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A Decision Support System for Rapid Evaluation and Selection of Engineered Equipment Suppliers

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A Decision Support System for Rapid Evaluation and Selection of Engineered Equipment Suppliers

by

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Dedication

To my parents Antonio and Maria, my brother Rafael, and my girlfriend Cara

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A Decision Support System for Rapid Evaluation and Selection of Engineered Equipment Suppliers

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Procurement's role in engineering and construction is changing. Procurement is evolving into a far more strategic discipline. Major equipment procurement in particular ties up a large proportion of construction cost, has long lead time, and is usually associated with the acquisition of complex or specialized technology. Selection of suppliers is a complex process which requires the evaluation of several suppliers and project targets. This analysis is usually performed manually, it is time consuming, and certain tradeoffs may be overlooked. This research advances state of the art to aid the commercial evaluation and selection of engineered equipment suppliers in the early stages of capital projects. A decision support system was developed in cooperation with several leading engineering-procurement-construction (EPC) and owner firms within industrial construction. The system integrates firms' market and supplier performance data with a decision aid method to support rapid tradeoff analysis and evaluation of sourcing alternatives in the early stages of capital projects.

The tool has been developed in Visual C#, in the form of simple and intuitive forms, with Microsoft Access as the back-end database. A supplier selection module uses the Aspiration Interactive Method (AIM) for providing rapid tradeoff analysis and points how each supplier is ranked in relation to the expected procurement targets. The system also includes a module for schedule analysis of the preferred supplier. Managers first need to assess unique project and supplier's characteristics to estimate most likely durations. These durations are used to run a PERT analysis and provide initial feedback on probability of equipment delivery success. Therefore, managers are able to check whether their procurement master schedule milestones are feasible or not.

Two actual selection cases were used to validate system's usefulness, completeness, and deployability. According to experienced managers, this tool brings intelligence to the traditional selection process. The ability to quickly generate what-if scenarios and rapidly perform tradeoff analysis based on real data improves the quality of decision making, and supports commercial assessment and recommendation of suppliers in the early phases of capital projects.

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CHAPTER 1: INTRODUCTION

1.1 PROCUREMENT: STRATEGIC ROLE

Procurement's role in engineering and construction is changing. Procurement is evolving into a far more strategic discipline. Scotti (2007) stated that almost two-thirds of the money spent on oil and gas projects goes to procure goods and services, and well-executed strategic procurement and supply chain management can result in a very high return on investment.

The cost of materials represents more than half of the total cost of a typical capital project. Lack of materials when needed at the job site can cause costly construction delays (CII 1999). Procurement professionals are directly responsible for ensuring materials will be delivered on time via integration of functions such as: materials requirements planning, purchasing, expediting, quality inspection, logistics, and site material management. Given the impact on cost and schedule, it is simple to associate the positive influence procurement can have on the cost of construction.

Major equipment procurement in particular ties up a large proportion of construction cost, has long lead time and is usually associated with the acquisition of complex or specialized technology. Major equipment pieces are engineered and fabricated specifically for the project (e.g. tanks, heat exchangers, pumps). Engineering, manufacturing, and delivery of these items are very uncertain and may disrupt construction schedule. As a consequence, procurement planning for engineered equipment is critical and needs to start during the early stages of capital projects either front end loading or conceptual design phase. Vorster et al. (1998) suggested that most strategic and project critical procurement transactions should occur prior to detail engineering. Early selection of engineered equipment suppliers can then influence and define detailed engineering, and provide unique input to project business and execution plans.

1.2 INDUSTRIAL PROJECTS: SUPPLY CHAIN CONSTRAINTS/CHALLENGES

Mounting global demand for oil and gas, energy, and infrastructure has been stressing the supply chain, and various constraints need to be taken into account when planning the execution of industrial projects.

Suppliers' capacity is a major concern. Suppliers have been declining attractive awards, because they are simply out of shop capacity to fulfill world current demand, especially from China. This lack of availability of material/equipment is an important constraint that needs to be considered in early sourcing plans.

Transportation is another potential constraint in the supply chain. There is also a capacity shortage to transport materials around the globe, especially ocean freight and rail transportation. A 12-18 month booking on heavy and extra heavy shipping is a common practice. Escalating transportation costs is also a major concern particularly for air freight, trucking and inland waterway.

This capacity problem has caused substantial increases in lead times and prices. Figure 1.1 illustrates the effects of shop load utilization on lead times. In 2008, lead times for such equipment are even longer. For example, equipment, which used to take 15 months to deliver, is currently delivered within 24 to 26 months. Continuous price fluctuation and escalation of raw materials (e.g. scrap metal, copper, and carbon steel) and engineered products have been impacting final customers. This is a key issue because a high percentage of materials acquired by industrial firms is major equipment - only approximately 13-15 % of products are commodities such as rebar, concrete, and pipe.

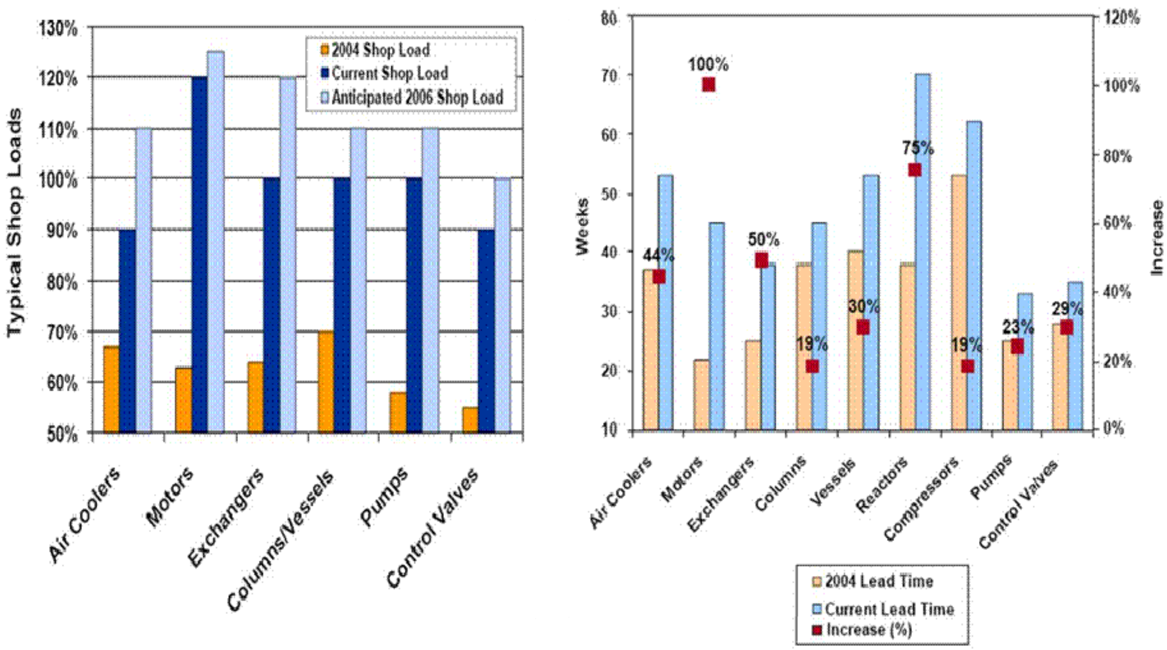


Figure 1.1: Effects of shop load on equipment lead times (Global Supply Trends 2005)

Finally, additional sources of uncertainty embedded in the procurement process of engineered equipment may possibly affect schedule performance of industrial projects. Examples of such uncertainties are as follows: several weeks are needed to negotiate terms and conditions, suppliers are either not bidding or need long time to quote because their engineering teams are extremely busy as well, and clients' approvals slow down the process especially if a reimbursable approach is used.

In summary, procurement has clearly become a more complex process and commitments need to be made much earlier in the capital project lifecycle. To survive in such a complex and dynamic scenario, firms need to identify and analyze sourcing alternatives, reduce supply risks, and improve scheduling and cost performance. Knowledge of market conditions is essential to supporting early planning and supplier selection decisions, however, getting, keeping, and analyzing updated market data is very challenging.

1.3 RESEARCH MOTIVATION

Procurement of engineered equipment is a complex process which requires the evaluation of several suppliers, performance variables and project targets (e.g. schedule and budget). This analysis is usually performed manually, it is time consuming, and certain tradeoffs may be overlooked. Therefore, there is a need to develop computer-based tools to support and speed up the work of procurement managers in better understanding the tradeoffs and risks involved in the acquisition of equipment.

Moreover, most firms that execute industrial projects have either rich data on market forecasting information and/or historical data on supplier performance. However, available data is commonly found in different paper files archived inside procurement managers' drawers or stored in firms' information systems. As a result, data is currently not integrated to support analysis and decision making.

The primary purpose of this research is to develop a decision support system to aid procurement managers selecting engineered equipment suppliers. This system electronically integrates firms' available market data with a proper decision aid methodology to support rapid tradeoff analysis and evaluation of sourcing alternatives in the early stages of capital projects. Additionally, a schedule analysis module is included in order to allow assessment of preferred supplier's schedule feasibility based upon unique project and supplier characteristics. At the moment, there is no commercial software package that is capable of performing such specific and integrated analysis tasks.

This system was built in collaboration with experienced professionals who provided their input since the conceptual model phase. The system was also validated based on manager's feedback and two recent actual selection cases.

1.4 RESEARCH SCOPE AND LIMITATIONS

The scope of this research is limited to:

- Research was conducted with experienced procurement managers working for large EPCs and owner firms executing industrial projects. These firms usually collect/maintain data on suppliers' performance and/or market forecasting. The Decision Support System was validated with EPC firms which are the potential users of this system. EPCs frequently purchase equipment for multiple projects and different owners, therefore, they are more capable than owners in collecting data and understanding the suppliers market.

- This research focuses on the evaluation of engineered equipment suppliers.
- The approach proposed for decision aiding focuses its analysis on quantitative data collected by EPC firms such as: lead time, price, capacity, delivery performance. This information is commonly used for commercial evaluation and recommendation of suppliers. Qualitative variables are used only to support schedule analysis of the preferred supplier.

1.5 READER'S GUIDE

This dissertation consists of seven chapters. The current chapter introduces the strategic importance and complexity of procurement of long lead equipment and highlights the scope of the research.

Chapter 2 includes a literature review of construction supply chain management, procurement and supply chain modeling tools, as well as an overview of selection methods and issues regarding schedule risk analysis in construction. This chapter ends with a summary which highlights existing gaps in the literature.

In Chapter 3, I list the research questions formulated to address the gaps along with my research methodology. The methodology section describes in detail each research phase. I conducted exploratory case studies, developed and tested a conceptual model, developed the decision support software, and validated it with EPC firms.

Chapter 4 focuses on the description of current procurement practices and supplier selection decision process. This chapter highlights the results of a set of exploratory case studies that I conducted with eight firms in industrial construction. The findings of these studies indicated other relevant gaps that still need to be addressed in construction practice and provided invaluable input for development of the system.

Chapter 5 explains step by step and in detail the system's components. I start the chapter describing the Aspiration Interactive Method (AIM) which is the approach used to support selection. This chapter also includes the description of the schedule analysis module. A pump selection case was used for building the conceptual model and served as example for discussion of each component.

In Chapter 6, I present the results of the validation meetings with procurement managers and describe two recent and comprehensive cases of equipment selection. Findings of validation helped me to determine software's characteristics such as: usefulness, completeness, and deployability. Moreover, I compare the results of manual analysis against computer-based selection using the system. This comparison allowed the identification of issues that need to be addressed in future system improvements and research. Finally, I show the results of a robustness analysis in the context of one case.

Chapter 7 wraps up the dissertation with conclusions, research contributions, and a discussion of future research directions. A set of appendices is arranged at the end with further details to supplement the content presented in the dissertation chapters.

CHAPTER 2: LITERATURE REVIEW

This chapter gives an overview of procurement and supply chain management research in construction. It further explains existing decision support tools and current gaps in the body of knowledge. Additional literature on methods for selection problems and techniques for schedule risk analysis conclude this chapter.

2.1 PROCUREMENT PLANNING IN CONSTRUCTION

Effective planning in the early stages of industrial projects can greatly enhance cost, schedule, and operational performance while minimizing the possibility of financial failures and disasters (Gibson and Dumond 1996). CII has published two popular tools that should be used at points throughout the Front End Loading (FEL) phase (also called pre-project planning or front end planning): The Project Definition Rating Index (PDRI) and the International Project Risk Assessment (IPRA) management tool.

PDRI for Industrial Projects (Gibson and Dumond 1996) is a powerful and easy-to-use tool that offers a method to measure project scope definition for completeness. It identifies and precisely describes each critical element in a scope definition package and allows a project team to quickly predict factors impacting project risk. It is intended to evaluate the completeness of scope definition at any point prior to detailed design and construction. Identification of long lead / critical equipment and materials is one of the scope definition elements included in the "Procurement Strategy" section (Figure 2.1). PDRI suggests that project teams need to identify engineered equipment and material items with lead times that will impact the detailed engineering for receipt of vendor information or impact the construction schedule with long delivery times.

CATEGORY Element	Definition Level						Score
	0	1	2	3	4	5	
L. PROCUREMENT STRATEGY (Maximum Score = 16)							
L1. Identify Long Lead/Critical Equip. & Mat'ls	0	1	2	4	6	8	
L2. Procurement Procedures and Plans	0	0	1	2	4	5	
L3. Procurement Responsibility Matrix	0	0	1	2	2	3	

Figure 2.1: Procurement Strategy using PDRI

IPRA (Walewski and Gibson 2003) is a systematic management tool to identify and assess the risks specific to international construction with the ultimate goal of improving project performance. The use of this tool and its guidance is especially critical during the business planning and FEL phases because failure to identify risks early in the project life cycle can result in serious ramifications. The IPRA tool consists of 82 risk elements that are assessed by likelihood of occurrence and relative impact to determine which elements have the greatest potential impact on the project. Risks associated with Procurement are included in the "Sourcing and Supply" category (Figure 2.2). This category defines that proper planning and follow-through on determining the source of materials and supplies are critical to meet the challenges of international projects. Issues to consider in the assessment of engineered equipment include: availability of suppliers to deliver on time with desired quality, financial stability of suppliers and capacity of suppliers. Logistics issues are addressed in the same category. Managing material logistics for international projects may impact scope or cause cost or schedule increases. These issues may include: available local infrastructure, deep sea port requirements, local overland transport (i.e., bridge, narrow road and river constraints), availability of trucks for inland transport, road/rail networks, air transport needs, warehousing/storage, weather, etc.

	Risk					Comments
	NA	L	M	H	E	
III.A. PROJECT SCOPE						
III.A1. Scope development process						
III.A2. Technology						
III.A3. Hazardous material requirements						
III.A4. Environmental, health, and safety						
III.A5. Utilities and basic Infrastructure						
III.A6. Site selection and clear title						
III.A7. Approvals, permits and licensing						
III.B. SOURCING AND SUPPLY						
III.B1. Engineered equipment/material/tools						
III.B2. Bulk materials						
III.B3. Subcontractors						
III.B4. Importing and customs						
III.B5. Logistics						

Figure 2.2: IPRA - Sourcing and Supply category

PDRI and IPRA provide useful tools for early planning and identification of risks associated with engineered equipment. These tools however do not offer a holistic and integrated view of the entire delivery process.

Engineered products have traditionally been less studied from the product delivery point of view (design, procurement and manufacturing) because of the belief that they are one-of-a-kind. Nevertheless, studies have demonstrated that even if products may be very different the delivery process is still largely the same (Alarcon et al. 1999, Elfving 2003, Yeo and Ning 2006). Major procurement schedule milestones associated with a generic engineered equipment delivery process are depicted in Figure 2.3. The engineering and design phase is the pre-procurement phase while the construction phase represents the post-procurement phase. The procurement processes include receipt of engineering or process data and drawings from engineering/design departments, documentation and issuing request for quotation (RFQ), receipt of bids from vendors, bid evaluation and approval, order placement with equipment manufacturer, equipment fabrication and assembly, testing of the assembled equipment, inspection and expediting by customer, shipping arrangement, delivery of installation drawings and test data, and actual shipping or delivery of major equipment, and receipt of equipment on site.

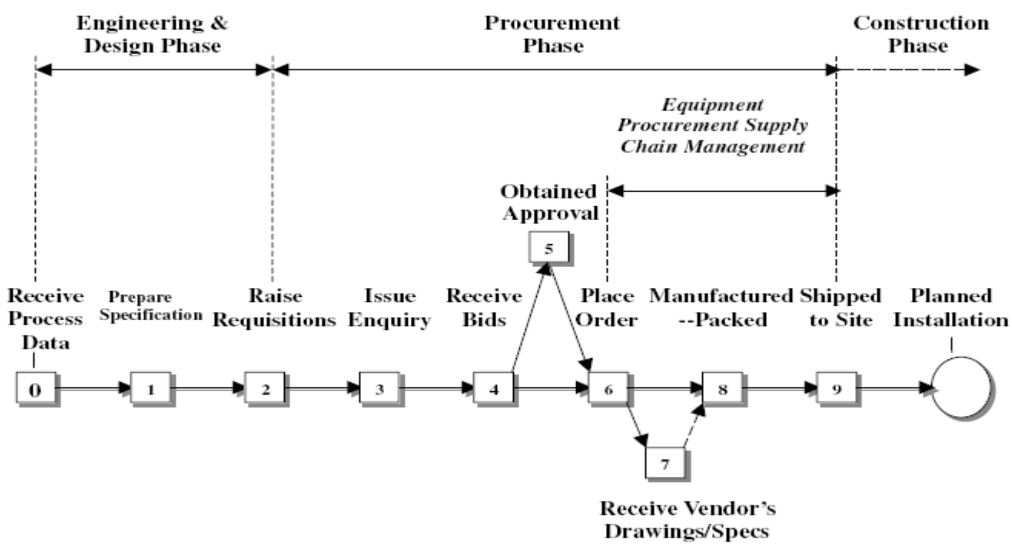


Figure 2.3: Typical Delivery Process of Engineered Equipment (Yeo and Ning 2006)

Over the last decade, research on delivery of materials and equipment has been somewhat overlapping with an emerging field of research and practice in construction: Supply Chain Management. Therefore, assessment of tools developed and used to support supply chain analysis can provide additional evidence for identifying their current limitations and opportunities for development. This is the topic of the next section.

2.2 TOOLS FOR ANALYSIS OF CONSTRUCTION SUPPLY CHAINS

The modeling of construction supply chains is a subject that has been mainly investigated since the early 1990s. The goal is to explore how manufacturing concepts can be transferred to construction context in order to improve production efficiency and reduce project costs. Initial case study descriptions and partial implementation has been reported by many researchers, especially those associated with the International Group for Lean Construction (IGLC). Their findings have shown insightful solutions or suggestions for improvement which demonstrate the usefulness of modeling production beyond the boundaries of construction sites.

Most studies have focused on descriptive rather than prescriptive analysis. Separation of models as descriptive and prescriptive is useful for examining the current state of construction supply chain modeling. Descriptive models are usually deterministic, meaning that all model parameters are assumed to be known and certain. Descriptive models are also often static, illustrating a snapshot of a supply chain current state. Prescriptive models, by contrast, generally take into account uncertain and random model parameters. They are dynamic and aim to mimic supply chain behavior and performance, allowing prediction and discovery of emergent behavior in the supply chain for optimization.

Perhaps due to the complexity of the construction supply chain, most studies have focused on case descriptions of supply chains for specific products (for example, rebar (Polat and Ballard 2003) and heating, ventilation, and air conditioning (HVAC) ductwork (Alves and Tommelein 2003). These descriptions usually deploy visual process modeling tools to illustrate or “map” the respective supply chains. Among the available mapping tools, construction researchers have predominately adopted variants of Value Stream Mapping (VSM), a tool developed by the Lean Enterprise Institute (Figure 2.4). The VSM is a process of representing the flows of information and materials, and other parameters such as inventory size and cycle time as they occur, summarizing them visually, and envisioning a future state with better performance (Jones and Womack 2003). The objective is to identify inefficiencies or waste in the supply chain and remove them. This is usually measured comparing supply chain lead time. VSM can be used to model current states of the supply chain as well as represent future states. In this sense the tool crosses between descriptive and prescriptive process analysis, although the tool lacks support for dynamic modeling or optimization. As such, it is employed primarily for descriptive analysis in construction.

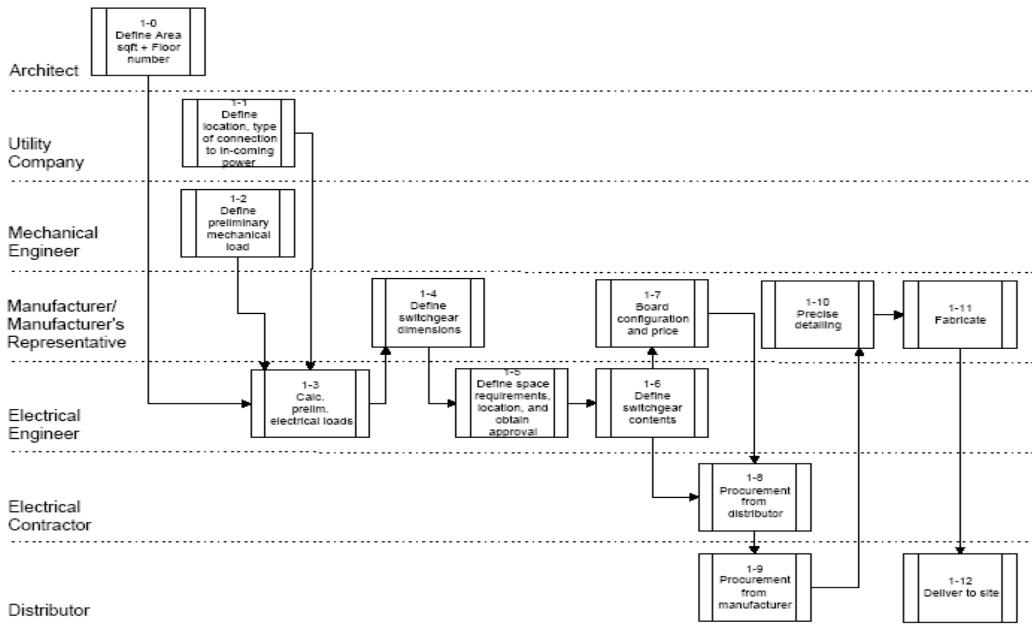


Figure 2.4: Value Stream Mapping

Elfving (2003) analyzed in detail the delivery process of power distribution equipment in three large construction projects with a particular interest in lead time reduction. He highlighted the causes of lead times ranging from 79 to 133 weeks and suggested improvements that can be extended to other engineered products. Other studies (Arbulu and Tommelein 2002, Polat and Ballard 2003) used a similar process-oriented approach, sketching engineering, procurement, fabrication, and installation activities to understand the behavior of different supply chain configurations on project schedule. Arbulu and Tommelein (2002) presented lead time data on the delivery of 680 pipe hangers and supports from a power plant construction project. Figure 2.5 illustrates lead times for different activities and handoffs (e.g. 61 calendar days between engineering and fabrication) for one of the five configurations evaluated. The delivery of supports had an average delay of 32 days and impacted pipe installation progress on the job site.

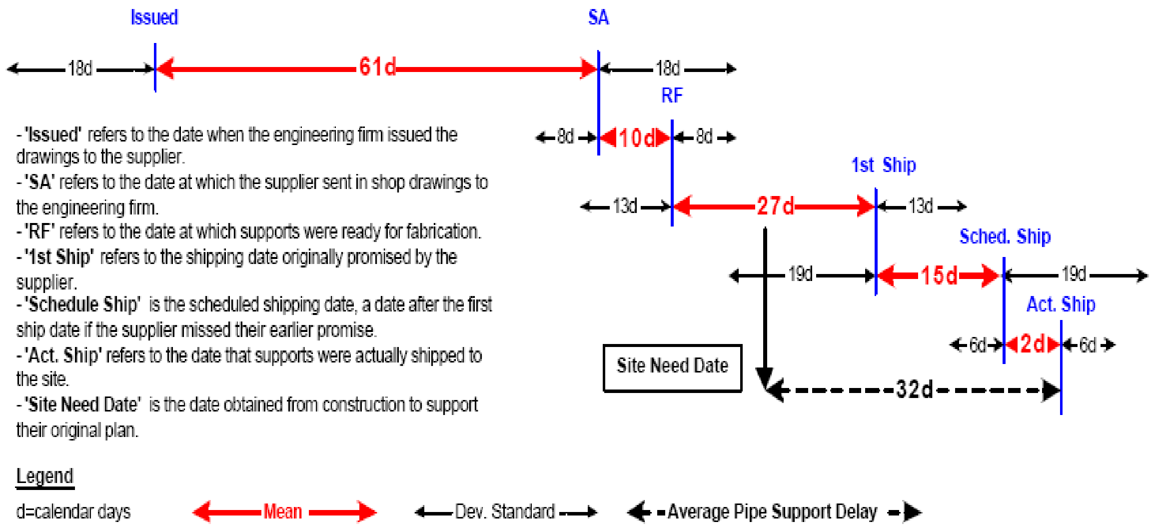


Figure 2.5: Impact of configuration on delivery milestones (Arbulu and Tommelein 2002)

Tommelein and Li (1999) and Tommelein and Weissenberger (1999) used the VSM to analyze the possibility of adopting a just-in-time production system through the strategic location of buffers (inventory and time) in the supply chain. Subsequent applications of VSM have mainly been used to support evaluation of different supply chain configurations (Arbulu and Tommelein 2002, Elfving et al. 2002, Polat and Ballard 2003, Azambuja and Formoso 2003). These models typically include a partial sketch of engineering, procurement, fabrication, and installation processes to provide insights for improvement of coordination and communication among firms, location of buffers to mitigate risks, and elimination of processes to reduce lead time.

