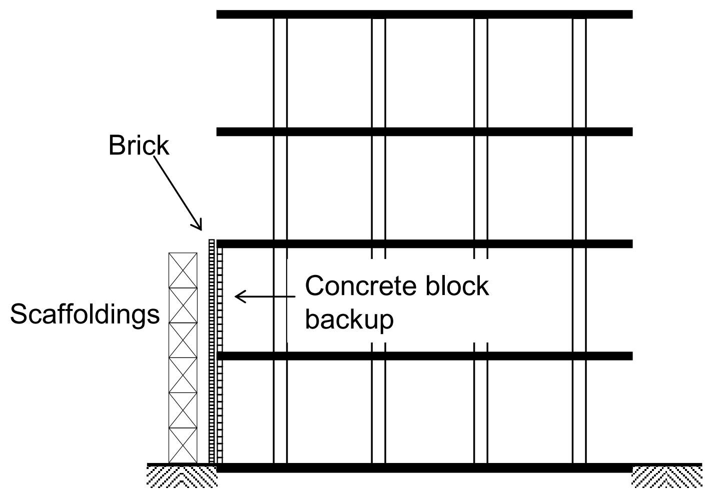


Figure 6.11 Two layers of exterior enclosure

However, the downstream activity (interior construction) does not require the completion of layering of both brick and block, but it does require the completion of the inner concrete block layer. Thus, there are two options of sub-sequence available to the subcontractor: simultaneous laying of both bricks and blocks, and laying of blocks before bricks.

In addition, scaffolding is indispensable equipment for laying bricks (or blocks). Since installation and dismantling of scaffolding require additional cost, it is assumed that subcontractor responsible for the masonry work prefers the completion of the wall on one side of the building enclosure and moving the scaffoldings to work on another side. However, scaffolding may be installed on all sides of the building perimeter at the same time for earlier completion of the enclosure at the expense of additional cost. As shown in Fig. 6.12.(a) and Fig. 6.12.(c), the least cost method is assumed to complete laying masonry on one side from the first floor to the third floor and to move to a next side. However, if all the masonry wall on a floor is built and then the wall on the next floor as shown in Fig. 6.12.(d), scaffolding should be installed on all perimeters of the building as shown in Fig. 6.12.(b).

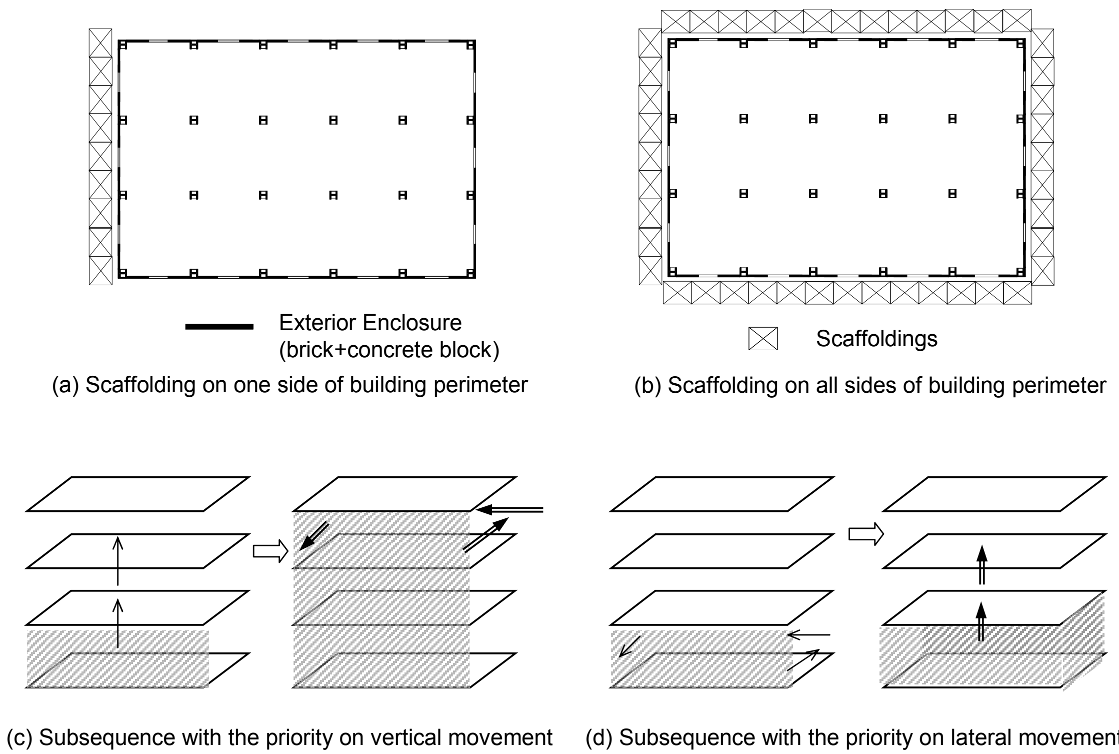


Figure 6.12 Two subsequences for exterior enclosure

Depending on the combination of the two factors, sequence of building two layers and direction of the movement (vertical or lateral), six work methods are developed as follows:

a) Method #1: Vertical movement and simultaneous laying of brick and block with scaffolding on one side of the perimeter and one crew (the base method)

b) Method #2: Vertical movement and laying of brick after block with scaffolding on one side of the perimeter and one crew
c) Method #3: Horizontal movement and simultaneous laying of brick and block with scaffolding on all sides of the perimeter and one crew
d) Method #4: Horizontal movement and laying of brick after laying of block with scaffolding on all sides of the perimeter and one crew
e) Method #5: Laying block with vertical movement followed by laying brick with vertical movement (scaffoldings on all sides of the perimeter) and two crews
f) Method #6: Laying block with horizontal movement followed by laying brick with horizontal movement (scaffoldings on all sides of the perimeter) and two crews

- **Interior construction**

This activity includes the sub-activities of installing partitions, interior doors and stair construction. Of the three, work methods are developed with a focus on partitions. For partition work, scaffolding or similar equipment is required for a 16' story height. It is assumed that steel tabular scaffolding is the common and the least expensive equipment for partitioning. However, a self-propelled lift can also be used at extra cost with the benefit of higher productivity or less duration than tabular scaffolding. Thus, it is assumed that using a self-propelled lift reduces the duration by one week, but it requires additional cost.

In addition, another factor is considered for the development of work methods: requirement of the completion of all sides of the enclosure. The start of interior construction usually requires constructing all sides of the enclosure so that the interior construction is not affected by adverse weather conditions. However, interior construction may start with three sides of the enclosure completed, if the area of floor is large. Thus, it is assumed that interior construction can start after three sides of the exterior wall is built. However, this small batch size may lead to lower productivity; simultaneous work by masonry work and interior construction may require more workers, and more work spaces in a floor, thus productivity can be deteriorated due to overcrowding. This factor is related with batch size. If the batch size of the interior construction is one whole floor area, then the interior construction requires the completion of all sides of the enclosure as shown in Fig. 6.13.(a). However, if the batch size is a half of one floor area, then the interior construction can start with three sides of the exterior walls built as shown in Fig. 6.13.(b). Thus, a small batch size can facilitate overlapping between the exterior enclosure and interior construction.

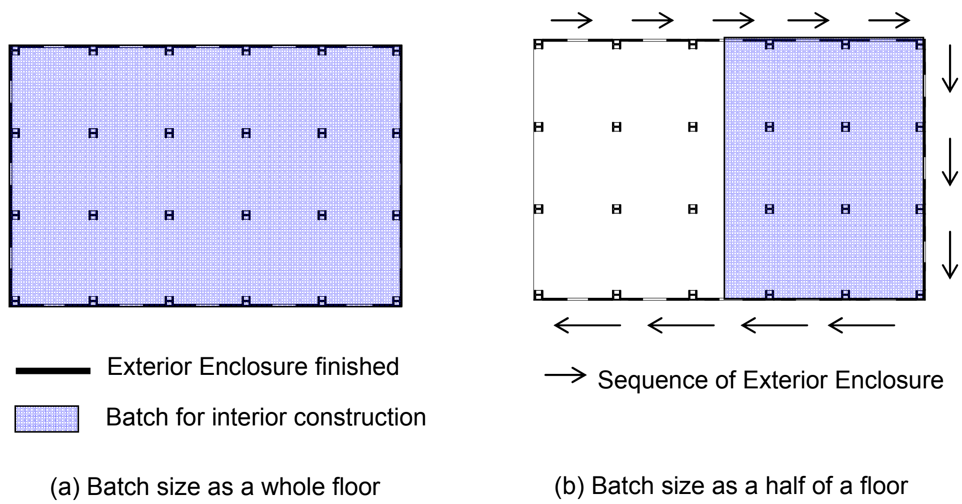


Figure 6.13 Different batch sizes of interior construction

Also, crew size was considered for the development of the work methods. Using two crews is assumed to perform the work for interior construction faster by two weeks with the cost of lower productivity (or additional cost). The six work methods developed for the interior construction is summarized as follows:

a) Method #1: Batch size as a whole floor with tabular scaffolding and one crew (the base method, all four sides of the enclosure should be completed)

b) Method #2: Batch size as a half floor with tabular scaffolding and one crew (at least three sides of the enclosure should be completed)

c) Method #3: Batch size as a whole floor with a scissor-lift and one crew (all four sides of the enclosure should be completed)

d) Method #4: Batch size as a half floor with a scissor-lift and one crew (at least three sides of the enclosure should be completed)

e) Method #5: Batch size as a whole floor with tabular scaffolding and two crews (all four sides of the enclosure should be completed)

f) Method #6: Batch size as a whole floor with a scissor-lift and two crews (all four sides of the enclosure should be completed)

- **Interior finishes**

Interior finishing includes the ceiling, wall and floor finishes with different finish materials. Similar to the upstream activity (interior construction), batch size, type of equipment and crew size were considered for the development of the work methods. However, the interior finish is assumed to have three different batch sizes; a whole floor area, a half floor area, and a quarter floor area. The compatibility of overlapping will be affected by the combination of the batch size of the interior construction and that of the interior finishes. And it is assumed that a batch size as a whole floor area requires the least cost, and smaller batch size causes a loss of productivity. Tabular scaffolding and a self-propelled scissor-lift are assumed to be the options available.

a) Method #1: Batch size as a whole floor with tabular scaffolding and one crew (the base method)

b) Method #2: Batch size as a half floor with tabular scaffolding and one crew

c) Method #3: Batch size as a quarter floor with tabular scaffolding and one crew

d) Method #4: Batch size as a whole floor with a scissor-lift and one crew

e) Method #5: Batch size as a half floor with a scissor-lift and one crew

f) Method #6: Batch size as a whole floor with tabular scaffolding and two crews

6.4.3 Cost estimation

Each activity in this case project is made up with quantity and unit cost as shown in Appendix 2. These cost estimates represent the cost for a normal schedule without time reduction and with the base work methods discussed above. In addition to the base cost estimate, additional cost for time reduction through overlapping with a selected pair of work methods is estimated as follows:

- **Additional cost for each work method with no overlapping**

Productivity is defined as the ratio of output to input as follows:

$$\text{Productivity} = \frac{\text{Output}}{\text{Labor cost}} = \frac{\text{Quantity installed}}{\text{Labor cost including equipments}}$$

Thus, productivity is assumed to represent the amount of quantity installed per dollar of labor cost including equipment. It is assumed that the material cost is not affected by a change in productivity, but labor cost and equipment cost are affected by a change in productivity. Based on this definition of productivity, the productivity of activity (i) with a selected work method (i, j) is calculated as Eq. (6.1).

$$\text{Productivity}(i, j)$$

$$= \frac{\text{Estimated quantity } (i)}{\text{Labor cost including equipments}(i, j)} \times \text{Productivity Coefficient}(i, j) \quad \text{--- Eq. (6.1)}$$

where, $\text{Productivity } (i, j)$ is productivity of activity (i) with method (j).

