MANAGING SUPPLY FOR CONSTRUCTION PROJECT WITH UNCERTAIN STARTING DATE

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complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

Managing Supply for Construction Project with Uncertain Starting Date

Azadeh Mobtaker

There is a growing interest in supply management systems in today's competitive business environment. Importance of implementing supply management systems especially in home construction industry is due to the fact that several risks arising from different sources can adversely affect the project financially or its timely completion. Some risks of construction projects are out of managers' control while other risks such as supply related ones can usually be controlled and directed by effective managerial tactics.

In this thesis, we address the supplier selection problem (SSP) in wood-base construction projects in the presence of project commencement uncertainties. The project could be delayed for any reason and thus materials required for the project may not be needed on the promised date, however, pursuing the supplier for new delivery date may not be easy and without risk. Accepting the delivery before the project commencement date will be again a costly option because of the high holding cost. In this thesis, we present two problem cases and present heuristic based solution approaches. In the first case we assume that price of the product increases with the delay. In the second case we assume that promised quantity at the agreed price reduces with the delay. The proposed approaches are tested on the randomly generated data set and compared with the optimal solutions.

The problems considered in this research are novel and the proposed approaches deal with the important and common risks in construction industry in order to achieve a robust supply chain. The solution approaches presented in this thesis can be applied to different industries to improve the quality and efficiency of supplier-buyer collaborations.

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Chapter 1:

Introduction

1.1 Background

In construction supply chain, there can be several risks associated with exogenous events such as delays in permit, inspection, material quality, supply and labor availability, etc. These events disrupt efficient functioning of supply chain. Some of these events are controllable. On the other hand there are several uncertainties due to factors like political issues, governmental regulations, changes in market, technological improvements and so on which are difficult to control.

Resource availability and work availability are two common limitations that constrain construction progress. Work availability limitations are usually expressed by internal or external dependencies in a construction project. Since these dependencies are related to the nature of work, normally the project manager is not able to control them. In contrast, resource availability limitations can be controlled by a project manager by means of resource plans and managerial decisions. It seems that construction management is nothing but resource management which leads to a huge number of resource management and procurement studies (Park 2005).

1.2 Problem Statement

In some industries raw material and supplies are required for a short duration, in which long term commitment with suppliers does not seem a wise decision. Moreover suppliers usually aren't interested in increasing their production capacity because of either absence of long term relationships or technical constraints. For example in wood-frame house construction projects, wooden material is supplied from forestry industry, in which suppliers cannot augment their capacity due to technical constraints. Forests are owned by several suppliers with limited number of trees. A desirable requirement (with particular quantity, quality, etc.) may not be met by one supplier due to either limited capacity or reserved capacity for other clients. Consequently, it is inevitable for the buyer companies (e.g. sawmills/furniture companies) to buy from multiple suppliers in order to maintain competition and avoid various risks such as price, quality and delivery uncertainties (Awasthi *et al*., 2009).

Additionally, studies have recommended that "single sourcing is a dominant strategy only when supplier capacities are large relative to the product demand and when the firm does not obtain diversification benefits. In other cases multiple sourcing is an optimal sourcing strategy" (Burke *et al.,* 2007).

In engineering, procurement and construction (EPC) industries, supply cost is a big portion of total expenses of a company. So having enough supply at the right time is crucial to complete the construction project on time and within the budget i.e. appropriate supply management and specifically supplier selection and quantity allocation methodologies are effective to improve the project performance indicators like cost and time and supply chain efficiency in general.

In today's highly competitive market, an effective supplier selection process and closer collaboration among buyers and suppliers are needed. In order to cope with market volatility and diversity, buyers have to establish and manage relatively flexible collaboration with the suppliers to be able to deal with unexpected market demands and thus reduce the dependence on the vendor (Ganesan, 1994).

Suppliers usually offer attractive deals like better price and quality while they add some restrictions to their contracts such as minimum order size, limited capacity, lead time, etc. The minimum order size is mainly for economies of scale (to cover transportation and production set ups cost). The limitation on maximum acceptable quantity by the supplier is basically due to production or transportation capacities. These constraints make supplier selection problem (SSP) more challenging and complicated.

Supplier selection in construction industry differs from manufacturing industry. Usually manufacturing companies face uncertain product demand from their customers. These companies should apply supplier selection methods well-suited for stochastic demand conditions; on the other hand demand in the construction projects can be considered stable and known (similar to make-to-order system) but due to various unexpected events the starting date of a specific phase of project may vary; so delivery time of material is subject to change. Consequently, proper suppliers should be selected to ensure availability of required material at building under condition of uncertain delivery time.

1.3 Thesis Contributions

The problem considered in this research is a supplier selection and quantity allocation problem. We assumed deterministic conditions for demand quantity, while delivery time of material is not certain due to some unexpected events. Based on the vendors' reaction towards these uncertainties in the delivery time, we explore two different situations. These situations are Supplier Selection with Buyer Penalty for a Delay (SSPD) and Supplier Selection with Quantity Reduction for a Buyer Delay (SSQRD). Heuristic approaches are proposed. The results of solution approaches are provided and compared to the optimal solution to evaluate the performance of proposed approaches. As far as we know, this aspect has not been considered before and our work is a novel study in this area.

1.4 Organization of the thesis

The first chapter contains a brief introduction of construction supply chain and supplier selection problem (SSP). The remainder of this research is organized as follows. In chapter 2 we investigate how resource management and procurement problem has been approached in literature by different researchers. Chapter 3 and chapter 4 demonstrate two supplier selection problems addressed in this thesis and the solution approaches. In conclusions and future works chapter we summarize the contributions of this thesis and we propose several future research directions. Finally the references and the appendixes complete the thesis.

Chapter 2:

Literature review

Nowadays project managers realize how risks associated with supply can have a huge influence on total cost of projects. Especially in construction industries, availability of resources at right time and with enough quantity is crucial in order to complete a project on time and within the budget. This shows the importance of supply risk management and supplier selection decisions.

Normally, supply risk management methods in a construction project, are categorized in two general groups: resource utilization optimization models and supplier selection models. Studies in the field of supply usage optimization lead to mathematical formulation for supply usage and show how resource (supply) planning can affect the project performance. Also applying more efficient supplier selection methods can decrease risks associated with supplies especially in the presence of supply chain uncertainties. Using appropriate supplier selection approaches is advantageous in engineering, procurement and construction (EPC) industries with high complexity plus high value of supplies. In literature we will review studies on these two perspectives of supply risk management.

Figure 2.1 illustrates how the literature review chapter is structured.

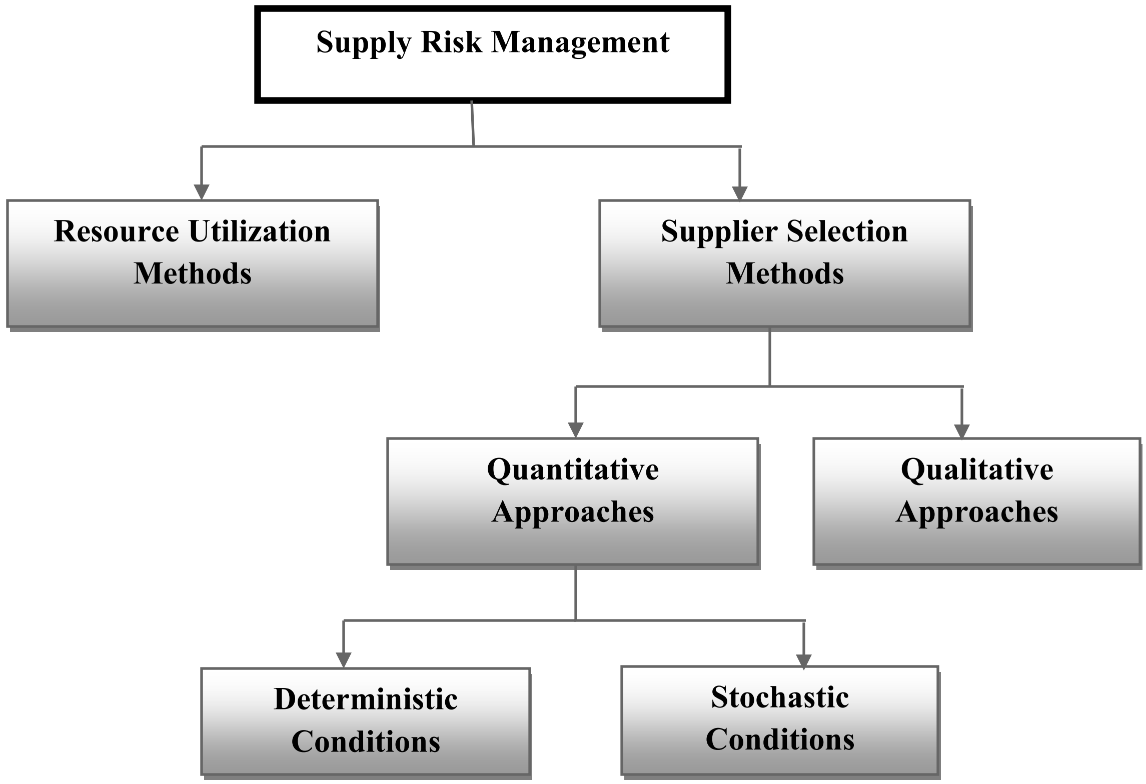

Figure 2.1: Structure of literature review

2.1 Resource utilization approaches

Park (2004) investigated the effect of resource coverage on schedule and cost performance of a construction project and evaluated the tradeoffs between these two performance factors. A system dynamic model is presented, and then by changing resource coverage scenarios from the base and running the model, the effect of resource coverage on project performance indices is examined. Park clarified policy implications such as: project performance does not change linearly relative to resource coverage; schedule performance is more sensitive to resource coverage than cost performance, and decreasing resource coverage does not always lead to project cost saving which is due to cost associate with the increase in idling of workforce when there is lack of material.

Caron *et al.* (1998) worked on supply management approaches in an Engineering, Procurement and Construction (EPC) industry. The main question in that research was: "How much material should be available at the site at a given time in order to guarantee a desired level of protection against interruptions due to the shortage of materials?"

Caron *et al.* (1998) proposed a stochastic model to plan delivery of material at building site. Although the model is not a detailed delivery plan in terms of delivery lots and delivery time, it identifies requirements that a delivery plan should meet to ensure the continuity of a construction process.

Nowadays, due to significant role of purchasing in profitability of a company, purchasing decisions have become more important and companies are becoming more and more dependent on their suppliers, therefore impact of poor decision making appears to be more severe. For instance, in industrial companies, purchasing share in the total turnover is between 50% - 90% (Telgen, 1994). So decisions regarding selecting suppliers are determinants of these organizations' financial success. In the next part we review some of the studies in the field of supplier selection.

2.2 Supplier selection approaches

2.2.1 Qualitative approaches

Qualitative approaches are used in lack of numerical data. In the case of supplier selection, often it is not possible to quantify parameters such as service quality level, reliability, flexibility, customer relationship, etc.; therefore, qualitative approaches are used. Examples of few qualitative approaches are Analytic Hierarchy Process (AHP), TOPSIS, or fuzzy logic based approaches.

Since variety of measures should be taken into account for supplier selection problems, they are mostly complex for purchasing managers to analyze. Analytic Hierarchy Process (AHP) can be used as a supplier selection tool; this method reduces the complex decisions to a series of one-to-one comparisons, and then synthesizes results based on a hierarchical structure (Wu *et.al*, 2006). Fuzzy Analytic Hierarchy Process (FAHP) is also utilized by Kahraman *et al.* (2003) to select the best supplier firm providing the most satisfaction for the criteria determined.

Lee (2010) used Fuzzy Analytic Hierarchy Process (FAHP) model to integrate benefits, opportunities, costs and risks (BOCR) concept while considering all the factors that positively or negatively are affecting the supplier-buyer relationship.