VSM models have been used to guide tactical and operational supply chain decisions. Akel et al. (2004), and Fontanini and Picchi (2004) presented more detailed models which included not only processes, but also material and information flow data. These models also dealt with lead time reduction, providing additional insights on transportation, batching, and material ordering issues. Supporting these studies, simulation based models have also supported analysis of tactical and operational decisions. In particular, simulation models have predicted lead times and/or throughput performance of construction supply chains. Several studies have assessed the effects of buffer and batch sizes (Al-Sudairi et al. 1999, Arbulu et al. 2002, Alves and Tommelein 2004, Walsh et al. 2004), variability in process durations (Alves et al. 2006), and product standardization (Tommelein 2006) on the above-mentioned performance measures. While generally based on a descriptive study, the simulation models allow exploration of variation in parameters and hence support either optimization or broader generalization of, for example, the value of buffers or deleterious effects of variability.

Perhaps due to the nature of the modeling tools, VSM and simulation based models tend to focus on supply chain configurations and processes that are well described in terms of production units (plants or work centers depending on the level of analysis), buffers, and materials flows. Measures such as throughput, lead time, and material buffer sizes are commonly used to measure performance in these models. As such, these models tend to focus on a subset of the supply chain decisions – in particular, tactical ones about specific and reasonably detailed supply chain configurations. Future models could investigate other important variables such as shop load utilization, supplier performance, currency exchange, and transportation constraints to support evaluation of different supply chain alternatives.

The process-oriented approach as deployed supports a variety of decisions. However, existing models do not easily scale to earlier strategic decisions for a given project where details about specific process and materials flows have not been firmly identified. Moreover, contractors and owners procure a wide range of materials and detailing each supply chain can be burdensome.

Little research has been done to evaluate how companies plan their supply chains during early phases of project lifecycle. Usually, major supply risks and constraints need to be identified and strategic decisions have to be made in order to mitigate these risks and ensure materials can be delivered on time at the job site. Construction lacks models that enable professionals to draw inferences about construction supply chain strategic decisions. Examples of such decisions include selection of suppliers and evaluation of supply chain configurations to reduce overall logistics costs (especially transportation costs) and schedule delay risks. These decisions are important as global materials sourcing is becoming common practice on a range of projects. Figure 2.6 summarizes the literature on supply chain operations in construction, illustrates tools and metrics that are commonly used, and indicates the lack of studies supporting analysis and selection of multiple supply alternatives.

	Modeling Approach	Material/Equipment	Lead time (reduction)	Time in process (Cycle time)	Time Buffer	Queue Time (waiting time)	Value x non-value adding activities	Batch Size	Buffers (RM, WIP and FP inventory)	Throughput (Maximize)	Shop Load Capacity	Delivery Performance	Cost (process, inventory, total)	Alternative Supply Chain Configurations?	Support tradeoff analysis & Selection?
(Tommelein and li 1999)	VSM	Concrete		√	√	√		√		√		√			
(Elfving 2003)	VSM	Switchgear	√	√		√	√	√							
(Polat and Ballard 2003)	VSM	Rebar	√	√		√			√					√	
(Akel et al. 2004)	VSM	Pre-engineered Metal components	√	√		√	√		√	√					
(Fontanini and Picchi 2004)	VSM	Aluminum Windows	√	√			√		√	√					
(O'Brien 1998)	---	Structural Steel			√			√	√		√		√	√	
(Walsh et al. 2004)	DE	Pipe Spools	√						√	√					
(Alves and Tommelein 2004)	VSM	HVAC	√	√		√		√	√	√					
(Azambuja and Formoso 2003)	VSM	Elevator	√	√		√									
(Arbulu and Tommelein 2002)	VSM	Pipe Supports	√	√		√								√	
(Polat et al. 2007)	DE	Rebar	√	√				√		√			√	√	√
(Alves et al. 2006)	DE	HVAC	√	√		√		√	√	√					
(Tommelein and Weissenberger 1999)	VSM	Structural Steel	√	√	√	√			√						
(Al-Sudari et al. 1999)	DE	Structural Steel		√					√	√		√			
(Vidalakis and Tookey 2006)	DE	Masonry		√				√	√	√		√	√		
(Walsh et al. 2004)	---	Lumber											√		

Figure 2.6: Summary of literature on construction supply chain

Few studies have started the discussion of such strategic issues in construction supply chain. Arbulu and Tommelein (2002) and Polat and Ballard (2003) used a process-oriented approach to sketch engineering, procurement, fabrication, and installation activities in order to understand the impacts of different supply chain configurations on a project schedule. Walsh et al. (2004) used simulation to determine the strategic positioning of inventory in the supply chain for stainless steel pipes. O'Brien (1998) proposed a qualitative model to predict supply chains' performance behavior. The model included a set of firms which were classified according to a typology of suppliers based on the suppliers' production technology, as well as the impact of site demand on their performance. The combination of different classes of suppliers resulted in a high level view of supply chain performance capabilities and intrinsic risks. His approach supports rapid analysis without the need for detailed models, and could be used to support a variety of strategic configuration decisions, but its use has not been further explored.

Not until recently have supply chain models reported results which include cost performance. For example, Vidalakis and Tookey (2006) simulated the flow of materials from building merchants to construction sites and assessed inventory and transportation costs. Additionally, Polat et al. (2007) built a model to assist contractors in selecting the most economical rebar management system prior to the start of construction by recommending batch sizes, scheduling strategy, and buffer sizes. The inclusion of cost analysis offers a promising next step in construction supply chain modeling. For example, many existing models address lead time reduction, but the costs associated with the reduction of time are not clear. Time-cost tradeoff type analyses can help managers make more informed strategic decisions.

2.3 METHODS FOR SELECTION DECISION IN CONSTRUCTION

Most selection methods tend to be ad-hoc methods that are based on experience and intuition. Unfortunately, these methods are difficult to package and use as a general framework for making decisions (Elmisalami et al. 2006).

Decision aid methods are very useful tools used to support managers making complicated selection decisions. There are a number of techniques and software products that have been developed in operations research area to aid solving selection problems. Olson (1995) reviewed various potential techniques – including Analytic Hierarchy Process (AHP), Multi-attribute Utility Theory (MAUT) and Aspiration Interactive Method (AIM) - and concluded that these techniques vary significantly in the type of problems they are suitable for and the amount of information required.

AHP is well known and used in various selection problems in construction such as: advanced construction technologies (Skibniewski and Chao 1992), contractor selection (Fong and Choi 2000), and selection of equipment (e.g. tower cranes, concrete pumps) for construction projects (Shapira and Goldenberg 2005).

MAUT has also been implemented in construction research. Few studies report the application of this approach to select procurement systems (Chan et al. 2001), dewatering systems (Wang et al. 2002), and for IT-related problems, such as selecting the appropriate computer networking technology (Abduh and Skibniewski 2003) and appropriate data capture technologies for a construction materials testing laboratory (Elmisalami et al. 2006).

Very little has been published on methods to aid managers making selection decisions on suppliers or supply chain configurations in construction. Only one study (Jiang et al. 2005) has shown the potential use of AHP to support supply chain selection. These authors proposed a framework based on the Analytic Hierarchy Process for ranking different supply chain configurations. Selected critical path activities, subcontractors and their respective time and cost estimates, and performance criteria were evaluated and the optimal alternative was identified. This study however was based on hypothetical data and the framework was not validated. Bernold and Treseler (1991) presented a vendor analysis system that is based on the best-buy concept. A vendor-rating approach to secure the best buy in construction was proposed and analyzed. According to these authors, benefits of the formal vendor-analysis and rating system include the standardization of evaluation criteria, which provided consistency and transparency. Their method also provided flexibility to adapt to individual contractors and projects using a nonrestricting listing of criteria that could be edited and weight factors that could be changed or expanded if appropriate. The best buy approach allows users to consider and weight their preferences; however, it does not provide the capability to identify the optimal vendor based on project and procurement targets.

2.3.1 Selection Methods: Overview and limitations

AHP is a technique for converting subjective assessments of relative importance into a set of weights. Decision makers need to develop a hierarchical structure of factors affecting the problem, provide judgments about the relative importance of each of these factors through pair-wise comparison matrices which are combined into an overall rating of available alternatives. Most of AHP studies focus on qualitative criteria analysis. Moreover, the pair-wise comparison process is somewhat tedious, subjective and several comparisons may affect accuracy because users tend to focus their effort on obtaining speed to complete the process (Olson 1995). Therefore, the method is not suited to decision problems involving various alternatives. Another difficulty associated with the use of AHP is that ranking of the alternatives, in certain situations, can be arbitrary (Dyer 1990). For example, given a pair of criteria Ci and Cj, if Ci is preferred to Cj when considering alternative k, the preference is not guaranteed to remain the same and can be reversed by inclusion of another alternative.

MAUT is a multiple criteria decision analysis method used by decision makers when they must choose among alternatives based on two or more criteria, where the criteria can involve risks and uncertainties (Dyer 1990). MAUT is an accepted approach used to provide an objective decision based on subjective, qualitative data. MAUT requires that a utility function be developed that will quantify qualitative decision criteria. These functions are constructed in a graphical form that captures the risk attitude of the decision maker (risk seeking, neutral, and risk adverse) and developed through an interview process. According to Larichev (1992), elementary operations of decomposing complex criteria into simple ones during problem structuring and the determination of quantitative equivalents of a lottery to compare different criteria are complex cognitive tasks. This method is not intended for evaluation of a large number of alternatives (Olson 1995). Finally, the interview process takes too long to be feasible for most situations. There are real limitations on the time one can expect to get from decision makers, and there are similar limitations on the time they can be expected to concentrate on a series of difficult questions. The administration of the questionnaire requires an interviewer sensitive to the interviewees' reactions as well as to the needs of the analyst. There is a real skill which must be developed before the results of an interview can be reliably employed.

The decision support system proposed in this study has to provide an objective and rapid method for tradeoff analysis to compare alternatives against real targets, and to support analysis of quantitative criteria. AHP and MAUT do not support these purposes, especially the first one.

The Aspiration Interactive Method (AIM), on the other hand, provides a technique useful to help decision makers learn about the tradeoffs among criteria considered in the selection of alternatives from large sets of available choices (Lotfi et al. 1992). The idea is to adjust aspiration levels of the objectives -which are used as targets for decision makers – and obtain the feedback regarding the feasibility of the aspiration levels. As these aspirations are adjusted, the nearest solution changes. Weights are generated by the aspiration levels and the nearest solution is determined by calculating a score for each alternative and ranking them according to the attainment levels against the set of aspiration levels. The method is straightforward, easy to learn and does not require complex mathematical iterations and knowledge from users. Based upon the review of literature, AIM has never been used in construction research but seems suitable for the supplier selection problem.

2.4 METHODS FOR SCHEDULE RISK ANALYSIS IN CONSTRUCTION

Program Evaluation and Review Technique (PERT), Monte Carlo simulation and Bayesian Belief Networks are common methods employed in studies of schedule risks in construction (Lee 2005, Lu and AbouRizk 2000, Nasir et al. 2003). These methods recognize the existence and effects of uncertainties in the execution of construction activities and try to solve the problem of deterministic schedules normally built by construction firms. None of these methods provide a "correct" solution for the analysis of uncertainties on project schedules and each one has its own set of advantages and disadvantages regarding implementation.

PERT is one of the first stochastic methods developed. According to PERT, expected task duration is calculated as the weighted average of the most optimistic, the most pessimistic and the most likely time estimates. The expected duration of any path on the precedence network can be found by summing up the expected durations. Two limitations of the technique are: 1) it is based on the central limit theorem that assumes all activities are independent, 2) significantly more effort is required to estimate three duration values than just the most likely value generally used in deterministic scheduling (Hinze 2004).

Monte Carlo analysis is used to approximate the distribution of potential results based on probabilistic inputs. Each trial is generated by randomly pulling a sample value for each input variable from its defined probabilistic distribution. These input sample values are then used to calculate results. This procedure is repeated until the probability distributions are sufficiently well represented to achieve the desired level of accuracy.

The main advantage of Monte Carlo is that it helps to incorporate risks and uncertainties in the process of project scheduling. However, Monte Carlo has the following limitations: defining distributions is not a trivial process. Distributions are a very abstract concept that some project managers find difficult to work with. To define distributions accurately, project managers have to perform a few mental steps that can be easily overlooked (Virine and Trumper 2008). Monte Carlo suffers from anchoring heuristic: when project managers come up with certain base duration, he or she tends to stick closely to it and build a distribution around it regardless (Williams 2004). Historical analysis of durations could support shaping probability distributions, however additional shortcomings are: creating sets of references or analog sets is not a trivial process because it involves analysis of previous projects. This is especially important in construction industry where projects are very unique and suppliers are not usually the same for different projects. Additionally, many firms may either not have any relevant historical data or data is available but cannot be easily retrieved.

Bayesian Belief Networks have been recently implemented in construction. This method uses conditional probability concepts to estimate the effects of risk variables on project schedule. The network consists of nodes that represent variables and arcs that represent conditional dependence relationships between those nodes. Users need to quantify and model the relationships between variables via probabilities which are usually a very subjective process. Furthermore, when a node has many relationships, the number of conditional probabilities becomes quite large. Nasir et al. (2003) developed a system to provide estimations of pessimistic and optimistic durations for eight activities where 476 probabilities were needed. Collecting this amount of data took significant time and experts found very difficult to translate qualitative issues into a quantified format. The system required large amount of input and manipulation of data, requiring managers to spend at least 2 hours to finalize this process.

Even though PERT limitations are somewhat criticized in some publications, the method is simple, classic, quick to implement and provides basic results of schedule risks. Moreover, project management professionals are familiar with the technique. Procurement managers, especially the ones involved in more strategic roles, usually do not spend time conducting detailed schedule analysis. Applications providing rapid analysis and a big picture view of the problem are usually preferred.

2.5 RESEARCH GAPS

Though the importance of engineered equipment procurement in construction is easily recognized, there is however relatively little published work examining the problems and uncertainties in the procurement process.

There is also a need to understand how companies plan the overall delivery process of engineered equipment during early phases of project lifecycle (e.g. FEL phase). Usually, major supply risks and constraints need to be identified and strategic decisions have to be made in order to mitigate these risks and ensure materials can be delivered on time at the job site. IPRA and PDRI tools support identification of risks, however their results have not been used neither as an input for generating realistic equipment delivery plans nor for predicting schedule performance. Identification of firms' data availability and organization is an essential step towards a better comprehension of early planning practices.

The process-oriented tools presented in the previous section demonstrate the potential benefits that could be achieved via supply chain planning however implementation is very limited in the construction industry. Construction lacks tools that are capable of integrating actual market data such as suppliers' capacity constraints, expected lead times and prices with procurement targets (schedule and budget) to ensure plans are realistic, feasible and achievable.

Realistic plans are also derived from a better understanding of the effects of uncertainties on equipment delivery process. Identification of major sources of uncertainties associated with stochastic schedule methods can provide additional insights regarding procurement schedule analysis.

Finally, available tools provide very limited or no support for exploration of tradeoffs of different supply chain configurations. Managers need to evaluate and compare multiple variables and parameters to select the right supply chain configuration to achieve project goals. The researcher believes that the development of a decision aid tool providing rapid evaluation and comparison of several supply alternatives may improve the quality of procurement plans as well as speed up the time managers spend carrying out analysis.

CHAPTER 3: RESEARCH QUESTIONS AND METHODOLOGY

3.1 RESEARCH QUESTIONS

The goal of this study will be achieved through answering adequately two high level research questions. Question one seeks to help the researcher understands the current industrial construction environment and to identify practical and theoretical issues that need to be addressed within the scope of this research. Question two guides the development and evaluation of the proposed decision support system.

Thus, the proposed research is defined by:

- **Research Question 1**: What are the current challenges involved in the procurement of engineered equipment for capital projects?
- **Research Question 2**: How can we systematically link project targets and available information on suppliers and supply chain constraints to support the selection decision in the early phases of capital projects?

Each question is then decomposed in sub questions that need to be answered and define focus areas of this research. The sub questions are listed as follows:

- **RQ 1: What are the current challenges involved in the procurement of equipment for capital projects?**
  - What are the key decisions procurement managers need to make?
  - What information is available about suppliers and other supply chain constraints?

- How this information is currently obtained and organized?
- In what level of detail is this information presented to procurement managers and which are the important variables that need to be considered?

- **RQ 2: How can we systematically link project targets and available information on suppliers and supply chain constraints to support the selection decision in the early phases of capital projects?**
  - How can we facilitate rapid evaluation of suppliers considering available and important variables?
    - What types of evaluation are possible given typical information availability?
    - Of these evaluation methods, which is(are) suitable for comparison against targets and analysis of tradeoffs involved in the selection decision?
    - Would additional or more precise information lead to improved evaluation?
  - Can we generate useful schedule risk analysis associated with preferred suppliers?
    - What procurement schedule milestones should be considered?
    - What are the major factors that affect scheduling of engineered equipment?

- How can managers use these factors to estimate durations and understand associated schedule risk?

3.2 RESEARCH METHODOLOGY

Figure 3.1 shows an overview of the research methodology. This research consists of four main phases: 1) literature review and a set of exploratory case studies, 2) development of a conceptual model and walkthrough meetings with procurement managers for collecting users' input and requirements gathering, 3) development of a user-friendly application for decision aid and preliminary schedule analysis, and 4) validation of the decision support system with experienced procurement professionals. Analysis of the results of validation phase and feedback from managers lead to the conclusions of the present research and recommendations for future investigations.

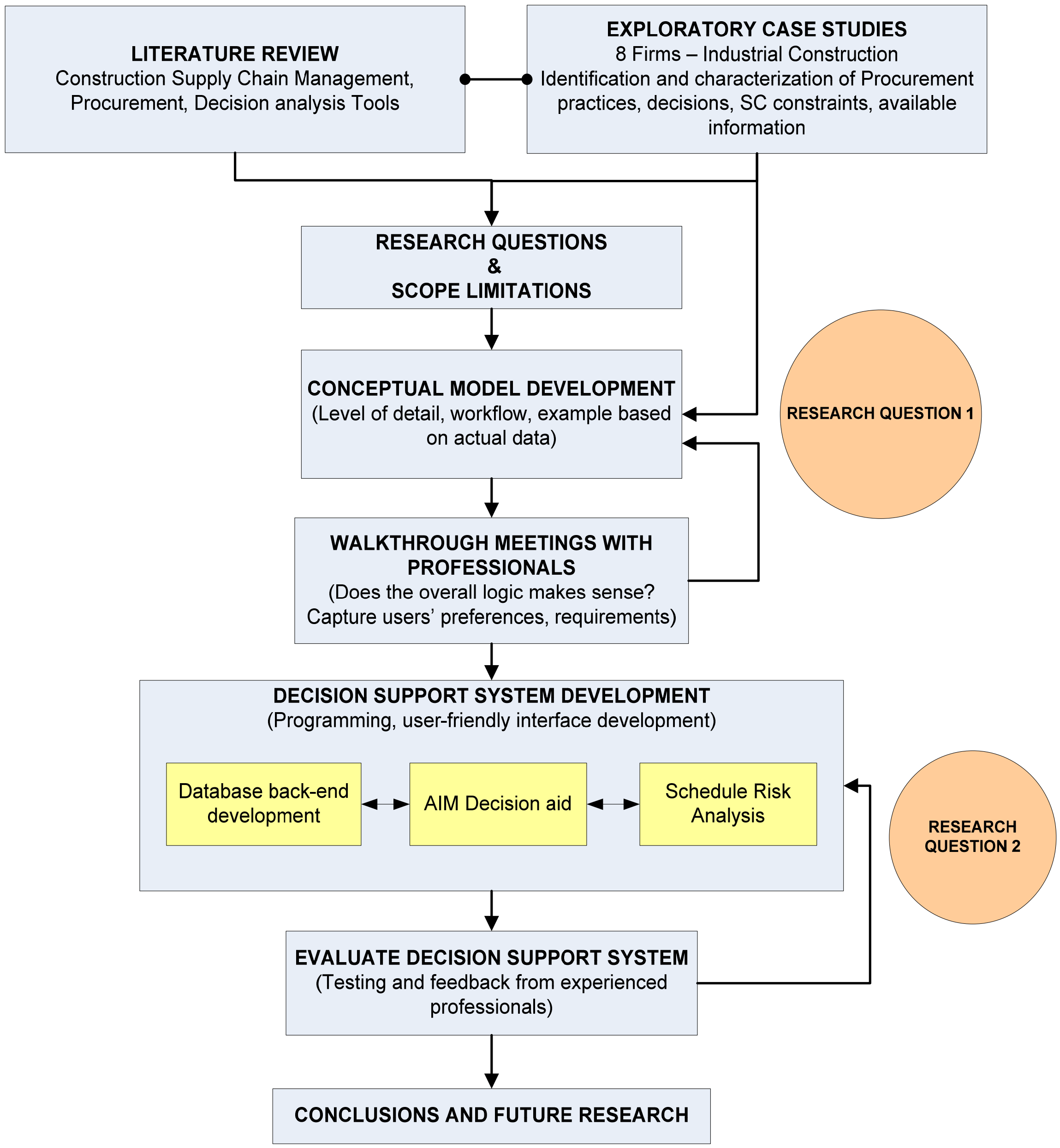


Figure 3.1: Research Methodology

3.2.1 Literature Review and Exploratory Case Studies

A literature review on procurement of engineered equipment, supply chain practices and tools, decision aid methods, and schedule techniques was conducted and presented in chapter 2. Due to the paucity of literature in industrial construction regarding procurement and supply chain management practices, it was decided to address research question 1 using the case study method. Exploratory and descriptive cases are excellent starting points for the exploration of a topic (Eisenhardt 1989). According to de Vaus (2001), this research approach is especially appropriate in new topic areas.

I needed to understand how procurement managers assess engineered equipment suppliers, learn their early planning practices and decisions, and identify information availability, organization, and most important variables guiding such decisions. To gather this data, I interviewed experienced procurement and materials management managers. Interviews were open-ended to encourage exploration of those topics (see Appendix A). Additionally, companies provided procurement documents currently used for planning their project sourcing strategy. Market reports, sourcing plans, bid spreadsheets enabled a better understanding of information organization, availability, and level of detail.

I carried out multiple case studies with similar type of firms to strengthen the collected evidence, identify patterns, and compare their similarities and differences. Detailed cross-case comparison enhances the probability that the researcher will capture the novel findings which may exist in the data (Eisenhardt 1989) and increases generality of the case study approach (Yin 1994).

3.2.2 Conceptual Model Development and Walkthrough

Results from exploratory case studies helped me to gather a better understanding of the overall procurement process of engineered equipment, data availability in the early phases of projects, and main variables procurement managers look at when making their decisions. However, at that point, it was not clear how I would support assessment of engineered suppliers based on the available data and key parameters. I believed that an interactive development approach would allow me to capture managers' preferences and, at the same time, I would collect invaluable input to deciding on how to structure the data to enable decision support.

A conceptual model which included a comprehensive example of a pump selection was built in Microsoft Excel and Microsoft Access. A database containing information on pump suppliers was integrated with Excel. Input data on equipment, procurement targets (schedule and budget) and desired supplier performance was provided in an Excel Spreadsheet serving as parameters for running a set of queries. These queries automatically retrieved valid suppliers from the database and displayed them in another spreadsheet. Figure 3.2 illustrates the conceptual model components and its main purpose identifying valid suppliers.

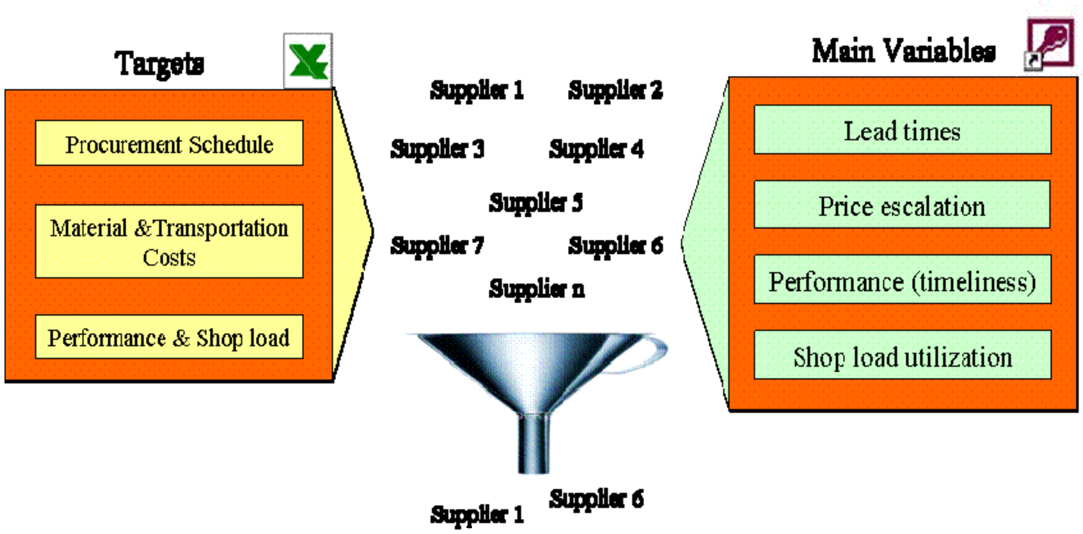


Figure 3.2: Conceptual Model of the Decision Support System

Once the conceptual model was completed, I scheduled meetings with procurement managers to get feedback on the overall logic, check out if the data being presented matched the level of detail of actual and available data used in the early phases of projects. I used a walkthrough approach and presented every single detail of the tool during two-hour meetings. Managers were able to test the tool which allowed them to quickly monitor suppliers that fulfilled schedule, budget and performance requirements. Then, I asked them to indicate their preferred supplier for the pump case.

These managers also expressed their opinions and concerns regarding the proposed level of detail and provided comments on conceptual model usefulness, applicability of the software in real case scenarios, and software interface preferences. This research phase served mainly as a requirements gathering phase and preceded the final application development.

3.2.3. Application Development

This phase entails the development of a decision support system. I developed a software with the support of a master student in computer sciences. The main idea at this phase was making sure I would translate all requirements gathered during the discussions of the conceptual model and ensure they were properly coded in the decision support system.