$\text{Estimated quantity } (i)$ is estimated quantity of activity (i)

$\text{Labor cost including equipments}(i, j)$ is estimated normal cost for labor and equipment of activity (i) with method (j)

$\text{Productivity Coefficient}(i, j)$ is coefficient of productivity in activity (*i*) affected by selected work method (*j*)

Since each activity is composed of several sub-activities, each of which has a different quantity and different unit, an estimated quantity of an activity cannot be calculated accurately from the estimation based on the square foot or unit cost. Therefore, each activity's quantity ($\text{Estimated quantity}(i)$) is assumed to be the quantity of the sub-activity which is the most dominant in terms of cost or time. Labor cost, including equipment for each activity (*i*) and work method (*i*, *j*) is estimated based on the estimated normal cost of each activity and estimated the price of additional cost for change of equipment. The $\text{Productivity Coefficient}(i, j)$ is assumed to be affected by the selected work method and it is assumed that the base method of an activity has a value of productivity coefficient as 1.0. Other work methods are assumed to have a lower value of productivity coefficient as lower than 1.0, thus, to have lower productivity (less amount of quantity installed per a dollar) than the base method. The estimated quantity of each activity, labor cost of each activity with a method, and productivity coefficient are shown in Appendix 4.

Based on the estimated productivity of an activity, the cost of an activity with a selected work method without overlapping is estimated by dividing the estimated quantity by the productivity as in Eq. (6.2). Cost for each work method is presented as an additional cost: the difference between the cost for the base method and that for a selected method.

$$C_{req}(i, j) = \frac{\text{Estimated quantity}(i)}{\text{Productivity}(i, j)} \quad \text{--- Eq.(6.2)}$$

$$C_{add}(i, j) = C_{req}(i, j) - C_{base}(i)$$

where, $C_{req}(i, j)$ is estimated cost required for a work method (*j*) in activity (*i*)

$C_{base}(i)$ is the estimated normal cost of an activity (*i*) along with the base method

$C_{add}(i, j)$ is the additional cost required for a work method (*j*) in activity (*i*)

Because it is less likely that the work method requiring higher additional cost is selected in a normal schedule, work methods for an activity are ordered by the amount of additional cost; the less additional cost, the lower order of work method in most cases. The work method which requires more resources and can reduce duration is assigned to the highest order of work method. This ordering of work methods in an activity is based on the assumption that the subcontractor (or the project manager) prefers the work method requiring the least cost and a next alternative is the work method requiring the next lowest cost.

- **Impact of the selected pair of work methods on the amount of work usable by downstream activity**

Since construction activity generally builds its own work on the products of its immediate upstream activity, it requires the upstream activity's work to be completed: in full or parts. As an upstream activity progresses, the amount of work finished from the upstream activity increases and this finished work (or Work-in-Progress inventory (WIP inventory)) is held by the upstream activity before it is released into the downstream activity. Under sequential execution of two activities, the finished work upstream is released after the predecessor is 100% completed and downstream activity begins with 100% of the work completed upstream. However, if the downstream activity starts before the predecessor is finished (overlapping), downstream activity starts its work only with some parts of the work finished upstream while the upstream activity is still in progress.

Under overlapping between two activities, the amount of work finished upstream is not always usable by the downstream activity: the finished work upstream becomes usable by the downstream activity only after it is released to the downstream activity. For example, one side of the building exterior masonry wall for all floors does not provide enough work space required by the following interior construction, thus the masonry wall on one side is not usable by the interior construction activity. However, if the exterior masonry wall for the perimeter of one floor is built and then the walls on next floor are built, interior construction activity can have the released work from the upstream activity earlier, thus it can start earlier.

The amount of work usable by the downstream activity can be affected by the compatibility between the work method upstream and the work method downstream if they are executed under overlapping. For example, if a subcontractor for concrete pouring plans to pour concrete for all of the columns on each floor at one time, he (or she) would not place concrete on each column as soon as the rebar and forms for each column are installed. Instead, he (or she) would wait until all columns on one floor get ready for concrete pouring. While the amount of work finished upstream (number of columns of which rebar and form are installed) increases, those columns with rebar and form installed become available to the concrete subcontractor only after all columns on one floor get ready for concrete pouring. However, if the concrete subcontractor plans to pour concrete for half of the columns on each floor at one time, (s)he can start pouring concrete earlier with a smaller amount of concrete: the downstream activity can get WIP inventory which is usable earlier, but in smaller amounts.

The impact of the selected work methods on the amount of work usable by the downstream activity is demonstrated with activity #4 (Exterior enclosure) and activity #5 (Interior construction). Of the total of 36 pairs of work methods available between activity #4 and activity #5, four pairs of work methods are selected for the explanation as follows:

- Pair #1: Method #1 in exterior enclosure + Method #1 in interior construction
- Pair #2: Method #1 in exterior enclosure + Method #2 in interior construction
- Pair #3: Method #1 in exterior enclosure + Method #3 in interior construction
- Pair #4: Method #3 in exterior enclosure + Method #4 in interior construction

Where, Method #1 in exterior enclosure: vertical movement and simultaneous laying of brick and block with scaffolding on one side of the perimeter

Method #3 in exterior enclosure: horizontal movement and simultaneous laying of brick and block with scaffolding on all sides of the perimeter

Method #1 in interior construction: batch size as a whole floor with tabular scaffolding and one crew (all four sides of the enclosure should be completed)

Method #2 in interior construction: batch size as a half floor with tabular scaffolding and one crew (at least three sides of the enclosure should be completed)

Method #3 in interior construction: batch size as a whole floor with scissor-lift and one crew (all four sides of enclosure should be completed)

Method #4 in interior construction: batch size as a half floor with scissor-lift and one crew (at least three sides of enclosure should be completed)

For the determination of the amount of WIP inventory, it is assumed for the simplicity in calculation that all activities are planned to be executed linearly with time; the same amount of work is scheduled for each time period (i.e., each week). Thus, the progress curve in each activity is not the usual S-curve, but is represented by a line.

In the case of the first pair of work methods (#1 in exterior enclosure and #1 in interior construction), both the interior concrete block wall and the exterior brick wall are constructed from the first floor to the third floor on one side of the building perimeter. Then, both of the two layers on a next side of the building are constructed. With consideration to the lengths of each side of the building (approximate ratio of 5 to 3), the enclosure of the first side of the building with a longer length is assumed to be finished in 7.5 weeks and the first two sides of the building are assumed to be enclosed in 12 weeks. However, if the selected work method for interior construction is method #1, which requires all sides of building in one floor enclosed, no work completed by the exterior enclosure activity would be usable until both the brick and block walls of the first floor on all four sides are completed in 24 weeks. And as all sides of the first floor are enclosed, interior construction can start its work. As shown in Fig. 6.14, this pair of work methods (method 1+1) will allow the interior construction activity to start its work on the 20th week at earliest.

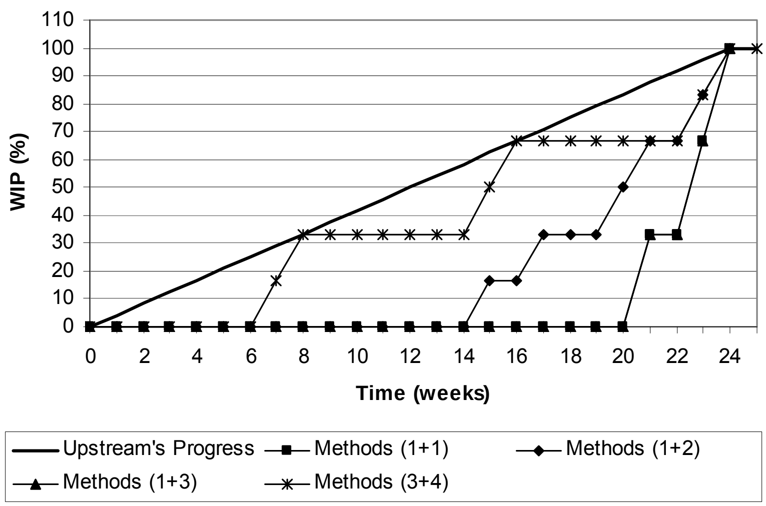


Figure 6.14 Example of amount of WIP inventory usable by downstream activity

If work method #2 for the interior construction activity is selected and paired with work method #1 for the exterior enclosure activity, the interior construction activity can be executed as long as at least three sides of a half floor area is enclosed. Thus, it can start its work when the first two sides and a half of the third side are enclosed, on 14th week. Then the amount of work usable by the interior construction activity increases more frequently, but by a lesser amount than the pair #1 as shown in Fig. 6.14.

If work method #3 is selected for the interior construction activity, there would be no difference between the amount of work usable from pair#1 (work methods (1+1)) and that from pair#3 (work methods (1+3)), but cost for the interior construction activity may be affected due to the change of equipment; tabular scaffolding versus a scissor-lift.

In the case of pair #4 (work method #3 for the exterior enclosure and work method #4 for the interior construction), when the first two sides and a half of the third side on the first floor are enclosed in 6 weeks, interior construction can begin. By laying the blocks and bricks on one floor after another, the interior construction activity can start earlier on the 6th week as shown in Fig. 6.14.

These four pairs of work methods between the exterior enclosure activity and the interior construction activity explain how selected work methods between two activities impact on the amount of work usable by downstream activity under overlapping.

- **Additional cost for a pair of activities with overlapping**

Based on the estimated amount of WIP inventory which is usable by the downstream activity, additional costs by overlapping for each pair of work methods are estimated. The estimation of additional cost for overlapping is based on the following assumptions.

- Productivity in the downstream activity is affected by the amount of WIP inventory

When two activities are overlapped and executed simultaneously, the downstream activity's productivity is assumed to decline depending on the amount of WIP inventory usable by the downstream activity. Sakamoto et al. (2002) insists that insufficient inventory leads to poor performance, but performance is not improved by excessive inventory. Therefore, the downstream activity's productivity is assumed to decrease with a lesser amount of WIP inventory, and it does not change with some amount of WIP inventory. This threshold value of WIP inventory is assumed to be 60 %. Figure 6.15 shows the impact of the amount of WIP inventory on the downstream activity's productivity.

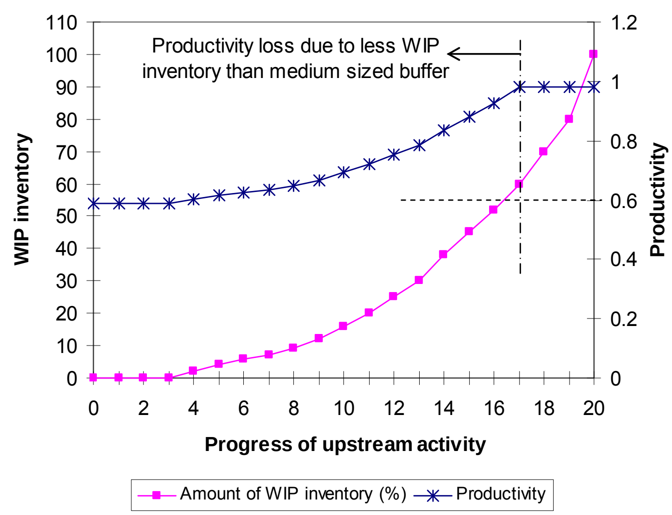


Figure 6.15 Change in downstream activity's productivity by WIP inventory

As shown in Fig. 6.15, if the amount of WIP inventory is larger than 60%, the downstream activity's productivity does not change. However, if the WIP inventory is less than 60%, the productivity declines with less WIP inventory.

- Productivity decreases with more crews.