Punniyamoorthy *et al.* (2011) used structural equation modeling and Fuzzy Analytic Hierarchy Process (FAHP) technique for supplier selection based on a survey of 151 respondents. Zeydan *et al.* (2011) explored supplier selection problem in two steps, first by use of Fuzzy AHP and Fuzzy TOPSIS suppliers are evaluated, second Data Envelopment Analysis methodology is utilized. Bhattacharya *et al.* (2010) integrated Analytic Hierarchy Process (AHP) with Quality Function Deployment (QFD) and Cost Factor Measure (CFM) to select suppliers in a multi-objective system where most of the objectives are in conflict with each other. Amid *et al.* (2010) developed a weighted max-min fuzzy model to overcome the vagueness of input information and importance level of different criteria in a supplier selection process. An Analytic Hierarchy Process (AHP) is also used to determine the weights of decision factors.

Tsai *et al.* (2010) investigated attribute-based ant colony system (AACS) to construct a better way to select the appropriate supplier in dynamic business environment.

Azadeh and Alem (2010) proposed a decision making system to select the best way of selecting suppliers among three common methods: Data Envelopment Analysis (DEA), Fuzzy Data Envelopment Analysis (FDEA) and Chance Constraint Data Envelopment Analysis (CCDEA). Saen (2010) used Data Envelopment Analysis (DEA) for supplier selection and defined a way to incorporate the preferences of decision makers in the supplier selection process, while it is possible to have some factors with both input and output roles in the selection process. Dash Wu *et al.* (2010) proposed a fuzzy multi-objective programming model to select suppliers with considerations of risk factors. Sanayei *et al.* (2010) investigated supplier selection as a multiple criteria decision making (MCDM) problem. In order to solve this problem, the authors used linguistic values to examine the weights for different criteria. These values can be defined as triangular fuzzy numbers. Finally, the researchers proposed a hierarchy multiple criteria decision making (MCDM) model based on fuzzy sets theory and VIKOR method.

Hassanzadeh *et al.* (2010) used SWOT (Strengths, Weaknesses, Opportunities and Threats) technique and then fuzzy logic and triangular fuzzy numbers are integrated with SWOT analysis to evaluate suppliers. Demand was assumed to be a fuzzy number. Fuzzy linear programming model was used to determine the quantity to be bought from each supplier.

Also some conceptualized studies have been done in the area of supply chain flexibility. For instance, Gosling *et al.* (2010) explored a method to deal with high uncertainty level in construction environment. In that research supply chain flexibility is defined with two factors: sourcing and vendor flexibility. Gosling *et al.* (2010) concluded that an appropriate level of supply chain flexibility can be achieved by balancing vendor and sourcing flexibility with maintaining a pool of suppliers in each of following three categories: framework agreement suppliers, preferred suppliers and approved suppliers.

Since the vagueness of information about decision criteria in a supplier selection system is an issue for decision makers, Zhang *et al.* (2010) proposed an approach based on vague sets group decision.

2.2.2 Quantitative approaches

Quantitative approaches are most commonly used when numerical data is available. Most of the studies in the area of supplier selection emphasize on optimal quantity allocation. Factors such as demand quantity and lead time can be considered either stochastic or deterministic in the process of supplier selection. Then in this review we divide the studies in two main groups of deterministic conditions and stochastic conditions. In the deterministic case demand quantity and lead time are known and fixed. In the stochastic situation, mentioned factors are subject to change and may vary over time.

Also suppliers may have limited capacity or unlimited capacity. In the first case, it is assumed that the supplier has limited capacity while in the second case, supplier is able to provide requested quantity for any demand.

Deterministic conditions

Chauhan and Proth (2003) explored supplier selection problem with fixed demand for two different situations: a manufacturing unit with several providers and multi-providers for multi-manufacturing units. In their study, each supplier quotes a fixed setup cost plus a concave increasing cost of the quantity delivered. The authors proposed a heuristic algorithm based on properties of an optimal solution to allocate appropriate quantities to the suppliers which should be within a maximum and minimum range. Burke *et al.* (2008) studied the same problem as Chauhan and Proth (2003) but instead of considering a fixed setup cost plus concave quantity discount for suppliers, Burke *et al.* (2008) studied three different pricing schemes including linear discounts, incremental units discounts and all units discounts. Burke *et al.* (2008) proposed a heuristic model to solve the problem.

Chauhan *et al.* (2005) proposed an optimal algorithm based on dynamic programming for supplier selection problem (SSP) for single buyer.

Burke *et al.* (2008) considered a procurement problem where suppliers offer concave quantity discounts. Authors solved the continuous knapsack problem by minimization of a sum of separable concave functions. Burke *et al.* (2008) identify several solvable special cases of the defined NP-hard procurement problem, and proposed an approximation scheme for the general problem.

Burke *et al.* (2008) studied a problem motivated by a purchasing organization that source from a set of suppliers, in which each supplier offers an incremental quantity discount purchase price structure. The objective is to obtain required supply at minimum cost. Authors solved this allocating order quantities problem by minimizing the sum of separable piecewise linear concave cost functions. A branch and bound algorithm was developed to reach the optimal solution.

Glock (2010) studied an integrated inventory system for a supply network, in order to minimize total system cost. Glock (2010) assumed deterministic conditions for all the parameters over time and proposed a heuristic model.

In a typical optimization problem there is one objective, but some time we may have multiple objectives of conflicting nature like objectives effective in supplier selection process and therefore managers explore the tradeoffs among the goals. Multi-objective methods are used in this case, which makes the decision maker able to incorporate his own experiences in supplier selection while there isn't such an opportunity for him in methods with an optimal solution; also the decision maker can easier see the effects of policy constraints (which purchasing department can directly influence) on the final selection. To deal with such problems where the objectives are in conflict with each other, we cannot find a solution that is optimal for all the objectives, so the term “optimal solution” will be replaced by “non-inferior” or non-dominant solution in which improving one objective will lead to degradation of at least another objective. There are two methods to provide non-inferior solutions: weighting method and constraint method. Weber and Current (1991) utilized the weighting method with a mixed-integer program to deal with three objectives: cost, delivery and quality. Also the authors put constraints on demand satisfaction (inequality), each supplier’s capacity, and number of suppliers in deterministic demand conditions. Eventually “value paths” method is utilized to demonstrate the tradeoffs between objectives.

A single item, multi-supplier system with fixed demand, price-quantity discount considerations, suppliers’ capacities constraints has been explored by Chang (2006). The author proposed a series of linearization strategies to obtain the global optimal values and used a mixed integer optimization approach to solve the procurement problem. Sawik (2010) explored supplier selection problem for a custom company in a make to order environment. He considered three factors in selection process such as: price, quality of custom parts and reliability of on time delivery. Business volume discount is also considered and a mixed integer program was proposed to solve the problem. Rezaei and Davoodi (2010) studied a multi-product, multi-supplier and multi-objective (cost, quality and service level) supplier selection problem and proposed two multi-objective mixed integer nonlinear models. Mendoza and Ventura (2010) investigated a system of supplier selection and inventory management to optimize the entire system. A mixed integer nonlinear programming model is used that gives an optimal inventory policy while allocating appropriate quantity to chosen suppliers. The authors assumed a single-product case and constant demand rate.

Kokangul and Susuz (2010) utilized hierarchy process and non-linear integer and multi-objective programming with consideration supplier capacity, total budget and quantity discount constraints; while the objective functions were maximizing the total value of purchase (TVP), minimizing the total cost of purchase (TCP) or maximizing TVP and minimizing TCP simultaneously.

Combination of analytic hierarchy process (AHP) and goal programming (GP) has been utilized in a study by Kull & Talluri (2008) as a tool for strategic supplier selection in the presence of risk measures and product life cycle considerations. Also Jolai *et al.* (2010) studied supplier selection and order allocation problem in a fuzzy environment. First suppliers are evaluated by use of fuzzy MCDM, fuzzy AHP and modified fuzzy TOPSIS; then with help of goal programming method the problem has been modeled in a mixed integer linear program.

Woo and Saghiri (2010) defined a supplier selection problem as a multiple-objective decision making problem under uncertainty and proposed a fuzzy multiple-objective mixed-integer programming model to assign quantity to each supplier. The authors assumed three main stage of the supply chain: the purchasing organization, suppliers, and third-party logistics providers. This was a multiple-product problem in which suppliers had limited capacity.

Ebrahim *et al.* (2010) approached vendor selection problem as a multi-criteria decision making problem with consideration of different discount schemes (such as all unit-cost, incremental discount, and total business volume discount) on the unit price at the same time. Suppliers' capacity and demand constraints are also considered. As a result of their study, a scatter search algorithm is proposed while using the branch and bound method.

Yeh and Chuang (2010) studied supplier selection problem in a multi-product, multi-stage supply chain. In their study a multi-objective genetic algorithm is used to reach a balance among four conflicting objectives such as cost, time, product quality and green criteria; capacity constraint and constant market demand had been assumed.

Micheli *et al.* (2009) found out that combination of total cost of ownership (TCO) approach and supplier-specific guidelines for immediate and later interventions will lead to some "present total cost profiles" (PTCP) which include the variability and the single value of total cost for each intervention for every supplier that can be used for decision makers to subjectively utilize their related experiences to make the best decision.

Wan and Beil (2009) studied how to choose a qualified supplier to win a contract by use of a combination of request-for-quotes (RFQ) reverse auction and supplier qualification screening. The authors explored how well determining the level of qualification prior and after auction can decrease total expected procurement cost. The authors utilized mathematical programming techniques to compute the expected prequalification, auction and post qualification costs and by the use of mathematical methods, the optimal auction is achieved.

There are a few researches with unrestricted supply conditions. For instance, Keskin *et al.* (2010) studied a supplier selection and quantity allocation problem with fixed demand for a multi-store firm and single-product; the authors proposed an integrated vendor selection and inventory optimization model by use of a mixed integer nonlinear programming.

Stochastic conditions

In opposite of deterministic conditions in supplier selection process, procurement problems can be explored when some conditions such as demand quantity, delivery time and lead time are subject to change. These circumstances are closer to real-world conditions, therefore approaches towards them usually lead to more robust supply chain partnerships.

Abginehchi and Zanjirani Farahani (2010) investigated multiple-supplier, single-item inventory systems with random lead-times and both constant and probabilistic demand. By the use of a mathematical model the researchers determined the reorder level and quantity allocation for each supplier to minimize cost including ordering, procurement, inventory holding and shortage cost.

For a single-item, multi-supplier system, Chang *et al.* (2006) considered fixed demand and variable lead-time, price-quantity discount (PQD) and resource constraints. To solve this problem a mixed integer approach was used to minimize cost. The cost function included total periodic purchasing with PQD, ordering, holding, and lead-time crashing cost.

In modern supply chains, lots of uncertainties and variations are related to demand quantity and supply lead-times which high lights the importance of flexibility in vendor selection process. Flexibility can be defined as robustness of buyer-supplier relationship under changing supply conditions. Das and Abdel-Malek (2003) formulated a measure for flexibility as a function of varying order quantities and varying supply lead-times.

Some of common criteria in supplier selection are cost, quality, delivery and flexibility. Liao and Rittscher (2007) made a summation of four functions for cost including expected purchasing cost, demand quantity increase penalty, demand quantity decrease penalty and demand timing decrease penalty; also for flexibility Liao and Rittscher used Das and Abdel-Malek (2003) flexibility measurement formulation and finally for quality and delivery, quality rejection rate and late delivery rate were evaluated. Two equality and inequality constraints were associated with demand satisfaction and capacity constraints respectively. Since dealing with equality constraints in multi-objective problems is relatively difficult, a problem specific operator *Demand* along with genetic algorithm method has been used to solve the problem.