My conceptual model still missed an objective and systematic methodology to rank the suppliers stored in the database. From the literature review on decision aid methods in construction and operations research, I identified an approach which is called Aspiration Interact Method (AIM) that seemed to be more suitable than other decision aid methods for the selection of suppliers. AIM's logic is easily applicable in the case users desire to identify and rank alternatives against a set of targets (my conceptual model). Other methods do not allow this type of analysis. AIM was then included as a module for supporting supplier selection and tested in actual selection cases (chapter 6).

A PERT schedule analysis module was also coded. This technique was chosen based on discussion with procurement managers. Managers mentioned PERT is relatively easy to understand and could provide useful inputs for project controls staff responsible for generating the project schedule. I also discussed Monte Carlo simulation - a very useful technique to provide schedule risk information - with procurement managers. However, this simulation analysis is not within their scope of work. This analysis is carried out by project controls staff during project execution. Therefore, PERT was the method implemented in this research. I contributed with a method to support estimate of most likely durations for conducting PERT analysis. This schedule module and the AIM module are detailed in chapter 5 of this dissertation.

3.2.4 Application Testing and Validation

The last phase of the research involves testing and validation of the decision support model. Once the application code was finished, the researcher built multiple testing scenarios using the pump selection database and compared the outputs provided by the application against the expected results. These tests helped me ensure that all parts of the software were internally consistent and accurate.

In this last phase, the goal was to verify that the decision support system can provide useful information for rapid assessment and selection of suppliers, and equipment delivery schedule risk. The system is also expected to be complete, intuitive, and easy to use. Once again, I chose to follow an interactive research approach to ensure I contributed with a valid model for construction practice as well as to improve the credibility of my research. First, I conducted meetings to present the software and discuss AIM and PERT modules. Next, I wanted to compare the solution of my system against the solutions recommended in actual selection cases. One EPC (EPC-1) that was also very interested in seeing this comparison provided actual data on two selection cases. The results of analysis were discussed in wrap-up meetings with this firm. EPC-4 also expressed their suggestions based on my description of the cases. Figure 3.3 summarizes the testing and validation phase of this research. The validation findings are presented in chapter 6.

I cannot say my approach is action research because there was no intervention or change in firms' current selection process. The idea of the application is supporting the work of procurement managers. No computer system can replace the human aspect of procurement managers' decision making process. The major anticipated distinction is that the computer tool may speed up and improve the quality of decisions which are currently the result of a somewhat informal and subjective process that requires manual integration of various sources of information.

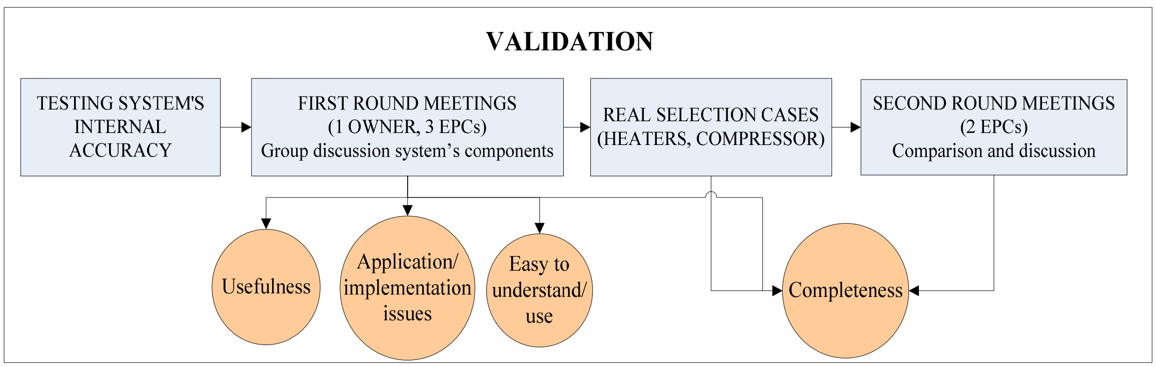


Figure 3.3.Research Validation

CHAPTER 4: CURRENT STATE OF PRACTICE – CASE STUDIES

In chapter 1, I described procurement increasing complexity and existing constraints in the supply chains of the industrial sector. In this environment, managers must commit with critical suppliers and plan their supply chains in the early phases of capital projects. The literature review (Chapter 2) revealed that literature on early planning of supply chains is still lacking in construction. Moreover, most of the studies have been conducted with either commercial or residential construction firms. Little is known about practices implemented by firms which execute complex industrial projects worldwide, source mostly engineered equipment from different parts of the globe, and operate in very dynamic market conditions.

This research is focused on firms within industrial construction. From the start, my intuition was that sophisticated and leading companies that perform global projects and face logistics challenges would provide us with invaluable information on procurement and supply chain practices. Exploratory case studies were conducted with EPC firms and owners. The researcher had initial access to these firms via contact with Construction Industry Institute (CII) members. Other contacts were made at a CII research meeting and also via researchers' networking. The final sample includes 5 EPC firms and 3 owners. Table 4.1 lists our sample population, firms' business segments, and interviewees' position. Their identities have been kept confidential.

Table 4.1- Exploratory Case Studies sample

Firm	Business Segments	Interviewees
EPC-1	Oil and Gas, Chemicals, Mining, Renewable Energy, Power, Nuclear New Build, Government	VP (Vice President) Procurement, Senior Director, Senior Director – Logistics, Senior Director - Materials Management, Executive Director – Material Management, Senior Director – Strategic Sourcing, Executive Director – Strategy and Risk
EPC-2	Civil Infrastructure, Communications, Mining and Metals, Oil, Gas, and Chemicals, Power, Government	Purchasing Manager, Materials Manager
EPC-3	Civil Infrastructure, Oil, Gas, and Chemicals, Technology, Government	Director Procurement & Materials, Director (Supply Technology Systems), Subcontracting Manager, and Manager (Logistics Simulation)
EPC-4	Chemical/Petrochemical, Refining, Power, Pulp and Paper, Polymers	VP Procurement, Procurement Manager
EPC-5	Petroleum, Power, Heavy Civil, Metals, Pulp and Paper, Pharmaceutical, Cement, Manufacturing, Commercial Building	Director of Procurement, Strategic Sourcing Manager, IT manager, Contracting Manager
Owner-A	Oil and Gas, Power	Contracting Manager, Upstream Sourcing Manager, Market Intelligence Owner
Owner-B	Manufacturing	Associate Director for Capital System Management organization
Owner-C	Oil and Gas	Manager –Energy Projects Implementation

I believe that a set of exploratory case studies in this area will be an important contribution for the current state of knowledge in construction supply chain management. A set of research questions were then posed to guide these studies:

- What are the current practices implemented by leading companies in industrial construction to overcome their supply chain challenges?

- What are the key decisions procurement managers need to make?
- What information is available about suppliers and other supply chain constraints?
- How is this information currently obtained, organized, and used?
- How do these companies integrate and relate with their suppliers?

In the following sections, I describe the main findings of these cases and present a summary of lessons learned. These lessons provide additional motivation for the development of the decision support system proposed in this research.

4.1 CASE FINDINGS - CURRENT PRACTICES

4.1.1 Focus on Early Planning and Strategic Decisions

Project sourcing strategy is part of any project execution plan. It is drafted before contract is awarded and further detailed to support project execution. EPCs are being pushed to build realistic supply plans based on market constraints. Many projects have been awarded due to effective and detailed plans which consider market constraints.

EPC-1 preliminary supply plans include decisions on standardization (motors, switchgear, etc), modularization, on site vs. offsite fabrication, procurement master schedule, contracting strategy, scope of responsibility, and logistics (shipping capacities, ports, access, ability to bring heavy equipment, volume, customs clearances). Models including detailed financial and economic analysis of different sourcing alternatives and risk mitigation plans are presented to clients. Decisions are heavily supported by the information and intelligence of the sourcing group, industry experts and supplier contacts. Visiting suppliers around the globe is a common practice as well. The executive director who manages this process said "I need to understand supplier capabilities and market characteristics and be on top of this information. Strategy comes when you got something different - a constraint – and constraints are driving changes in Procurement."

The other four EPCs listed a very similar set of decisions. These firms are usually concerned with the following issues: commodities availability, potential suppliers in different countries, low cost country options, cost behavior and currency fluctuation data (pricing), logistics, and long lead items. EPC-3, EPC-4, and EPC-5 typically focus on identifying long lead equipment (e.g. reactor, compressor), and determining the strategy around these pieces. According to the procurement director a key decision is determining how early they need to commit and what the associated risk of ordering early is. EPCs need to increase delivery certainty, i.e. have the material available on site when needed since schedule delay is the most costly problem that can happen to a project. EPCs normally do not evaluate inventory costs resulting from early ordering strategy. A manager quoted "inventory is not the key driver. Space conflicts are very rare to happen but we are aware of it. We do not practice JIT because the key driver is to have a sufficient margin of material buffer prior to installation on site." A strategy to support the project schedule is needed and directly supports estimates. Typically, equipment suppliers are selected from a list of approved suppliers which are rigorously pre-qualified and evaluated according to their work history, financial, operations, insurance, and safety performance. Any supplier can only supply from its approved plants.

All owner firms also evaluate when to purchase long lead materials and how they can get them earlier on the job site. An additional decision is: who will buy the material? Owner-A usually buys pipes and tanks in advance because the bidder may not be awarded and the firm has money to invest. Moreover, Owner-A cannot wait for the bidding process, otherwise material delivery delays may occur. A contract manager said that his firm has been working with EPCs to understand their capabilities and negotiation power with suppliers, because sometimes EPC firms are in a better position to manage these risks.

Dealing with this vast number of decisions and alternatives is not an easy task and requires the integration of information from multiple procurement functions, information systems, and firms. EPCs have reported that there is no specific tool that integrates this information and support decision making during pre-project planning. EPC-1 common practice is sharing demand and supplier capacity information with strategic suppliers. This information is used for early planning and negotiations (e.g. buy/commit shop capacity in advance). An annual market report is also used as input to understand price/lead times/shop load forecasts, and other market constraints. Daily basis communication with industry experts, fabricators to get market intelligence data is usual. EPC-2 and Owner-A use historical models to guide their decisions before detailed engineering phase. Managers have a rough idea (baseline) and can somewhat predict the quantity of materials needed (e.g. steel, pipes, concrete) depending on the type of project. EPC-3 uses simulation to plan and communicate logistics decisions to their clients. Monte Carlo and discrete event simulation models (e.g. Arena) are used to predict schedule risks, ocean transportation planning (number of ships and barges, their capacity), job site logistics planning (e.g. unloading zones and flows), warehouse space planning, among others. EPC-5 performs lead time and cost/pricing analysis with four to five suppliers of major equipment. A traditional bid tab is then prepared with this data and risks are identified. EPC-4 also makes decisions based on bid tabs and requests information on shop load (e.g. monthly fabrication capacity, monthly estimated loading) during bid phase to evaluate supply risks.

Owners have their own particular strategies to mitigate supply risks. Owner-A analyzes the marketplace to understand supply risks (currency exchange, prices, capacity constraints) and assign them to who is better able to control it. This is done by an aggressive allocation of risks in contracts. Sometimes, Owner A pays only for getting detailed execution plans from EPCs. Owner-C requires detailed supply and logistics plans from potential EPCs and also enforces them to work with a predetermined list of suppliers.

4.1.2 Market Intelligence to Support Early Planning

All studied firms excepting EPC-5 execute projects around the world. Their goal is to develop knowledge of key markets and suppliers to create competitive advantage through informed supply decisions during early phases of the project lifecycle. EPC-1 and Owner-A publish very detailed market intelligence reports once or twice a year. These reports include historical data and forecasting on equipment and materials prices, lead times, shop capacity around the globe, global demand, and major risks and challenges. Information on global logistics capabilities is also described to support early planning. EPC-1 usually books transportation in advance, especially when offsite modules or heavy equipment needs special planning. Figure 4.1 shows one example of how forecast information is currently organized and summarized. Information is provided by product directors who are responsible for understanding suppliers' capabilities, cost drivers and market conditions. The centralized sourcing group use this report to support early procurement decisions. Owner-A also maintain a market intelligence website with other owners including detailed information about EPCs and suppliers.

January 2007	North America						
	Equipment/Material Lead Time (Weeks)		Price Escalation (%)		Q1 - Q2 2007 Bid Validity (Days)	Q1 - Q2 2007 Bid Cycle Time (Days)	Comment on any observations, weaknesses, issues, or concerns for the Jan. to Jun. 2007 Forecast market
	Q1 - Q2 2007	Q3- Q4 2007	Q1 - Q2 2007	Q3- Q4 2007			
Structural Steel							
Fabricated Structural Steel	30-40	30-40	3-5	2-5	30	20	Fabrication shop space will be at a premium. Long material lead times will be experienced.
Pressure Vessels / Heat Exchangers							
Low Alloy CS Reactors - Wall Thickness less than 6"	100-104	100-104	4-8	4-7	30	4-6+	Plate material is setting delivery schedules
Low Alloy CS Reactors - Wall Thickness 6" and above	150-156	150-156	4-8	4-7	30	4-6+	Limited capability in North America
Medium to Large Trayed / Packed Towers	100-104	100-104	4-8	4-6	30	4-6+	Availability of material and skilled labor are primary concerns of fabricators
Small to Medium Trayed / Packed Towers	78-100	78-100	4-8	4-6	30	4-6+	Availability of material and skilled labor are primary concerns of fabricators
Shell & Tube Exchangers	52-72	52-80	4-8	4-6	30	4	Suppliers are selective in projects they pursue
Air Cooled Heat Exchangers	52-60	60-70	4-10	4-8	30	4	Availability of material, skilled labor and logistics

Figure 4.1: Information Organization Framework

EPC-2, EPC-3, Owner-B also utilize databases to monitor their supply base. EPC-2 maintains a global supplier and contractor information system. This system includes around 100,000 suppliers/contractors from different countries for 300 to 400 products. One procurement manager said that this system provides global visibility and competitive advantage – especially when a firm executes projects in different geographic locations. A quotation from the same manager points to a trend that goes against the supply chain concepts found in the literature: “SC strategies say that we need to consolidate suppliers, reducing the number and standardizing the product. We don’t do that. It does not work in our environment, our dynamic is different, and we need to consider different frontier locations.” EPC-4 does not have staff supporting the collection of market intelligence data. Experienced buyers and managers make decisions based on their own knowledge. The VP of Procurement however, acknowledges that the market is very dynamic and has been spending part of his time summarizing market outlooks (forecasts) provided by third-party companies or suppliers. These summaries include three subjects - price escalation, lead times and material availability – and are sent to the whole procurement group. EPC-5 requires that every supplier needs to have a “domestic presence”. Their supplier base is somewhat limited compared to other companies. Familiarity with the suppliers and their location are important factors considered by EPC-5 when selecting their suppliers in the USA.

4.1.3 Supplier Integration and Long Term Relationships

EPC-1 has been extensively using strategic supplier agreements and aggressive supplier integration. EPC-1 considers supplier integration a catalyst that generates competitive advantage. Suppliers of critical components are involved since conceptual project engineering. This practice helps to reduce engineering effort, rework, shortens cycle times and project risks. Alliance with freight forwarders is also viewed as fundamental. In the last few years EPC-1 has reduced the number of partners from 17 to

4, which helped streamlining operations and improved the monitoring effort. The firm will not consider building a strategic relation with suppliers if they are not able to integrate their systems (automation, interfaces). One executive director said: “Engineering integration enables the use of more standard components, save fabrication time “fabricability concept” and engineering cost. Integration with suppliers is a must; together we can do more work. Engineering resources are scarce for suppliers as well.” EPC-1 is moving to a direct integration with suppliers, where the procurement effort will be reduced and commercial frameworks will be already in place from engineering to execution. Examples of best practices are: 100% vendor design, performance specifications (equipment); model based engineering – vendor extract 3D models for detailed design; and their main electrical vendor which already designs and execute everything.

EPC-2 and EPC-3 do not have global alliances, agreements, partnership with suppliers. Their relation is informal and based on communication between top managers. EPC-2 usually works with 15,000 suppliers. One thousand are considered core or strategic suppliers because often work with the firm. Suppliers of major equipment exchange their standard 3D models which can be directly imported in EPC’s design tool, others (e.g. piping, structural steel, electrical), work on EPC-2’s digital models. 3D models are utilized during the whole project lifecycle. During construction, EPC-2 uses the models to check space conflicts and construction execution status. EPC-3 has also been working on design and work process integration. In the future, the firm plans to involve suppliers in engineering efforts, pricing agreements, and partnerships. EPC-3 managers said some major suppliers have agreed to maintain a fixed price.

EPC-4 has only project agreements with pre-qualified suppliers. There is no design integration via advanced technology or aggressive participation of suppliers in early engineering phases.

EPC-5 selects their best partners and work with them over and over again. This partnership approach reflects on the involvement of suppliers in the early phases of projects. A critical supplier's office is located within the EPC-5 facilities. According to managers, estimates are more accurate and there is continuity from the planning phase to execution. This relationship really engages the supplier since pre-award phases, improving the planning process since the GC can really trust in the information they receive.

As for the owners, many changes have been occurring regarding relationships and contracting approaches with EPCs and suppliers. There are fewer big players in the market due to firms' consolidation, joint ventures, and consortiums. Strategic agreements are taking place more than ever. Owner-A quoted a strategic decision on selecting a supplier as an exclusive sourcing for some products. This relationship reduced inventory costs, the owner got better deals, and it improved maintenance and operations as well. Owner-B is working with strategic alliances and unit cost pricing agreements in order to know which reliable contractors are available in the marketplace and reduce the time spent bidding.

4.1.4 Supply Chain Visibility Using IT

All EPCs have complex materials management information systems which contains equipment and materials data (drawings, schedule, purchase order, approvals) and tracks their status through procurement lifecycle – from pre-ordering process, purchase, fabrication, shipments, until receiving on site. Any change or update is reflected real time on the system. This way managers have supply chain visibility and can anticipate delays, place time buffers if needed (before final installation) as wells as assess the costs associated with required actions to manage deliveries more effectively. The expediting team is in the frontline monitoring if the supplier fabrication is on schedule and delivery is on time. The information system also includes supplier evaluation data. This evaluation is saved for supporting future decisions and may determine further awards. Suppliers are rated based on their performance regarding cooperation (e.g. problem solving and timeliness), quality (e.g. adherence to specifications, tolerances), schedule (e.g. meeting required delivery, maintain scheduling), and commercial (e.g. effort needed to ensure performance) criteria.

Owners' teams also tracks order status of critical equipment. Owner-B has what is called "Equipment status memorandum" which shows current delivery status. Videos and photos are also collected to check fabrication status.

4.2 LESSONS LEARNED AND SUMMARY

The results of the case studies allow us to compare the current state of practice against the body of literature. Table 4.2 summarizes the State-of-the-knowledge and the current practices implemented by firms within industrial construction and lists lessons learned. Many lessons can be drawn from this study. Most of them illustrate how much emphasis the studied companies place on early planning, collaboration and integration with suppliers, and visibility of their supply chains. Managing projects in such complex and globalized scenario has forced these firms to think strategically. If firms executing residential and commercial construction have been commonly described as being traditional and inefficient, the same cannot be said regarding the practices adopted by sophisticated firms in the industrial sector.

Table 4.2: Summary of Literature Review, Case Findings, and lessons learned

	State of Knowledge	*Current Practice*	*Lessons Learned*
Sourcing Decisions	**• Usually decisions are made too late in the project lifecycle (e.g. supplier selection during project execution).**	**• Focus on strategic decisions which can impact project results (schedule/costs)**	**• A broader perspective of the supply chain improves planning and risk mitigation early in the project lifecycle.**
	• Price is the dominant factor for deciding who will be the supplier.	**• A big picture of suppliers' fabrication capacity and historical performance, and transportation issues are as important as price.**	
Supplier Involvement/ Integration	**• Little input of suppliers during engineering. If suppliers are involved, this usually happens during the execution phase.**	**• Critical suppliers are involved since pre-project phase. These suppliers actively participate of engineering decisions early on.**	**• Involvement and integration of suppliers in the early phases is crucial.**
Market intelligence	**• Minimal use of market data to generate alternatives.**	**• Managers assess multiple alternatives with support of market intelligence data to support supply decisions and to mitigate associated risks.**	**• Market information allows exploration of supply alternatives, mitigation of risks. Firms' use this knowledge to create competitive advantage.**
IT Support	**• Lack of visibility of material status in the supply chain. IT tools for tracking material are rare.**	**• IT tools provide quasi real time visibility of order status.**	**• IT tools support materials management and warn managers of potential delays in real time. Overall planning process is facilitated.**
Relationship with Suppliers	**• Usually adversarial relations.**	**• Strategic Alliances and Partnerships are commonly pursued.**	**Firms are experiencing excellent results because of a change in the way they relate with their suppliers.**

Literature indicates that planning focus on tactical and operational issues late in the project lifecycle, mainly during construction phase. Recent studies indicate how inefficient procurement planning is in construction. Lack of materials on site is still one of the main causes affecting site production (Alarcon et al. 2005). Usually, suppliers are also chosen very late, making it difficult to anticipate their needs in terms of storage area, paths for handling products, among others. Moreover, ordering and deliveries take place when the production comes to a halt due to lack of materials required. Early supplier involvement and integration is suggested by Vorster et al. (1998) to improve this scenario, however, little has been published on early integration after this publication. The state of practice, on the other hand, shows that strategic planning and knowledge of suppliers' capabilities is crucial to increase schedule and cost certainty.

Current practices emphasize alliances and integration with key suppliers in the early phases of the project, and advanced planning via exchange of fabrication/logistics information and forecasting of market conditions. These practices are poorly reported in the literature which mostly describes residential and commercial construction cases. Tommelein et al. (2003) performed an extensive study on capital projects supply chains in which they concluded that firms have feared to enter a long-term transparent relationships might place them in disadvantageous negotiating position. Their study also shows that alliance relationship is not a common practice in construction and relationships are usually set up on project by project basis and are often characterized by adversarial contract management styles aiming at pricing reduction rather than a holistic improvement strategy.

Firms have been investing time and money in order to get information about market conditions. With this information in hand, managers are able to assess multiple supply alternatives, and consequently prepare better plans and mitigate some risks that may potentially harm the project execution. This practice has not been described in the construction supply chain operations literature. However, it provides a starting point for discussing the importance of using knowledge of market conditions and supply chain structures to generate more realistic supply operations plans. This topic has been suggested in the industrial organization literature but no publications have directly addressed this issue yet.

Finally, firms have been using IT systems to get quasi real time supply chain visibility to improve execution. Managers are able to control equipment or material fabrication and delivery status as well as anticipate potential delays. This advanced technology facilitates execution planning. In the construction literature, cases of firms that utilize IT to support material planning and tracking are rare. Studies often describe the lack of visibility of material status in the supply chain and how it makes construction planning a more challenging task. Even though the studied firms are able to improve planning during the execution phase, it was identified that there is a lack of IT tools to support early planning and identification of supply risks.

Currently, market knowledge information – either forecasting or historical data on supplier performance - is not integrated with scheduling and estimating tools. Thus, evaluation and selection of supply alternatives is complex and time consuming process. Firms do not have tools capable of providing procurement visibility and constrained capacity planning to ensure plans are realistic, feasible, and achievable. The decision support system proposed in this dissertation aims to improve this process and help managers building more realistic procurement plans based on market knowledge data.

CHAPTER 5: DECISION SUPPORT TOOL

This chapter presents the main components of the decision support system which was developed to provide intelligence to the traditional procurement of engineered equipment. Specifically, this system aims to support rapid evaluation and selection of equipment suppliers based on project targets, and to provide information on equipment delivery schedule risks. Several pieces of evidence have motivated the development of this tool: gaps found in the literature in construction (Chapter 2), challenging market conditions (Chapter 1), lack of computer-based tools to support decisions, and other supplier selection issues observed during case studies (Chapter 4).

The system is composed of a back-end database and two modules. A supplier selection aid module uses the Aspiration Interactive Method (AIM) for providing rapid tradeoff analysis and indicating how each supplier is ranked in relation to the expected targets defined by users. Procurement managers will be able to quickly generate what-if scenarios based on real data included in the selected database. A change in the input targets also triggers different solutions and different suppliers might become better options according to these new targets. It is expected that this process will speed up the overall evaluation process, improve the quality of decision making process, and support the selection of strategic suppliers in the early phases of capital projects. A second module allows preliminary evaluation of schedule risks of preferred supplier. Ideally, this supplier should be the top supplier ranked by the AIM approach. The purpose is to present managers with an initial idea of how uncertainties might affect equipment delivery. Stochastic scheduling using PERT generates probabilities of equipment delivery success and delay as well as provides insights on risk factors. The analysis of factors to help managers estimating most likely procurement durations is a contribution of this study. As a result, managers may build more realistic procurement schedules even before the project award.

Figure 5.1 provides an overview of the main steps involved in the assessment of suppliers and how the decision support system's modules fit in this process. Chapter 6 presents a detailed supplier selection process model which was built in collaboration with EPC firms.