Under overlapping, upstream activity and downstream activity allocate their own labor and equipment at the same time, thus it may cause overcrowding and the productivity of both upstream activity and downstream activity may deteriorate. A decrease in productivity is assumed to be linearly proportional to the combined crew size for both upstream activity and downstream activity.

With these two assumptions, productivities of both upstream activity and downstream activity are estimated. If an insufficient amount of WIP inventory is available to the downstream activity, which is overlapped by some degree, some of the crew in the downstream activity becomes idle. Thus additional cost is incurred by the idle resources. In the next time period, the downstream subcontractor needs to allocate more resources than originally planned, but allocation of more crew leads to loss in productivity. The required amount of additional cost due to the loss in productivity is estimated by multiplying the productivity by the amount of cost with regard to labor and equipment as discussed earlier.

Fig. 6.16 shows examples of the calculated additional costs for time reduction with the four pairs of work methods between activity #4 (Exterior enclosure) and activity #5 (Interior construction). Since the pair of method #1 in upstream activity and method #1 in downstream activity is the base method, this pair does not require additional cost for no time reduction. However, if these two activities are overlapped by four weeks, the amount of WIP inventory would be zero as shown in Fig. 6.15. Thus, the required additional cost for time reduction of four weeks or more would increase abruptly.

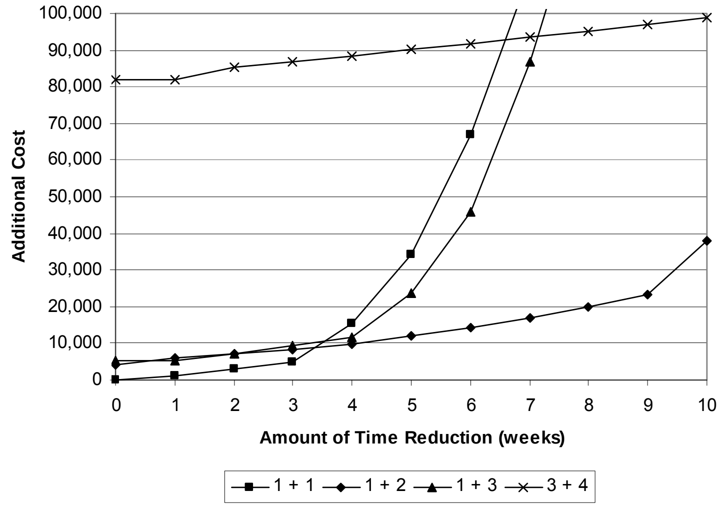


Figure 6.16 Estimated additional costs for time reduction

In the case of pair #2 (method #1 in upstream activity and method #2 in downstream activity), this pair of work methods requires more cost than the base methods in the normal schedule. However, this combination allows more WIP inventory availability to downstream activity than the pair of base methods until the activities are overlapped by nine weeks. Thus, the loss in productivity is smaller than the pair of base methods and the increased rate of additional cost is lower than that of the pair of base methods. If the activities are overlapped by ten weeks, no inventory is available to the downstream activity, thus the additional cost increases abruptly.

In the case of pair #3 (method #1 in upstream activity and method #3 in downstream activity), the downstream subcontractor should pay more due to the rental cost of scissor-lifts instead of tabular scaffoldings in the normal schedule. However, since it is assumed that interior construction can be completed one week earlier than the normal schedule if scissor-lifts are used, this pair does not require additional cost for one week's time reduction as shown in Figure 16. As for the WIP inventory, this pair incurs the same amount of inventory as the pair of base methods. Thus, additional cost increases abruptly with more than four weeks' overlapping.

In the case of pair #4 (method #3 in upstream activity and method #4 in downstream activity), this combination facilitates overlapping the best out of the four pairs in that the upstream activity's product is available earlier to the downstream activity. The viability of overlapping with this pair is represented as the lowest cost-increase rate. However, method #3 in the upstream activity requires the installation of scaffoldings on all sides of the building, thus the initial cost for equipment is much higher than the others as shown in Fig. 6.16. The estimated additional cost for all combinations of work methods between all pairs of activities are shown in Appendix 4.

6.4.4 Duration estimation

The duration of each activity is estimated by using the quantity and the productivity of the base work methods discussed above as shown in Appendix 2. While these duration estimate represent the normal schedule of each activity, an activity's duration can be reduced by using a different work method: by using two crews instead of one crew the duration can be reduced. The amount of time which can be reduced with a specific work method depends on the productivity and number of crews as shown in Appendix 2.

6.5 Priori Analysis for the Two Decision-making Approaches

6.5.1 Specific conditions of the base case

In addition to the work methods and estimates of additional cost and time for this case project as mentioned above, key parameter values for the base case are determined as follows:

- **Number of work methods to be examined in each activity:** *Project manager and subcontractors prefer small solution space.*

If the project manager and subcontractors need to find a solution concerning the selection of the best set of methods and the best degree of overlapping, the size of the solution space which is affected by the number of work methods available in each activity affects the quality in the solution and required resources for the calculation. Thus, they would not consider many work methods for the calculation unless they are sure that an increase in benefit is obtained. Therefore, the number of work methods available in each activity for the base case is selected as three and this number of work methods for the base case leaves ample opportunity for increase.

- **Uncertainty in project manager's cost estimates**: *Project manager's knowledge is less reliable than the subcontractors'.*

It is generally accepted that the project manager's knowledge about the additional costs required for time reduction with many pairs of work methods is less reliable than those by subcontractors. Therefore, the project manger may require more cost to improve the credibility of his cost estimation; for example, the project manager may hire a specialist for the detailed knowledge. Thus, the value of the parameter, the degree of relative uncertainty in the project manager's knowledge, is selected as 2.0 for the base case.

- **Project manager's solution capacity**: *Project manager's solution capacity is low*.

  Since the project manager's solution capacity means more cost in terms of resources or computing time (i.e., computing capacity or more laborers), the project manager is assumed not to be willing to increase the solution capacity, if not required. Thus, the value of the project manager's solution capacity for the base case is selected as 10 (10 maximum iterations for selecting a new set of work methods) and this low value leaves the opportunity to observe the improvement in RoR by an increased solution capacity.

- **Attitude to risk both by project manager and by subcontractors**: Both the project manager and subcontractors are assumed to be risk-neutral.

6.5.2 Input variables for the baseline schedule

In the main simulations, the coefficient of variation (CoVs) for the baseline schedule is set relatively high. A baseline RoR without any overlapping is determined to have CoVs of higher than 40%. The high variance in the main simulations could even lead to a negative RoR for the baseline schedule, which may happen in the real world. In addition to the PM's knowledge about the baseline schedule, it is assumed that the PM's knowledge about additional cost required for time reduction is less reliable than the subcontractors' by up to 1.5 times.

If the PM has a long experience with the same type of construction projects, then he (or she) may have a better knowledge of the baseline schedule. On the other hand, if the PM does not have experience, there may be a high variance in the estimating cost, duration and RoR even for the sequential execution of the project. As discussed in the previous section, the results of the main simulations, and the degree of variance in the baseline schedule may affect the hypothesis tests.

Therefore, for the case study, it is assumed that the uncertainty in the PM's knowledge about the baseline schedule is better than in the main simulation, but the uncertainty in the PM's knowledge about the additional cost required for time reduction is higher (up to 2.0) than in the main simulation. CoV (Coefficient of Variation) of input variables are set for the case study as follows:

- Project life with future revenues
    - Mean: 240 months
    - Coefficient of variation: 0.05
    - It is assumed to be distributed normally.
- Future revenues
    - Mean value of monthly future revenues is determined to satisfy a target RoR of 20%.

- Coefficient of variation: 0.1
- It is assumed to be distributed normally.

- Project construction durations

  While the case project is composed of a total of nine activities, there are six activities on the critical path. In addition to the critical activities, three non-critical activities (Mechanical, Electrical, and Fire Protection) will be executed as well. The estimated durations of six activities on the critical path have the mean values as shown in Table 6.1.

Table 6.1 Estimated mean of durations for the base case

Activity	Excavation	Sub-structure	Super-structure	Exterior Enclosure	Interior Construction	Interior Finish	Total
Mean of duration (weeks)	3	9	27	24	10	22	95

- Estimated durations of all the activities are assumed to be correlated with each other with a correlation coefficient of 0.9.
- Estimated duration of each activity is assumed to be independent of the cost of the activity.
- Estimated duration is assumed to be distributed log-normally with a longer tail to the right.
- Coefficient of variation of estimated duration for each activity is set as 0.1.

It is assumed that the critical path is not changed, while it is plausible that the critical path is changed or there are multiple critical paths in a real situation. Therefore, the durations of the non-critical activities are not counted to determine the total duration of the case project.

- Project construction costs

  Estimated costs of six activities on the critical path for the base methods have the mean values as shown in Table 6.2.

Table 6.2 Estimated mean of costs for the base case

Activity	Excavation	Sub-structure	Super-structure	Exterior Enclosure	Interior Construction	Interior Finish	Total
Mean of cost ($)	5,463	278,588	1,463,950	1,229,063	267,663	1,785,145	5,029,872

- Estimated costs of all the activities are assumed to be correlated each other with a correlation coefficient of 0.9.
- Estimated cost of each activity is assumed to be independent of estimate duration of that activity.
- Coefficient of variation of estimated cost for each activity is set as 0.1.
- Estimated cost is assumed to be distributed log-normally with a longer tail to the right.
- Estimated cost and duration are assumed not to be correlated with each other for easier calculation.

In addition to the critical activities, the estimated cost of other activities on non-critical paths is $2,453,755. Similar to the duration estimates, the cost for non-critical activities is not accounted as random variables. Instead it is assumed that the costs for those activities are fixed and constant.

6.6 Plan for Sensitivity Analysis and Model Simulation

To answer the questions about which parameter should be changed and how, the sensitivity of the change in each parameter value to the selection of the better decision-making approach is analyzed. The sensitivity analysis is implemented with five different values for each key parameter as shown in Table 6.3.

From this sensitivity analysis the owner can be advised about required change in the key parameter values for the use of a non-optimal decision-making approach and he (or she) will be able to have more flexibility in the selection of the decision-making approach.

Table 6.3 Changes in the parameter values for the sensitivity analysis

Parameter						**Base case**				
No. of activities						**6**				
No. of methods						**3**	4	5	6	
PM's uncertainty	1.0	1.2	1.4	1.6	1.8	**2.0**				
PM's solution capacity						**5**	25	45	65	85
Attitude to risk						**Neutral**	Averse			

6.7 Results for the Base Case

From above input variables for baseline schedule, RoR for baseline schedule without any overlap is distributed with a mean of 20.23% and a standard deviation of 0.05 as shown in Fig. 6.17.

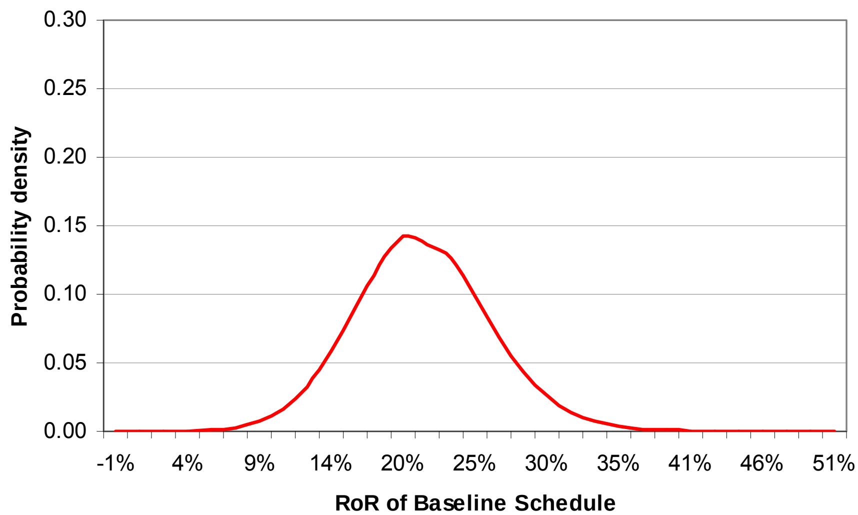


Figure 6.17 Probability distribution of the RoR of the baseline schedule

Also, the summary statistics of the input random variables and the resulting RoR of the baseline schedule are summarized in Table 6.4. As discussed above, Construction Duration and Cost of each activity are assumed to be distributed log-normally and both Economic Life and Future Revenues are assumed to be distributed normally. The resulting RoR of the baseline schedule is positively skewed (0.1452) as shown in Table 6.4.