Zhang and Zhang (2010) explored supplier selection and purchase problem with uncertain demand quantity. The authors assumed minimum and maximum constraint on the order quantity for each supplier. The objective was to minimize the total cost. It was assumed that at the time of signing the contract with suppliers, buyer does not know the certain amount of demand. If the buyer orders more than the realized demand, the excess stock causes a holding cost or on the other hand if order quantity is less than the real demand, a penalty cost is incurred. So several cost types have been considered including selection, purchase, holding and shortage costs. Finally the problem was modeled by a Mixed Integer Program (MIP).

Jafari *et al.* (2010) investigated the supplier selection and quantity allocation problem in two evaluation and allocation phases: first a data envelopment analysis (DEA) model is used with consideration of several factors like cost, time and quality (ordering and transportation costs are inputs for the DEA model while lead-time mean and variance (lead-time is assumed to be a stochastic variable), and supplier quality score are output variables in the DEA model); second a multi-objective mixed integer programming model had been developed to minimize the total costs and maximize the overall efficiencies. Also it was assumed each supplier has a limited capacity.

Shi and Zhang (2010) combined multi-product acquisition and pricing problems where there is uncertain demand, budget constraint and supplier quantity discount. A mixed integer non-linear program is used to model this problem.

Awasthi *et al.* (2009) used a similar heuristic method to Chauhan and Proth (2003) for supplier selection problem while facing stochastic demand with fixed product price. Burke *et al.* (2007) also studied supplier selection problem with uncertain demand and consideration of suppliers' capacities and cost, product price, firm inventory costs and historical supplier reliabilities. Authors proposed an optimal approach in the case where a set of selected suppliers with limitations on minimum order size, must supply to a buyer facing uncertain demand. The main difference of their work and Awasthi *et al.* (2009) is that Burke *et al.* (2007) only assigned quantities to the suppliers who must supply a positive quantity while Awasthi *et al.* (2009) identify and allocate the suppliers.

Li and Zabinsky (2009) incorporated uncertainties in demand and supplier capacity in the supplier selection process. These uncertainties are captured by scenarios or with a probability distribution in two models: a stochastic programming (SP) model and a chance-constraint programming (CCP) model have been proposed to find minimal set of suppliers and order quantities with consideration of business volume discounts. Quality, delivery and cost (including purchasing, transportation and inventory costs) are the objectives considered in these models. Moreover, in order to analyze the tradeoffs between cost, risk of not meeting the demand and number of suppliers, multi-parametric programming techniques have been utilized.

At the end of this section we are going to review a few papers regarding supplier-buyer relationship and risk management in construction industry.

Yates (1993) demonstrated development of the delay analysis system program for construction industry, its purpose, technical parameters and the program output.

In a research by Odeh and Battaineh (2002) the results of a survey has been analyzed to identify the most important causes of delay in construction projects with traditional type contracts from the view point of construction contractors and consultants. As the result of this analysis owner interference, inadequate contractor experience, financing and payments, labor productivity, slow decision making, improper planning, and subcontractors are indicated among the top ten most important factors.

Sweis et al. (2008) explored the causes of construction delays in residential projects. In this research the data was collected in a survey conducted to residential projects consultant engineers, contractors, and owners, and interviews with senior professionals in the field. As the result of this study factors like financial difficulties faced by the contractor and too many change orders by the owner are the leading causes of construction delay.

Assef and Al-Hejji (2006) did a survey on time performance of construction projects. The most common cause of delay identified by contractors, consultants and owners was “change order”.

In a research by Luu *et al.* (2009), it is described that how Bayesian belief network (BBN) is applied to quantify the probability of construction project delays in a developing country. A questionnaire survey of 166 professionals has been conducted. A belief network system has been modeled and this model has been validated by using two realistic case studies. The result of this study has shown that financial difficulties of owners and contractors, contractor’s inadequate experience, and shortage of materials are the main causes of delay on construction projects in Vietnam.

Baloi and Price (2003) identified major global risk factors affecting cost performance of a construction project. Different decision-making technologies such as classical management science techniques and DSSs, KBSs were explored and evaluated. In this study Baloi and Price show that Fuzzy Set Theory is a viable technology for modeling, assessing and managing global risk factors affecting construction cost performance.

2.3 Conclusion

Supply risk management studies can be narrowed down in two categories: supply utilization methods and supplier selection methods. Also these studies can be categorized in the two groups of qualitative studies and quantitative studies. In some quantitative approaches demand and lead time were assumed to be stochastic; while other studies considered these factors are deterministic. Suppliers’ capacity was assumed to be limited in most of the researches, although there are some studies that did not consider any constraint on suppliers' capacity.

As far as we know, uncertainty in starting date of a phase in construction projects was not studied in any previous research. Since it is necessary to have enough material on time at building site in order to complete a project successfully, we were motivated to investigate the effect of uncertainty in starting date of a phase of a construction project on the supplier selection process and explore how severely this type of uncertainty can affect the project progress and success.

Chapter 3:

Supplier Selection with Buyer Penalty for a Delay (SSPD)

3.1 SSPD Definition

In construction projects, predicting starting time of an activity with certainty is difficult while successful completion of such projects highly depends on availability of required resources at building site on time. Then managing supply risk is crucial for completing the project on time and within budget. This work considers one such case where project start date is uncertain and demand will be managed by a right team of suppliers.

Due to delicate construction items and limited or no safe storage space at the open construction sites, project managers prefer to receive items very close to project starting date. In other words if the project get delayed, project manager postpones the scheduled delivery date. But in reality suppliers have restricted production and storage capacities and may have more than one client. In the event of project delay, for some suppliers, it may not be viable to deliver promised quantity at a later date. Moreover, the price of commodities are volatile and stocking the materials for later use incurs holding costs and therefore suppliers may offer either a new price (higher than the promised price) or may reduce promised quantity as a penalty for not accepting the delivery on the agreed date.

The case in which suppliers offer a new pricing scheme as a penalty for the delay (SSPD) is considered in this chapter. The objective in SSPD is to select a set of suppliers, from a pool of pre-qualified suppliers, which minimizes the expected purchasing cost.

3.2 Assumptions

We consider a building contractor (e.g. wooden home constructor) who wants to buy raw material from a set of suppliers. These suppliers are assumed to be prequalified in different aspects of supplier's business such as financial strength, management approach and capability, technical ability, quality etc. The goal is to select a group of suppliers that together can fulfill the demand at a minimum possible cost. We assumed that the demand is known and fixed. The delivery lead time is fixed and is assumed to be same for all suppliers. We also assume that the contractor knows the probability distribution (f) of the project delay or the expected starting date of the project. Normally building construction is done in several phases. In this work we assume that that these suppliers are providing material for a single phase. All the suppliers are providing the same material with characteristics acceptable to buyer i.e. suppliers cannot be discriminated w.r.t. the quality of material.

In this chapter we consider the first case where suppliers quote different price, per unit, for different delays. We consider k delay scenarios (S). Suppliers provide the buyer (constructor) with the modified price regarding each delay scenario $s \in S$. Since, every supplier has limitations on minimum order size and maximum order size, selection of more than one supplier is imperative. Since, we assume that suppliers supply the material very close to the project starting date, even in the case of delay; we do not consider inventory holding costs. We assume transportation costs are included in the prices quoted by the suppliers.

This approach will help constructor (buyer) to select a set of suppliers and decide how much to order from each of the selected suppliers.

3.3 Mathematical Formulation of SSPD

A set of suppliers $N = \{1, 2, \ldots, n\}$ can deliver raw material to the site of a construction project. In the current construction phase demand quantity is constant and equal to D. There are two constraints that apply to any supplier $i \in N$:

- The minimum quantity that supplier i prepares to deliver for economical reason is denoted by m_i.
- The maximum quantity that supplier i is able to deliver due to restrictions in production capacity, or reserved capacity for other customers and restricted time lines. This quantity is denoted by M_i.

Thus, the quantity x_i, $i \in N$ delivered to the building site is such that

$$x_i \in \{0\} \cup [m_i, M_i]$$

In this chapter we suppose suppliers' prices are discrete function of delay. The price quoted per unit by supplier $i \in N$ for delay scenario $s \in S$ is denoted by $P_{i,s}$.

Also the discrete probability distribution function for delay (f) is known.

Parameters and Decision Variables	Description
m_i, M_i	Minimum and maximum restriction on order size imposed by supplier i
D	Demand
x_i	Quantity ordered from i^{th} supplier
$P_{i,s}$	Price quoted per unit by supplier i for delay scenario s
N	Set of suppliers $(1, \dots, n)$
S	Set of delay scenarios $(1, \dots, k)$
f	Discrete probability distribution function for delay

Table 3.1: Description of parameters and decision variables of SSPD

Table 3.1 summarizes the notations used in mathematical formulation of SSPD.

The mathematical formulation of SSPD is presented as follows:

Objective:

SSPD: Minimize $$Z = \sum_{i \in N} \sum_{s \in S} P_{i,s} x_i f_s \tag{3.1}$$

Subject to:

$$\sum_{i \in N} x_i = D \tag{3.2}$$

$$m_i I_i \leq x_i \leq M_i I_i \qquad \forall\, i \in N \tag{3.3}$$

$$I_i \in \{0, 1\} \qquad \forall\, i \in N \tag{3.4}$$

The objective is to select order quantity, x_i corresponding to supplier i to minimize the expected total purchasing cost (3.1). Constraint (3.2) is to assure that the summation of ordered quantities is equal to demand; constraint (3.3) makes sure that the order quantity, for a selected supplier, lies between the corresponding minimum order size m_i and the maximum permitted M_i. Equation (3.4) is used to define binary variables, I_i which ensure that either a supplier delivers a quantity or do not supply at all.

3.4 Basic results

Proposition1:

The problem $SSPD$, is NP-hard even if all suppliers are quoting the same unit-selling-price.

Proof:

The proof we present here is on the line to the proof presented in Chauhan *et al*. (2002). Assume that a polynomial time algorithm exists for $SSPD$. Now consider the special case of problem $SSPD$ where delivery time of material is certain and each supplier supplies a single quantity i.e. minimum order quantity, say m_i, is equal to M_i. In this case each supplier either supplies m_i or nothing ($x_i \in \{0, m_i\}$). Furthermore, because of the unique selling price the whole problem reduces to selecting a combination of suppliers who can supply, collectively, D units where D is the given demand quantity. Now the remaining problem can be expressed as follows:

$$\sum_{i \in N} m_i I_i = D \tag{3.5}$$

$I_i \in \{0,1\} \quad \forall \; i \in N$ (3.6)

This problem is NP-hard since the partition problem (Garey and Johnson, 1979) is a special case of (3.5) and (3.6). ■

Proposition2:

In an optimal solution to $SSPD$ at most one supplier may not satisfy the following $x_i \in \{0\} \cup \{m_i, M_i\}$.

Description:

Assume that in an optimal solution supply correspond to two suppliers $j$and k, is such that the condition of Proposition 2 is not satisfied i.e. $m_j < x_j < M_j$ and $m_k < x_k < M_k$.

Based on the objective function we have defined in equation 3.1, we denote the coefficient of order quantity x_i with β_i:

$$x_i \sum_{s \in S} P_{i,s} f_s = x_i \beta_i \tag{3.7}$$

Now consider coefficients β_j and β_k, one of the following can exist:

$$\beta_j < \beta_k \;\; or \;\; \beta_j > \beta_k \; or \;\; \beta_j = \beta_k$$

Assume that the first case is true and therefore increasing the order size of supplier j by δ units: $\delta > 0$, $\delta = \min(M_j - x_j, x_k - m_k)$ and reducing the order size of supplier k by δ units will improve the solution. We can follow the same approach in the other cases. In the case that $\beta_j = \beta_k$, either of supplier $j \; or \; k$ can obtain a value of restrictions on order sizes. This completes the description. ■

3.5 Solution Approach for SSPD

Since SSPD is a NP-hard problem it is less likely that an exact algorithm could guarantee a polynomial run time. This encouraged us to focus on an efficient solution approach which could propose a good solution, if not optimal, in an acceptable run time.