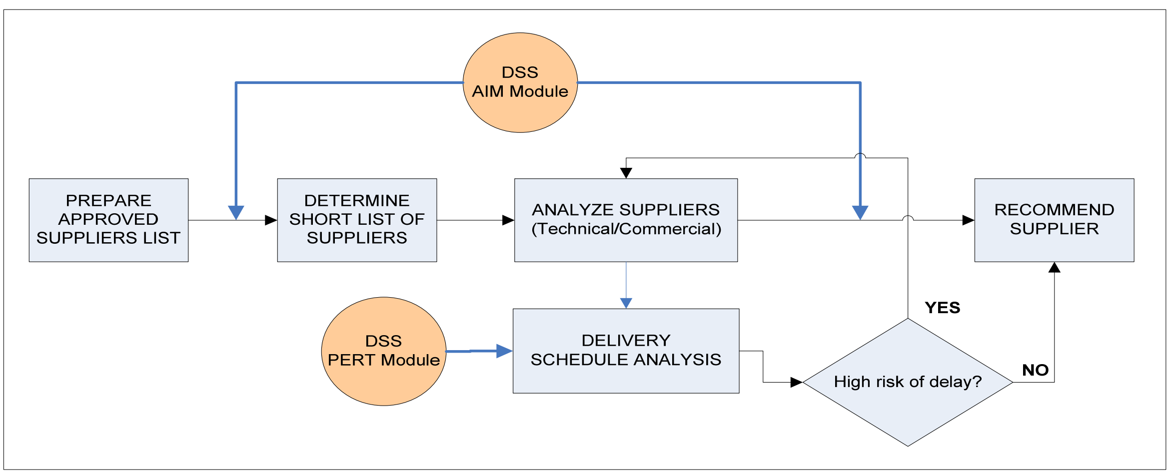


Figure 5.1: Supplier assessment steps and the decision support system's modules

In the next sections, I detail each component of the decision support system. In section 5.1, I justify and explain the Aspiration Interactive Method (AIM) which is the decision aid approach chosen to support supplier selection. Section 5.2 details the schedule analysis module included in the system. Finally, I close this chapter describing the software which was developed and further implemented in actual selection cases (Chapter 6).

5.1 The Aspiration Interactive Method (AIM)

AIM provides a technique useful to help decision makers learn about the tradeoffs among criteria considered in the selection of alternatives from large sets of available choices. The idea is to adjust aspiration levels -- which are the users' targets – and obtain the feedback regarding the feasibility of these aspiration levels. As the aspirations are adjusted, the nearest solution changes. Weights are generated by the aspiration levels and the nearest solution is determined by calculating a score for each alternative and ranking them, according to the attainment levels, against the set of aspiration levels. The method is straightforward and does not require complex mathematical iterations.

AIM involves the definition of few sequential steps. First, decision makers need to establish a set of objectives (k), usually maximization or minimization from targets (A_k). Second, Ideal (I_k) and Nadir (N_k) objective levels need to be identified from the data set. The Ideal objective represents the best case scenario (highest value for maximization or the lowest value for minimization) and Nadir the worst case (lowest value for maximization or greatest value for minimization). The difference between the ideal and nadir values establish the working distance over which attainments are evaluated. Third, a set of weights is calculated by dividing the distance from the aspiration level to the nadir level by the distance between the ideal and the nadir level: $W_k = (A_k - N_k)/(I_k - N_k)$. This set of values is normalized by dividing each ratio by the sum of ratios. A measure as good or better than the ideal receives a measure of 1. A measure as poor or worse than the nadir receives a measure of 0. Finally, AIM allows the user to explore alternatives and tradeoffs. Each alternative's (X_k) distance from the current aspiration levels is measured, indicating the proportional attainment over the range aspiration-nadir, or D_k = (X_k-

$N_k)/(A_k-N_k)$. Again, the maximum score is 1 (no extra credit for exceeding the aspiration level). The final score used for ranking the alternatives is the result from ΣW_k*D_k. Figure 5.2 summarizes all steps needed to conduct the AIM analysis.

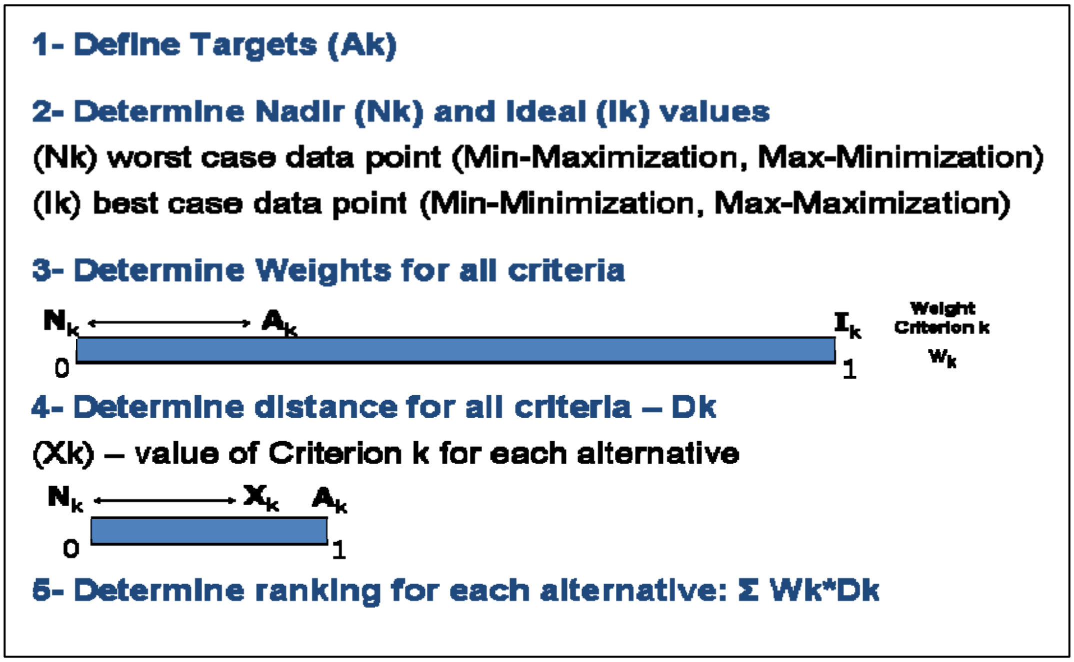


Figure 5.2: AIM summary steps

The main purpose of the method is to give the decision maker a chance to quickly see the impact of changing aspiration levels (targets) and the potential attainment within the alternative set (Lotfi et al. 1992). A step by step example is presented in the next section, illustrating the pump supplier case used during the walkthrough meetings.

5.1.1 Ranking and Selection of Pump Suppliers using AIM

During the conceptual model phase of the software development, I collected actual data and used AIM to validate managers' decision on preferred pump suppliers. The following example clarifies the whole logic behind the software calculations. The case dealt with evaluation of seventeen pump suppliers, but for the sake of simplicity only data on three of them is shown.

First step corresponds to establishing a set of targets which are called Aspiration levels (A_k):

Schedule targets

- Request for Quotation (RFQ): Aug 01 - 2008
- Site need date (SN): Aug 17 – 2009
- Total duration = 76 weeks

Cost targets

- Material: 28,000 USD
- Transportation: 2,000 USD

Supplier performance targets

- On time Fabrication: 90%
- On time Shipment: 95%
- Shop load Utilization: 80%

Second, users determine their **objectives**. In this case, managers wish to:

- Minimize total duration
- Minimize Material Cost (Mc)
- Minimize Transportation Cost (Tc)
- Maximize On Time Fabrication (Fontime)
- Maximize On Time Shipment (Sontime)
- Minimize Shop Load Utilization (SLU)

Third, N_k and I_K values are extracted from the database for supporting the calculation of weights. N_k values correspond to the worst case alternative (supplier) found in the database and I_k values the best case alternative for the objectives. Table 5.1 details the values and weights of the pump supplier case. On-time shipment aspiration level is very close to the ideal value, thus its value is almost equal to 1 and is the objective with highest weight.

Table 5.1: Calculation of Weights

Objective	**A_k**	**N_k**	**I_k**	**$(A_k-N_k)/(I_k-N_k)$**	**W_k (normalized)**
Duration (weeks)	**76**	**83**	**71**	**0.583**	**0.137**
Material cost ($)	**28,000**	**41,400**	**23,310**	**0.741**	**0.174**
Transportation cost ($)	**2,000**	**2,560**	**1,470**	**0.514**	**0.120**
On-time fabrication (%)	**90**	**73**	**97**	**0.708**	**0.166**
On-time shipment (%)	**95**	**76**	**96**	**0.950**	**0.223**
Shop load utilization (%)	**80**	**97**	**75**	**0.773**	**0.181**

Fourth step calculates the distance (D_k) between each supplier values (X_k) and the aspiration levels (input targets). The objectives nearest to the aspiration levels will receive a value of 1, the worst a value of 0. Alpha, Beta, and Gamma are three pump suppliers. Their values X_k (from historical, current, or forecasting data) are presented and the D_k for each objective is then obtained.

Table 5.2: Calculation of distance - D_k

Objective	A_k	N_k	***X_k Alpha***	**$D_k = (X_k-N_k)/(A_k-N_k)$**
Duration (weeks)	**76**	**83**	**73**	**1.42 = 1**
Material cost	**28,000**	**41,400**	**23,310**	**1.35 = 1**
Transportation cost	**2,000**	**2,560**	**2,033**	**0.94**
On-time fabrication %	**90**	**73**	**94**	**1.235 = 1**
On-time shipment %	**95**	**76**	**92**	**0.842**
Shop load utilization %	**80**	**97**	**85**	**0.706**
Objective			***X_k Beta***	**$(X_k-N_k)/(A_k-N_k)$**
Duration (weeks)			**73**	**1.42 = 1**
Material cost			**33,000**	**0.627**
Transportation cost			**1,575**	**1.759 = 1**
On-time fabrication %	**Same A_k and N_k**		**73**	**0**
On-time shipment %			**86**	**0.526**
Shop load utilization %			**80**	**1**
Objective			***X_k Gamma***	**$(X_k-N_k)/(A_k-N_k)$**
Duration (weeks)			**78**	**0.714**
Material cost			**45,000**	**-0.269 = 0**
Transportation cost			**1,819**	**1.323 = 1**
On-time fabrication %	**Same A_k and N_k**		**77**	**0.235**
On-time shipment %			**80**	**0.211**
Shop load utilization %			**95**	**0.118**

Fifth and final step corresponds to the generation of the final ranking of suppliers. This is obtained via expression $\sum W_k*D_k$. The closer to value 1 the better the supplier is.

In the case of pump supplier, Alpha is the supplier that provides the nearest solution for all the objectives. Tradeoffs can also be rapidly identified. Overall, Alpha is ranked the top supplier, however it is not the best supplier in terms of transportation cost and shop load utilization objectives. Finally, once the inputs (targets) are modified, Alpha might not be the best overall alternative.

Table 5.3: AIM based ranking

Supplier	**Duration**	**Material cost**	**Transportation cost**	**On-time fabrication**	**On-time shipment**	**Shop load utilization**	**$\sum W_k*D_k$**
Wk	***0.137***	***0.174***	***0.120***	***0.166***	***0.223***	***0.181***	
Alpha	**1**	**1**	**0.94**	**1**	**0.842**	**0.706**	**0.905**
Beta	**1**	**0.627**	**1**	**0**	**0.526**	**1**	**0.664**
Gamma	**0.714**	**0**	**1**	**0.235**	**0.211**	**0.118**	**0.325**

The results of AIM approach validate and corroborate the results obtained from observations with procurement managers regarding the identification of the preferred supplier. Alpha was also chosen by managers without help of any support tool.

5.2 STOCHASTIC SCHEDULING FOR PRELIMINARY RISK ANALYSIS

Managers want to increase the certainty of equipment delivery. PERT and other methods previously described in the literature review chapter provide a big picture of schedule risks as output. I decided to integrate the AIM approach with PERT analysis. In the next paragraphs, I explain why PERT was considered the most suitable approach for schedule analysis.

Observation from data collection during exploratory case studies shows that even sophisticated firms do not know the historical behavior (probabilistic distribution) of procurement activities durations. Instead, they work with duration range information, coming mainly from forecasting studies, inquiries with suppliers or historical records. One of the common critiques to PERT is that estimating three durations for each activity can be burdensome. In this research, once managers select their preferred equipment supplier using the AIM method, they will be able to visualize supplier's durations. Pessimistic and optimistic durations are suggested and displayed since the ranges are imported from the database. The next step consists of deciding the most likely duration for each delivery phase. Managers still need to come up with this number after carefully considering how several risk factors may affect each phase. Figure 5.3 depicts the four main phases that are within the scope of this research. The four phases are as follows:

- **Bidding**: from request for quotation (RFQ) date to receive bid (RB) date
- **Bid Conditioning**: from RB to Purchase order (PO) date
- **Fabrication**: from PO to ready to ship (RS) date
- **Transportation**: from RS to site need (SN) date

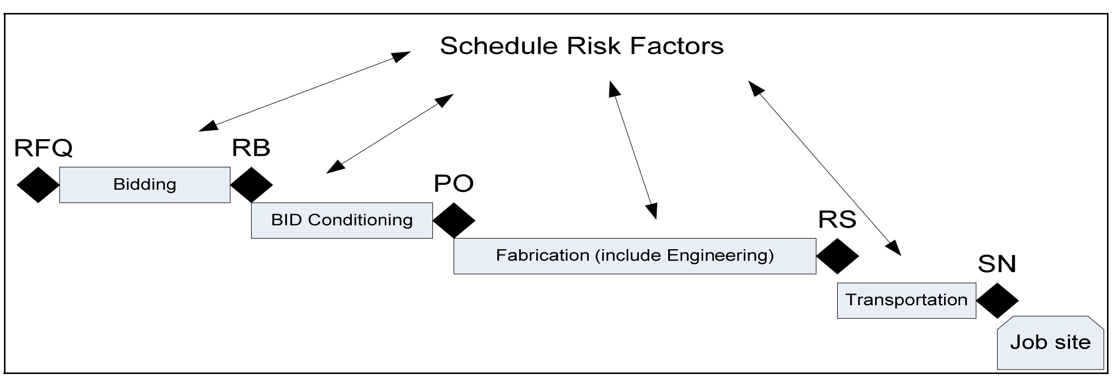


Figure 5.3: Milestones and phases of equipment delivery schedule

Additional characteristics of the delivery process that support PERT application are: durations can be assumed as being independent because there is no competition for resources, they are estimated without considering the impact of delays on each other, and the activities executed within the scope of each phase are usually performed by different firms, excepting bid and bid conditioning.

Risk factors were identified through interviews during the conceptual model development. A list including these factors was refined during the validation phase of this research. This list aims to guide managers choosing the most likely durations which determine the shapes of the probabilistic distributions for PERT analysis. The list is somewhat comprehensive. I believe I was able to identify all major factors; however, unique project and supplier characteristics may need to be considered to decide the most likely duration. Table 5.4 lists the major factors by equipment delivery phase.

Table 5.4: Major factors affecting delivery of Equipment

Delivery Phases	Schedule Risk Factors
Bidding	o **Supplier's responsiveness to quote** o **Bid evaluation complexity** o **Owner's approval responsiveness** o **Quality of design**
Bid Conditioning	o **Degree of owner's involvement** o **Familiarity with supplier's commercial staff** o **Equipment complexity** o **Complexity of terms and conditions** o **Equipment life cycle costs** o **Total installed costs**
Fabrication	o **Supplier's ability to provide detail drawings** o **Approval process of shop drawings** o **Shop load utilization** o **Familiarity with supplier's fabrication process and performance** o **Equipment complexity (# critical raw materials, components)** o **Market conditions of critical raw materials, components**
Transportation	o **Geographical distance between supplier and site location** o **Transportation mode(s)** o **Available infrastructure to transport the equipment,** o **International shipping issues (documentation, customs)** o **Available capacity to transport** o **Weather (e.g. winter, hurricane, flooding, etc)**

Managers need to determine how each of the factors may affect durations and suggest their own most likely durations. I developed a matrix that can be used to determine these estimates (Figure 5.4). Each factor can have a different impact on the most likely duration. For example, in the figure below, a supplier is usually very responsive to a quote and the owner's approval responsiveness in general delays the bid process. In this case, the first factor pushes the most likely duration towards the optimistic side while the second factor pushes it to the pessimistic side. If a certain factor is not important in the analysis, managers can select N/A and the factor will be ignored. Managers can also modify the durations suggested by the system after their evaluation using the matrix.

		Most likely duration					
		O				P	N/A
Bidding	Supplier's responsiveness to quote	x					
	Bid evaluation complexity				x		
	Owner's approval responsiveness					x	
Bid Conditioning	Degree of owner's involvement				x		
	Familiarity with supplier's commercial staff			x			
	Equipment complexity		x				
	Complexity of negotiating terms and conditions			x			
	Equipment life cycle costs are critical	x					
Fabrication	Supplier's ability to provide detail drawings	x					
	Approval process of shop drawings		x				
	Shop load utilization				x		
	Familiarity with supplier's fabrication process and performance					x	
	Equipment complexity (# critical raw materials, components)			x			
Transportation	Geographical distance between supplier and site location	x					
	Transportation mode(s)	x					
	Available infrastructure to transport the equipment,	x					
	International shipping issues (documentation, customs)						x
	Available capacity to transport				x		
	Weather						x

Figure 5.4: Matrix for assessment of impacts of risk factors on phase durations

Moreover, some factors may be more important them others. To solve this problem, I added a weighting score option which varies from 1 to 5 (5 for high importance level) and represents the importance of each factor in the most likely duration. This weighting idea was also included in other tools developed for construction applications. One example is the PPMOF tool developed by the Construction Industry Institute (CII 2002).

After all durations and weights are chosen, the system automatically calculates the most likely durations for each phase, provides the probability of equipment delivery success, and risk of delay associated with the procurement schedule target. The most likely duration (ML) is the result of a weighted average calculation of all factors' durations (F) and respective weights (W) for each phase. All managers agreed with this logic for the calculation of the most likely duration.

$$ML = (W_1F_1 + W_2F_2 \ldots + W_nX_n)/(W_1 + W_2 + \ldots W_n)$$

Figure 5.5 illustrates the output of the analysis of the pump supplier selection case. The preferred supplier would most likely delay the delivery of the pump in such scenario.

Suggested durations (weeks)	*Optimistic (a)*	*Most likely (m)*	*Pessimistic (b)*	*PERT durations (a+4m+b/6)*
Bidding phase	12	14	15	13.8
Bid Conditioning phase	5	6	6	5.8
Fabrication phase	54	57	59	56.8
Transportation phase	2	2	3	2.2
			Expected mean delivery time (weeks)	78.7
			Z value	-2.67
Procurement schedule target (weeks)	76		*Probability of delivery success (%)*	0.38
			Chance of delay (%)	99.62

Figure 5.5 Output of PERT schedule analysis

The schedule analysis is the last step of the application. This approach supports estimating procurement durations taking into account the influence of major uncertainty factors in the early phases of the project lifecycle. These factors are automatically integrated with PERT analysis. As a consequence, managers are capable to rapidly assess how realistic and feasible their procurement schedules are, taking into account a set of uncertainty factors and the preferred supplier's lead times that are stored in the database. This type of analysis is crucial to minimize the risk of delay of any critical path equipment

5.3 THE DECISION SUPPORT SYSTEM

A decision support system which integrates market data on supplier performance with procurement targets to aid equipment supplier selection has been developed. Managers have the choice to use historical, current, or forecasting information which are stored in different databases. Figure 5.6 shows the initial screen and the option for selecting a database before proceeding with analysis.

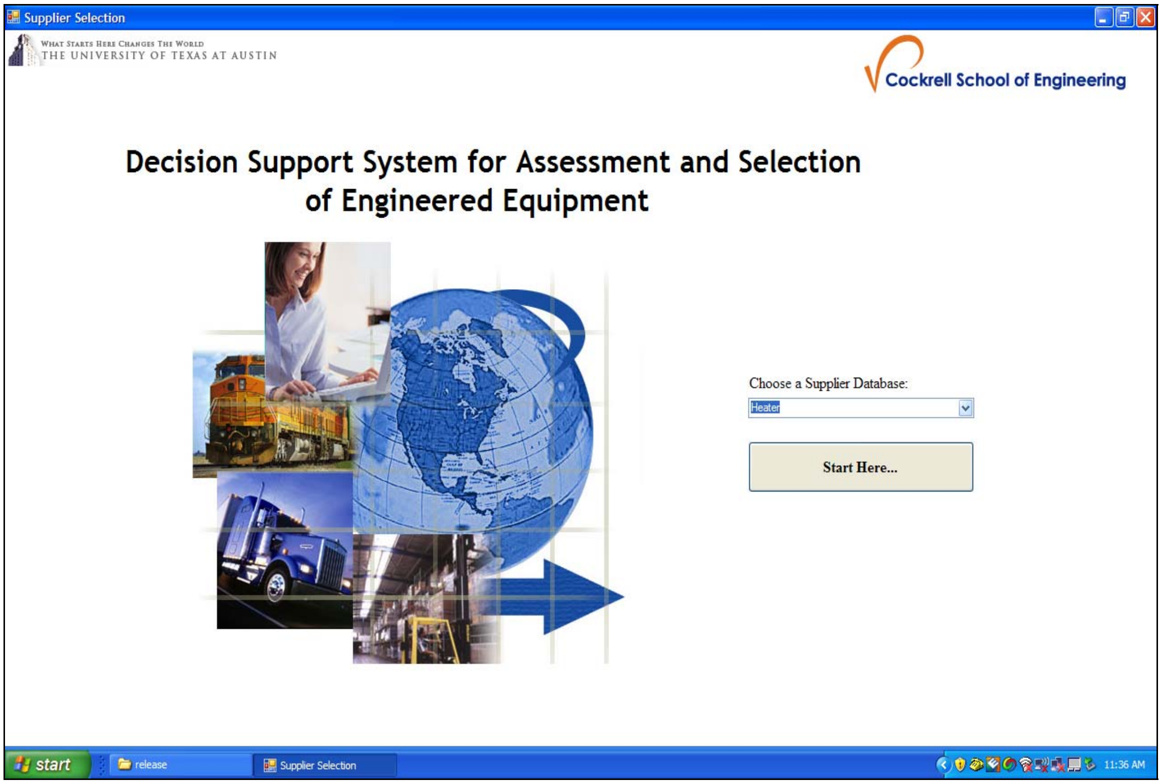


Figure 5.6: Database selection

Three major goals have been kept in mind while developing the software: 1) to provide a step-by-step process capturing the needs of supplier selection; 2) to help users make better decisions by ranking suppliers based on the Aspiration Interactive Method (AIM) approach, and 3) to support schedule analysis of the preferred supplier. The application has been implemented in Visual C#.NET as a Windows Form Project, with Microsoft Access as the backend database.

5.3.1. Database back-end

As described in the methodology chapter, the database was developed based on inputs gathered from experienced procurement managers. Database's elements, logic, and terminology were discussed during conceptual model phase of this research.

A relational model is used for designing the database, and it consists of the following tables:

- **Equipment**: represents a list of equipment and its associated categories.
- **Suppliers**: represents a list of suppliers, along with the country and geographic location.
- **Manufacture_Info**: stores lead times, costs, shop load utilization, fabrication performance, and quality data from various suppliers for different equipment; this table includes all data associated with fabrication phase.
- **Transportation_Modes**: represents the estimated cost escalation for each mode of transport in different quarters.
- **Logistics_Partners**: represents a list of partners used for transportation.
- **Logistics_Information**: represents transportation estimates from various logistics partners and its performance metrics.

Unique Identifiers have been used to link the tables. The database is kept simple, and is not optimized for any type of retrieval. Figure 5.7 shows the database structure and relationships.

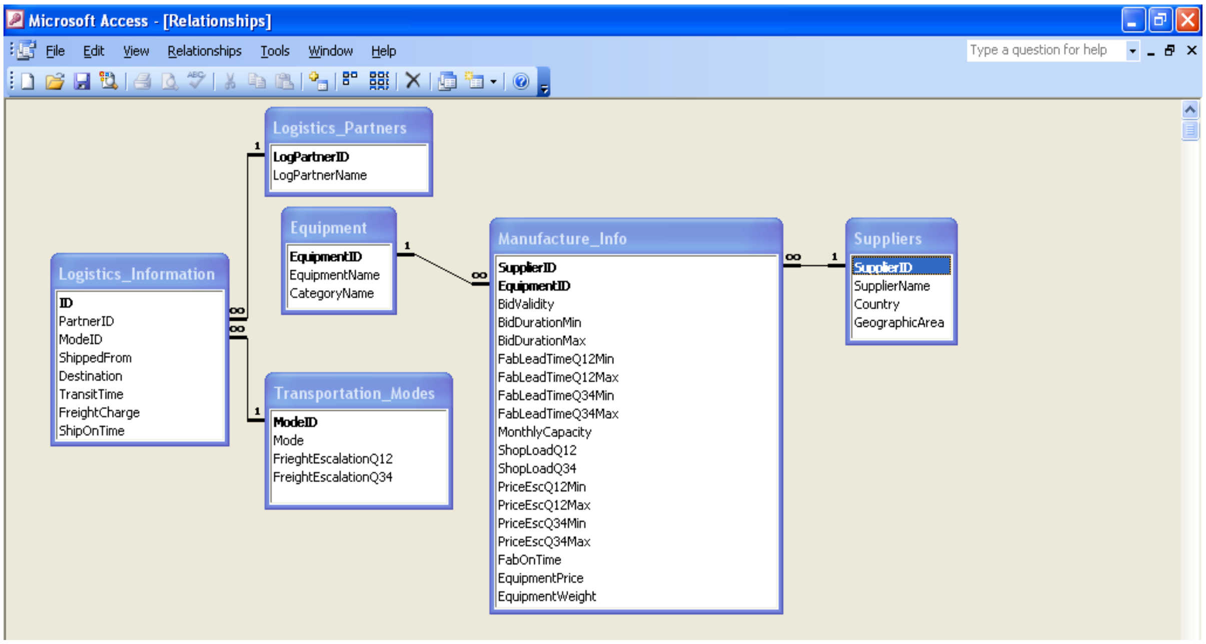


Figure 5.7: Database tables and their relationships

5.3.2 C# Application

The core application logic is implemented in terms of C# classes, and Windows forms are used to display the result and to get input from the user. The application has three core components (for more details on the software, see appendix B):

1) Data entry component, which allows a user to enter data into the database, and the supplier selection component, which walks the user through the selection process. The user interface is kept simple, and error checking is minimal; these attributes can be extended and enriched when this application is deployed in an organizational context.

2) The supplier selection component which captures three phases: input criteria, selection of suppliers based on the criteria, and automatically ranking a subset of suppliers based on AIM.