Table 6.4 Summary statistics of the baseline schedule

	Economic life of project	Future Revenues*	Construction Duration	Construction Cost	RoR of baseline schedule
	(months)	($)	(Weeks)	($)	(%)
Mean	239.8	150,242	92.1	7,988,139	20.23%
Standard deviation	24.09	29,959	18	1,061,532	0.05
Skewness	0.0056	0.0198	0.5822	0.6073	0.1452
CoV	10.05%	19.94%	19.92%	13.29%	24.66%

While the mean value of the future revenues is calculated with a target mean RoR of 20%, the resulting mean RoR from the simulations is slightly increased to 20.23%. This difference is caused by the positive correlations between costs (or durations) of activities. The correlation coefficient between costs (or durations) of activities is assumed to be positively high (0.9), because the total cost of a bigger project (with more activities) would have a smaller variance than a smaller project with zero correlation. Fig. 6.18 shows the change in mean of baseline RoR as well as confidence intervals (the 5% percentile value and 95% percentile values from the simulated data) with a higher correlation coefficient between costs (or durations) of activities. As the correlation coefficient increases, it is observed that skewness of baseline RoR increases, and mean of baseline RoR increases also. When costs are independent of each other (correlation coefficient is 0.0), the mean of baseline RoR (20.03%) is not significantly different from the target RoR (20%).

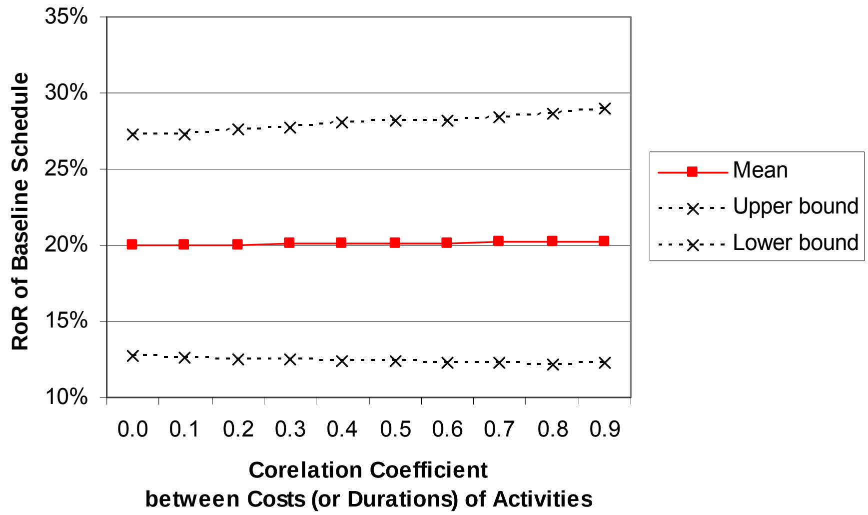


Figure 6.18 Impact of correlation coefficient on RoR of the baseline schedule

In the centralized approach, the PM can find a better solution based on his estimated cost even with a high uncertainty of 2.0. However, due to the high uncertainty in the PM's knowledge the PM needs to offer an additional markup to the subcontractors or some of the subcontractors may reject the PM's solution. The resulting centralized RoR is lower than the PM's own RoR in terms of the mean value. While the PM's own solution has a mean value of 23.02%, the mean of centralized RoR is 21.03% as shown in Fig. 6.19.

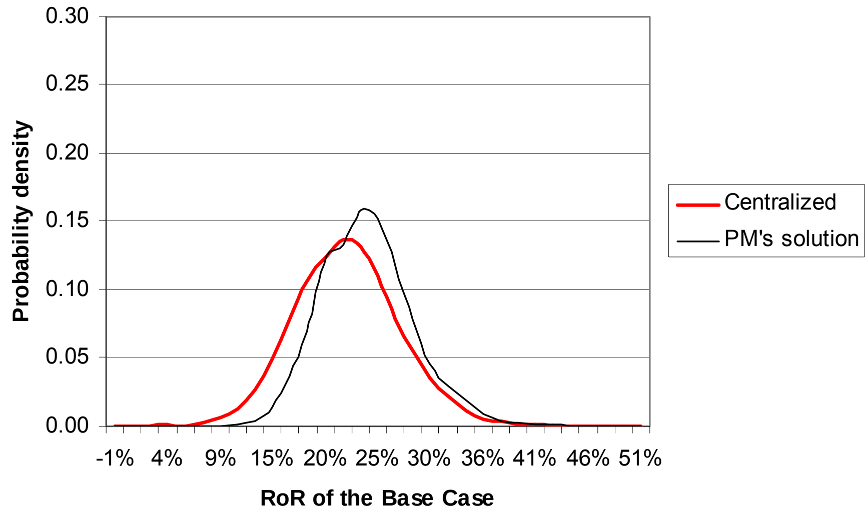


Figure 6.19 Comparison of probability distributions between centralized RoR and PM's own RoR for the base case

In the PM's own solution, the PM may underestimate the costs required for a time reduction and it is more likely to find a better solution (or a higher RoR). However, since the PM's own solution is based on his knowledge, which is less reliable than the subcontractors', the PM's own solution may not be accepted by the subcontractors. Or the PM may offer an additional markup to make his offer more attractive. Due to a possible rejection by the subcontractors or an additional markup, the Centralized RoR may be lower than the PM's own solution. However, as for variance, centralized RoR is observed to have a bigger variance (or higher standard deviation value) than the PM's RoR (0.0457 for PM's own RoR vs. 0.0520 for centralized RoR). From a statistical test, it is determined that the mean of centralized RoR is significantly different from that of the PM's own solution as follows:

Null hypothesis is that the mean of centralized RoR is the same as mean of PM's own RoR. $H_0 : \mu_{Cent.} = \mu_{PM}$ where $\mu_{Cent.}$ is the mean of centralized RoR and μ_{PM} is the mean of PM's own RoR.

$\alpha = 0.10$

The test statistics is $t_0^* = \dfrac{\overline{x}_{Cent.} - \overline{x}_{PM} - 0}{\sqrt{\dfrac{s_{Cent.}^2}{n_{Cent.}} + \dfrac{s_{PM}^2}{n_{PM}}}}$

where $\overline{x}_{Cent.}$ is sample mean of centralized RoR and $\overline{x}_{PM}$ is sample mean of PM's own RoR

$s_{Cent.}$ and s_{PM} are sample standard deviations of centralized RoR and PM's RoR respectively.

$n_{Cent.}$ and n_{PM} are sample sizes of centralized RoR and PM's RoR respectively.

The degrees of freedom on t_0^* are

$$v = \frac{\left(\dfrac{s_{Cent.}^2}{n_{PM}} + \dfrac{s_{Cent.}^2}{n_{PM}}\right)^2}{\left(\dfrac{(\frac{s_{Cent.}^2}{n_{Cent.}})^2}{n_{Cent.}+1} + \dfrac{(\frac{s_{PM}^2}{n_{PM}})^2}{n_{PM}+1}\right)} - 2 = 39{,}336 \rightarrow \infty$$

Test statistic $t_0^* = 40.83$ is larger than $t_{0.10,\infty} = 1.28$ and the null hypothesis is rejected. Therefore, the mean of centralized RoR is determined to be significantly different (smaller than the mean of the PM's own RoR). However, the difference in variance is determined not to be significantly different. The statistics of RoR are summarized in Table 6.5. The lower bound and upper bound are determined by the 5% percentile value and 95% percentile value of the simulated data respectively.

Table 6.5 Statistics of RoRs for the base case

	Centralized Approach		Decentralized Approach
	PM's own RoR	Centralized RoR	Decentralized RoR
Mean	23.02%	21.03%	21.39%
Standard deviation	0.0457	0.0520	0.0268
Coefficient of variation	19.84%	24.75%	12.52%
Skewness	0.4309	0.1509	0.1578
Lower bound	16.06%	12.74%	17.09%
Upper bound	31.12%	29.78%	25.98%

Under the decentralized approach, a decentralized RoR is calculated to have a mean of 21.39%. The mean of decentralized RoR is different from the centralized RoR based on a confidence level of 90%. Therefore, the decentralized approach is preferred to the centralized approach in the base case.

The probability distributions of RoRs for both approaches are shown in Fig. 6.20. Clearly, the difference in the means is very small but the standard deviations are quite different. Therefore, the centralized method is much riskier for a low RoR and this higher risk is due to the PM's high uncertainty and low solution capability.

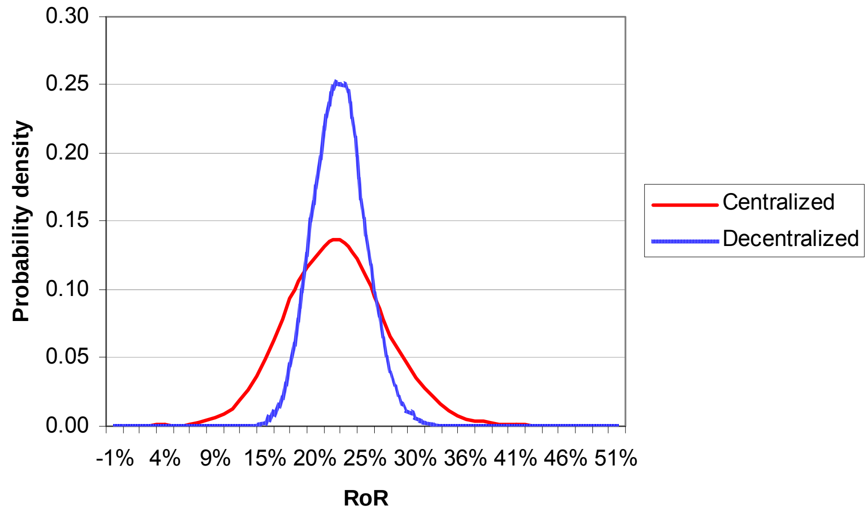


Figure 6.20 Comparison of the centralized RoR to the decentralized RoR for the base case

6.8 Sensitivity Analysis

It is calculated that there is no big difference between the mean of centralized RoR and mean of decentralized RoR in the base case, although the mean of decentralized RoR is slightly better than that of the centralized RoR. However, under different conditions (or under different parameter values) the preference of one approach to the other may change. If the project owner wants to take the centralized approach, the values of some parameters may need to be changed. In the following section, it is examined which conditions favor the centralized approach by changing the value of each parameter.

6.8.1 Work methods in each activity

The base case for this case study assumes that three methods for each activity are taken into consideration to find a better solution. In the base case, it is observed that the decentralized approach provides a little bit higher RoR to the project owner than the centralized approach.

However, if more work methods are considered, the means of RoR in both the centralized approach and the decentralized approach may be improved. Thus, it is tested if both RoRs can increase with more methods. Since the means of the cost data for overlap in this case study are estimated based on a cost data book (RS Means manual (2005)) instead of a random generation, different results may be found.

- ***More methods do not improve the centralized RoR.***
- ***Mean of decentralized RoR increases with more methods.***

In the centralized approach considering more methods is calculated to not help improve even the mean of the PM's own RoR. Since the PM's solution capacity is very low (5), it becomes less likely to find the optimal solution with more methods. Accordingly, the mean of centralized RoR does not increase with more methods.