In this chapter, we propose two heuristic algorithms in order to find efficient solution for SSPD. These algorithms are explained comprehensively in the following pages, also more detailed explanation is provided in Appendix A.

Algorithm SS-1

Please refer to Table 3.1 for description of parameters and decision variables mentioned in SS-1.

Part 1

Arrange suppliers in ascending order of their expected prices. Let us denote the ordered providers by $1, 2, \dots, n$. Consider d as a variable which will be updated, and initialize $d = D$.

Expected prices are calculated as follows:

$$p_{avg_i} = \sum_{s \in S} P_{i,s} \times f_s \; ; \; \forall \; i = 1, 2, \dots, n$$

1. For $i = 1, 2, \dots, n$

1.1. If $d > M_i$, then

(a) Set $x_i = M_i$.

(b) Compute $d = d - x_i$.

1.2. If $d \in [m_i, M_i]$, then

(a) Set $x_i = d$.

(b) Compute cost of assignment and stop.

1.3. If $d < m_i$,

(a) $i^* = i$ and go to part 2.

2. End of loop i

Part 2

3. For $i = i^*, i^* + 1, \dots, n$

3.1. Allocate m_i to supplier i

3.2. Assign the remaining quantity among suppliers $\{1, \dots, i^*\}$ in the most economical way; this involves part 1 of the algorithm again (see appendix A).

3.3. If the assignment is successful, compute the cost for the assignment. Keep the assignment in the memory if the cost of this assignment is better than all previous assignments.

Proposition 3:

If the algorithm terminates at 1.2 b (without entering part 2) the solution is optimal.

Proof:

In such cases the solution always satisfies the Proposition 2. Since the suppliers are arranged in the increasing order of their price, the solution obtained is the minimum cost solution.

Algorithm SS-2

In this section we introduce another heuristic algorithm (SS-2) for supplier selection problem with buyer penalty for a delay.

In algorithm SS-2 for each delay scenario, first we arrange suppliers in increasing order of their quoted unit prices, then by using similar method of SS-1 the best solution for each delay scenario will be computed and finally we will select the solution with minimum cost.

In brief algorithm SS-2 consists of the following steps:

1. For each delay scenario $s \in S$,

1.1 Arrange suppliers in ascending order of their unit prices for delay scenario s.

1.2 Use algorithm SS-1 to compute the best assignment say A_s.

1.3 Compute the expected cost of the assignment A_s and if it is less than cost of all previous assignments, keep the assignment in the memory as the best assignment.

3.6 Illustration

Illustration of algorithm SS-1

In this section, the proposed algorithm SS-1 is illustrated through an example of 6 suppliers and 1 buyer. Table 3.2 provides the data used in this example: number of suppliers (n), number of delay scenarios (k), demand quantity (D), probability of each delay scenario($f_s, s \in S$), suppliers' quoted prices for each delay scenario($P_{i,s}$, , $i \in N$ and $s \in S$, minimum and maximum order sizes acceptable by suppliers($m_i$and M_i, $i \in N$).

$n = 6, k = 4, D = 77$
$f_1 = 0.1, f_2 = 0.4, f_3 = 0.3, f_4 = 0.2$
$P_{1,1} = 10.4818, P_{1,2} = 10.5919, P_{1,3} = 11.1889, P_{1,4} = 11.6195$ $P_{2,1} = 10.5199, P_{2,2} = 11.2506, P_{2,3} = 11.5118, P_{2,4} = 11.6066$ $P_{3,1} = 10.7134, P_{3,2} = 11.0215, P_{3,3} = 11.4239, P_{3,4} = 12.3081$ $P_{4,1} = 11.5179, P_{4,2} = 11.9689, P_{4,3} = 12.609, P_{4,4} = 12.741$ $P_{5,1} = 11.5057, P_{5,2} = 12.2063, P_{5,3} = 12.4482, P_{5,4} = 13.208$ $P_{6,1} = 11.9867, P_{6,2} = 12.4395, P_{6,3} = 13.0917, P_{6,4} = 13.9187$
$\mathrm{m}_1 = 15, \mathrm{m}_2 = 18, \mathrm{m}_3 = 12, \mathrm{m}_4 = 10, \mathrm{m}_5 = 2, \mathrm{m}_6 = 2$ $\mathrm{M}_1 = 52, \mathrm{M}_2 = 20, \mathrm{M}_3 = 59, \mathrm{M}_4 = 58, \mathrm{M}_5 = 28, \mathrm{M}_6 = 40$

Table 3.2: Data of SSPD example

Here we give details on how SS-1 solves this example of six suppliers.

Suppliers' expected prices are calculated as follows:

i.e. supplier1 (S_1) expected price is equal to

$$p_{avg_1} = \sum_{s \in S} P_{1,s}\, f_s$$

$$p_{avg_1} = 10.4818 \times .1 + 10.5919 \times .4 + 11.1889 \times .3 + 11.6195 \times .2 = 10.9655$$

Supplier's number(i)	**Expected price**
1	10.96
2	11.33
3	11.37
4	12.27
5	12.41
6	12.88

Table 3.3: Expected prices of suppliers in SSPD example

Table 3.3 shows the suppliers arranged in ascending order of their expected prices.

Algorithm SS-1 starts assigning quantities as follows:

1) $d = D$ $(D = 77)$;
2) $d > M_1$; $x_1 = M_1 = 52$; $d = d - x_1 = 77 - 52 = 25$
3) $d > M_2$; $x_2 = M_2 = 20$; $d = d - x_2 = 25 - 20 = 5$
4) $d < m_3$ $(5 < 12)$

When the remaining demand quantity $(d = 5)$ is less than the minimum limit on order quantity of next cheapest supplier($d < m_3$), SS-1 enters part 2.

In part 2 of SS-1 four cases are investigated. First SS-1 selects S_3 as an obligatory supplier (algorithm SS-1 buys at least m_i units from S_i). This case will result in quantity allocation #1 in Table 3.4. In the second case SS-1 picks S_4 as an obligatory supplier and then by means of part 1 on algorithm SS-1 quantity allocation #2 in Table 3.4 is achieved. In the same manner quantity allocations #3 and #4 are obtained in Table 3.4.

For more clarification we will explain how SS-1 obtains quantity allocations #1 in Table 3.4.

Now SS-1 enters part 2 (see appendix A):

5) Initialize $flex = 0$.
6) Allocate m_3 to supplier3: $x_3 = m_3 = 12$.
7) Calculate the flexibility for supplier 3: $flex = flex + (M_3 - m_3)$

   $flex = 0 + (59 - 12) = 47$.
8) Compute $d = D - m_3 = 77 - 12 = 65$.
9) Call the algorithm SS-1 with following additional conditions

Allocate $d = 65$ among supplier $\{1, 2\}$ using part 1 of algorithm SS-1.

10) $d > M_1$; $x_1 = M_1 = 52$; $d = 65 - x_1 = 13$.
11) $d = 13 < m_2$

Since $d \leq flex$ $(13 < 47)$; we adjust $d = 13$ in x_3: $x_3 = m_3 + d = 25$. Then we compute the cost of the assignment $x = (52, 0, 25, 0, 0, 0)$ and keep it if the cost is better than previous allocations (if any).

Similar procedure will be followed when we select each supplier $i \in \{4, 5, 6\}$ as an obligatory supplier and then solutions #2 to #4 (Table 3.4) will be achieved.

Finally the quantity allocation with minimum cost among all 4 solutions (see Table 3.4) is selected as the final result of algorithm SS-1: $x = [52, 0, 25, 0, 0, 0]$; $cost = 854.4$.

Table 3.4 provides quantity allocations checked by SS-1.

#	Quantity Allocations obtained by means of algorithm SS-1					
	Supplier1	**Supplier2**	**Supplier3**	**Supplier4**	**Supplier5**	**Supplier6**
1	52	0	25	0	0	0
2	52	0	0	25	0	0
3	52	20	0	0	5	0
4	52	20	0	0	0	5

Table 3.4: Quantity allocations obtained from SS-1

Illustration of algorithm SS-2

In order to solve this example by means of algorithm SS-2, for each delay scenario $s \in S$, arrange suppliers in ascending order of their quoted unit prices and then apply algorithm SS-1 to get the best allocation for the specific delay scenario s. Calculate total expected cost for each successful quantity allocation and compare it with previous allocation and keep the minimum. Eventually the allocation with the minimum total cost ($x = [52, 0, 0, 0, 25, 0];\ cost = 854.4$.) would be the final solution of algorithm SS-2 for this example.

In this example the results obtained by use of SS-1 and SS-2 are same as optimal solution.

3.7 Experimentation

In order to evaluate the performance of two proposed algorithms SS-1 and SS-2, 1300 experiments have been done; the results of these two algorithms have been compared with optimal solution. The two algorithms SS-1 and SS-2 in companion with optimal solution algorithm have been modeled by a C++ program written in Visual Studio 2008.

All required data including supplier quoted-unit-selling prices for each delay scenarios, order size limitations, delay scenario probabilities and demand quantity have been generated randomly in Visual Studio C++, in the random data generation part the method used to generate random data is explained.

Several tests have been conducted starting with problem size 3 (number of suppliers is equal to three) till problem size 15. For each problem size (number of suppliers), 100 tests are done.

Relative error of each experiment is calculated as follows:

Relative Error for SS1 result in percentage $=$

$$\frac{Cost\ of\ SS1 - Cost\ of\ Optimal\ Solution}{Cost\ of\ Optimal\ Solution} \times 100 \qquad (3.8)$$

Similar formula is used in order to calculate the relative error of algorithm SS-2 results.

And finally the mean relative error of each problem size is calculated as follows:

$$\text{Mean Relative Error} = \left(\sum_{i=1}^{100} Relative\ Error_i\right)/100 \qquad (3.9)$$

Standard deviation of relative errors of 100 experiments is computed for every problem size using the following formula:

$$\text{Standard Deviation of Relative Error} = \sqrt{\frac{1}{n-1} . \sum_{i=1}^{n} (x_i - \bar{x})^2} \qquad (3.10)$$

In the standard deviation formula, n stands for number of experiments (here n is equal to 100). x_i is the relative error of experiment $\#i$ calculated by equation #3.8, and $\bar{x}$ indicates mean relative error of 100 tests calculated by formula #3.9.

Random data generation

(i) Number of delay scenarios (k) is a random number between two and five.

(ii) Probability of each scenario is generated randomly using the following formula:

$$f_s = Rand(0, 1 - \sum_{j=1}^{s-1} f_j)$$

(iii) Also for minimum acceptable order quantities (m_i) we have generated random integer numbers between zero and 20 and each maximum acceptable order quantities (M_i) is equal to m_i plus an integer random number between five and 25.

(iv) In order to generate quoted unit prices $(P_{i,s})$ randomly we followed next steps:

Initialize $price = 0$ (Consider a function called $GetRandomBetween(a, b)$ which generates a random number between a and b).

For every supplier $i \in N$:

1) $price = price + GetRandomBetween(0.5, 1)$
2) $P_{i,0} = price$

Then for each delay scenario $s \in S$:

3) $P_{i,s} = P_{i,s-1} + price * GetRandomBetween(0,3.1)$

(v) Demand quantity (D) is an integer random number between summation of all m_i ($i \in N$) and sum of all M_i ($i \in N$):

$$D = Rand(\sum_{i \in N} m_i, \sum_{i \in N} M_i)$$

By means of above explained methods, we generated random data and ran the C++ program for SS-1, SS-2 and Optimal algorithms one hundred times for every problem size. Table 3.5 provides the mean relative error and standard deviation for each problem size (from 3 to 15) using SS-1 and SS-2.