3) The schedule analysis component which provides the evaluation of preferred supplier's schedule based on PERT technique using the matrix of risk factors as input.

Figure 5.8 illustrates the input screen of the decision support system. Users need to choose one type of equipment, a project geographic location, and input schedule milestones and target costs associated with the equipment and its transportation. Users also need to input their desired supplier performance attributes, such as shop load utilization, on time fabrication, on time shipment, and quality rating.

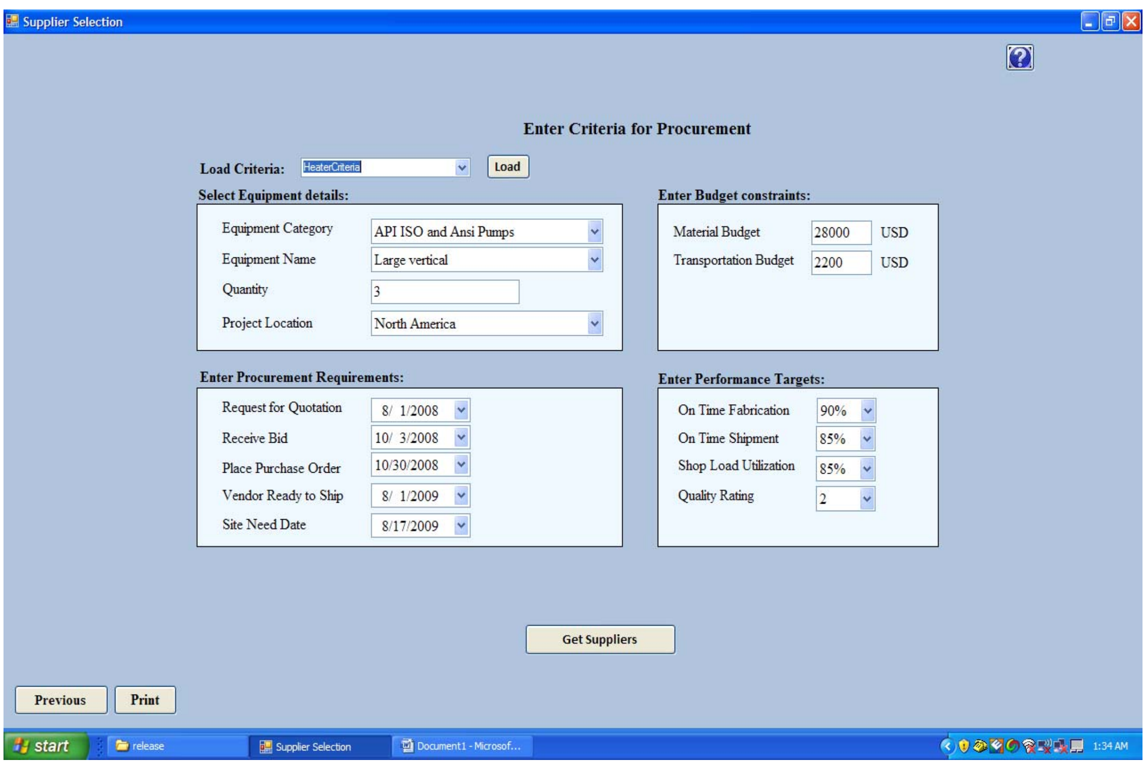


Figure 5.8: Input Screen

Based on users' inputs, the database is queried to find all the suppliers who match users' requirements. Multiple queries were built to retrieve the information from the database. These queries are illustrated in appendix C of this dissertation. All the suppliers are then displayed in a data table, highlighting the rows (suppliers) which match users' inputs. Managers can rapidly visualize and identify which suppliers fulfill their requirements in different phases of the engineered equipment delivery process. A schematic picture illustrating the data flow and criteria used for categorizing valid suppliers is shown in appendix D.

Managers may also negotiate with certain suppliers who do not fulfill one or more criteria, or modify their initial targets to accommodate more valid supply alternatives. Finally, managers can also update the supplier data, add new suppliers, and use custom data for supplier evaluation. This is useful when data in the database does not reflect current market conditions. Figure 5.9 shows a screen capture of the selection form. Appendix E shows all application's screens in enlarged versions.

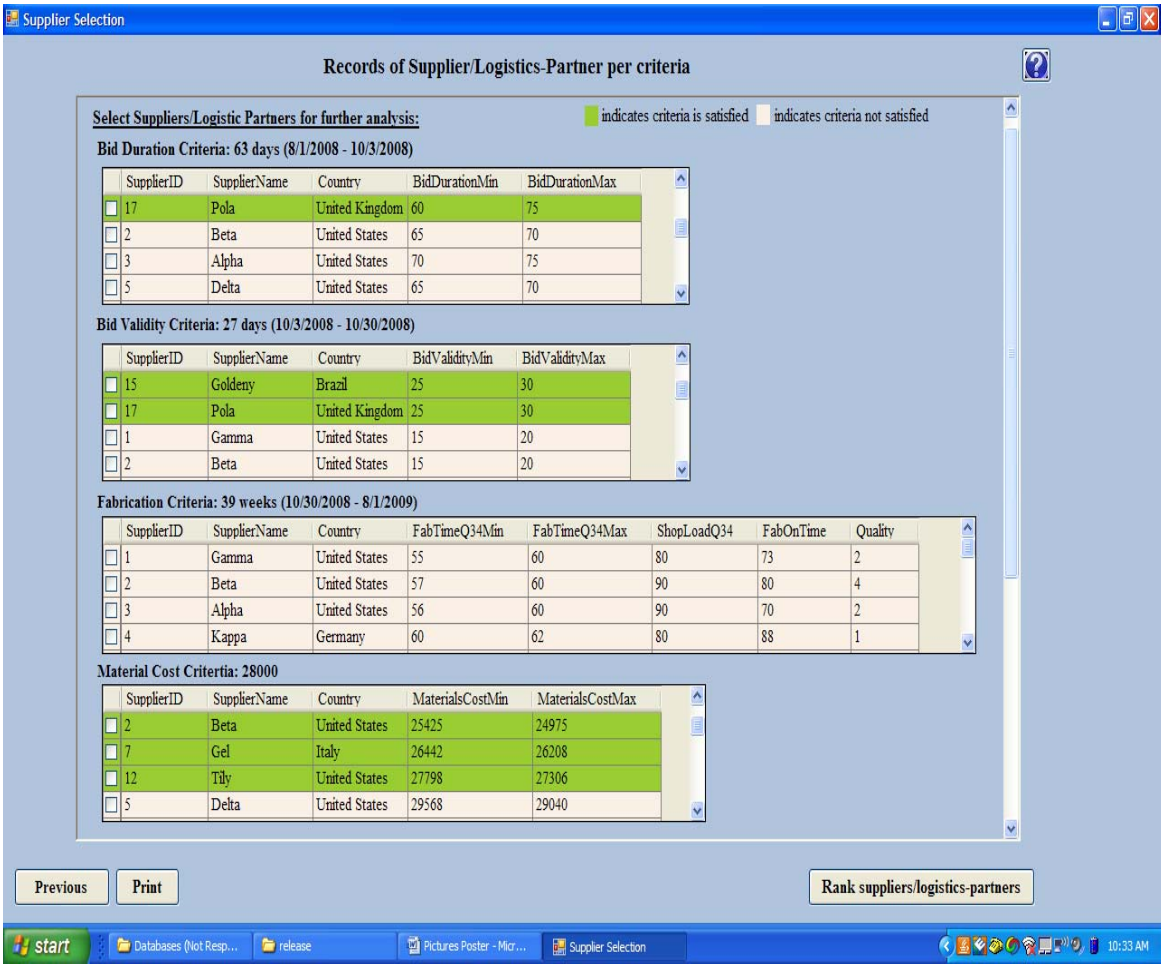


Figure 5.9: Evaluation of valid suppliers

Even though it was considered very useful, this list of alternatives still does not provide support for ranking and selecting valid suppliers. Identification of best suppliers is very complex given the large amount of information that is usually presented to procurement managers. It was needed to develop a method to guide users in the identification of the nearest supply alternatives based on their desired targets. This was done via the AIM method. AIM uses the users' inputs and a set of optimization objectives to intelligently assign weights to different criteria used in the selection process. The result of the method is represented as a graph and the values for several objectives are shown in a data table which highlights how each parameter affects a supplier's rank. Figure 5.10 shows a screen shot of the Ranking form. This component of the application aids managers quickly ranking and evaluating a set of suppliers based on the values of their inputs (aspirations). Moreover, managers can identify the ranking of their preferred supplier against other sourcing alternatives.

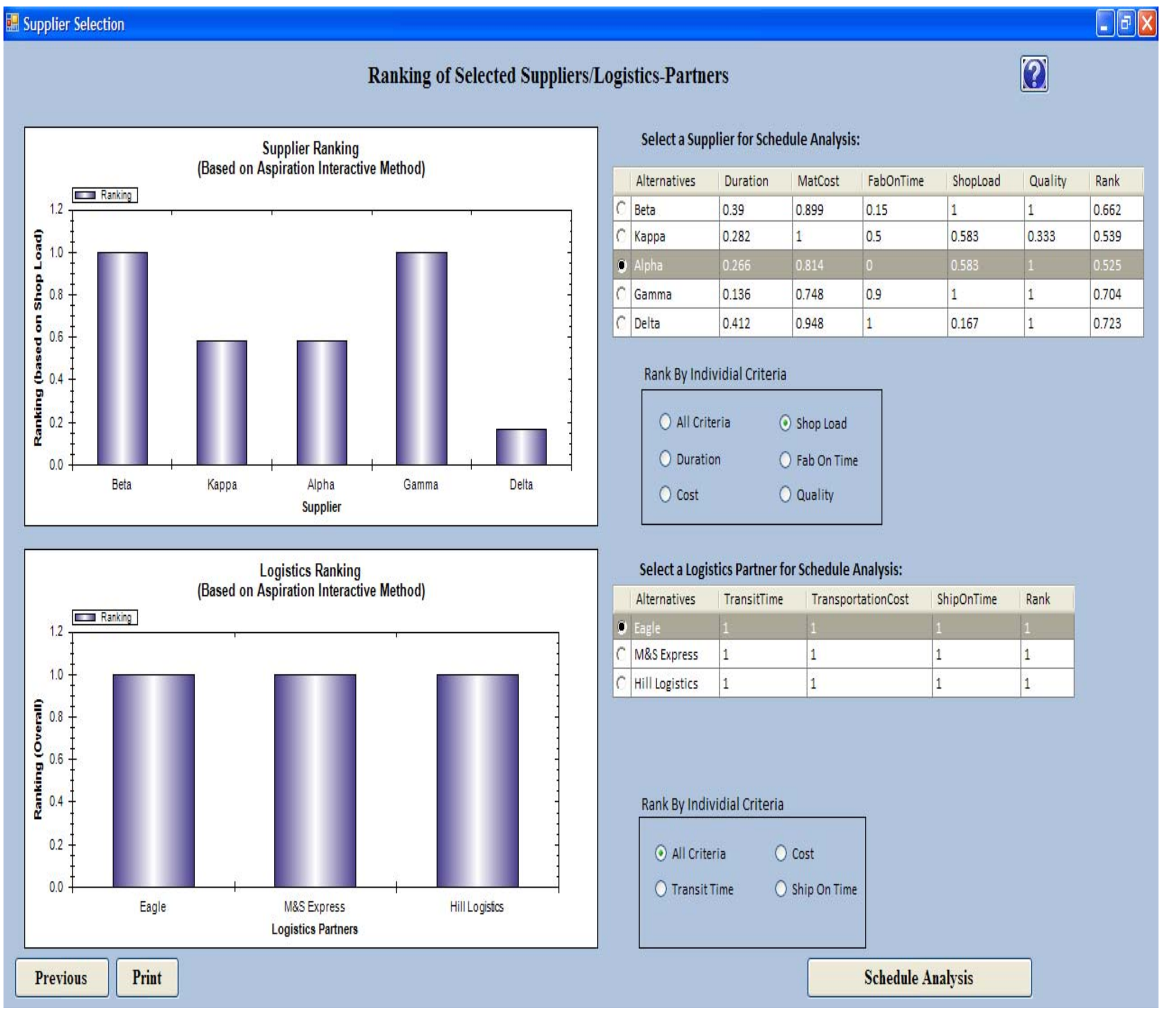


Figure 5.10 AIM Based Supplier Ranking

Finally, they can rapidly perform what-if analysis based on real data stored in the database, recent market data, or historical data. A change in the input targets also triggers different solutions, and different suppliers might become better options according to these new set of targets. Results of AIM analyses are automatically generated by the system. Users just need to inform or play with their targets to generate different scenarios and analyze tradeoffs. The results of the AIM approach validate and corroborate the results obtained from observations with procurement managers regarding the identification of the preferred pump suppliers. However, the computer-based analysis only took a couple of minutes to suggest a solution. The evaluation of pump suppliers and final selection decision -- without using any decision aid approach -- usually took more than an hour.

Custom Control components were used to design these phases in a single windows form. Opensource ZedGraph project is used to represent information in graphs. Apart from these, only basic windows form controls were used.

5.3.3 Schedule Analysis of Preferred Supplier

The logic used to determine most likely durations and to gather information on schedule feasibility were previously explained in Section 5.2. Figures 5.11 and 5.12 illustrate on example extracted from the pump supplier selection case.

According to the database, the preferred supplier should be able to deliver pumps within 59 weeks. After careful assessment and weighting of all major risk factors (Figure 5.11), the most likely durations are automatically calculated and serve as input for the PERT analysis (Figure 5.12). The resulting duration from this analysis is 69.7 weeks.

This duration include manager's judgment on various uncertainties as well as unique project and supplier's characteristics. The expected target according to the schedule milestones is 54 weeks, therefore the probability of delay related to this target is 100%. This analysis may warn managers about how realistic their master schedules are. In this case, working with the selected supplier would be very risky. Alternatively, managers could review their milestones and make sure this supplier fulfill procurement schedule.

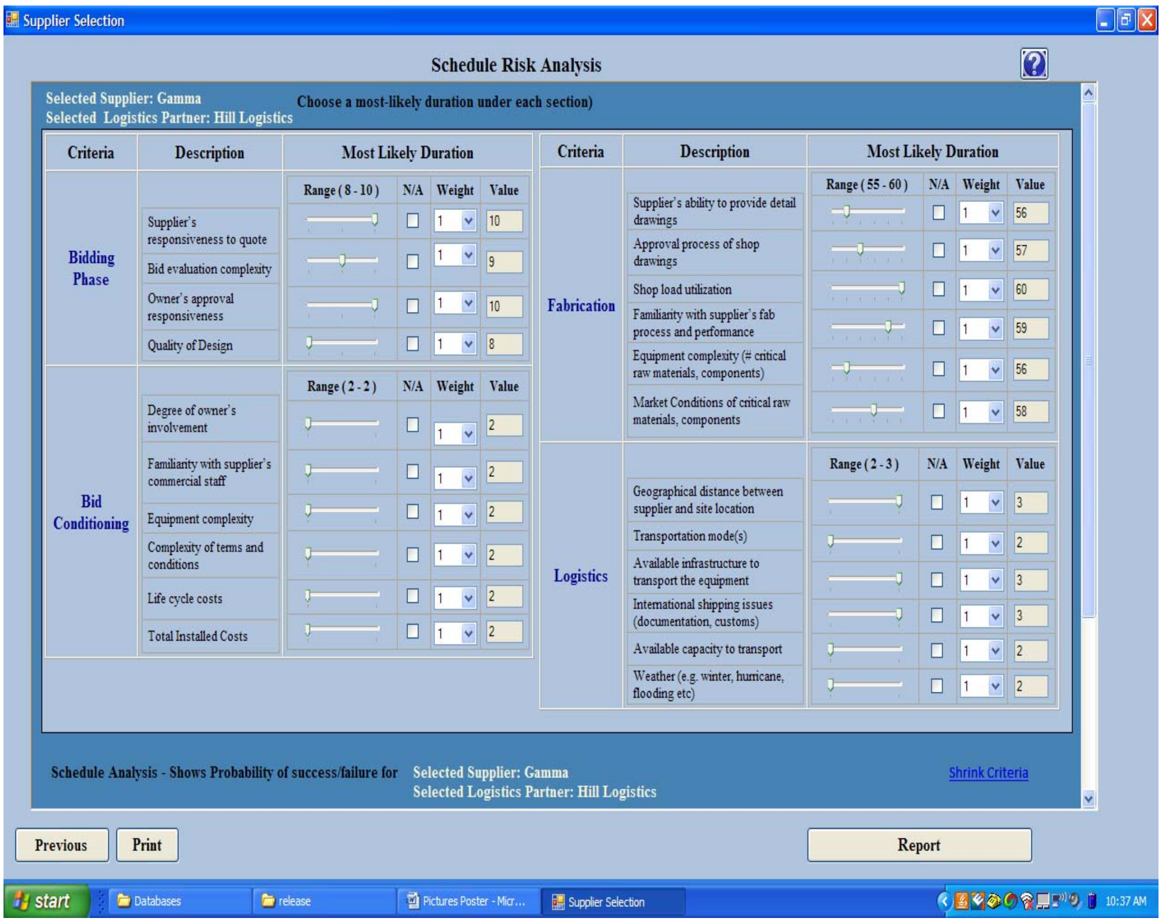


Figure 5.11: Screen for assessment of schedule risk factors

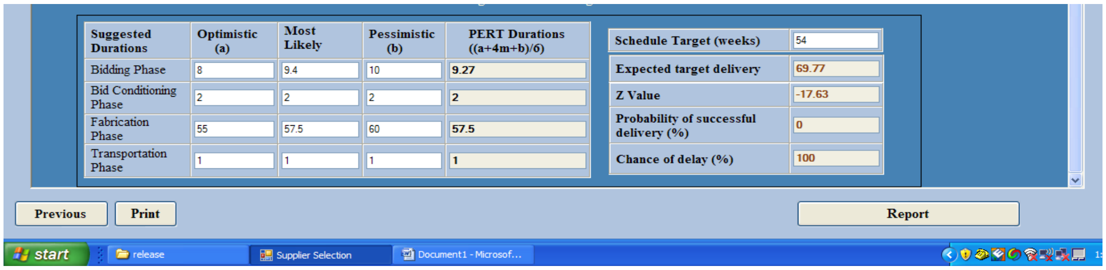


Figure 5.12: PERT results are generated automatically

There is no right or wrong answer for the supplier selection and risk evaluation issues. Figure 5.13 illustrates the final output report screen provided to managers once they complete all steps of the evaluation.

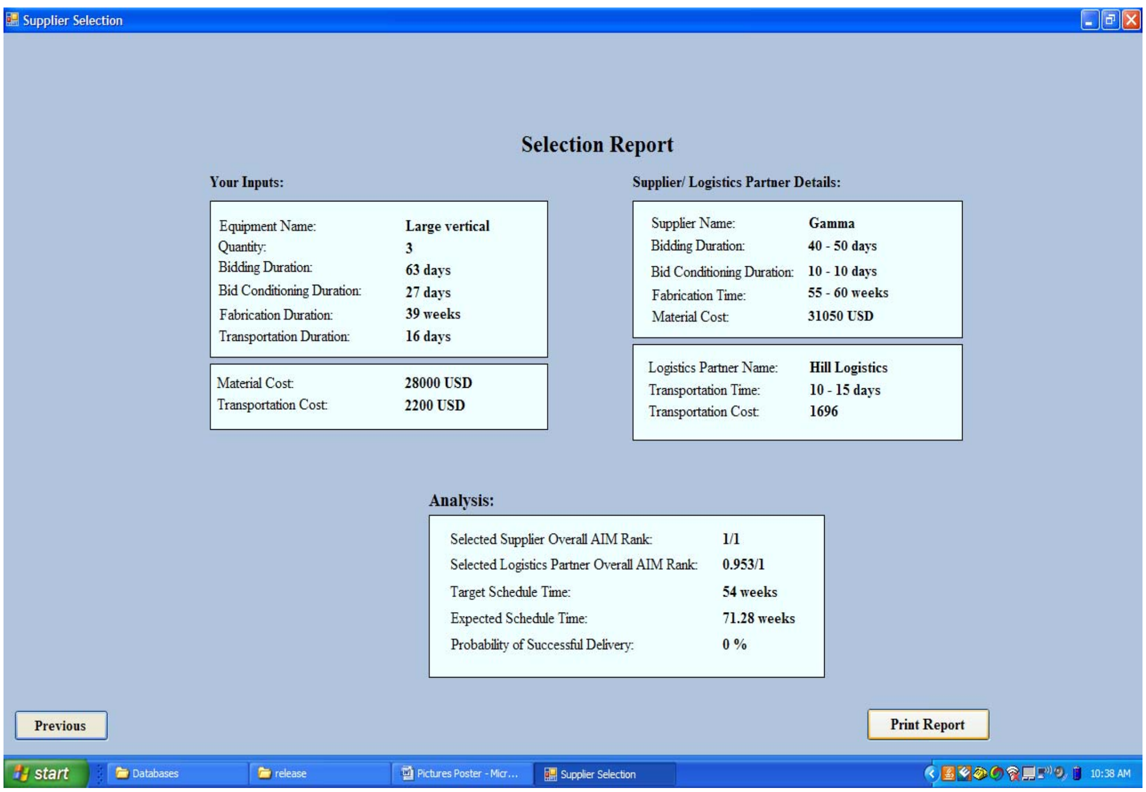


Figure 5.13: Report including all aspirations, selected suppliers, and summary of results

Rapid generation of what-if scenarios using both AIM and PERT to analyze the chances of success/delay can be very useful for procurement planning; especially, during the early phases of capital projects. My intention as a researcher is to increase managers' awareness of factors that can possibly affect equipment delivery and project execution. This is the topic of the next chapter which describes the results obtained during the validation of this system with EPC firms.

CHAPTER 6: DECISION SUPPORT VALIDATION

In this chapter, I report the main findings of the decision support validation. The validation phase aimed at collecting observations and evidence regarding the system's usefulness, completeness as well as its potential applications (deployability) and implementation issues. I also had to verify whether the proposed approach is intuitive and easy to understand.

To gather this data, I scheduled first round of meetings with one owner (Owner 1) and three EPC firms (EPC-1, EPC-4, and EPC-5). Ten experienced managers participated in this first round. Depth of analysis with experienced managers (more than 20 years of industry experience) was considered more important than length (# of managers) in the development of this application. I started these meetings with a short presentation and discussion of all system's components in order to make sure managers were able to understand the approach. Then, I showed the software and explained how each component works. The last part of the meetings was used to gather feedback and discuss the next step in the validation process – actual selection cases - through group discussion. Few adjustments were made in the application based on managers' suggestions. The discussion covered the subjects included in an interview guide which is shown in Appendix F. The results of these interviews are described in Chapter 6.

Validation also included the analysis of the decision support system application in two real cases involving the selection of equipment. Data was provided by one EPC firm (EPC-1) which is executing a refinery project in Indiana, USA. The cases describe the selection of the best suppliers of fired heaters (2) and a recycle compressor for this project. The firm provided a set of documents containing all information managers used to guide their final supplier recommendation for both cases. I was not informed of which suppliers were selected in order to conduct an unbiased analysis.

Finally, I scheduled a second round meeting with two EPC firms (EPC-1 and EPC-4) to discuss the results of the analysis using the application. I first met with the EPC which provided the cases. In this meeting, the managers told me the suppliers they selected and we were able to compare the solutions. In the second meeting, I presented the data and asked the managers to select their preferred suppliers and explain the reasons for their decision. Then, I let them know which ones were chosen by the other EPC and presented the software solution. This validation step points to the need of additional information to improve the evaluation which is one of the research questions of this study.

I start the chapter detailing how the EPCs currently select their equipment suppliers. Getting a better understanding of the selection process is critical and supports the answers for most of my validation questions. In Section 6.1, I report the results of meetings with EPCs and their opinion about the system. Selection cases are presented in Section 6.2. This section describes the results suggested by the software as well as the real reasons behind the selection of equipment. A comparison between actual and software selection was also carried out. Finally, I conducted a robustness assessment of the software results for one of the cases through sensitivity analysis. Results of this assessment indicate which supplier is commonly ranked as the best option for several scenarios.

6.1 VALIDATION MEETINGS WITH EPC FIRMS

Meeting with experienced procurement managers was a great learning experience. Their knowledge of the process and perspective on future developments in the area are invaluable evidence for validation of this research. This section details their understanding of the selection process and feedback regarding software's usefulness, completeness, and potential application/implementation issues.

6.1.1 Current Selection Process

The three EPCs that participated in this validation phase described a very similar – if not the same – process to select equipment suppliers. These firms also provided information during the conceptual model development and exploratory case studies. They were named as follows: EPC-1, EPC-4, and EPC-5.

Figure 6.1 illustrates the overall process used to select equipment suppliers. During late front end loading phase (FEL), firms usually prepare an approved suppliers list for the project. This list includes suppliers from both EPC and Owner individual lists. These companies look at their previous purchase orders and the current market for non-traditional suppliers which fulfill their minimum requirements. Managers commented that an initial list with 80 suppliers is not uncommon. Once the list is evaluated, EPCs issue request for inquiries to several suppliers (approximately 20 to 30 suppliers). Suppliers then send information regarding expected lead times, costs, specifications, and interest in participate in the bidding phase. After gathering all this information, EPCs prepare a short list of suppliers which will be requested to send a formal quotation for evaluation (5 to 10 suppliers). According to procurement managers, coming up with a short list of suppliers is a very complex task because of the number of alternatives available at this point of the process. Finally, after receiving the quotes, EPCs prepare technical and commercial bid tabs for analyzing and recommending the supplier. Technical bid tab is assessed and validated by the engineering department to ensure suppliers are technically capable of producing equipment according to the specifications. The commercial bid tab, which includes data on lead times, costs, and previous performance, is prepared and analyzed together with technical recommendations by the procurement department. Typically, commercial bid tabs are presented in spreadsheet format (Appendix G).A final recommendation is based upon analysis of both tabs.