On the other hand, the decentralized RoR may increase with more methods, since it is assumed that the subcontractors can find their best solution (local optimal). The mean of decentralized RoR is determined to increase with more methods and the increase in the mean of RoR is determined to be significant. The changes of the mean RoRs with more methods are shown in Fig. 6.21.

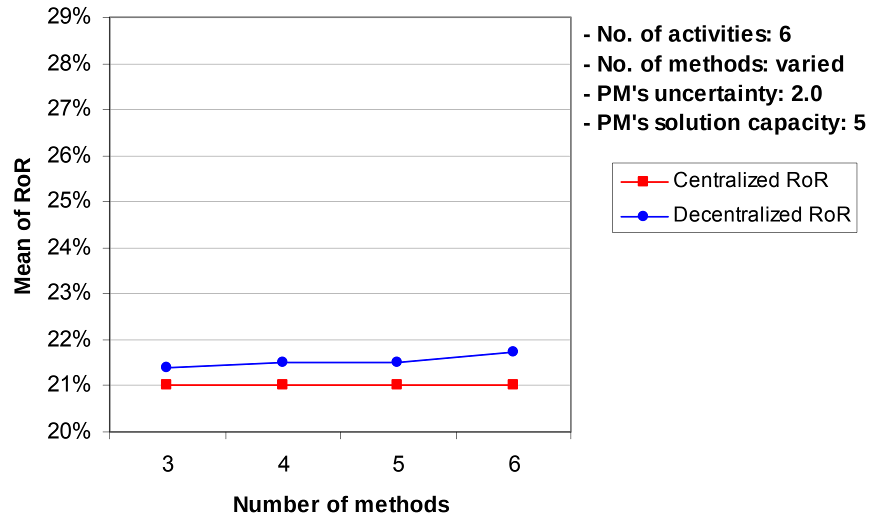


Figure 6.21 Comparison of the change both in the centralized RoR and the decentralized RoR with more methods

When comparing the mean of centralized RoR to the mean of the decentralized RoR, the decentralized approach would be preferred to the centralized approach as more methods are considered. Thus, even if six methods in each activity are considered, the decentralized approach would still be recommended.

6.8.2 Increase in PM's solution capacity

No significant impact of the PM's solution capacity both on centralized RoR and on decentralized RoR.

The fact that the PM has a small solution capacity of 5 may be one of the conditions in the base case which contributes to the preference of the decentralized approach over the centralized approach. Due to this limited solution capacity, the PM is not expected to be able to find the optimal (or near optimal) solution, particularly for more complex solution spaces under the centralized approach.

By increasing the PM's solution capacity, the PM's own solution is expected to be improved. Fig. 6.22 shows the improvement of the PM's own RoR with more solution capacity. While the improvement in the PM's solution capacity from 5 to 25 is apparent, no further significant improvement is found.

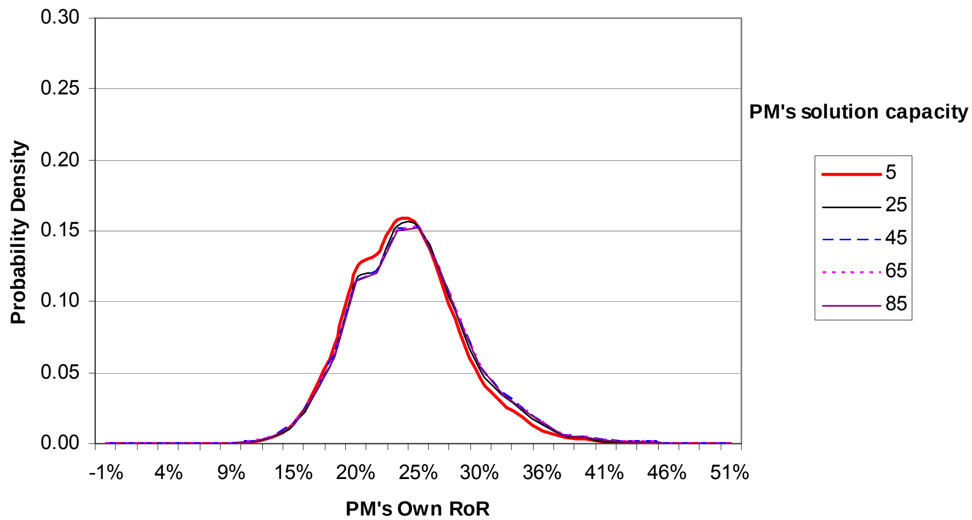


Figure 6.22 The impact of different PM's solution capacity on the PM's own RoR (probability distributions)

In addition to probability distributions of RoR, the change in the mean value of the PM's own RoR is shown in Fig. 6.23.

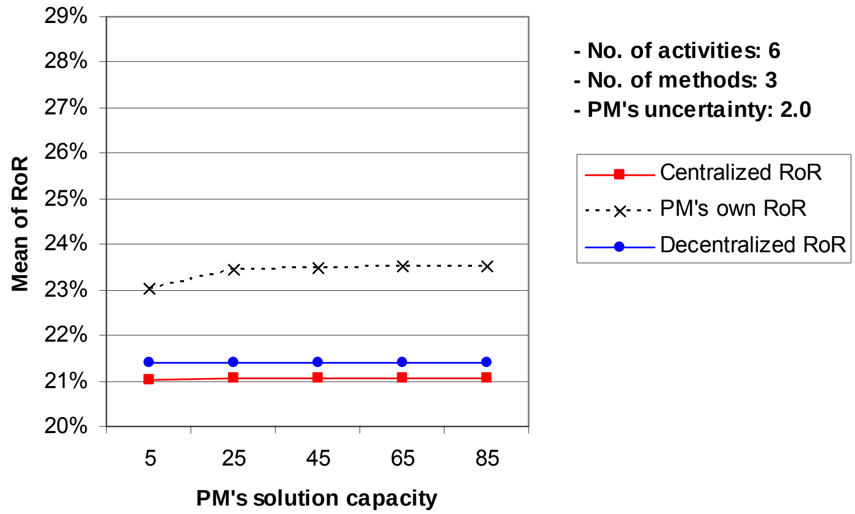


Figure 6.23 Comparison of the impacts of PM's solution capacity on different RoRs

While the PM's own solution increases by more solution capacity, the increase in the centralized RoR is not significant. This means that in the centralized approach increasing the PM's solution capacity is not beneficial to the project owner if the uncertainty in the PM's knowledge is high. The increase in the PM's solution capacity by the PM is offset by the high uncertainty in the PM's knowledge.

In the decentralized approach, the PM's solution capacity is expected not to affect a decentralized RoR. The constant mean of a decentralized RoR is shown in Fig. 6.23.

When comparing both RoRs, it is calculated that the decentralized approach is still preferred even with more PM's solution capacity.

6.8.3 Improvement of PM's knowledge

While the improved PM's knowledge does not affect the decentralized RoR, the mean of centralized RoR decreases slightly with improved PM's knowledge.

In the base case, it is assumed that the uncertainty in the PM's knowledge is high (PM's uncertainty is 2.0) and this condition may be why the mean of decentralized RoR is higher than the mean of centralized RoR. Therefore, the case study is extended with more accurate PM's knowledge and the impact of the PM's uncertainty is examined.

As the PM's knowledge becomes more accurate, the PM's estimates of additional cost for overlap are expected to have less variance under a risk-neutral attitude. Less variance in estimated costs may reduce the probability of a high RoR from considerable under-estimates. Thus, the mean of the PM's own RoR is expected to decrease. Fig. 6.24 shows the distributions of the PM's own RoR with different degrees of the PM's uncertainty. As the PM's knowledge becomes more accurate, the variance of the PM's own RoR decreases and skewness decreases also.

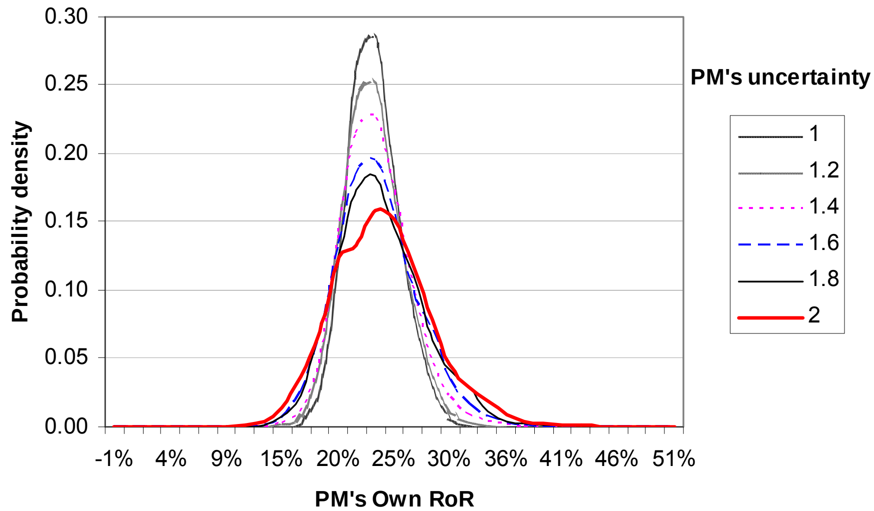


Figure 6.24 Impacts of PM's uncertainty on the PM's own RoR

The mean of the PM’s own RoR is calculated to decease as the PM’s knowledge becomes more accurate. The PM’s own RoR is based on the PM’s own knowledge which may not be accurate, and may not be acceptable by the subcontractors. If the PM’s knowledge is less accurate, then the PM can find a good solution, but a wrong solution. As shown in the Fig. 6.26, the reduction in the mean of the PM’s own RoR is determined to be significant.

Since the PM’s own RoR may be wrong, it may not be accepted by the subcontractors, or may require additional markup for the subcontractors’ acceptance. The centralized RoR is expected to reduce from the PM’s own RoR. As the PM’s knowledge is improved, the amount of reduction of RoR would be smaller. Fig. 6.25 shows the probability distributions of the centralized RoR with different degrees of the

PM's uncertainty. Similarly, as in the PM's own RoR, variance and skewness of RoR decrease as the PM's uncertainty is reduced.

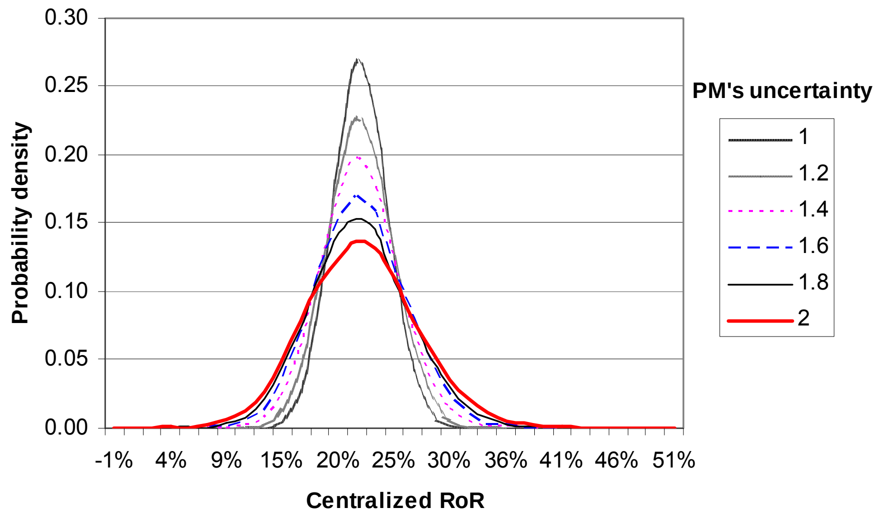


Figure 6.25 Impacts of PM's uncertainty on the centralized RoR

Mean of the centralized RoR is calculated to increase slightly as the PM's knowledge becomes more accurate. From a hypothetical test, it is determined the increase in the mean of centralized RoR is significant. (The test statistic ($t_0 = 6.66$) is larger than $t_{0.05,4} = 2.132$ based on $\alpha = 0.10$ and two-tailed test, thus the null hypothesis $H_0 : \beta(slope) = 0$ is rejected.)