Number of Suppliers	Mean Relative Error SS-1 (%)	Standard Deviation of Relative Error SS-1	Mean Relative Error SS-2 (%)	Standard Deviation of Relative Error SS-2
3	0	0	0	0
4	0.00517	0.05174	0.01846	0.18464
5	0	0	0.00653	0.06527
6	0.01094	0.09919	0.01042	0.09882
7	0.01081	0.05399	0.02902	0.14834
8	0.01461	0.07618	0.02939	0.27538
9	0.03747	0.20348	0.01103	0.06984
10	0.01235	0.08647	0.0451	0.17401
11	0.01095	0.07368	0.06303	0.28514
12	0.02555	0.22256	0.09858	0.38802
13	0.01399	0.09734	0.06155	0.20913
14	0.02629	0.14651	0.08368	0.33231
15	0.00131	0.01314	0.05213	0.21153

Table 3.5: Mean relative error and standard deviation of relative error for SS-1 and SS-2 experiments

Both approaches are quite effective in obtaining a very good solution (mean relative error is less than 1%), however it seems SS-1 is offering much closer solutions to optimal solution than SS-2 (Table 3.5 and Figure 3.1) based on randomly generated problems. In algorithm SS-1 we allocate quantities based on the expected price which could be misleading and it is possible that expected price may leave some good/competitive suppliers out the selection system. In other words both algorithms have their own importance.

Also the following table shows the mean relative error for SS-1 and SS-2.

Mean Relative Error (%)	
SS-1	0.013
SS-2	0.039

Table 3.6: Mean relative error for results of SS-1 and SS-2 algorithms

Table 3.6 shows the result of algorithm SS-1 on average lead to lower relative error than the results from using algorithm SS-2.

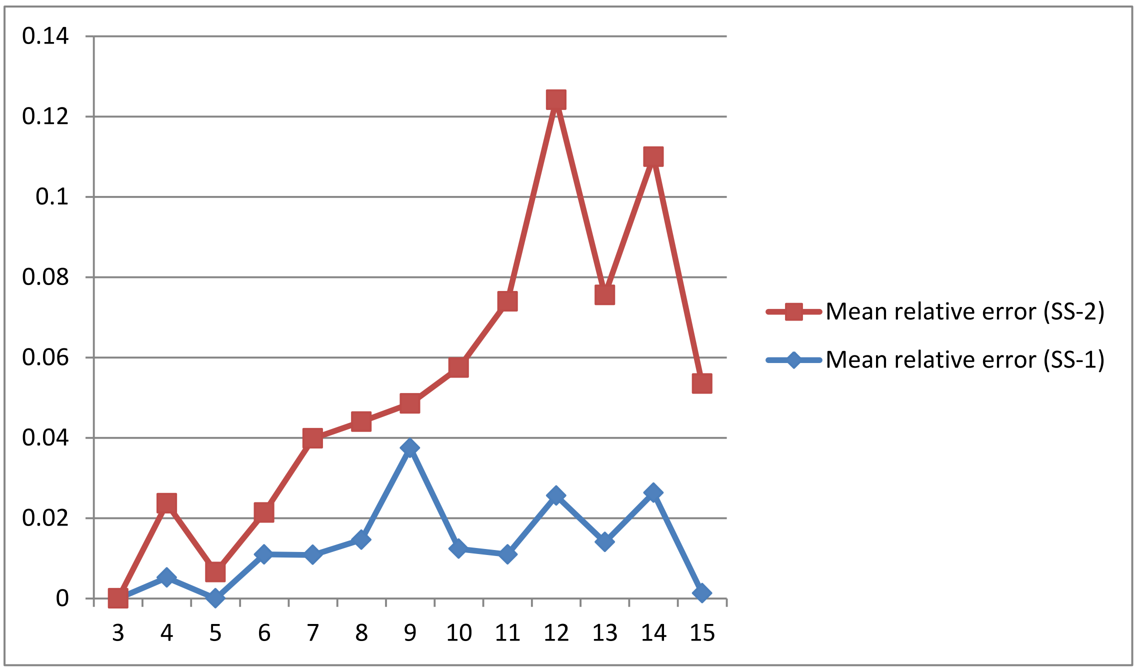

Figure 3.1: Mean relative error of SS-1 and SS-2

3.8 Conclusion

Lots of construction projects in Canada are timber frame and log house constructions, in which wood is the main supply. Normally in forestry industry, wood suppliers own limited number of trees of specific species in a forest. So due to limited capacity suppliers set a limit on maximum order size they can provide, while for the economies of scale they only accept orders above a minimum limit.

A very common risk threatening the success of a construction project is an unexpected delay in a phase of the project. As a result of such delays and in order to have the required material at the right time (exactly when they are required), it is necessary to update the delivery time for the suppliers. In this case suppliers will charge the construction company a higher price because they may have bear inventory cost to meet the new schedule.

In supplier selection literature some authors presented qualitative approaches like Analytic Hierarchy Process (AHP), TOPSIS, etc. while other researchers studied optimization and allocation models. As opposed to deterministic demand conditions, in some researches the effect of uncertainty (stochastic demand, stochastic lead time) was taken into account in the selection of suppliers.

As far as we know there is not any study that considers the effect of uncertainty in staring date of a construction project phase in the supplier selection process. This motivates us to integrate uncertainty in starting date of a project and the fact that suppliers accept order sizes in specific ranges into the supplier selection process. Result of this integration is presented in the form of a mixed integer linear programming (MILP) problem (SSPD) in section 3.3.

After formulating SSPD mathematically the computational complexity of this problem is explored; and SSPD is proved to be a NP-hard problem in Proposition 1. Most likely there is no polynomial time algorithm to solve SSPD; therefore we focused on developing efficient heuristic approaches.

Moreover a feature of optimal solution is introduced in Proposition 2 as a guideline for designing proper heuristic algorithms.

In order to solve SSPD, two heuristic algorithms are proposed: Supplier Selection-1 and Supplier Selection-2. Also, for evaluating these algorithms an optimal solution algorithm is designed. The optimal solution algorithm explores all possible solutions for a given problem; for a problem of n suppliers the optimal algorithm will search among $2^n - 1$ possible solutions to find the most economical quantity allocation. The optimal solution algorithm is an exponential time algorithm. Complexity of proposed algorithms SS-1 and SS-2 is much less than the optimal approach. In most of the cases (simple problems), the proposed algorithms find solutions in n computational steps, but in worst case the number of steps required is n^2.

Algorithms are tested on the randomly generated data set and the results are compared with the optimal solution. In most of the cases the average error is less than 1%. From the solution quality, we can conclude that algorithms are capable of obtaining solutions very close to the optimal solutions.

Chapter 4:

Supplier Selection with Quantity Reduction for a Buyer Delay (SSQRD)

4.1 SSQRD Definition

A typical construction project involves several activities performed in different phases. For instance in one phase the project team will build the walls of a house and in the next phase they build the roof and so on. So starting one phase can depend on completion of previous phases. Then delay in any phase is detrimental to subsequent phases.

Procurement of construction material constitutes an essential activity in each phase. In order to have a successful construction project both timely and financially, it is necessary to have required material for each phase exactly at the beginning of that phase when they are required. Due to the uncertainty associated with commencement of each phase, a special procurement agreement should be negotiated with suppliers.

In the event of delay in a project phase a project manager may ask the suppliers to deliver raw material at a new schedule to synchronize the project progress with delivery of product. The case in which suppliers decrease the promised quantity as a penalty for the delay (SSQRD) is studied in this chapter. The objective in SSQRD is to select a set of suppliers, from a pool of pre-qualified suppliers, which minimizes the expected purchasing cost.

In this chapter we investigate how decreasing the signed quantity by suppliers after the event of delay can affect the purchasing decision making at the time of signing a contract with suppliers.

In the section 4.2, we describe the assumptions made for supplier selection problem with quantity reduction for a buyer delay (SSQRD). Part 4.3 defines the SSQRD problem mathematically. We provide the basic propositions of our study in section 4.4. The solution approach for SSQRD is presented in section 4.5 and it has been demonstrated in an example in part 4.6. The experimentation result for SSQRD is provided in section 4.7, and finally the conclusion of this chapter is summarized in section 4.8.

4.2 Assumptions

It is assumed that a set of pre-qualified suppliers are available to supply required material at a building site. These suppliers have met the preliminary selection criteria such as financial stability, technical capability and support, reputation in the industry, quality etc. If because of delay in the project, the total quantity delivered by the selected suppliers is less than the demand, it is assumed that the remaining quantity will be acquired from the market albeit at a higher price. For simplicity, we assume market has no limitations on order quantity and its price is fixed. The goal is to acquire specific quantities from a group of suppliers and buy the remaining quantity from market at a minimum possible cost.

We assume that demand is known and fixed. Delivery lead time is assumed to be fixed and is the same for all suppliers. We also assume that the building contractor (buyer) knows the probability distribution (f) of the project delay or the expected starting date of the project. Moreover in this research we assume that suppliers under consideration are associated with only one phase of the construction project. It is assumed that suppliers provide material with the same acceptable quality level.

The suppliers may impose restrictions on the minimum and the maximum order size. The unit selling price quoted by any supplier is fixed and may differ from each other.

In this chapter we consider the case where supplier reduces the promised quantity, with a known factor, as project delays. We consider k delay scenarios(S). Suppliers provide the buyer (constructor) with the reduction factor $\left(1-\alpha_{i,s}\right)$ of promised quantity regarding each delay scenario $s \in S$. In SSQRD, we consider a discrete distribution for project delay and therefore the suppliers' quantity reduction functions are discrete as well.

The objective for SSQRD is to minimize the expected purchasing cost. The purchasing cost only includes the mean cost that the buyer pays to the suppliers. It is assumed that suppliers are able to deliver material very close to project starting date, so inventory cost is excluded. We also assume transportation cost is included in the suppliers' quoted unit prices.

4.3 Mathematical Formulation of SSQRD

A set of suppliers $N = \{1, 2, \dots, n\}$ can deliver raw material to the site of a construction project. In the current construction phase demand quantity is constant and equal to D. There are two constraints that apply to any supplier $i \in N$:

- The minimum quantity that supplier i prepares to deliver for economical reason is denoted by m_i.
- The maximum quantity that supplier i is able to deliver due to restrictions on the production capacity. This quantity is denoted by M_i.

Thus, the quantity x_i, $i \in N$ delivered to the building site is such that

$x_i \in \{0\} \cup [m_i, M_i]$

For delay scenario $s \in S$ in delivery time of material, supplier $i \in N$ will decrease the promised quantity by a reduction factor $1 - \alpha_{i,s}$. The price quoted per unit by supplier $i \in N$ is denoted by P_i and is fixed. If the set of selected suppliers are not able to satisfy the demand, the contractor (buyer) will fulfill the missing quantity from the market at price P_M, where $P_M \geq P_i, i \in N$.

The discrete probability distribution function for delay (f) is known.

The following table summarizes the notations used in the problem formulation:

Parameters and Decision Variables	Description
m_i, M_i	Min and Max restriction on order size imposed by supplier i
D	Demand
x_i	Quantity ordered from i^{th}supplier
$x_{M,s}$	Quantity ordered from market in scenario s
P_i	Price quoted per unit by supplier i
P_M	Market price per unit
N	Set of suppliers $(1, \dots, n)$
S	Set of delay scenarios $(1, \dots, k)$
$\alpha_{i,s}$	1-reduction factor of supplier i for delay scenario s
f	Discrete probability distribution function for delay

Table 4.1: Description of parameters and decision variables of SSQRD

The mathematical formulation of SSQRD is presented as follows:

Objective:

SSQRD: Minimize $Z = \sum_{s \in S} f_s(\sum_{i \in N} P_i x_i \alpha_{i,s} + P_M x_{M,s})$ (4.1)

Subject to:

$$\sum_{i \in N} \alpha_{i,s} x_i + x_{M,s} \geq D \quad \forall\, s \in S \tag{4.2}$$

$$m_i I_i \leq x_i \leq M_i I_i \qquad \forall\, i \in N \tag{4.3}$$

$$I_i \in \{0,1\} \quad \forall\, i \in N \tag{4.4}$$

In SSQRD, the objective is to select order quantity, x_i corresponding to supplier i for minimizing the expected total purchasing cost (4.1). Constraint (4.2) is to assure that sum of ordered quantities is at least equal to demand quantity; Constraint (4.3) makes sure that the order quantity, x_i for a selected supplier, lies between the corresponding minimum order size m_i and the maximum permitted M_i. Constraints (4.4) impose the restrictions on the value of variables I_i .