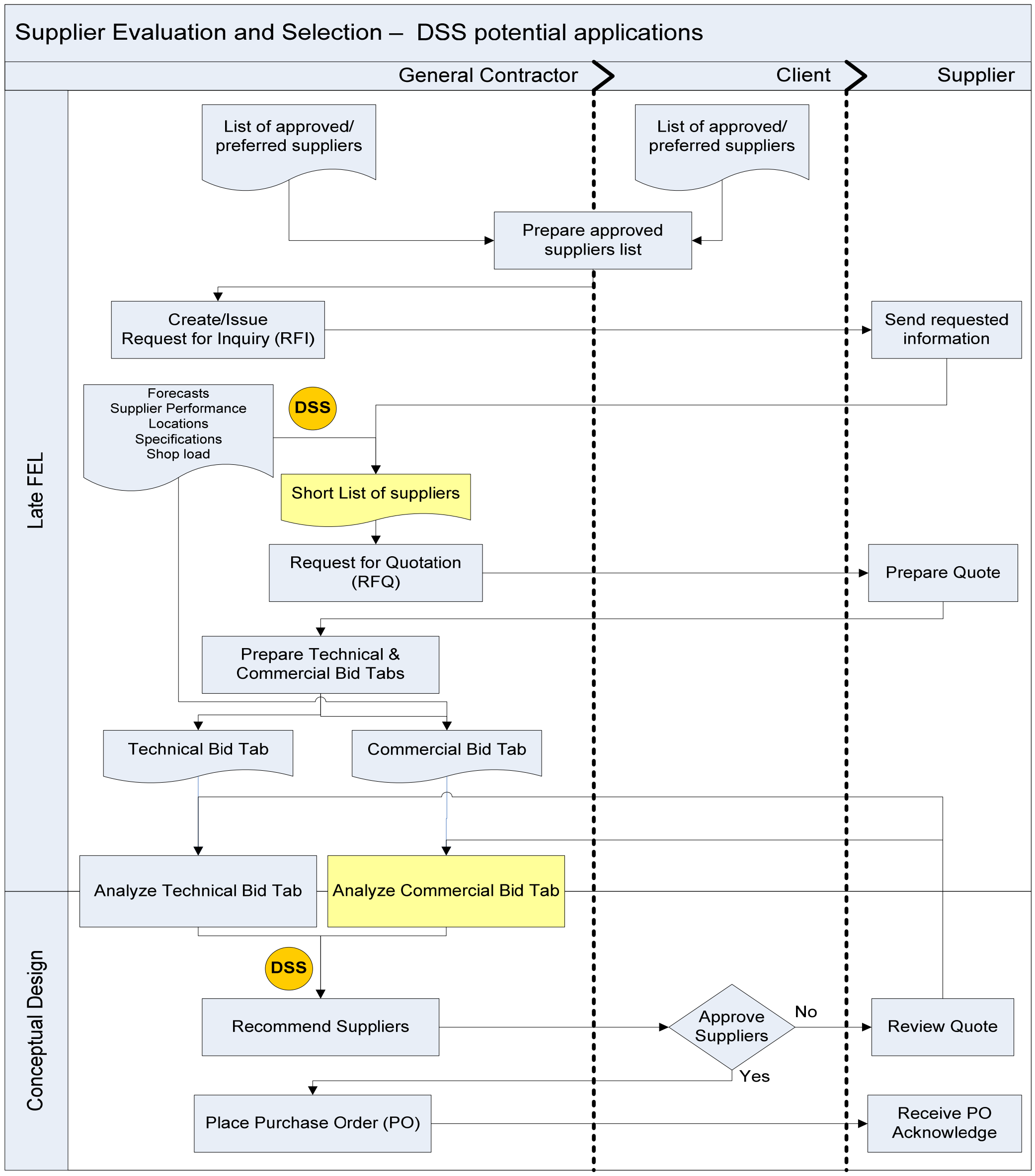


Figure 6.1: Supplier selection process

As I mentioned before, the differences between the way companies select equipment suppliers are almost unnoticeable. The main difference is on the preparation of the short list of suppliers. EPC-1 has an internal strategic group which is responsible for collecting and updating procurement managers about historical, current, or forecast market conditions. This knowledge is used as an input for short list preparation with clients. EPC-4 and EPC-5, on the other hand, usually include most of the clients' suppliers on the short list. Only few of their preferred suppliers are included. These EPCs information on suppliers are normally based on past experience and anecdotal stories since information is not well organized to convince major clients in their business. The VP of procurement of EPC-4 mentioned that his firm gets a list from the clients, therefore most of the time the firm is restricted to working with those suppliers. Even if the company knows that historically some suppliers perform poorly, sometimes clients enforce the firm to work with them.

Another difference, perhaps also due to knowledge of market alternatives, is the number of suppliers these EPCs include in their competitive bidding. EPC-1 usually involves 5 to 10 suppliers while EPC-4 and EPC-5 typically get quotations from 2 to 5 suppliers.

6.1.2 How does the DSS fit in?

As part of the validation I also wanted to understand how my decision support system would fit in each EPC firm. There are two main potential uses for this software:

1) Help EPCs narrowing down the approved suppliers list in order to come up with an appropriate short list.

2) Support commercial bid tab analysis before final supplier recommendation.

Figure 6.1 illustrates where the system fits in the overall selection process. The potential application and implementation for achieving those two purposes depends upon how EPC firms organize their information. EPC-1 for example can use the system for both purposes since information is often available and organized to support analysis during the preparation of the short list. EPC-4 and EPC-5 still need to organize their supplier information – which is available in their computer systems – before thinking about using the tool to identifying which suppliers should be shortlisted.

All EPCs can use the system to analyze commercial bid tabs. According to EPC-1, the software can help procurement managers identifying an optimal or realistic decision based on existing data. EPC-4 and EPC-5 also commented that the software fits very well this purpose. EPC-4 emphasized the support offered for analyzing tradeoffs of commercial bid tabs and justifying their final supplier recommendation to clients. Basically, this company needs a tool to communicate the reasons why they selected a certain supplier out of the long list of suppliers. Likewise, EPC-5 highlighted that the software can support intelligent analysis of current data in the bid tabs. The procurement director also recognized the use for short listing based on analysis of their historical data. He said the company wants to move towards this direction, however they are not ready yet.

6.1.3 At what point of the project would you use it?

The selection of equipment suppliers is conducted in the early phases of the capital projects. The interviews with EPCs clarified when the software can be implemented in the capital project lifecycle (see Figure 6.1). The points below describe the responses from each firm:

EPC-1 would use the software at late Front End Loading phase (Pre-bid) and most likely during Conceptual design phase. In the first case, they would employ it as a tool to support validation of planning, scheduling, and understanding risks on the material side. Also, the firm would employ it to narrow down the list of suppliers when preparing the bidders list. Basically, they want to identify which suppliers should be included on the list. In the conceptual design phase, the tool will support the supplier recommendation task.

EPC-4 and EPC-5 would like to use the software for bid conditioning which usually happens during early phases of the conceptual design. At this phase, they usually have hard data from suppliers (instead of speculation based on historical or forecast information available during FEL). Managers of these firms demonstrated interest in performing this analysis automatically. They suggested running the application using data from their commercial bid tabs.

6.1.4 How can the DSS aid/support you in this decision process?

According to EPC-1, this software will not replace their analysis. Instead, it is a toolkit that adds to the current analysis. Managers emphasized the support with Post award analysis, i.e. confirming that decision and recommendation of supplier is adequate. The same managers would like to use it to conduct backward analysis, i.e. identifying that other alternatives or schedule can be a better option for the project.

EPC-4 commented that the software would not speed up the selection process because this analysis would add one more step in the whole process. Moreover, feedback from managers indicated that the software can definitely work as a comparison tool to support their evaluation and to validate what they found in their competitive bidding. They also need tools to support their supplier recommendation to clients, explaining the reasons why they selected a specific supplier out of a long list presented by the client.

EPC-5 does not use any method to rank their suppliers. The decision is based on analysis of a bid tab presented in an Excel spreadsheet. The procurement director said that they end up looking at dollar values and deciding for the lowest cost supplier. Alternatively, they may choose a supplier just because they are familiar with it and want to work with it again. During the meeting, this director questioned his managers about the way they currently select equipment suppliers. He asked if the software, which makes it explicit tradeoffs between many variables, would change a recent decision made by the team. The team agreed that having a tool like the one developed in this dissertation would definitely improve their analysis, providing a supplier ranking and recommendation for critical pieces of equipment. This firm also mentioned that the cost information stored in the database could serve as input for early estimates conducted before project award.

All EPCs mentioned that the system can be used internally by procurement managers for communication and discussion between different departments such as Engineering, Project Controls, and Estimating. Moreover, the system can be used collaboratively with clients (owners) and other project stakeholders to explore tradeoffs among factors and justify commercial selections based upon an objective methodology.

6.1.5 What is missing?

The answer to this question helped me to understand software's completeness. When I met with these companies, managers provided very useful feedback for improvement. Some of the suggestions were implemented before the cases studies using the software, others will be included in future software improvements and research. This is the list of variables or functions that EPCs would like to see in the software package:

1) EPC-1 would like to see a metric for supplier quality as an aspiration. Quality is too important to be ignored. This metric was added in the software before using it for analysis of actual selection cases. I also assessed EPC-1 spreadsheets used for commercial bid analysis. Based on this analysis, items such as warranty, duration for delivery of drawings, terms of payment are missing in my tool. Delivery of drawings is implicitly considered within the fabrication lead time value. Other useful questions asked in the tab are: Is the bidder technically acceptable? Has the bidder accepted terms and conditions?

2) EPC-4 would add technical data to the analysis. The same question was suggested: Is the bidder technically acceptable? This firm also commented on the importance of having the value of total installed cost, even though the managers admitted that it is very difficult to come up with such a number.

3) EPC-5 strongly suggested the inclusion of a bid tab function. That would allow them to tie their Excel bid tabs to AIM approach. Analysis of the Excel file indicates that this firm also collects data on technical evaluation summary, labor costs, and warranty to support their analysis. Even though supporting data is available, the cheapest alternative is selected in most of the cases.

6.1.6. Is the DSS useful?

Previous sections described the potential for application and implementation of the software. The answers to those questions implied that it is a useful tool. However, I decided to explicitly ask this question and these are the responses from the firms:

1) EPC-1: the software is very useful. The company just needs to know how to share their historical, current or forecast data to populate the back-end database. As a consequence, managers will trust the data and can make sure the software is behaving as it should.

2) According to EPC-4, the software would be easily implementable. They demonstrated interest in the system and suggested that it could be sold for commercial use.

3) EPC-5 highlighted that the software is useful and it could be implemented to be the decision module in their supplier database.

6.1.7 Data issues - organization, availability, and trustworthiness

The software's ability to provide useful analysis depends heavily upon the availability and organization of information. Managers also need to trust their data in order to be confident in the output of the analysis. I investigated some of these issues in order to understand how ready these companies are today to employ the software.

EPC-1 mentioned that you have to have historical data. An executive manager of materials management said that for this category of products any decision maker should look at least at 5 years back to guide the analysis. In his opinion, if one wants to have good data and control for this category a wider span is suggested. For example, analysis of last year's data shows how suppliers performed in the overheated market. However, the market is different now and understanding of previous market cycles and how suppliers used to perform at those conditions is very important. Forecasting is also very important to EPC-1. Procurement managers communicate with product managers to validate some information they get from suppliers and to support negotiation once the bids come in. This information is not used for planning purposes though. Managers trust in their data because they know that there are people who just dedicate their time to understand specific suppliers' conditions (shop load, lead times, price) and raw materials market.

Unlike EPC-1, the other two EPCs have not been able to organize their historical information in such a way that it can provide support for decision. They recognize that they could be doing a much better work in organizing and analyzing this information. They blamed the lack of internal resources of this lack of organization. The same happens for forecasting information. These firms mentioned that keeping up with current and future market conditions is very challenging due to lack of resources. Market conditions are very dynamic. Therefore, the ability to build and keep an up to date database is crucial for analysis

EPC-4 commented that the firm does not have the data (historical performance, forecast) they trust in place to conduct the analysis proposed in this dissertation. The information needs to be organized because it can be retrieved from their enterprise information system. This company trusts in their buyers' experience and knowledge since data is not easily retrievable to support their judgments.

EPC-5 does not have the information they trust either. Their approved suppliers list has not been organized yet. The procurement director said they need to hire someone to organize this information. Currently, the firm only uses their Excel spreadsheets to make decisions.

EPC-4 and EPC-5 recognized that the software could help them building this database from evaluation of current bids. The system would store several bid evaluation cases and, in a few years, these companies would be capable of retrieving historical information for analysis as well.

6.1.8 AIM approach: why does it work?

EPCs considered the software very easy to use and to understand. The AIM approach is very intuitive according to managers.

According to EPC-1, AIM presents a consistent methodology that supports managers making a rational selection based on objective metrics. Nowadays, there is a lot of subjectivity in this process. The approach is very intuitive and would provide companies with an objective way to screen potential supplier list against criteria. This is especially important in the current economic environment where clients are concerned with profit margins and have been requesting evaluation of at least 6 to 9 bidders for each piece of equipment. Moreover, each bid package usually takes 3 months worth of analysis before the final recommendation is announced. The AIM approach can provide feedback more quickly than any manual based analysis. Therefore, there is a potential to shorten the analysis cycle time and perform more what if type of analysis to assess multiple alternatives.

EPC-4 mentioned that AIM works because it enables tradeoff analysis and analysis of several alternatives at the same time. For example, managers described one recent 14 billion USD project in which three people took 18 months to analyze 250 quotations associated with equipment. Analysis was conducted manually with support of spreadsheets. In such a scenario, AIM will be very welcome to support recommendations. This company usually selects the lowest price bidder but lately its clients have been asking them to look at other parameters such as shop load utilization and historical performance. This data can be extracted from their vendor evaluation system; however, no effort has been made to retrieve this information.

EPC-5 qualified their supplier recommendation process as a subjective and ad hoc decision. The company uses collective intelligence based on previous experience with suppliers to come up with a recommendation. According to the managers, AIM would enable them to remove this subjectivity from the bidding process. Moreover, they liked the idea of introducing multiple targets in this process because they will be able to know which supplier is the nearest solution using multiple criteria.

6.1.9 Schedule analysis module

Procurement managers were satisfied with the PERT module. In general, detailed analysis is conducted by project controls department, however the software provides great input for master schedule preparation and consideration of risks that may potentially delay equipment delivery.

EPC-1 stated that this module would add great input in the preparation of realistic master schedules and enforce early consideration of schedule risks. One procurement manager identified the time buffer that was built into their delivery schedule after a simulation with the software. Finally, the software can also help them justifying and explaining certain durations to their project controls staff and clients.

EPC-4 found the schedule analysis very useful. One of the reasons is because the project controls staff always asks their procurement managers for duration estimates in the early phases of the project. Project controls wants to know what to expect in terms of total delivery for certain equipment, and especially, the few critical ones. Today managers call suppliers to gather this information because no historical information is available. EPC-4 believes the software may help them to come up with a much better guess without spending time calling suppliers for collecting this information.

EPC-5 was mostly impressed with the comprehensive list of factors which affect delivery durations. All managers were satisfied with the weighted average approach proposed to automatically suggest most likely durations. Managers also stated that this schedule module certainly supports the task of building more realistic master schedules for equipment.

6.2 USING THE SYSTEM TO SUPPORT ACTUAL SELECTION CASES

This section describe the results obtained using the software to evaluate two actual selection cases conducted by EPC-1. The first case details the selection of two fired heaters. The second case reports the selection of a compressor for the same project.

These cases can illustrate the response of the software for evaluation of current data which are included in commercial bid tabs. For each case, I present an overview of the scenario, the results suggested by the software, and the description of the reasons that actually guided the selection of equipment supplier. After reporting both cases, I compared the suppliers I suggested using my software against the ones actually awarded by EPC-1 and EPC-4. EPC-4 listed their preferred suppliers based on the same information that was provided to me by EPC-1.

6.2.1 Case 1 – Selection of Fired Heaters

Overview

This heater package was originally floated to four potential bidders, one of which declined to bid. The heaters were competitively bid by the remaining three vendors according to the respective proposed venue of shop fabrication (Domestic or International). All bidders are on the Client Approved Manufacturers List (AML), Level 1 which indicates current or recent Client experience with supplier. The result of the initial quotations is as follows:

Bidder 1

- Bid was found to be conditionally technically acceptable per the RFQ.
- Proposal includes cost for modularization per the specification.

- Offered price which is based on Domestic fabrication was competitive and within the project budget.
- Proposed delivery of 70 ~ 76 weeks is not critical.

Bidder 2

- Bid was found to be conditionally technically acceptable per the RFQ.
- Offered price which is based on International fabrication shop was competitive and within the project budget.
- Proposal did not include modularization per the specification. Additional cost to be expected for compliance to this requirement; however, additional fabrication time for modularization (2 ~ 3 months' time) poses no impact to site need date.
- Proposed delivery of 61 to 67 weeks is not critical.

Bidder 3

- Bid was offered only as an estimate, with no intent for supplying firm pricing until time of award.
- Proposal did not follow EPC's requirements.
- Offered price—though strictly budgetary--was highest among all bidders.

Bidder 4

- Declined to bid at initial RFQ-floating stage, stating the heater package was too small for them to be competitive.

In conclusion, both Bidder 1 and Bidder 2 were short-listed, and a decision was made for further technical bid-conditioning by means of clarification meetings at EPC with each bidder. Bidder 3 was eliminated/not conditioned further for technical clarifications due to the reasons previously listed.

A total of 35 or so technical requirements were identified, and both bidders were instructed to submit a revised proposal confirming each requirement. Further bid conditioning was done upon receipt of both bidders' proposals to confirm all technical requirements from the meetings were incorporated. Bidder 2 included in their proposal two separate options, one for International modularization and one for US modularization. For the latter, the equipment would still be of International origin.

The technical compliance of additional requirements and their associated costs were detailed in the commercial bid tab. Bidder 1 accepted the majority of additional requirements at no extra cost. Due to lack of time to obtain outside sources' pricing, Bidder 2 could not reply to several requirements beyond their proposal, among which were those with potential commercial implications. These costs could not be carried over, since Bidder 1 included the items at no extra cost, and in-house estimating for those items was not performed by EPC-1.

Software results

Previous section provided an overview of the bidders' technical and commercial characteristics. In this section, I describe the analysis conducted using data extracted from the commercial bid tab. EPC-1 also provided a report which contains additional information on schedule milestones and suggested values for supplier performance that were not shown in the bid tab (on time fabrication, on time shipment, and shop load utilization). After collecting and assessing all documents, I was able to build the case scenario for inclusion in the software. Targets or aspirations for this case are illustrated in Figure 6.2. Tables 6.1 and 6.2 summarize Bidders' data which was entered and stored in the back-end database. Table 6.1 presents information on material and fabrication while Table 6.2 lists information associated with transportation criteria.

- **Equipment**: Fired Heaters
- **Project Location** Indiana, USA
- **Quantity** 2

Schedule Milestones

- **RFQ**: 6/20/2007
- **Receive BID**: 7/27/2007
- **PO**: 9/14/2007
- **Ready to Ship**: 7/25/2009
- **Site date**: 8/15/2009

Budget

- Material Cost: 1,341,700
- Transportation Cost: 592,000

Supplier Performance

- On time Fabrication: 95%
- On time Shipment: 90%
- Shop load utilization: 80%
- Quality: 2

Figure 6.2: Aspiration levels for selection of fired heaters

Table 6.1: Bidders information on Material/Fabrication

MATERIAL/FAB	Bidder 1	Bidder 2	Bidder 3
Location	USA (city not specified)	Asia (city not specified)	USA (city not specified)
Bid Validity (days)	30	30	30
Material Costs (USD)	4,331,050 (unit cost: 2,165,525)	3,843,541 (Unit cost: 1,921,770)	4,303,541 (Unit cost: 2,151,770)
Material Escalation (%)	+ 2 at PO	0	0
Fabrication lead time (weeks)	70-76	61-67	71-77
Shop load utilization (%)	80	85	75
On time fabrication (%)	85	92	96
Quality	3	2	1

Table 6.2: Bidders information on transportation

TRANSPORTATION	Bidder 1	Bidder 2	Bidder 3
Transportation mode	Inland Freight (Truck or Barge)	Ocean	Inland Freight (Truck or Barge)
Transportation Costs (USD)	73,000	512,000	226,500
Escalation (%)	0	0	0
Transit time (weeks)	2-4	3-5	1-3
On time Shipment (%)	90	85	80

Figure 6.3 illustrates the overall ranking of Bidders for both material/fabrication criteria (top of the figure) and transportation criteria (bottom of the figure). The graphs shown on the left hand side plot the overall ranking results. These results indicate that Bidder 3 is ranked the top supplier for material/fabrication criteria (AIM =1), followed by Bidder 2 (0.621), and Bidder 1 (0.245). Bidder 3 however is the worst ranked supplier for transportation (0.333). Bidder 1 is the supplier with best overall score for transportation (1). This figure allows a first assessment of tradeoffs involved in the decision.

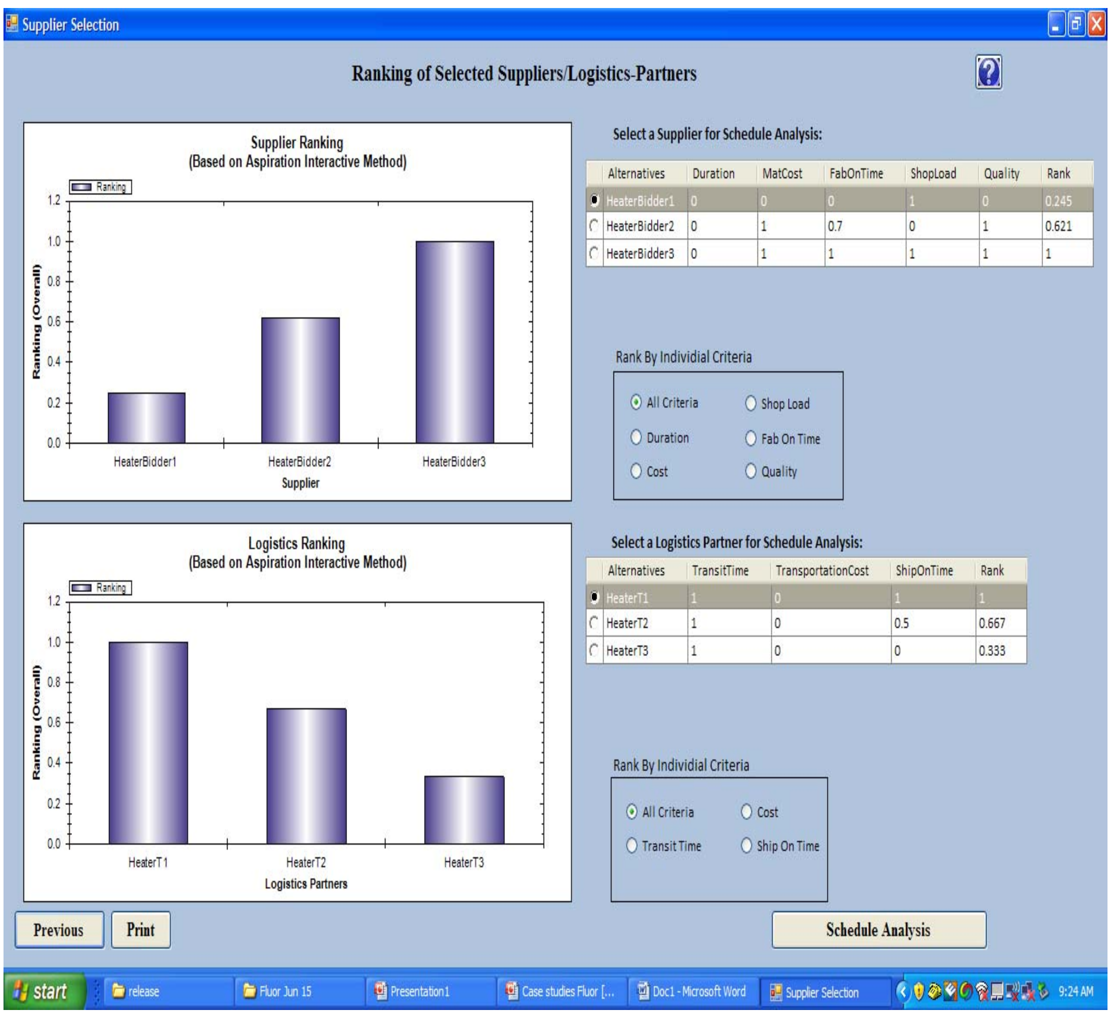


Figure 6.3: Overall AIM ranking – Fired Heaters

Managers can also rapidly assess how each Bidder performs in each criterion. Clicking on the buttons located beside the graph will quickly display this information. Figure 6.4 illustrates all possible tradeoffs the software offers to users for material/fabrication. Fabrication duration got 0 values for all suppliers. This happened because the aspiration level required by the users is worse them the worst value found in the database, i.e. all suppliers can deliver within the desired procurement schedule. Therefore, AIM approach informs managers that this variable will not affect their final decision since all suppliers share the same value (0). Figure 6.5 shows all possible tradeoffs for transportation criteria. All suppliers' transportation costs are equal to 0. This means that all suppliers are well within the estimated transportation budget.