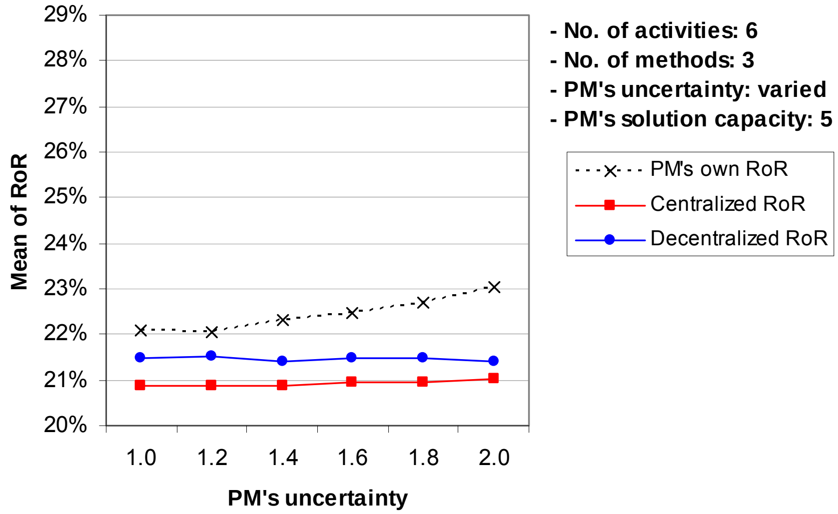


Figure 6.26 Changes in mean RoRs with different PM's uncertainty

On the other hand, in the decentralized RoR, the uncertainty in the PM's knowledge does not affect the subcontractors' solution (or their bids) and the decentralized RoR. Fig. 6.26 shows this result.

When comparing the centralized RoR to the decentralized RoR, the decentralized approach is still preferred even when the PM's knowledge becomes more accurate as shown in the Fig. 6.26.

6.8.4 Attitude to risk: risk-aversion

If the project owner is risk-neutral, he makes a decision between centralized and decentralized based on the expected value of the RoR for each. However, if the owner is risk-averse, he makes his decision based on the mean and variance of the RoR for each condition.

If both the PM and subcontractors are risk-averse for the base case, the PM's own solution based on the mean value is expected to be smaller than that under a risk-neutral attitude. Since it is assumed that less conventional methods have higher variance in estimates than more conventional methods, the estimated cost for less conventional methods would be more expensive than under a risk-neutral attitude. Thus, the PM's own solution is more likely to select more conventional methods and a smaller amount of time reduction is determined. Furthermore, under a risk-averse attitude project performance regarding the rate of return on the investment is assumed to be measured by the value at risk (VaR) based on a 95% confidence level, not by expected value.

Centralized RoR is also expected to be affected by a risk-averse attitude similar to the PM's own solution. Since the PM estimates additional cost for time reduction conservatively, he is assumed to not add more mark-up for time reduction. While the amount of time reduction under a risk-averse attitude would be smaller than that under a risk-neutral attitude, additional cost for additional markup under a risk-neutral attitude can be avoided. The conservative (or risk-averse) attitude would lead to a smaller overlap, but improve the RoR by reducing additional costs for a higher markup. Fig. 6.27 compares the PM's own RoR to the centralized RoR under a risk-averse attitude for the base case.

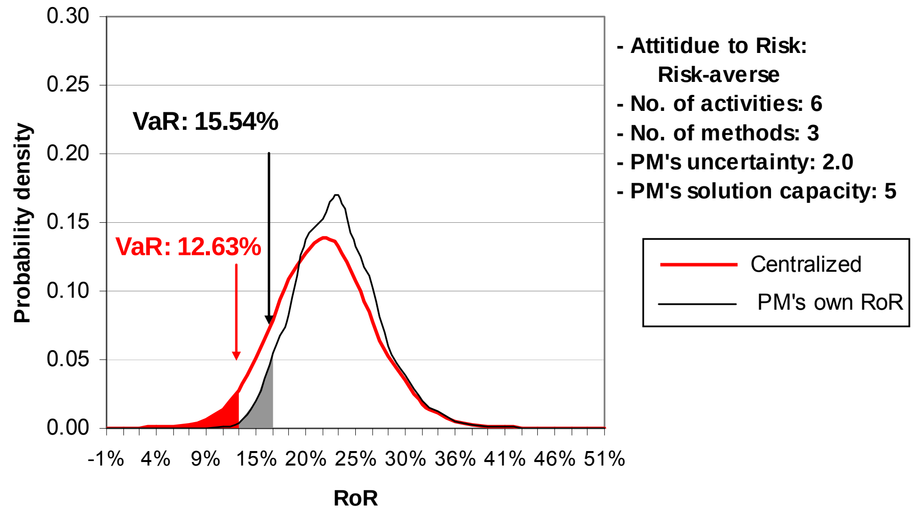


Figure 6.27 Comparison of VaRs of the centralized RoR and PM's own RoR

In the decentralized approach, a risk-averse attitude will cause the selection of more conventional methods and a smaller overlap by subcontractors. If more conventional methods are selected by risk-averse subcontractors, those methods are expected to be more compatible with each other. Thus, in final decentralized RoR, the decrease in RoR due to incompatible methods selected by each pair of subcontractors under a risk-averse attitude is expected to be smaller than under a risk-neutral attitude. Therefore, a risk-averse attitude would cause a smaller overlap by subcontractors, but a decrease in RoR due to incompatible methods would be reduced.

Fig. 6.28 shows the probability distributions of both a centralized RoR and a decentralized RoR. While the mean values in the following figure are not quite different (centralized mean of 20.86% vs. decentralized mean of 21.37%), VaRs at a 95% confidence level are affected by the variances. Since the centralized RoR has a bigger variance due to a higher uncertainty in the PM's knowledge than the decentralized RoR, VaR of the centralized RoR is smaller than that of the decentralized RoR. Some statistics of both the centralized RoR and decentralized RoR are summarized in Table 6.6.

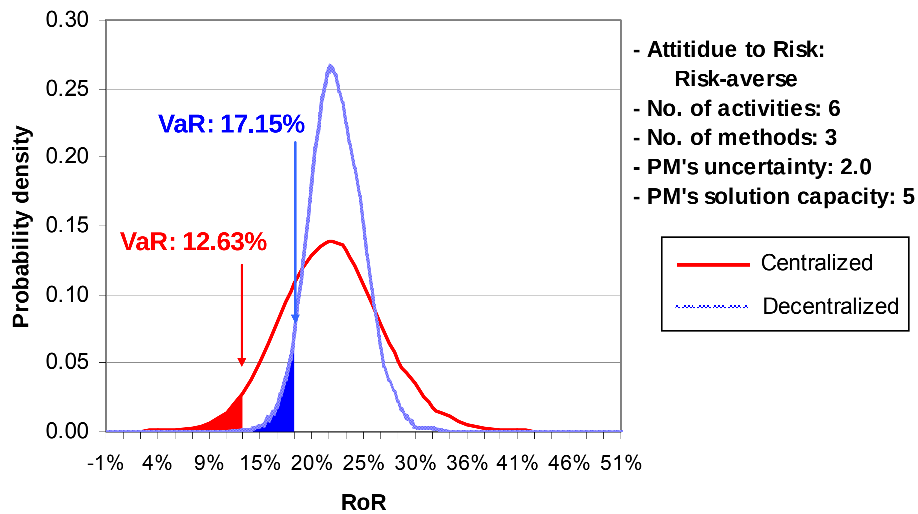


Figure 6.28 Comparison of VaRs from the centralized RoR and the decentralized RoR

The project owner is 95% confident that his RoR will not be less than 17.15 % if he chooses the decentralized approach, but his 95% confidence is only 12.63 % if he chooses the centralized method. As 17.15% is far better than 12.63%, the decentralized approach will be recommended all the time if both the PM and subcontractors are risk-averse.

Table 6.6 Summary of the comparison between the centralized RoR and the decentralized RoR under risk-averse attitude

	Centralized Approach	Decentralized Approach
Mean	20.86%	21.37%
Standard deviation	0.051	0.027
CoV	24.67%	12.46%
Skewness	0.138	0.169
Value at Risk for the 5^{th} percentile	12.63%	17.15%

6.9 Conclusion of the Case Study

The simulation model is applied to an imaginary construction project of which cost estimates and duration estimates are based on RS Means cost data. In the case project, multiple methods for the execution of each activity are introduced and their costs are estimated based on the RS Means cost data. Since the methods and their costs are based on real cost data, this case study is for the application of the simulation model into a hypothetical construction project.

In the base case of the case project, the parameter values for the simulation model are summarized in Table 6.7.

Table 6.7 Parameter values of the base case

Parameter	Value	
No. of activities	Medium	6
No. of methods	Small	3
PM's uncertainty	High	2.0
PM's solution capacity	Low	5
Attitude to risk	Risk-neutral	

In the base case, the decentralized approach is recommended under a risk-neutral attitude. And each parameter is changed with multiple values to investigate under which condition the centralized approach is preferred.

- Increase in number of methods

The project owner benefits by considering more methods in the decentralized approach, but he has no benefit in the centralized approach. Thus, the decentralized is preferred to the centralized approach if more methods are considered.

- Improvement of PM's knowledge

By reducing the uncertainty in the PM's knowledge, the decentralized RoR is not affected, and the centralized RoR decreases slightly. Thus, the decentralized approach would be recommended even if the PM's knowledge is improved.

- Increase in PM's solution capacity

The project owner has no significant benefit from increasing the PM's solution capacity in the centralized approach due to the high uncertainty in the PM's knowledge. In the decentralized approach the PM's solution capacity does not affect the decentralized RoR. Thus, the decentralized approach would be recommended.

- Change of attitude to risk

A risk-averse attitude leads to a more conservative schedule for overlap and a better solution (or higher RoR) can be provided in the decentralized approach even under risk-aversion. The preference of the decentralized approach is due to a high uncertainty in the PM's knowledge.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Concurrency in construction projects to reduce construction project delivery time and to accelerate future revenues can be beneficial to the project owner. While overlapping between activities (or concurrency) requires additional cost, any additional cost required for overlapping can be justified if the discounted future revenue is higher than the discounted expense (or construction cost).

Additional cost for overlapping between activities is affected by the methods selected in the activities under overlapping. A pair of methods between activities may be more compatible with each other than other pairs, thus they can facilitate overlapping and require less additional cost.

However, considering more methods to facilitate the overlap between activities leads to more expanded solution space to be explored by the centralized project manager who determines the solution. If the project manager's limited solution capacity is small, he may not be able to find the optimal solution. Furthermore, his knowledge about additional cost required for overlapping may not be as accurate as the subcontractors'. On the other hand, the subcontractors can determine their own solutions based on more accurate knowledge about additional cost for overlapping than the project manager, but from their myopic viewpoints. Who (the centralized project manager or subcontractors) can provide more benefit to the owner, is the fundamental question for this research. In addition, the solutions from the centralized decision-making approach and/or from the decentralized approach can be affected by factors such as the project manager's solution capacity and the accuracy of the project manager's knowledge.

To solve the optimization problem regarding concurrent construction planning, simulation models were developed both for the centralized decision-making approach and the decentralized approach. Since two different approaches are constrained and/or facilitated by several conditions of projects, five hypotheses with respect to different conditions (or different factor values) were developed and were tested.

7.1 Contributions of This Research

The main contributions of this research to the construction industry are:

(1) Consideration of multiple methods for concurrent construction planning was proposed.