4.4 Basic results

In the case of continuous probability distribution, following propositions can be observed:

Proposition1:

For SSQRD, in the case of single supplier with unit price P, we show the optimal order quantity (Q) should satisfy the following condition:

$$\int_0^{\frac{Q-D}{\alpha}} f(t)dt = \frac{P_M}{P_M + P} \quad \text{or} \quad \text{Probability}\left(t < \frac{Q-D}{\alpha}\right) = \frac{P_M}{P_M + P}$$

Proof:

Consider a single supplier that decreases the agreed quantity by α units in the event of each delay scenario (α is a linear reduction factor and its unit is unit of quantity/time unit).

The buyer has signed a contract for delivery of Q units of product at the agreed delivery time. Q is the appropriate quantity to cover the delay $t = \frac{Q-D}{\alpha}$. In other words Q is sufficient to absorb the demand delay of t periods.

For simplicity of the mathematical calculation, we assumed that the probability distribution function is a continuous function of delay and denoted by $f(t)$. We assumed $f(t)$ follows any continuous distribution functions.

The cost C expresses the cost of excess product as well as cost of product shortage.

Also the order quantity Q satisfies the following constraint: $Q \geq D$.

$$C = \int_{0}^{\frac{Q-D}{\alpha}} P(Q - D - \alpha t) f(t) dt + \int_{\frac{Q-D}{\alpha}}^{\infty} P_M (D - Q + \alpha t) f(t) dt$$

$$\frac{\partial C}{\partial Q} = \frac{1}{\alpha} \times 0 + \int_{0}^{\frac{Q-D}{\alpha}} P f(t) dt - P_M \frac{1}{\alpha} \times 0 + \int_{\frac{Q-D}{\alpha}}^{\infty} -P_M f(t) dt$$

$$\frac{\partial C}{\partial Q} = 0 \text{ (For first order optimality condition)}$$

$$\int_{0}^{\frac{Q-D}{\alpha}} P f(t) dt - \int_{\frac{Q-D}{\alpha}}^{\infty} P_M f(t) dt = 0$$

$$P \int_{0}^{\frac{Q-D}{\alpha}} f(t) dt - P_M \left[1 - \int_{0}^{\frac{Q-D}{\alpha}} f(t) dt \right] = 0$$

$$(P + P_M) \int_0^{\frac{Q-D}{\alpha}} f(t)dt = P_M$$

$$\int_0^{\frac{Q-D}{\alpha}} f(t)dt = \frac{P_M}{P_M + P}$$

Observations:

I. In the case of single supplier problem, if market price is equal to supplier's price ($P_M = P$), then we have to buy enough quantity to cover the periods which brings the cumulative probability up to 50%.

$P = P_M$

$$\int_0^{\frac{Q-D}{\alpha}} f(t)dt = \frac{P_M}{P_M + P} = 0.5$$

II. If the product of interest is much more expensive in market than buying it from supplier, then we have to buy enough quantity to cover all the possible delays.

$P_M \gg P$

$$\int_0^{\frac{Q-D}{\alpha}} f(t)dt = \frac{P_M}{P_M + P} \to 1$$

III. In the case of multiple suppliers, if suppliers' quoted prices have been arranged in ascending order as follows $P_1 < P_2 < \cdots < P_n$, then

$$\int_0^{\frac{Q_1-D}{\alpha}} f(t)dt = \frac{P_M}{P_M + P_1} = b_1$$

$$\int_0^{\frac{Q_n-D}{\alpha}} f(t)dt = \frac{P_M}{P_M + P_n} = b_n$$

Since $P_1 < P_n$ then $b_1 > b_n$.

Since the effective price must be between P_1 and P_n, the optimal order quantity should cover delays which brings the cumulative probability to β^*, where $b_n \leq \beta^* \leq b_1$.

IV. Consider there are two suppliers with the same price $P_1 = P_2$, only one supplier will be selected and $\alpha_1 > \alpha_2$, then the quantity we order from supplier 1 (Q_1) should be always greater than the quantity we order from supplier $2(Q_2)$.

Proof:

Optimal order quantity must satisfy the following relation:

$$\int_0^{\frac{Q-D}{\alpha}} f(t)dt = \frac{P_M}{P_M + P}$$

Let's assume $\alpha_1 > \alpha_2$, i.e. $\alpha_1 = \alpha_2 + \delta$, then:

$$\int_0^{\frac{Q_1-D}{\alpha_1}} f(t)dt = \int_0^{\frac{Q_2-D}{\alpha_2}} f(t)dt = \frac{P_M}{P_M + P}$$

This implies

$$\frac{Q_1 - D}{\alpha_1} = \frac{Q_2 - D}{\alpha_2}$$

$$Q_1 - Q_2 = \frac{\delta}{\alpha_2}\,(Q_2 - D)$$

$\frac{\delta}{\alpha_2}$ is a positive constant. Since market price is always bigger than supplier's price: $Q_1, Q_2 \geq D$. The right hand side of the above equation is positive so the left hand side should be positive, and thus: $Q_1 > Q_2$.

4.5 Solution Approach for SSQRD

In this chapter, we propose a heuristic algorithm in order to find efficient solution for SSQRD. Based on proposition 1 and the observations obtained in section 4.4, we develop a heuristic algorithm to select and assign suppliers in order to minimize total expected cost.

Next the proposed algorithm is explained comprehensively and more detail explanation is provided in Appendix B.

Algorithm SS-3

The following figure illustrates the basic structure of algorithm SS-3.

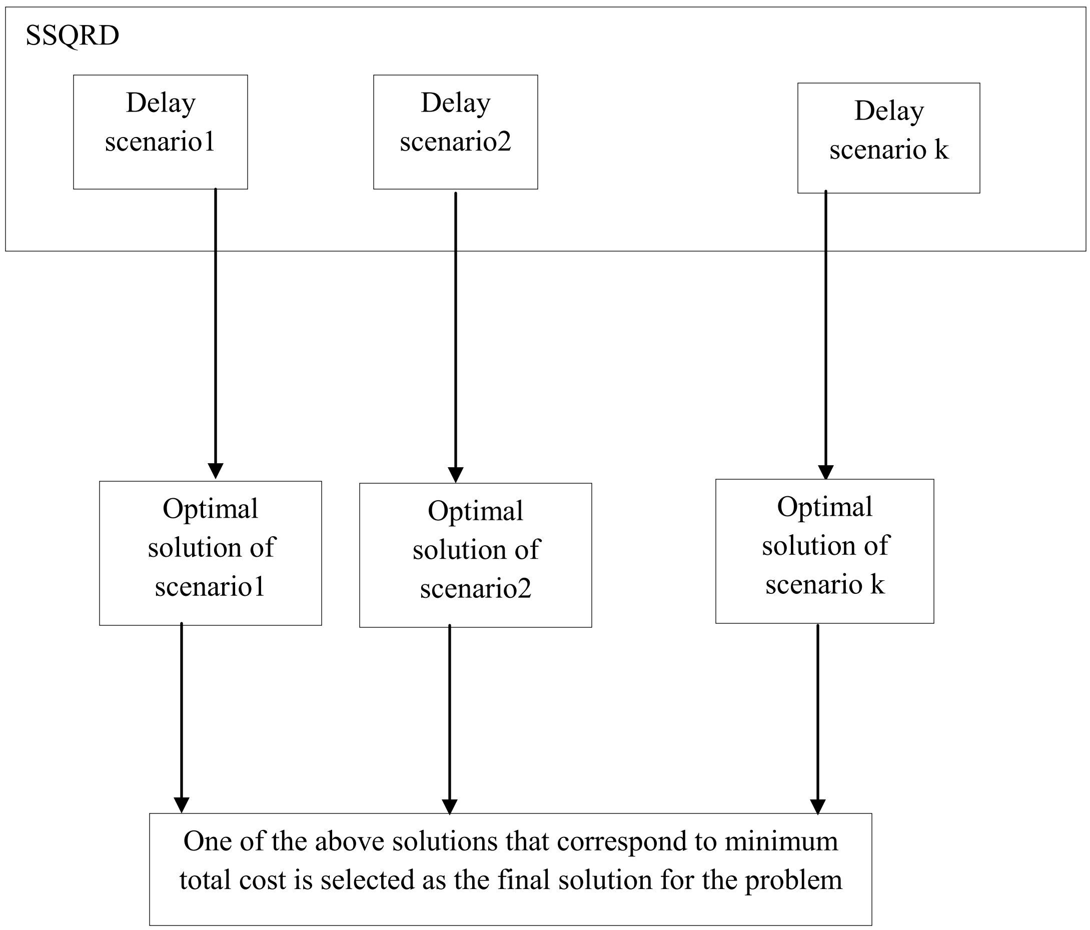

Figure 4.1: Structure of SS-3 methodology

Part 1

First arrange suppliers based on their effective unit prices. Effective unit price for supplier i is calculated as follows:

Compute the expected supply(es_i) for supplier i as minimum between demand quantity (D) and supplier i maximum acceptable order size (M_i).

$es_i = minimum\ (D, M_i)$

Then calculate the effective unit price (eup_i) as follows:

$$eup_i = (\sum_{s \in S} f_s\big(es_i \times \alpha_{i,s} \times P_i + es_i \times (1 - \alpha_{i,s}) \times P_M\big))/es_i$$

In the next step, based on observation III, we determine the delay scenarios that we have to examine say $s \in R$.

Define $d = D$.

In this approach we assume market as $(n+1)^{th}$ supplier with no limitation on minimum and maximum order size.

For each delay scenario $s \in R$ compute the following:

1 For $i = 1, 2, \dots, n+1$

1.1 If $\frac{d}{\alpha_{i,s}} > M_i$ then

(a) Set $x_i = M_i$.

(b) Compute $d = d - \alpha_{i,s}\, x_i$.

1.2 If $\frac{d}{\alpha_{i,s}} \in [m_i, M_i]$, then

(a) Set $x_i = \frac{d}{\alpha_{i,s}}$.

(b) Compute cost of assignment and stop.

1.3 If $\frac{d}{\alpha_{i,s}} < m_i$,

(a) $i^* = i$ and go to Part2.

2. End of loop i.

Part 2

3. For $i = i^*, i^* + 1, \dots, n + 1$

3.1. Allocate m_i to supplier i

3.2. Assign the remaining quantity among suppliers $\{1, \dots, i^*\}$ in the most economical way; this involves part 1 of the algorithm again (see appendix B).

3.3. If the assignment is successful, compute the cost for the assignment. Keep the assignment in the memory if the cost of this assignment is better than all previous assignments.

4.6 Illustration

In order to explain comprehensively how algorithm SS-3 works an example of seven suppliers and one buyer is solved in this section.

Table 4.2 includes the data of this example: number of suppliers (n), number of delay scenarios (k), demand quantity (D), probability of each delay scenario$(f_s, s \in S)$, market price(P_M), suppliers' quoted prices$(P_i, i \in N)$, one minus reduction factor of each supplier for each delay scenario in percentage$(\alpha_{i,s},, i \in N$ and $s \in S)$ and suppliers' minimum and maximum acceptable order sizes$(m_i$and $\mathrm{M}_i, i \in N)$.