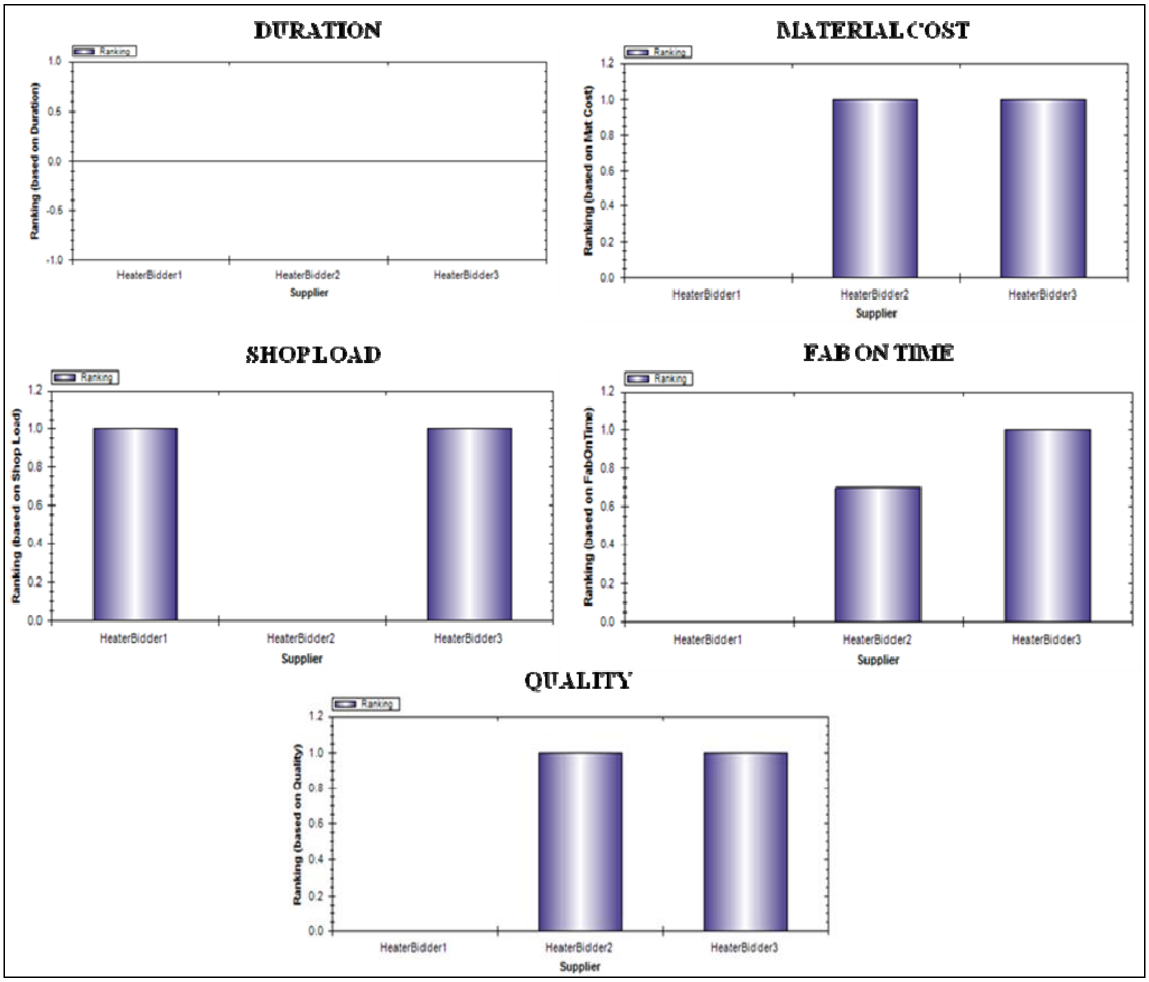


Figure 6.4: Material/Fabrication tradeoffs – Fired Heaters

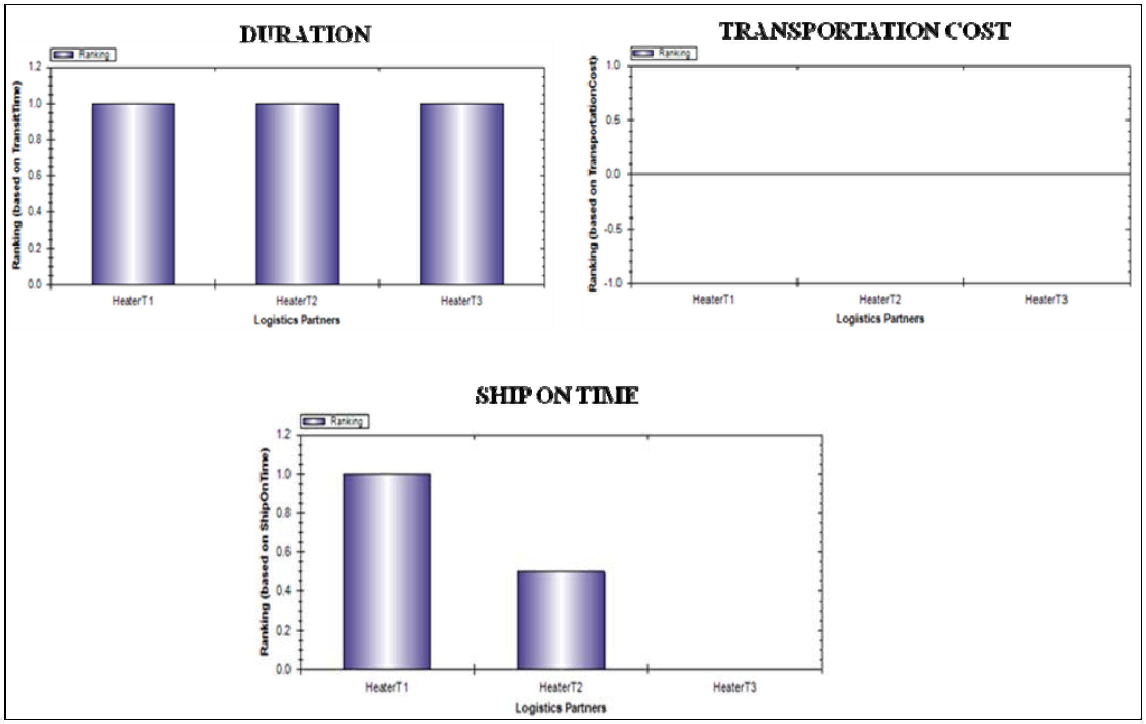


Figure 6.5: Transportation tradeoffs – Fired Heaters

Procurement managers were very satisfied with the tradeoff analysis they were able to visualize. The option for separating material/fabrication from transportation was based on feedback gathered in the early phases of the software development. In the last meeting with EPC-1, when we discussed the results using the software, an executive director suggested to me to put together material/fabrication and transportation in the form of a cumulative table. This is a missing piece of analysis that can be added in the future versions of the software. Figure 6.6 displays the results of the cumulative analysis which was used to suggest the top ranked supplier for all criteria. I conducted the analysis using a spreadsheet. Bidder 3 is the top ranked supplier suggest by AIM (0.66), followed by Bidder 2 (0.56), and Bidder 1 (0.52). These values are somewhat similar which reflects how close the three bidders were from the set of aspirations. The executive director mentioned that this case illustrates a very challenging example of supplier selection because there is no clear preference for any supplier based on individual commercial criterion.

	Duration	Total Cost	On time Fab	Shop load	Quality	On time Ship	Ranking
Weight	0.000	0.000	0.313	0.172	0.172	0.344	
Heater1	0.00	0.00	0.00	1.00	0.00	1.00	0.52
Heater2	0.00	0.00	0.70	0.00	1.00	0.50	0.56
Heater3	0.00	0.00	1.00	1.00	1.00	0.00	0.66

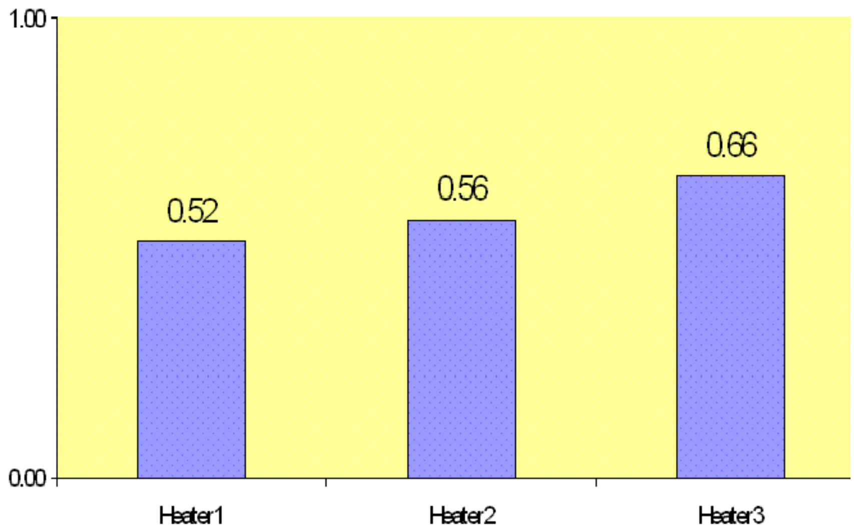


Figure 6.6: Cumulative results – Fired Heaters

Actual Supplier Recommendation

Bidder 1 was the recommended bidder to award the Heaters based on the following reasons:

1) Fabrication in the US means lower logistics cost (i.e., no overseas ocean freight); less handling (no port-to-port on-loading / off-loading) for lower risk of damage;

and ease of project execution. For the lattermost, this translates to no pre-inspection meeting or inspection/expediting shop visits in overseas locations.

2) To accommodate the planned plant start-up, Bidder 1 offers extended warranty at no cost. Warranty is good for one year after plant start-up with site storage done in accordance with Bidder 1 procedures. Bidder 1 will also make one visit to the site to inspect the equipment prior to start-up at no cost. This is not to be confused with field service or start-up assistance.

3) Bidder 1's two minor comments to client's terms and conditions have already been accepted by client; hence, there is no roadblock to this commercial matter should Bidder 1 be awarded the heaters.

4) Deliverables schedule (especially for critical documents such as general arrangements, foundation loading diagrams, and data sheets) is within the project requirements and shorter than Bidder 2.

5) Equipment cost is comparable to Bidder 2 (not considering freight value), but Bidder 2 equipment cost would probably be higher if all technical requirements were to be confirmed. Freight values in the commercial bid tab were provided for comparison purposes only and are not included in the purchase price.

6.2.2 Case 2 – Selection of a Recycle Compressor

Overview

The Recycle Gas Compressor package is a critical component to the project for Engineering, Materials and Fabrication. During the initial RFQ stage this compressor package was sent to four manufactures as a steam driven recycle compressor. All bidders are on the Project Bidders List, Qualification level 1 (long standing and current Client experience with supplier). Once all bids were received a short commercial and technical review was performed on all bidders.

EPC-1 issued new specifications and changed the compressor from steam turbine driven to a synchronous electric motor. The Electrical system applied restraints on EPC to determine what size motor could be accepted during start-up without upgrading the electrical system at the site. EPC received 3 bids on time and 1 bid late. Due to the high priority of this package, one bid was considered not acceptable due to an incomplete, late submission of bid. The review result of the bids is as follows:

Bidder 1

- When comparing base prices, Bidder 1 has the lowest cost.
- After considering the upgrades to the Project Electrical Grid at site to start the offered 16,000 HP Motor Bidder 1 become the highest bidder.
- The motor quoted by Bidder 1 requires the Electrical Grid upgrade in order to effectively start their proposed 16,000HP motor.

Bidder 2

- Bidder 2 offered a 12,500 HP motor which multiple studies were performed and the motor meets the EPC starting requirements.
- EPC-1 Engineering believes no electrical upgrades are needed at site to start the proposed motor.
- Bidder 2 provided EPC with a project discount to purchase the Recycle Compressor Package. Bidder 2 was previously awarded the Centrifugal Compressor.
- EPC-1 has conducted 2 bid review meetings with Bidder 2 to review the start-up conditions of the motor and the overall compressor selection.
- Bidder 2 has been very responsive to the EPC technical and commercial team throughout the duration of this RFQ package which has lasted over a year.

Bidder 3

- Bidder 3 commercially offered a very competitive quote while the 13,410 HP Motor was questionable, whether or not the existing Project Electrical system could start the motor.
- EPC-1 requested more information from Bidder 3 i.e. start-up curves, start-up operating conditions to research more and determine if the jobsite would be capable of starting this motor. This information was never received from Bidder 3.

- Bidder 3 failed to provide sufficient information to verify the motor could be started under EPC-1 specified conditions; therefore, Bidder 3 was deemed technically unacceptable.

Bidder 4

Bidder 4 was eliminated due to a late, incomplete submission of bid.

Software results

Previous section provided an overview of the bidders' technical and commercial characteristics. In this section, I describe the analysis conducted using data extracted from the commercial bid tab. EPC-1 also provided a report which contains additional information on schedule milestones and suggested values for supplier performance that were not shown in the bid tab (on time fabrication, on time shipment, and shop load utilization). Like in the previous case, I was able to create a scenario for inclusion in the software. Targets or aspirations for this case are illustrated in Figure 6.7. Tables 6.3 and 6.4 summarize Bidders' data which was entered and stored in the back-end database. Table 6.3 presents information on material and fabrication while Table 6.4 lists information associated with transportation criteria.

- **Equipment**: Recycle Gas Compressor
- **Project Location** – Indiana, USA
- **Quantity** – 1

Schedule Milestones

- **RFQ**: 2/12/2007
- **Receive BID**: 3/26/2007
- **PO**: 6/27/2007
- **Ready to Ship**: 4/30/2009
- **Site date**: 6/1/2009

Budget

- Material Cost: 7,985,465
- Transportation Cost: 1,090,000

Supplier Performance

- On time Fabrication: 95%
- On time Shipment: 95%
- Shop load utilization: 85%
- Quality: 1

Figure 6.7: Aspiration levels for selection of compressor

Table 6.3: Bidders information on Material/Fabrication

MATERIAL/FAB	Bidder 1	Bidder 2	Bidder 3
Location	USA (city not specified)	Europe (city not specified)	Europe (city not specified)
Bid Validity (days)	35	90	300
Material Costs (USD)	9,587,783	7,685,313	8,351,552
Material Escalation (%)	0	0	0
Fabrication lead time (weeks)	58-62	60-62	72-74
Shop load utilization (%)	65	80	75
On time fabrication (%)	90	98	85
Quality	2	3	3

Table 6.4: Bidders information on transportation

TRANSPORTATION	Bidder 1	Bidder 2	Bidder 3
Transportation mode	Inland Freight (Truck or Barge)	Ocean	Ocean
Transportation Costs (USD)	32,700	357,700	357,700
Escalation (%)	0	0	0
Transit time (weeks)	1-3	3-5	3-5
On time Shipment (%)	85	90	97

Figure 6.8 illustrates the overall ranking of Bidders for both material/fabrication criteria (top of the figure) and transportation criteria (bottom of the figure). The graphs shown on the left hand side plot the overall ranking results. These results indicate that Bidder 2 is ranked the top supplier for material/fabrication criteria (AIM =0.688), followed by Bidder 1 (0.462), and Bidder 3 (0.234). Bidder 2 however is the second ranked supplier for transportation (0.557). Bidder 3 – the worst supplier for material/fabrication - is the supplier with best overall score for transportation (1). This figure allows a first assessment of tradeoffs involved in the selection decision.

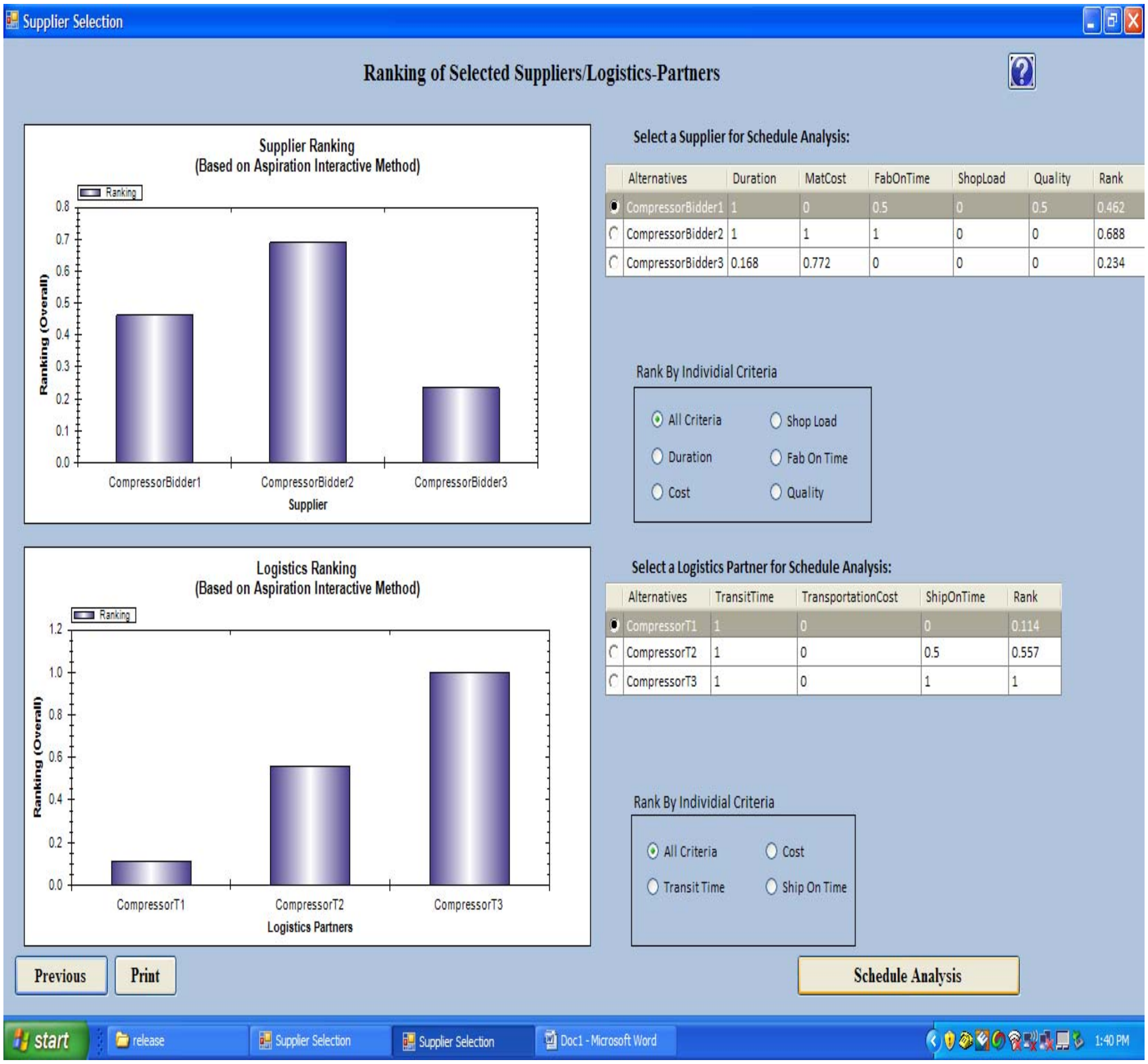


Figure 6.8: Overall AIM ranking – Compressor

Once again, managers can also rapidly assess how each Bidder performs in each criterion. Figure 6.9 illustrates all possible tradeoffs the software offers to users for material/fabrication. In this case shop load utilization got 0 values for all suppliers. This happened because the aspiration level required by the users is worse them the worst value found in the database, i.e. all suppliers have enough shop load utilization to fabricate the compressor. Therefore, AIM approach informs managers that this variable will not affect their final decision since all suppliers share the same value (0). Figure 6.10 shows all possible tradeoffs for transportation criteria.

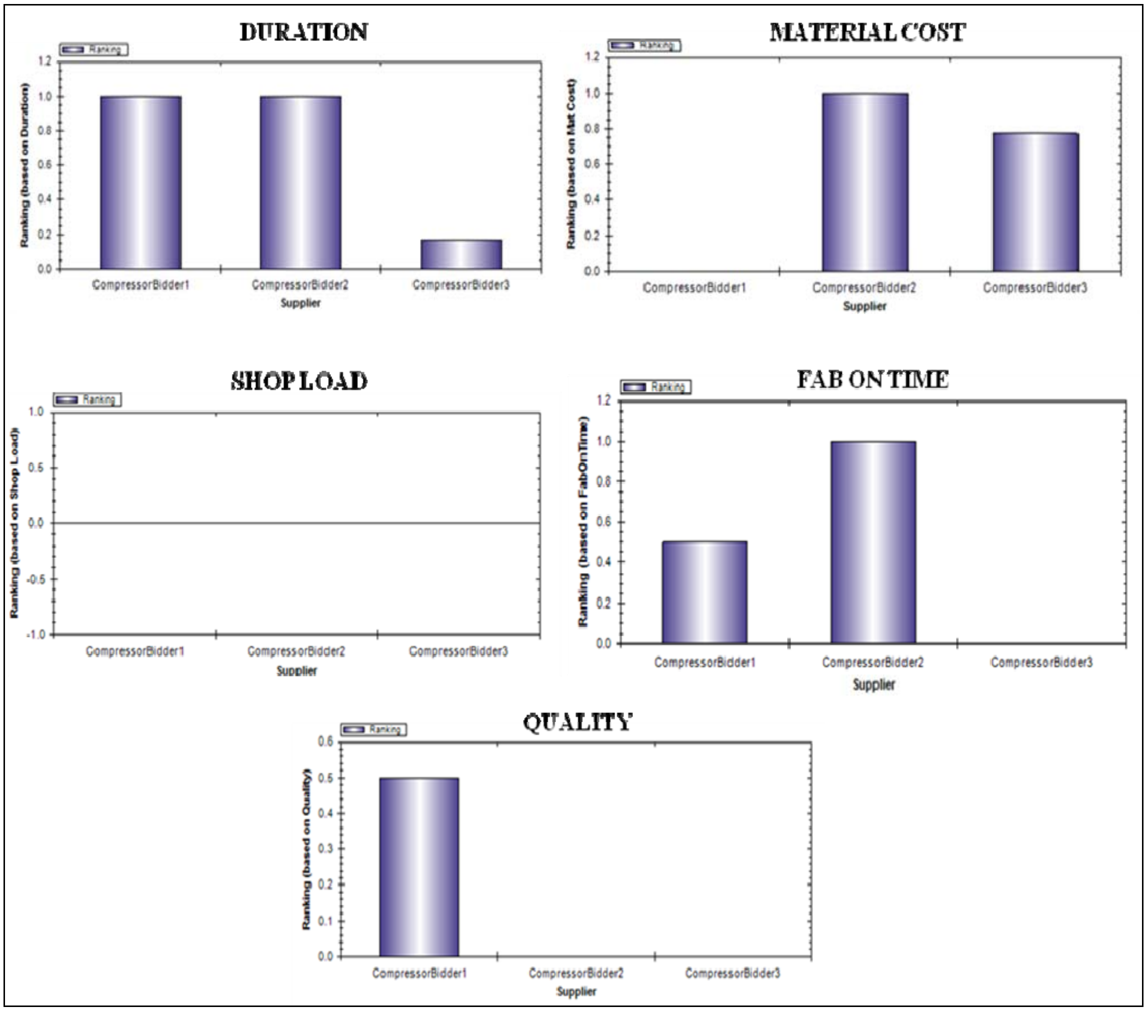


Figure 6.9: Material/Fabrication tradeoffs – Compressor

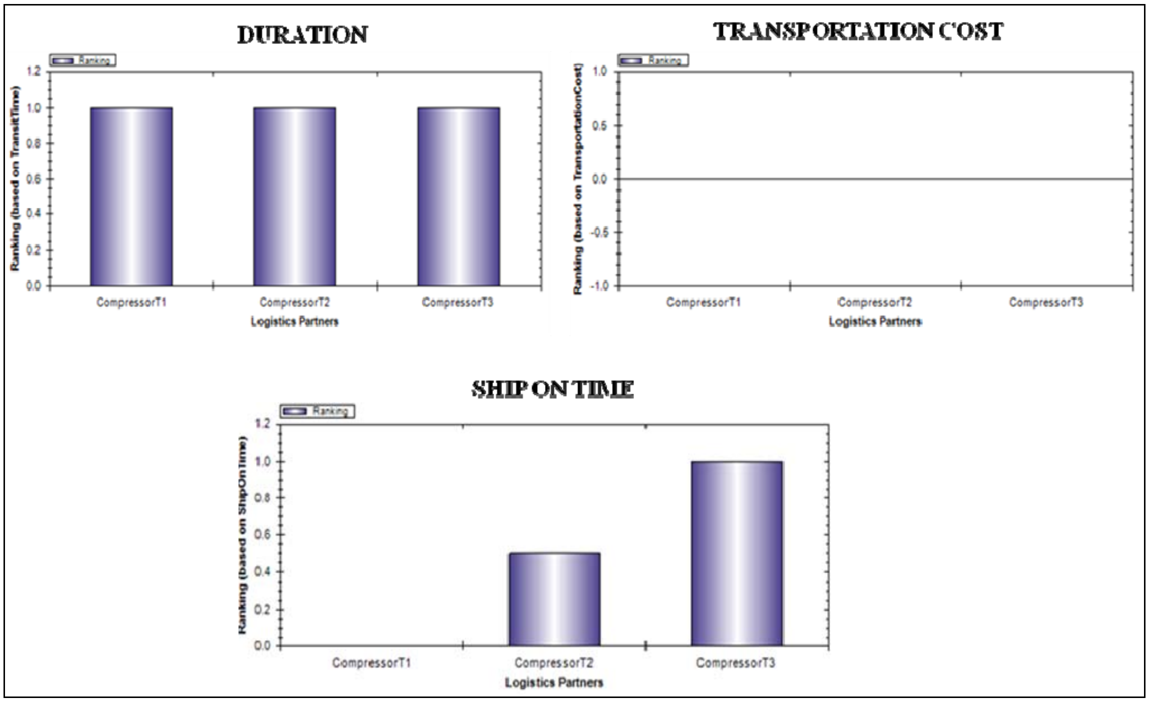


Figure 6.10: Transportation tradeoffs – Compressor

Figure 6.11 displays the results of the cumulative analysis which was used to suggest the top ranked supplier for all criteria (material/fabrication & transportation). Bidder 2 is the top ranked supplier suggest by AIM (0.53), followed by Bidder 3 (0.42), and Bidder 1 (0.32).