Some researchers have focused on finding the optimal degree of overlapping for concurrent planning (e.g. Roemer and Ahmadi 2004; Krishnan et al. 1997), and some others have focused on finding the optimal set of methods to minimize cost or to minimize construction duration (e.g. Zheng et al. 2004; Feng et al. 2000; Feng et al. 1997). These approaches were combined to find a higher return of the investment (RoR) in this research. In this research a construction work method is defined to be determined by several factors, and multiple work methods to execute each activity were considered to find a set of methods which are compatible with each other.

The benefit of the consideration of multiple methods for concurrent construction planning depends on additional cost required for overlapping: If additional cost for the optimal solution from the consideration of multiple methods cannot be justified by accelerated future revenues, consideration of multiple methods would be a waste of time. However, if innovative methods which cost more than the base method, but are more compatible with other activities under concurrency are developed, more benefit can be obtained.

The owner could benefit from the consideration of multiple methods from the case study in this research. Furthermore, it can be beneficial to subcontractors also in that they would be paid with an incentive bonus for earlier completion. Therefore, the result shows the need to develop innovative methods. While innovative methods may require additional cost and may not be used under the objective of minimized construction cost, those can contribute to concurrent execution and more benefit both to the owner and subcontractors.

(2) The decentralized decision-making model to concurrent construction planning was developed.

In this research the decentralized decision-making model was developed in addition to the centralized decision-making model. Some researchers developed a more efficient centralized approach for construction planning, while others advocate the decentralized construction planning due to the complexity and impracticality. Furthermore, concurrent construction planning with the consideration of multiple methods makes the solution space more expanded and the information about additional cost for overlapping less reliable. Therefore, the decentralized decision-making model was developed to find a better solution based on the subcontractors' knowledge. This model accounts for two features of a decentralized approach: a myopic view point of the subcontractor and information asymmetry. First, while the subcontractors' knowledge about any additional cost required for overlapping is more reliable than the project manager's, the subcontractors' best solution (or local optimal) may not be the best solution for the owner (or the global optimal) due to their narrow-minded viewpoint. In the decentralized model the project manager compares the bids from each pair of subcontractors and checks the compatibility of the proposed methods. Thus, some bids may be rejected due to incompatible methods and the benefit to the owner may become less viable. Second, the information asymmetry between the project manager's knowledge and subcontractors' knowledge is accounted for by multiple rounds of bidding as suggested by Beil and Wein (2003). In each bidding round the project manager proposes an amount of unit incentive for earlier completion to the subcontractors and the project manager can find a better incentive amount which leads to a higher RoR value by repeating bidding rounds.

This decentralized decision-making model proposes coordination between subcontractors for concurrent construction planning and the benefit of the coordination between subcontractors under the decentralized approach is recommended from the results of this research. This approach would be useful for subcontractors and project owners in that the best methods are determined by coordination between the parties who know the methods best.

(3) With the concurrent construction planning models both for the centralized approach and for the decentralized approach developed in this research, the simulation results were compared and a recommended approach for each condition was identified.

The two decision-making models for concurrent construction planning were simulated under different conditions and their results were compared to identify a recommended approach for each condition. Different conditions in the simulation represent combinations of several decision-making factors: 1) number of activities, 2) number of methods considered, 3) the project manager's solution capacity, 4) relative uncertainty of the project manager's knowledge compared to subcontractors' knowledge, and 5) attitude to risk. By identifying a recommended approach for each condition, the project owner will be beneficial with an insight about which decision-making approach should be used for concurrent construction planning for his own project. Furthermore, the findings in this research provide some helpful perspective to project owners to improve concurrent construction planning under one decision-making approach (either centralized or decentralized approach): i.e., should more estimators be hired (should the solution capacity be increased) under the centralized approach?

7.2 Conclusions

The major conclusions of this research are: (1) The decentralized approach becomes preferred with more activities; (2) Considering more methods provides more potential for higher benefit to the owner in the decentralized approach; (3) The decentralized approach is recommended under a risk-averse attitude and high uncertainty in the project manager's knowledge.

(1) The decentralized approach becomes preferred with more activities.

More activities provide opportunities for more overlap which can lead to a higher benefit for the project owner. In the centralized decision-making approach the opportunity was found to be heavily affected by the uncertainty in the project manager's knowledge: when the uncertainty in the project manager's knowledge is high, the project manager proposes additional markup to the subcontractors to make his solution more attractive. Then RoR is reduced due to the additional cost which is caused by the additional markup. On the other hand, in the decentralized approach it was observed that overlapping between subcontractors lead to a higher benefit for the owner. Compared to the centralized approach, the decentralized RoR in terms of mean value was found to increase more with more activities than the centralized RoR. Therefore, subcontractors who have more accurate information are recommended to coordinate with each other and to participate in planning of concurrent construction projects, especially for bigger projects.

In addition, the impact of increasing the number of activities by splitting activities was investigated. In the centralized approach the project manager's solution was constrained by: 1) the maximum amount of time reduction from overlapping and 2) the project manager's solution capacity. When one activity is split into two or multiple activities, the maximum possible amount of time reduction through overlapping is reduced also. Furthermore, more activities from splitting caused more solution space, thus it became less likely that the project manager found the optimal solution. Also in the decentralized approach, splitting was found not to increase RoR due to a smaller maximum amount of time reduction allowed in overlapping and the subcontractors' myopic viewpoints. Therefore, it is not recommended that the project owner have more activities which have smaller work scopes to facilitate overlapping.

(2) Considering more methods provides more potential for higher benefit to the owner in the decentralized approach.

In the centralized approach it was found that the centralized RoR was not improved significantly by considering more methods. While the solution improved a little by increasing the project manager's solution capacity, it is not statistically significant. Similarly the decentralized RoR was not improved significantly by considering more methods also. However, in the case study in which the cost data was estimated, the decentralized approach could provide a higher benefit to the owner by considering more methods while no improvement was found in the centralized approach. These results show that the owner can benefit from considering more methods for concurrent construction planning in the decentralized approach. Furthermore, it is recommended that subcontractors develop and/or invent innovative methods.

(3) The decentralized approach is recommended under a risk-averse attitude and high uncertainty in the project manager's knowledge.

The centralized solutions were found to have more variance with a higher uncertainty in the project manager's knowledge. Thus, when the project manager is risk-averse and makes a decision based on value-at-risk, his solution becomes lower with higher uncertainty. On the other hand, the decentralized solution is not affected by the uncertainty in the project manager's solution. And it was found that the centralized approach is recommended under risk-averse attitudes only when the project manager's knowledge is as accurate as the subcontractors. Therefore, the results show that the decentralized approach should be used when the project manager's knowledge is less accurate than the subcontractors' and he is risk-averse. These results indicate that the information asymmetry between the project manager and subcontractors plays a significant role in concurrent construction planning when the decision-makers are risk-averse.

7.3 Discussion about Assumptions and Suggestion for Future Research

Major assumptions made and used to develop the two decision-making models in this research are: 1) Overlapping between only critical activities, 2) Estimation of cost data required for overlapping and 3) Pair-wise coordination between subcontractors in the decentralized approach.

(1) Overlapping between only critical activities

In this research it was assumed that the duration of the construction project is not affected by non-critical activities, thus overlapping between critical activities were taken into consideration. However, it is likely that critical activities are changed or there are multiple critical paths due to overlapping between critical activities. Furthermore, some non-critical activities need to be carried out concurrently with critical activities. For example, mechanical and/or electrical activities which are non-critical activities may need coordination or partial concurrent execution with super-structure activity or interior construction activity in building construction projects. Partial overlapping with a non-critical activity as well as overlapping with a critical activity at the same time would increase the solution space to be explored by the project manager and require coordination among at least three subcontractors. In this more complicated case, the preferred decision-making approach may contradict with the results in this research and this issue is recommended for future research.

(2) Estimation of cost data required for overlapping

It was assumed that both the project manager and subcontractors can estimate any additional cost required for overlapping between activities with some degree of uncertainty in this research. For the main simulations the cost data was randomly generated based on another assumption that cost increases convexly, while the cost data was estimated based on RS Mean cost data (RS Means-Square foot costs (2004) and RS Means-Building Construction Cost Data (2003)) for the case study. Furthermore, it was assumed that overlapping between activities affects the amount of work-in-progress (WIP), thus affecting the productivities of the activities under overlapping. These approaches to estimating cost required for overlapping are acceptable in this research, since two solutions, both from the centralized approach and from the decentralized approach, are compared to identify a preferred approach. However, cost data for overlapping is critical in the viability of the benefit from the consideration of multiple methods for concurrent construction planning: if all additional costs for overlapping are so high that acceleration with additional cost cannot be justified, no need to consider multiple methods is required. Therefore, it is suggested that any cost increase due to overlap is researched with real construction project cases in order to investigate the impact of overlapping on cost.

(3) Pair-wise coordination between subcontractors in the decentralized approach

In the decentralized approach it was assumed that each pair of subcontractors coordinates for overlapping. However, more than two subcontractors can coordinate with one another for overlapping as argued by Hegazy et al. (2004) and Choo (2003). Especially the coordination among more than two subcontractors would be required when considering multiple overlapping at the same time as discussed in *Overlapping between only critical activities* above. The results of this research show that the decentralized approach has more potential for a higher benefit to the owner for concurrent construction planning than the centralized approach in many conditions. Thus it is suggested that concurrent construction planning by coordination among all subcontractors should be researched and the approach is compared to the centralized approach and/or the decentralized approach by pair-wise coordination in this research.

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APPENDICES

Appendix 1. Cost estimation of the case project

			Unit	Unit cost	Cost per S.F.	%	Calculated quantity
A. Excavation							
Basement Excavation	Site preparation for slab and trench for foundation wall and footing		S.F. Ground	0.14	0.05	0.07%	33,929
B. Sub-structure							
Standard Foundation	Poured concrete; strip and spread footings		S.F. Ground	2.64	0.88		31,667
Slab on Grade	4" reinforced concrete with vapor barrier and granular base		S.F. Slab	3.65	1.21	3.72%	31,493
Basement Walls	4' foundation wall		L.F. Wall	108	0.46		405
C. Superstructure							
Floor Construction	Concrete slab, metal deck, beams, steel columns		S.F. Floor	17.28	11.52	19.56%	63,333
Roof Construction	Metal deck, open web steel joists, beams colums		S.F. Roof	5.64	1.88		31,667
D. Building Enclosure including Roofing							
Exterior Walls	Face brick with concrete block backup	(90% of wall)	S.F. Wall	22	7.46		32,214
Exterior Windows	Storefront	(10% of wall)	Each	34	1.26	16.42%	3,521
Exterior Doors	Revolving and sliding panel, mall-front		Each	8314	1.22		14
Roof Coverings	Built-up tar and gravel with flashing; perlite/EPS composite insulation		S.F. Roof	3.81	1.27		31,667
Roof Openings	Roof hatches		S.F. Roof	0.12	0.04		31,667
E. Interior Construction							
Partitions	Gypsum board on metal studs	(60S.F. Floor/L.F. Partition)	S.F. Partition	4.26	0.71		15,833
Interior Doors	Single leaf hollow metal	600 S.F. Floor/Door	Each	572	0.95	3.58%	158
Stair Construction	Concrete filled metal pan		Flight	7475	0.79		10
F. Interior Finishes							
Wall Finishes	70% paint, 20% vinyl wall covering, 10% ceramic tile		S.F. Surface	7.26	1.21		15,833
Floor Finishes	50% carpet tile, 40% marble tile, 10% terrazzo		S.F. Floor	11.61	11.61	23.85%	95,000
Ceiling Finishes	Mineral fiber tile on concealed zee bars		S.F. Ceiling	4	3.52		83,600
G. Mechanical							
Conveying							
Elevators & Lifts	One hydraulic passenger, one hydraulic freight		Each	165300	1.74		1
Escalators & Moving Walks	Four escalators		Each	101887	4.29		4
Plumbing							
Plubming Fixtures	Toilet and service fixtures, supply and drainage	(1Fixture/2570 S.F. Floor)	Each	1105	0.43	19.14%	37
Domestic Water Distribution	Gas fired water heater		S.F. Floor	0.06	0.06		95,000
Rain Water Drainage	Roof drains		S.F. Roof	0.66	0.22		31,667
HVAC							
Heat Generating Systems	Included in Terminal & Package Units						
Terminal & Package Units	Multizone rooftop unit, gas heating, electric cooling		S.F. Floor	6.37	6.37		95,000
H. Fire Protection							
Sprinklers	Springklers, light hazard		S.F. Floor	1.39	1.39	2.03%	95,000
I. Electrical							
Electrical Service/Distribution	1200 ampere service, panel board and feeders		S.F. Floor	0.85	0.85		95,000
Lighting & Brach Wiring	Fluorescent fixtures, receptacles, switches, A.C. and misc. power		S.F. Floor	6.52	6.52	11.62%	95,000
Communications & Security	Alarm systems and emergency lighting		S.F. Floor	0.33	0.33		95,000
Other Electrical Systems	Emergency generator, 50 kW		S.F. Floor	0.26	0.26		95,000
			Sub-Total		**68.5**	**100.00%**	
Contractor Fees (General Requirements: 10%, Overhead 5%)				15%	10.28		
			Total Building Cost		**78.78**		
			Total Cost		**$7,483,625**		