$n = 7, k = 4, D = 56$
$f_1 = 0.32, f_2 = 0.3, f_3 = 0.21, f_4 = 0.17$
$P_M = 10$ $P_1 = 4, P_2 = 4.5, P_3 = 5, P_4 = 5.5, P_5 = 6, P_6 = 6.5, P_7 = 7$
$\alpha_{1,1} = 1, \alpha_{1,2} = 0.94, \alpha_{1,3} = 0.79, \alpha_{1,4} = 0.78$ $\alpha_{2,1} = 1, \alpha_{2,2} = 0.88, \alpha_{2,3} = 0.86, \alpha_{2,4} = 0.66$ $\alpha_{3,1} = 1, \alpha_{3,2} = 0.88, \alpha_{3,3} = 0.59, \alpha_{3,4} = 0.57$ $\alpha_{4,1} = 1, \alpha_{4,2} = 0.82, \alpha_{4,3} = 0.74, \alpha_{4,4} = 0.68$ $\alpha_{5,1} = 1, \alpha_{5,2} = 0.80, \alpha_{5,3} = 0.72, \alpha_{5,4} = 0.52$ $\alpha_{6,1} = 1, \alpha_{6,2} = 0.85, \alpha_{6,3} = 0.74, \alpha_{6,4} = 0.61$ $\alpha_{7,1} = 1, \alpha_{7,2} = 0.86, \alpha_{7,3} = 0.57, \alpha_{7,4} = 0.50$
$\mathrm{m}_1 = 9, \mathrm{m}_2 = 24, \mathrm{m}_3 = 5, \mathrm{m}_4 = 7, \mathrm{m}_5 = 16, \mathrm{m}_6 = 12, \mathrm{m}_7 = 9$ $\mathrm{M}_1 = 14, \mathrm{M}_2 = 29, \mathrm{M}_3 = 10, \mathrm{M}_4 = 12, \mathrm{M}_5 = 21, \mathrm{M}_6 = 17, \mathrm{M}_7 = 14$

Table 4.2: Data of SSQRD example

SS-3 first arranges suppliers in ascending order of the effective unit prices, which are computed as follows:

For each supplier $i \in N$ follow the next procedure:

Compute the expected supply for supplier i as the minimum of D and M_i. Then calculate the total effective cost of ordering the expected supply from supplier i .

Then calculate the unit effective price of supplier i , by dividing the total cost over the expected supply.

For instance the effective unit price of supplier1 is calculated as follows:

Expected supply = Minimum (D, M_1)

Expected supply = Minimum $(56, 14) = 14$

Effective unit price$_1$

$$= [0.32 \times (14 \times 1 \times 4 + 14 \times 0 \times 10) + 0.3 \times (14 \times 0.94 \times 4 + 14 \times 0.06 \times 10) + 0.21 \times (14 \times 0.79 \times 4 + 14 \times 0.21 \times 10) + 0.17 \times (14 \times 0.78 \times 4 + 14 \times 0.22 \times 10)]/14$$

Effective unit price$_1$ $= 4.597$

Supplier's number(i)	**Effective unit price**
1	4.597
2	5.1776
3	5.976
4	6.2335
5	6.8016
6	7.08065
7	7.6519

Table 4.3: Effective unit prices of suppliers in SSQRD example

Table 4.3 shows the effective unit prices for all seven suppliers. Suppliers are arranged in ascending order of the effective unit prices.

Then based on the result of observation III for SSQRD, SS-3 determines which delay scenarios have to be examined.

The minimum and maximum quoted unit prices are $P_1 = 4$ and $P_7 = 7$. Then $\frac{P_M}{P_M+P_1} = 0.71$ and $\frac{P_M}{P_M+P_7} = 0.59$. Probability of delay scenarios #1, 2 and 3 collectively covers 0.71. Delay scenarios that collectively cover a probability of 0.59 are scenarios #1, 2 and 3. So based on observation III we have to investigate scenarios $s \in \{s_1, s_2, s_3\}$.

Algorithm SS-3 starts solving the problem in case of scenario1 as follows:

1) $d = D = 56$
2) $d > M_1\alpha_{1,1};\ x_1 = M_1 = 14; d = d - x_1\alpha_{1,1} = 42$
3) $d > M_2\alpha_{2,1};\ x_2 = M_2 = 29; d = d - x_2\alpha_{2,1} = 13$
4) $d > M_3\alpha_{3,1};\ x_3 = M_3 = 12; d = d - x_3\alpha_{3,1} = 1$
5) $d < m_4\alpha_{4,1};$

When condition $d < m_4\alpha_{4,1}$ happens algorithm SS-3 enters part 2.

In part2, for every supplier $i \in \{4, 5, \dots, n + 1\}$ algorithm SS-3 allocates m_i to supplier i and then SS-3 allocates the remaining demand among suppliers $j \in \{1, 2, \dots, i\}$ in the most economical way. This process leads to five quantity allocations for the first delay scenario as presented in Table 4.4.

Quantity Allocations obtained by means of algorithm SS-3									
Supplier#	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Expected Cost**
Scenario 1	14	29	6	7	0	0	0	0	293.9989
	14	26	0	0	16	0	0	0	307.8012
	14	29	0	0	0	13	0	0	306.5569
	14	29	0	0	0	0	13	0	313.9831
	14	29	10	0	0	0	0	3	304.268
Scenario 2	14	29	10	10.3902	0	0	0	0	288.7823
Scenario 3	14	29	10	0	19.583	0	0	0	316.1397
	14	29	10	7.054	0	12	0	0	316.4331
	14	29	10	12	0	0	9.1578	0	323.2594
	14	29	10	12	0	0	0	5.22	291.83

Table 4.4: Quantity allocations obtained from SS-3

In the same way quantity allocations for scenarios s_2 and s_3 are obtained and listed in the Table 4.4. In this example the solution that SS-3 gets is same as optimal solution. The optimal solution is $x = [14, 29, 10, 10.3902, 0, 0, 0, 0]$ and the total cost is equal to 288.7823.

4.7 Experimentation

We conducted two set of experiments:

First set of experiments

In a set of 600 randomly generated experiments for SSQRD, 88.6% of the cases the optimal solution for SSQRD is an optimal solution for one of the delay scenarios.

These experiments have been run in Visual Studio C++ 2008 for a range of 4-15 suppliers. For each number of suppliers, 50 tests were generated.

Random data generation

All the data of these experiments have been generated randomly. The following paragraphs explain how the random data have been generated:

(i) Number of delay scenarios is a randomly generated number between two and five.

(ii) Probability of each delay scenario is a random number between zero and one minus the summation of probabilities of all previous delay scenarios (if any):

$$f_s = Rand\ (0,1 - \sum_{j=1}^{s-1} f_j)$$

(iii) Reduction factor of all suppliers for the first delay scenario is equal to zero. For each supplier the reduction factor for delay scenario $s \in \{2, 3, \dots, k\}$ is randomly generated between the successive previous scenario reduction factor and one.

(iv) Each supplier's minimum order size m_i is a random number between zero and 20. Maximum order size of supplier i is equal to summation of m_i with a random number between five and 25.

(v) Demand quantity is generated randomly between summation of all minimum acceptable order sizes (m_i) and summation of all maximum acceptable order sizes (M_i).

(vi) Supplier i's quoted unit price (P_i) is equal to the price of previous successive supplier (P_{i-1}) plus a random number between 0.5 and five.

Consider a function called $GetRandomBetween(a, b)$ which generates a random number between a and b. Initialize variable $price = 0$, this variable will be updated.

For $i \in N$:

1) $price = price + GetRandomBetween(0.5, 5)$
2) $P_i = price$

(vii) Market price is equal to a randomly generated number between the maximum unit price (P_n) and multiplication of that to three ($3P_n$).

Second set of experiments

In this section, we perform the numerical experimentation in order to evaluate performance of algorithm SS-3. 1300 random problems were generated and solved by means of SS-3, and then the results were compared with the optimal solutions of each problem.

The exact algorithm is modeled by linking a C++ program in Visual Studio 2008 to ILOG CPLEX 11.2 software. Also the proposed algorithm SS-3 is modeled by a C++ program in Visual Studio 2008.

One hundred randomly generated problems were solved for each problem size three to fifteen suppliers. Average of relative errors and standard deviation of the relative error were calculated.

Random data generation

All the random data generations have been done by Visual Studio C++ software. In the following paragraph it is explained how each set of data have been generated randomly.

(i) Number of delay scenarios (k) is a random number between two and six.

(ii) Probability of each delay scenario is a random number between zero and one minus the summation of probabilities of all previous delay scenarios (if any):

$$f_s = Rand\ (0,1 - \sum_{j=1}^{s-1} f_j)$$

(iii) Minimum acceptable order quantities (m_i) are integer numbers, generated randomly between zero and 10. Maximum acceptable order quantity of supplier i (M_i) is equal to m_i plus a random integer number between 10 and 25.

(iv) In order to generate supplier i quoted unit price (P_i) randomly($i \in N$), next steps were followed:

Consider a function called $GetRandomBetween(a, b)$ which generates a random number between a and b. Initialize variable $price = 5$, this variable will be updated.

For $i \in N$:

3) $price = price \times GetRandomBetween(1.01, 1.25)$

4) $P_i = price$

(v) Market price is generated randomly as follows:

$$Market\ price = P_n + GetRandomBetween(1, 2) \times P_n$$

(vi) Demand quantity (D) is an integer random number between summation of all m_i ($i \in N$) and sum of all M_i ($i \in N$).

(vii) Reduction factor $(1 - \alpha_{i,s})$ of all suppliers for the first delay scenario is equal to zero. For each supplier the reduction factor for delay scenario $s \in \{2, 3, \ldots, k\}$ is randomly generated between one and the successive previous scenario reduction factor.

One hundred experiments for each problem size are generated randomly based on the above mentioned methods. For each experiment relative error is calculated with the following formula:

Relative Error of SS-3 result (in percentage) $=$

$$\frac{\text{Cost of SS.3 solution - Cost of optimal solution}}{\text{Cost of optimal solution}} \times 100$$

Then the total average relative error is calculated:

$$\text{Mean Relative Error} = \left(\sum_{i=1}^{100} \text{Relative Error}_{\text{i}}\right)/100$$

For each problem size, the standard deviation of one hundred experiments is computed as follows:

$$\text{Standard Deviation of Relative Errors} = \sqrt{\frac{1}{n-1}.\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

In the standard deviation formula, n stands for number of experiments (here n is equal to 100). x_i is the relative error of experiment $\#i$, and $\bar{x}$ indicates mean relative error of 100 tests.

Table 4.5 provides the mean relative error and standard deviation for each problem size (3-15) using SS-3.