Appendix 2. Estimation of each activity's duration for the case project

Acitivities	Sub-activities	Work Descpriton	Unit	Quantity	Crew	Daily output	No. of crew	Weekly output	Required duration	**Estimated Duration**
Excavation	Basement Excavation	Site preparation for slab and trench for foundation wall and footing	C.Y.	700.00	B-12C	200	1	1000	0.7	
		Excavating, Structural, Machine excavation, for spread and mat footings,								
		elevator pits, and small building foundations								
		Including site preparation								
	Subtotal Duration									**3**
Substructure	Standard Foundation	Poured concrete; strip and spread footings	S.F.	31,667						
		Concrete in Place including forms (4uses), reinforcing steel,	C.Y.							
		including finishing unless otherwise indicated								
		Quantity of Spread Footings:	C.Y.	14	C-14C	81.04	1	405.2	0.04	
		4'×4'×12"×24(EA)=384(C.F.)=14.22 (C.Y.)								
		Quantity of Strip Footings:	C.Y.	72	C-14C	61.55	1	307.75	0.24	
		1'×36"×((223'-4'×5(Ea))+(134'-4'×3(Ea)))×2=1,953 (C.F.)= 72.33 (C.Y.)								
	** Concrete Curing								2	
	Basement Walls	4' foundation wall	L.F.	405						
		Quantity of Basement Wall	C.Y.	106	C-14D	64.32	1	321.6	0.33	
		12"×4'×(223'+134')×2' = 2,860 (C.F.)=105.93 (C.Y.)								
		4' Column over Spread Footing, Square 12"×12", Average reinforcing								
		Quantity of Columns over Spread Footings	C.Y.	1	C-14A	10.13	1	50.65	0.02	
		12"×12"×4'×8 (Ea)=32 (C.F.)=1.19 (C.Y.)								
	** Concrete Curing and uninstalling forms (Curing period: 2 weeks)								2	
	** backfill & Compaction								0.5	
	Slab on Grade	4" reinforced concrete with vapor barrier and granular base	C.Y.	389	C-14E	60.75	1	303.75	1.28	
		Quantity of Slab on Grade								
		31,493 (S.F.)×4"=10,497.6 (C.F.)=388.8 (C.Y.)								
	** Concrete curing								2	
	Subtotal Duration								8.40	**9**
Superstructure										
	Floor Construction	Concrete slab, metal deck, beams, steel columns								
	** Calculation for each Floor	Steel columns	L.F.	384	E-2	960	1	4800	0.08	
		Quantity: 16' ×24 (Ea)=384								
		Beams	L.F.	1877	E-2	750	1	3750	0.50	
		Quantity: 268' ×5 + 89.5'×6=1,877'								
		metal deck	S.F.	31666.67	E-4	1330	1	6650	4.76	
		Concrete Slab- Placing Concrete and vibrating, including labor & equipment	C.Y.	781.92	C-20	160	1	800	0.98	
		Quantity: 31666* (S.F.)×8"=21,117 (C.F.)=781.92 (C.Y.)	C.Y.	781.92	C-7	110	3	1650	0.47	
	** Concrete Curing								2	
	** Form Uninstallation								0.2	
	** Duration for each floor (with pump)								8.52	**9**
	** Duration for each floor (with crane and bucket)								8.99	9
	**** Subtotal Duration for 3 floors (with pump)**									**27**
	Roof Construction	Metal deck, open web steel joists, beams colums								
	**** Roof construction is assumed to require same time as lower floor.									

Appendix 2. Estimation of each activity's duration for the case project (continued)

Acitivities	Sub-activities	Work Descpriton	Unit	Quantity	Crew	Daily output	No. of crew	Weekly output	Required duration	**Estimated Duration**
Exterior Enclosure										
	Exterior Walls	Face brick with concrete block backup		32,214						
		Face brick	S.F.	32,214	D-8	290	2	2900	11.11	
		Concrete block backup	S.F.	32,214	D-8	395	2	3950	8.16	
	Exterior Doors	Revolving Doors	Opng.	8	4 Sswk	0.3	1	1.5	5.33	
		Sliding Panels	Opng.	6	2 Glaz	1.3	1	6.5	0.92	
	Exterior Windows		S.F.	3,521	2 Sswk	200	1	1000	3.52	
	Subtotal duration (Duratin for Brickwork + some portion of the duration for Exterior Windows)**									**24**
Interior Construction										
	Partitions	Gypsum board on metal studs	. Parti	15,833	2 Carp	330	1	1650	9.60	
	Interior Doors	Single leaf hollow metal	Each	158	2 Carp	13	1	65	2.43	
	Stair Construction	Concrete filled metal pan	Riser	201	E-4	30	1	150	1.34	
	Subtotal duration (Duratin for Partition + some portion of the duration for Interior Doors)**									**10**
Interior Finishes										
	Wall Finishes	70% paint,	S.F.	11,083	1 pord	650	2	6500	1.71	
		20% vinyl wall covering,	S.F.	3,167	1 Pape	435	2	4350	0.73	
		10% ceramic tile	S.F.	1,583	D-7	190	1	950	1.67	
	Ceiling Finishes	Mineral fiber tile on concealed zee bars	S.F.	83,600	1 Carp	150	10	7500	11.15	
	Floor Finishes	50% carpet tile	S.F.	47,500	1 Tilf	150	5	3750	12.67	
		40% marble tile	S.F.	38000	D-7	60	10	3000	12.67	
		10% terrazzo	S.F.	9500	J-3	130	5	3250	2.92	
	Subtotal Duration									**22**
Total Project Duration										**95**

Appendix 3. Estimated additional cost for each work method

Activity (Base Cost/ Base quantity)	Method	Work method description: Crew size[1)]	Work method description: Equipment	Work method description: Subsequence	Work method description: Batch size	Labor Cost incl. equipments	Productivity Coefficient	Adjusted Productivity	Additional Cost ($)	Amount of time reduction
						($)		(Unit quantity/$)	($)	(weeks)
Excavation	1	1		Going down to the footings on next row		5,321	1.00	6.38	**-**	0
	2	1		Going right to the footings on next column		5,321	0.97	6.18	**165**	0
$5,463	3	1		Moving to next group of footings		5,321	0.95	6.06	**280**	0
33,929	4	1		Outer strip footings followed by inner spread footings		5,321	0.94	5.99	**340**	0
(S.F.)	5	1		Inner spread footings followed by outer strip footings		5,321	0.91	5.80	**526**	0
	6	2		Outer strip footings and inner spread footings at the same time		5,321	0.84	5.36	**1,014**	1
Substructure	1	1		Going down to the footings on next row	A floor area	108,479	1.00	0.29	**-**	0
	2	1		Going right to the footings on next column	A floor area	108,479	0.98	0.28	**2,214**	0
$278,588	3	1		Going down to the footings on next row	A half floor area	108,479	0.96	0.28	**4,520**	0
31,493	4	1		Going right to the footings on next column	A half floor area	108,479	0.94	0.27	**6,924**	0
(S.F.)	5	1		Going down to the footings on next row	A quarter floor area	108,479	0.92	0.27	**9,433**	0
	6	2		Going down to the footings on next row	A quarter floor area	108,479	0.85	0.25	**19,143**	2
Superstructure	1	1	Pump		A half floor area	204,014	1.00	0.31	**-**	0
	2	1	Pump		A quarter floor area	204,014	0.98	0.30	**4,164**	0
$1,463,950	3	1	Crane & bucket		A half floor area	236,526	0.96	0.26	**42,368**	0
63,333	4	1	Crane & bucket		A quarter floor area	236,526	0.94	0.25	**47,610**	0
(S.F.)	5	1	1 Tower Crane & bucket		A half floor area	333,403	0.92	0.17	**158,381**	0
	6	1	1 Tower Crane & bucket		A quarter floor area	333,403	0.90	0.17	**166,434**	0
Exterior Enclosure	1	1	Scaffolding for one side	Vertical movement + simultaneous laying bricks and blocks		582,591	1.00	0.06	**-**	0
	2	1	Scaffolding for one side	Vertical movement + laying bricks after blocks on one side		582,591	0.96	0.05	**24,275**	0
$1,229,063	3	1	Scaffolding for all sides	Horizontal movement + simultaneous laying bricks and blocks		644,316	0.98	0.05	**74,874**	0
32,214	4	1	Scaffolding for all sides	Horizontal movement + laying bricks after blocks on one floor		644,316	0.95	0.05	**95,636**	0
(S.F.)	5	1	Scaffolding for all sides	Laying all bricks after laying all blocks with veritcal movement		644,316	0.89	0.04	**141,359**	0
	6	1	Scaffolding for all sides	Laying all bricks after laying all blocks with horizontal movement		644,316	0.88	0.04	**149,586**	0
Interior Construction	1	1	Tabular scaffolding	Initiating after the completion of masonry work on 4 sides	A floor area	76,219	1.00	0.21	**-**	0
	2	1	Tabular scaffolding	Initiating after the completion of masonry work on 3 sides	A half floor area	76,219	0.95	0.20	**4,012**	0
$267,663	3	1	2 Scissorlifts	Initiating after the completion of masonry work on 4 sides	A floor area	79,881	0.98	0.19	**5,292**	1
15,833	4	1	2 Scissorlifts	Initiating after the completion of masonry work on 3 sides	A half floor area	79,881	0.96	0.19	**6,990**	1
(S.F.)	5	2	4 Scissorlifts	Initiating after the completion of masonry work on 4 sides	A floor area	82,729	0.87	0.17	**18,872**	2
	6	2	4 Scissorlifts	Initiating after the completion of masonry work on 4 sides	A half floor area	82,729	0.85	0.16	**21,109**	2
Interior Finishes	1	1	Tabular scaffolding		A floor area	541,197	1.00	0.36	**-**	0
	2	1	Tabular scaffolding		A half floor area	541,197	0.96	0.34	**22,550**	0
$1,785,145	3	1	Tabular scaffolding		A quarter floor area	541,197	0.95	0.34	**28,484**	0
194,433	4	1	15 Scissorlift		A floor area	605,280	0.94	0.30	**102,718**	1
(S.F.)	5	1	15 Scissorlifts		A half floor area	605,280	0.92	0.30	**116,716**	1
	6	2	Tabular scaffolding		A floor area	541,197	0.88	0.32	**73,800**	4

1) Crew size: multiple of base-crew

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