Number of Suppliers	Mean Relative Error (%)	Standard Deviation
3	2.396346	7.946597
4	1.751612	5.936568
5	1.898349	6.695997
6	2.177347	5.602607
7	3.696116	9.184954
8	2.451351	7.496033
9	2.21378	5.2393
10	2.609696	7.56612
11	2.160598	7.048407
12	2.902341	9.415888
13	1.863592	5.694208
14	1.449375	2.860838
15	2.312779	4.946434

Table 4.5: Mean relative error and standard deviation of relative error for SS-3 experiments

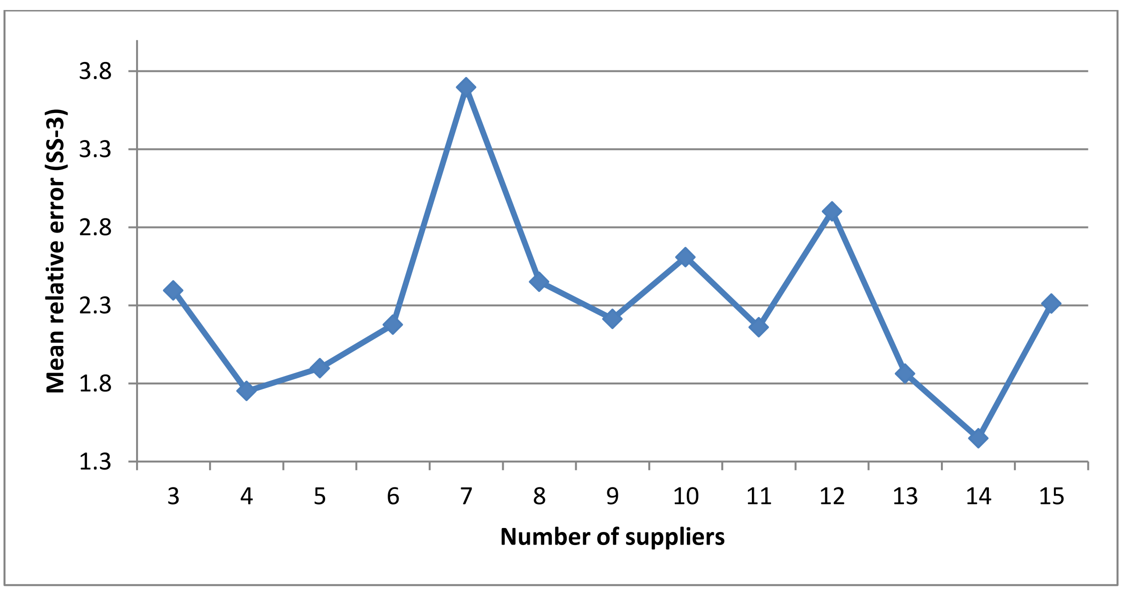

Figure 4.2: Mean relative error of SS-3 results

The total average relative error of algorithm SS-3 is equal to 2.3% (based on results showed in Table 4.5). Since the maximum mean relative error is 3.69% (which is less than 5% as showed in Figure 4.2), SS-3 proves to be efficient in providing solutions close to optimal solution.

4.8 Conclusion

In construction projects delay in any phase of a project threatens success of the whole project both financially and timely. Normally the share of supplies in the total turnover of a construction project is very high, and therefore it is very important to keep the purchasing cost of required supply to minimum possible. Moreover in the event of any delay in a project, project manager has to ask suppliers to provide the material at a later time. In SSQRD, the case where suppliers decrease the promised quantity when buyer asks for new delivery schedule is studied. SSQRD is expressed as a mixed integer linear programming problem (MILP).

Based on 600 experiments with random data, it is observed that in 88% of cases the optimal solution to the problem is an optimal solution for one of the delay scenarios. Also observation III based on some approximation illustrates that we can select a number of delay scenarios that are most probable to give us the optimal solution.

In order to get the optimal solution for this problem we formulated the MILP and solved it using IBM ILOG CPLEX 11.2. For problems with integer variables, CPLEX uses a branch and cut algorithm which solves a series of LP, sub-problems. Because a single mixed integer problem generates many sub-problems, even small mixed integer problems can be computationally very intensive and require significant amounts of physical memory and time.

The proposed approach is very fast and can be easily implemented using spreadsheet without using commercial optimization software.

Examining the proposed algorithm SS-3 with 1300 randomly generated experiments resulted in a maximum average relative error of 3.7%. We assumed that the heuristic algorithm would be efficient if its maximum average relative error is less than 5%. Since 3.7% is less than 5%, SS-3 is verified to be capable of providing economically acceptable solutions. Also the average relative error achieved by SS-3 is 2.3%, which is acceptable and cost-effective from business point of view.

Chapter 5:

Conclusions and future works

5.1 Summary

In industries such as forestry industry, there can be several occasions when the preferred suppliers fail to provide required supply for a flexible timeline and buyer has to look for short term partnership with other suppliers. Usually suppliers have limitation on minimum order size for the economies of scales; they also may accept orders under a specific limit which can be due to commitments to other suppliers or limitation on the capacity. Supplier selection problem with limitation on minimum order size is a complex problem. Incorporating this problem with uncertainties in the supply chain makes this problem more complicated. This study focused on uncertainties linked to delivery date of material which is very common in construction industry.

This research presents an approach to select required number of suppliers to fulfill future demand. This problem is computationally complex and the approach presented (based on the properties of the problem) could give a solution very close to the optimal solution. The experimental studies, on randomly generated data set, promise a consistent performance. The tool presented here could be very handy for managers who dynamically want to add/remove suppliers or modify quantities as the project progresses and demand changes. The approach presented here could be helpful in complex model where more than one product is required from the same supplier sets. The following figure summarizes the procedure of work done in this research:

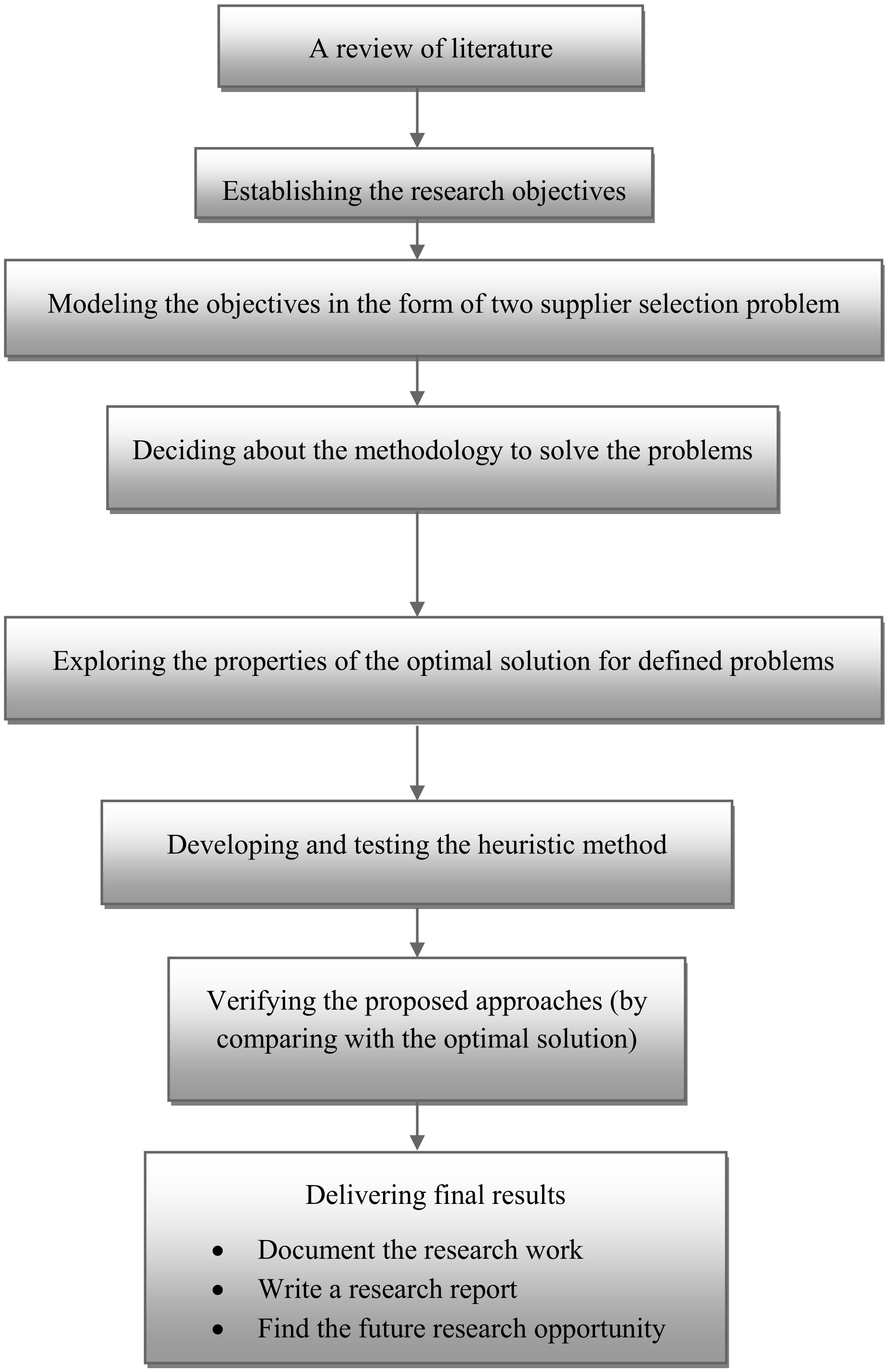

Figure 5.1: Procedure followed in conducting this thesis research

5.2 Limitations and Future work

In the current work we assume fixed price and single product. In reality suppliers give discounts on quantity. In future, model can be extended to incorporate various types of quantity discounts such as non-linear price discount. Moreover in future a fixed set up cost can be added to the cost function of suppliers.

The model can also be extended to handle the cases where suppliers are associated with more than one consecutive phase (in our study we assumed that suppliers are associated with one phase of a construction project).

The model can also be extended to handle multi-client i.e. selecting suppliers for various clients with a client specific minimum order size limitation. In the multi-client case the presented approach can be helpful in solving sub-problems (decomposition based approaches).

Also in future the model can be extended to evaluate the situations where both cases of penalty and quantity reduction are offered by suppliers as a penalty for delays imposed by the buyer; and to find the most economical combination of suppliers.

The proposed models can be evaluated in future on the basis of stochastic numbers generated with consideration of dependencies between market events and supplier conditions.

In future the proposed model for SSQRD can be extended to consider the inventory holding cost in the cases where the buyer order more than demand quantity.

Advanced approaches such as bender decomposition could be investigated in future to develop exact algorithms.

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Appendix A

In algorithm SS-1 if the problem enters part 2, after allocating m_{i^*} to supplier i^*, SS-1 will distribute the remaining demand ($d = D - m_{i^*}$) among suppliers $i = 1, \dots, i^*$ in the most economical way.

The following steps assign the suppliers in the most economical way:

For each supplier $i \in \{i^*, \dots, n\}$:

1. Initialize $flex = 0$.
2. Allocate m_i to supplier$i$: $x_i = m_i$.
3. Calculate the flexibility for supplier i: $flex = flex + (M_i - m_i)$.
4. Compute $d = D - m_i$.
5. Call the algorithm SS-1 with following additional conditions.

Allocate d among supplier $\{1, 2, \dots, i - 1\}$ using Part1 of algorithm SS-1. If the condition # 1.2 happens compute the cost for the assignment and continue.

In the case of condition # 1.3:

If $d \leq flex$ adjust d in x_i: $x_i = m_i + d$. Compute the cost of the assignment and keep it if the cost is better than previous allocations (if any).

Note: d may be assigned to more than one supplier with the flexibility (that is $m_i \leq x_i < M_i$).

Appendix B

In algorithm SS-3 if the problem enters part 2, after allocating m_{i^*} to supplier i^*, SS-3 will distribute the remaining demand ($d = D - \alpha_{i^*,s}\, m_{i^*}$) among suppliers $i = 1, \dots, i^*$ in the most economical way in the following steps:

For each supplier $i \in \{i^*, \dots, n+1\}$:

1. Initialize $flex = 0$.
2. Allocate m_i to supplier$i$: $x_i = m_i$.
3. Calculate the flexibility for supplier i: $flex = flex + \alpha_{i,s}(M_i - m_i)$.
4. Compute $d = D - \alpha_{i,s} m_i$.
5. Call the algorithm SS-3 with following additional conditions

Allocate d among supplier $\{1, 2, \dots, i-1\}$ using Part1 of algorithm SS-3. If the condition # 1.2 happens compute the cost for the assignment and continue.

In the case of condition # 1.3:

If $d \le flex$ adjust d inx_i: $x_i = m_i + \frac{d}{\alpha_{i,s}}$. Compute the cost of the assignment and keep it if the cost is better than previous allocations (if any).

And if $d > flex$, this means we identify one more supplier which cannot accommodate the remaining amount of demand. We set this new supplier as $i^*$and follow again the same steps (1-5 of Appendix B).

Note: d may be assigned to more than one supplier with the flexibility (that is $m_i \le x_i < M_i$).