	Duration	Total Cost	On time Fab	Shop load	Quality	On time Ship	
Weight	0.032	0.113	0.253	0.000	0.328	0.274	Ranking
Compressor 1	1.00	0.00	0.50	0.00	0.50	0.00	0.32
Compressor 2	1.00	1.00	1.00	0.00	0.00	0.50	0.53
Compressor 3	1.00	1.00	0.00	0.00	0.00	1.00	0.42

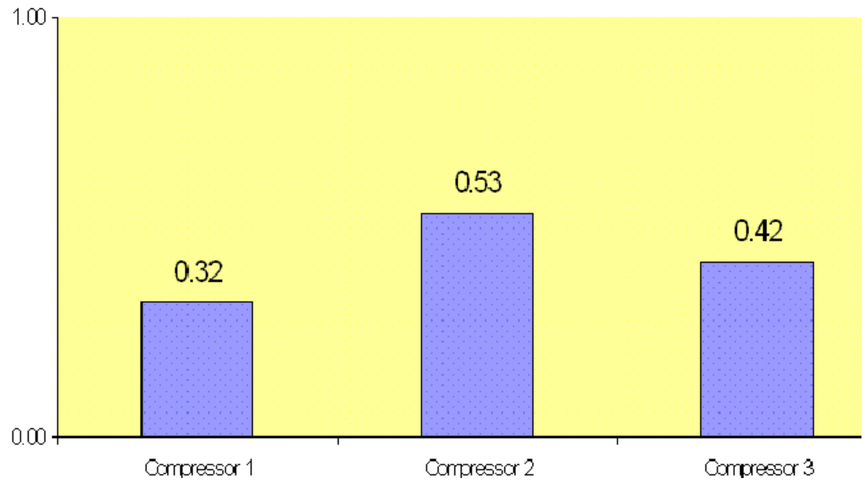


Figure 6.11: Cumulative results – Compressor

<u>Actual Supplier Recommendation</u>

EPC-1 recommends issuing a Purchase Order to Bidder 2 in order to secure a fabrication slot with Supplier and Motor manufacturer to meet the construction site need date. Issuing a Purchase Order allows EPC-1 to take advantage of the packaged project discount offered for purchasing the Centrifugal Compressor and the Recycle Compressor. Moreover, issuing a Purchase Order at this time helps to maintain the overall schedule.

Selection of Bidder 2 will allow EPC-1 to use the same project team that is currently being used for the other compressor package and possibly combine drawings review meetings, inspection, testing, etc.

6.3 COMPARISON OF ACTUAL RECOMMENDATIONS VS. SOFTWARE RESULTS

Table 6.5 describes the solutions suggested by the software and each EPC. The main reasons for the recommendation are also summarized. This information allows the comparison of software solutions against actual solutions recommended in the actual selection cases.

EPC-4 selected the bidders after evaluation of the commercial bid tab summary data and description of scenarios provided by the researcher during the validation meeting. EPC-4 would have selected bidder 3 for case 1 (Heaters) and bidder 2 for case 2 (compressor). In the first case, managers selected a domestic supplier because of their bad experiences with international suppliers (costs of inspection, expediting, coordination meetings) and also because bidder 3 presents the best quality rating. In the second case, they evaluated bidder 2 and mentioned that material plus transportation costs were good. Therefore, the decision was cost driven.

Table 6.5: Supplier recommendation - DSS vs. EPCs

	Case 1 Fired Heaters	Reasons for selection - Heaters	Case 2 Compressor	Reasons for selection - Compressor
DSS	Bidder 3	Aim Ranking	Bidder 2	Aim Ranking
EPC 1	Bidder 1	Location (logistics costs), Warranty, technical capabilities	Bidder 2	Secure fabrication, discount, keep schedule, same project team
EPC 4	Bidder 3	Location (coordination and logistics costs), Quality	Bidder 2	Material + Logistics costs

In summary, managers clearly ignored tradeoff analysis of the available parameters in their actual selection. Even though there was some choice disagreements in the heaters case, managers appreciated the system and highlighted that it appears to fit in their selection process. They also commented that graphic visualization of tradeoffs provides more transparency to the data of their bid tabs, enabling quick identification of potential unusual values that may be provided by bidders.

Further tradeoff analysis might be useful to explore the range of solutions in the context of the heaters selection. The suggested solutions for each case were result of one set of aspiration levels (targets). Analysis of several aspiration levels might indicate the best solution when varying one criterion or two criteria, showing also threshold points for suggested solutions. Robustness evaluation was carried out through sensitivity analysis in the context of the heaters case to illustrate the points above. This analysis appears to provide richer information about the different tradeoffs involved in the decision. The next section presents the findings of this evaluation.

6.4 SYSTEM'S ROBUSTNESS EVALUATION

In this section, I explore the idea of robustness in decision making. The robust solution is one that is optimal for many different preferences. In the AIM framework, one that has many different aspiration levels mapping to it (Wang and Zionts 2006). The results of this section are heavily inspired in the publication by Wang and Zionts (2006) in which those authors introduce the concept of robustness of solutions using AIM.

The robustness analysis attempts to identify the most preferred solution rather than a value. For the purposes of the robustness analysis, it is assumed that the decision maker has imprecise preferences. In this case, the solution process is not simple and sensitivity analysis certainly can help.

To conduct the experiment, it is necessary first to generate a set of aspiration levels. I used interval aspiration levels which is one of the approaches suggested by Wang and Zionts (2006). The idea is to consider the best and worst achievable levels of each objective. Then, I chose 3 intermediate levels which are used to space the interval aspiration levels uniformly over the total range. For example, I chose 77.5, 81.5, and 85.5 as my interval aspiration levels for the duration range (73.5 – 89.5 weeks). Once all values were defined for each parameter (duration, total cost, quality), I was ready to conduct the sensitivity analysis to identify the robust solution (most mapped top supplier) for a set of scenarios. I chose to work with data from fired heaters case since it seemed the solution was not that dominant and clear to procurement managers.

In the first three experiments, I conducted one-way sensitivity analysis. First, I wanted to understand how the variation of quality aspirations would impact the suggested selection solution, i.e. the top ranked bidder (Table 6.6). Second, I changed cost aspirations and reported the suggested solutions (Table 6.7). Finally, duration aspirations were the focus of the experiment (Table 6.8).

Table 6.6: Sensitivity analysis of Quality aspirations

Quality	Solution (Bidder)
1	3
2	3
3	1
4	1
5	1

Table 6.7: Sensitivity analysis of cost aspirations

Cost (USD)	Solution (Bidder)
4,530,041	3
4,486,416	2 and 3
4,442,791	2
4,399,166	2
4,355,541	2

Table 6.8: Sensitivity analysis of Duration aspirations

Duration (Weeks)	Solution (Bidder)
89.5	3
85.5	3
81.5	3
77.5	3
73.5	2

I also conducted two-way sensitivity analysis to understand the impact of varying two different sets of aspiration levels on the robust solution suggested by AIM. I built two scenarios for this analysis. In the first, I vary quality and cost aspirations and mapped the top ranked bidders (Table 6.9). In the second, I modify duration and cost aspirations to identify the robust solution (Table 6.10). Each experiment contains 25 scenarios that needed to be simulated as shown in the tables below.

Table 6.9: Two-way sensitivity analysis: Quality and Cost

Scenario #	Quality rating	Cost (USD)	Top ranked Bidder
1	1	4,355,541	2
2	1	4,399,166	3
3	1	4,442,791	3
4	1	4,486,416	3
5	1	4,530,041	3
6	2	4,355,541	2
7	2	4,399,166	2
8	2	4,442,791	2
9	2	4,486,416	2 and 3
10	2	4,530,041	3
11	3	4,355,541	1
12	3	4,399,166	1
13	3	4,442,791	1
14	3	4,486,416	1
15	3	4,530,041	1
16	4	4,355,541	1
17	4	4,399,166	1
18	4	4,442,791	1
19	4	4,486,416	1
20	4	4,530,041	1
21	5	4,355,541	1
22	5	4,399,166	1
23	5	4,442,791	1
24	5	4,486,416	1
25	5	4,530,041	1

Table 6.10: Two-way sensitivity analysis: Duration and Cost

Scenario #	Duration (weeks)	Cost (USD)	Top ranked supplier
1	73.5	4,355,541	2
2	73.5	4,399,166	2
3	73.5	4,442,791	2
4	73.5	4,486,416	2
5	73.5	4,530,041	2
6	77.5	4,355,541	2
7	77.5	4,399,166	2
8	77.5	4,442,791	2
9	77.5	4,486,416	2
10	77.5	4,530,041	3
11	81.5	4,355,541	2
12	81.5	4,399,166	2
13	81.5	4,442,791	2
14	81.5	4,486,416	3
15	81.5	4,530,041	3
16	85.5	4,355,541	2
17	85.5	4,399,166	2
18	85.5	4,442,791	2
19	85.5	4,486,416	2 and 3
20	85.5	4,530,041	3
21	89.5	4,355,541	2
22	89.5	4,399,166	2
23	89.5	4,442,791	2
24	89.5	4,486,416	2 and 3
25	89.5	4,530,041	3

The results of all experiments are summarized in the following table. This table presents the robust solution for each sensitivity analysis. The data illustrates how often a supplier was top ranked in each scenario.

My original recommendation based on the cumulative results of the fired heaters case was Bidder 3. This was the bidder which mapped to a specific aspiration level. The robustness analysis can provide insightful information in the context of this case. Managers can observe for example that bidder 3 is the best solution when they target for a quality rating at least equal to 2 (best quality rating = 1). In case quality expectations are not so high, the solution changes to bidder 1 which is better in other aspects (see Table 6.6). Taking into account the range of possible values for quality (1-5), bidder 1 is the best solution 60% of time. The same logic can be used to understand the best solutions when varying other individual parameters such as cost and duration within the possible ranges of values found in the data sample. In case of variation of two parameters at the same time, bidder 2 is the best solution in 76% of the 25 scenarios evaluated within the possible ranges of duration and cost. Table 6.11 provides a comprehensive view of existing tradeoffs involved in the selection of heaters.

Table 6.11: Robust solution for each sensitivity analysis

Robust solution					
Alternatives	**Quality**	**Duration**	**Cost**	**Duration & Cost**	**Quality & Cost**
Heater 1	**60 %**	**---**	**---**	**---**	**60%**
Heater 2	**---**	**20%**	**70%**	**76%**	**18%**
Heater 3	**40 %**	**80%**	**30%**	**24%**	**22%**

CHAPTER 7: CONCLUSIONS

This chapter presents the conclusions and contributions of this research to the body of knowledge and construction practice. Finally, some possibilities for future research are outlined.

7.1 CONCLUSIONS

This research presents a systematic approach that can be used to assess and select equipment suppliers. This approach provides rapid analysis capabilities and it is integrated with a PERT analysis technique which is insightful as a preliminary schedule risk identification tool. During the course of this research, a computer-based tool which integrates firms' data with the selection and schedule approaches was implemented to demonstrate its applicability to two actual cases. According to experienced procurement managers, the decision support system provides an objective methodology which is useful, consistent, and applicable. The validation indicated that the approach was easily understood by the target audience –procurement managers – and it adds value to the overall supplier selection process.

Specifically this research has shown that:

1) The decision support system allows electronic integration of market data to support selection of equipment suppliers. This integration contributes to improve a set of current issues in the selection process such as: manual analysis and the time consuming process due to difficulties to retrieve data from paper based files or supplier evaluation systems.

2) The system also allows rapid tradeoff analysis and ranking of suppliers. All firms that participated in this research do not have objective methods to carry out this analysis and recommend their suppliers. AIM provides such capability and can play a significant role in the selection of equipment suppliers.

3) The schedule module provides a very useful set of risk factors which provides insights on early duration estimates. By analyzing the results of the PERT analysis, managers were able to identify floats or time buffer in the delivery of equipment associated with different risk assessment scenarios. The tool can support the creation of more realistic equipment delivery schedules in the early phases of the project.

4) The tool supports commercial assessment/recommendation of suppliers. I understand that technical assessment is very important and, in some cases, can guide the decision for the best supplier. However, technical analysis is responsibility of engineering staff. The target users of this system are experienced procurement managers who need to carry out commercial assessment of the suppliers before coming up with their final supplier suggestion. The system proposed in this dissertation is very useful to support this purpose. Managers can also use the system to create a short list of suppliers before requesting formal quotes; however, data availability and organization is needed to achieve this second purpose.

7.2 RESEARCH CONTRIBUTIONS

The results of this research contribute to the academic knowledge. Practical application of this knowledge in the form of a feasible and useful tool to support procurement decisions during early phases of capital projects is still missing, and these results can begin to fill this gap.

The primary contribution of this research is aiding decision making on engineered equipment either during front end loading or conceptual design phases of capital projects. As for the academic contributions, this study provides a new and meaningful method for analysis and selection of suppliers – Aspiration Interactive Method (AIM). To my knowledge, this is the first time this method which has been applied to solve selection problems in operations research area is being used and tested in construction. Other academic contributions are: the improved understanding of early selection process and a recommended process for use the decision support system.

This research also contributes to the knowledge of schedule risks. I suggested a set of risk factors that may potentially impact the duration of individual phases of engineered equipment delivery cycle. A matrix is built to facilitate evaluation of the impact of these factors on procurement durations. These factors are integrated with the traditional PERT technique allowing managers to carry out preliminary schedule risk analysis associated with any chosen equipment supplier.

The results of this research also contribute to industrial construction practice. Observations from the current state of practice indicate that there is still a need to develop tools and processes for planning the procurement process. In particular, tools that will enable firms to select products, identify qualified suppliers, and procure the best products at the best prices with the ability to deliver on time and within budget. This research provides a description of current challenges and main variables that need to be considered in early procurement plans. This information is analyzed and serves as inspiration for the development of a decision support system. The system provides automatic integration of actual firms' market data, supplier decision aid logic and schedule analysis, allowing managers to quickly generate what-if scenarios. Managers can also ensure their targets are realistic and achievable. The system takes into account variables that have been somewhat ignored in current models developed in construction such as shop load utilization, supplier performance, and price.

The system's capabilities can improve the quality of decision making and provide intelligence to the traditional evaluation and selection of engineered equipment suppliers in the early phases of capital projects. The risk analysis module in particular can be very useful for a systematic and rapid identification of critical equipment that might affect project schedule performance.

Finally, the system was developed and evaluated based on direct inputs from experienced procurement managers who contribute to the credibility and validity of this study.

7.3 RECOMMENDATIONS FOR FUTURE RESEARCH

Future research can address some of the following needs and applications:

1) Identification of the robust solution based on sensitivity analysis has been a very useful exercise to understand the complexity of supplier selection within a set of possible targets. This capability could be added in the system and investigated in more detail in future studies.

2) Analysis using concepts from design of experiments and/or cluster analysis may provide interesting feedback regarding selection decision from large amount of data and could be investigated in future studies.

3) Future research is needed in order to compare the results obtained using AIM approach against other selection methods such as AHP and MAUT. Firms need to be first introduced to these methods because most of them still conduct ad-hoc selection.

4) This system provides insights for evaluation of schedule risks using PERT. In the future, research should address more explicitly cost evaluation of different supply alternatives. Monte Carlo simulation and Bayesian methods are potential methods that could be investigated to generate additional schedule risk information. Comparison of results provided by these different methods could be an interesting contribution to the state of knowledge in construction.

APPENDIX A: Interview guide – Procurement and Supply Chain issues

Topic 1 - Setup of the procurement organization

- Could you briefly describe how the procurement process is organized in your company?

- Have you been using any type of E-commerce tool? Advantages and disadvantages.

Topic 2 – Market characteristics

- What type of market assessment does your company perform to keep track of the behavior of critical products/suppliers (capacity constraints, price fluctuation, number of qualified suppliers)?

- Has your company assessed international markets? For what type of materials? Why?

Topic 3 – Supplier integration and involvement

- Is there any type of supplier involvement in the early phases of projects (e.g. pre-project planning, design)? What are the major challenges?

- Are there any differences or trends between the present and past relationships with suppliers (or the way contracts are being developed)? Please explain.

Topic 4 - Supply risk analysis and planning during Procurement

- How does your company evaluate supply risks during procurement? Do you get any input from other phases (e.g. pre-project planning)?

- Do you use any tool to identify/compare supply risks and help you planning your supply chain? What tool?

Topic 5 – Types of SC problems and mitigation strategies (Engineered products and commodities)

- Could you give me some examples of SC problems your company has been facing lately?

- What strategies have been/could be implemented to mitigate them?

Topic 6 – Monitoring of supplier and logistics information

- Do you have real time visibility of supplier info (supplier updated schedule; supplier capacity and inventory availability; progress of fabrication or transportation)?
- How does your company monitor this information? Please describe current challenges.

Topic 7 –SC practices implementation during construction

- Are there any practices that you have been implementing together with suppliers to avoid material delays? (Vendor managed inventory; Just in time deliveries; transportation planning, Logistics Centers; Last Planner System)

APPENDIX B – Understanding Supplier Selection Codebase

Important Components:

1. SupplierSelection.sln - VS2005 C# solution file containing the entire source
    a. MainForm.cs: Main form which acts as a container of all the screens
    b. Criteria.cs: Criteria Screen
    c. Selection.cs: Screen which displays all the suppliers and logistics partner
    d. Aim.cs: Screen which ranks the selected suppliers and logistics partners
    e. PERT_container.cs: It contains PERT and risk user controls
    f. PERT.cs: Displays a list of subjective criteria to analyze a supplier/logistics partner using PERT analysis
    g. Risk.cs: Displays the PERT analysis results
    h. Help_*.cs: Help Content for each of the screens
    i. *_designer.cs: The C# UI corresponding to each user control (automatically managed by the IDE). These files should never be changed
    j. All other files: They are all automatically generated by the IDE, and the application developer needn't know about them
2. MS Access Databases in the Databases folder

Explanation:

The **UI** is modeled as follows: There is a single windows Form (named Form1) which acts as a container for all user controls used for the project.

Whenever a user moves forward/backward through the pages, the appropriate user controls are made visible. Hence the container form is maintained intact.

Such a strategy has several advantages:

- Form dimensions can be varied once and applied to all pages;
- we can design a navigation control and easily plug-in to the application;

- the theme can be modified without too many changes;
- data sharing between user controls is easily enabled as all user controls share a common container (MainForm)

Database: MS Access is used as a back-end database because of its ease of use and quick integration with the C# application. A simple relational database model is employed in structuring the data amongst various tables;

Overview of each of the user controls:

MainForm:

- This is the main form of the application
- All subsequent pages Criteria, Selection, AIM based ranking, PERT analysis, and the report are all created as user controls, and embedded into the main form
- The main logic in this code is to keep track on which page we are in, and display the controls relevant for that page, and hide the other controls
- Since this is the main form of the application, the form also acts as the center of all information
- Any information that need to be transferred between the user controls are intercepted via this form

Criteria:

- Criteria user control is a form for entering the criteria required for selection
- We use the ADO database interface to connect to the ACCESS Database, and create ACCESS queries to access contents from the database
- Equipments Categories and Names are automatically pulled out of the database to enable users to choose from among the existing equipments

Selection:

- Uses several Criteria (Bid Validity Criteria, Bid Duration Criteria, Fabrication Time, Material Cost, Transportation Time, Transportation Cost) based on the inputs from Criteria screen
- For each of the criteria, a list of suppliers/logistics-partners who satisfy the criteria is displayed followed by those who have not met the criteria (ACCESS queries are used to pull the data from the database)
- Uses DataTables to merge the valid selections from the invalid selections
- Uses DataGridViewControl of C# to display all the selected entries
- Distinguishes between the valid and invalid entries by separate colors
- Uses a Check-box control for selecting from among the displayed supplier/logistics-partner entries
- The DataGridViews are non-editable, sortable, and selection is based on entire row
- DataGridView Event handlers are used to color the entries, resize the columns for fitting, and for onClick events
- Validation is done to ensure that at least one of the supplier is selected before moving to the ranking screen
- The information about the selected suppliers/logistics-partner are stored for use by the AIM and the PERT screen, to avoid querying the database again

Aim:

- The Selected Suppliers/Logistics partners are ranked based on Aspiration level Interactive Method (AIM)
- The criteria entered by the user in the Criteria Screen are called Aspiration Targets (represented as ak_)

- The deviation (distance) between the values corresponding to the each supplier and the aspiration targets are represented as distance values dk
- Weights specify how significant each parameter is
- Objective of the method is to minimize or maximize any particular parameter
- If the objective is to maximize a parameter, the ideal and nadir values are the max and min values respectively
- If the objective is to minimize a parameter, the ideal and nadir values are the min and max values respectively
- A Relative rank is calculating using the weights, distance and aspiration values
- This rank captures the an ordering of the suppliers/logistics-partners according to the user criteria
- This file codes all the methods necessary for coding the AIM method logic
- Wherever a selected supplier/logistic-partner's data is required it is fetched from the selection screen
- Wherever details of all suppliers/logistics-partners are required, database is queried (for example, min and max values)
- The code uses an open source graph library (ZedGrpahControl) for rendering the rank graph,
- The ZefGraphControl.dll is shipped as part of the executable under the open source license

PERT Container:

- This page acts just as a container for the PERT and risk subcontrols
- It acts a medium of transfer of information between the PERT and risk subcontrols

PERT:

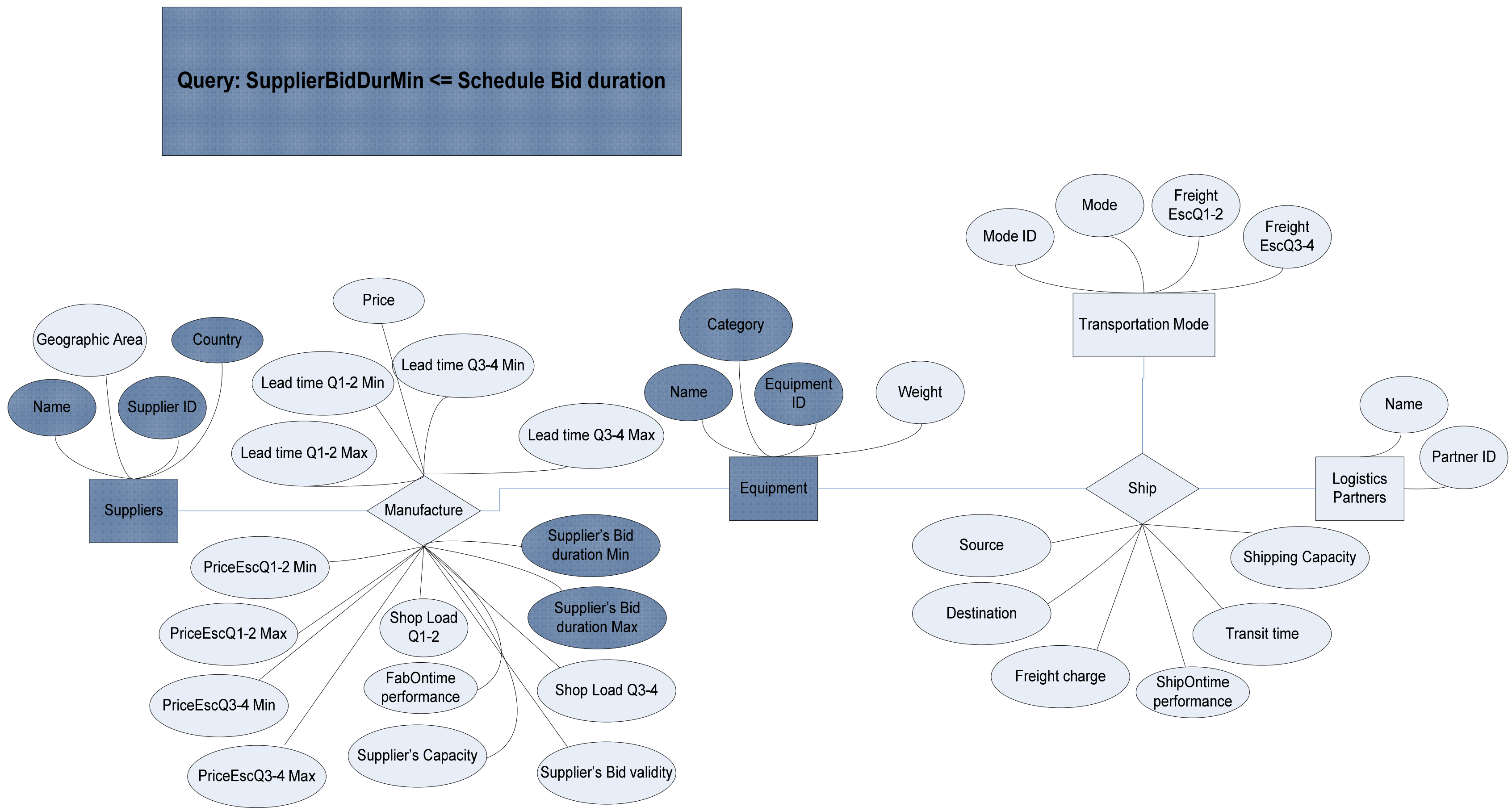
- This screen provides a list of questions for qualitative evaluation of the supplier based on past performance
- For each of these questions, the user chooses from a range, and sets the supplier with a particular value (TrackBar control is used for sliders representing this range)
- The average of the values under each criteria is used for the schedule analysis in the risk sub-control
- Every change in the control is passed to the Risk sub-control and the results are immediately reflected
- This code file encodes the logic necessary for PERT analysis
- This code uses DataGridView exhautively for presenting the questions

Risk:

- This screen does a schedule analysis of the selected supplier/logistic-partner
- The Schedule analysis is based on PERT method
- The average of the values answered in the PERT sub control for each criteria is used for the schedule analysis
- The Schedule analysis calculates the Expected Mean and Variance of the resultant supplier values, and uses a Z table to fetch the probability of success / failure
- This code file encodes the logic necessary for PERT risk analysis
- This code also hard-codes the entire Z table as a hash table for quick look-up, and since all entries are static it consumes constant space

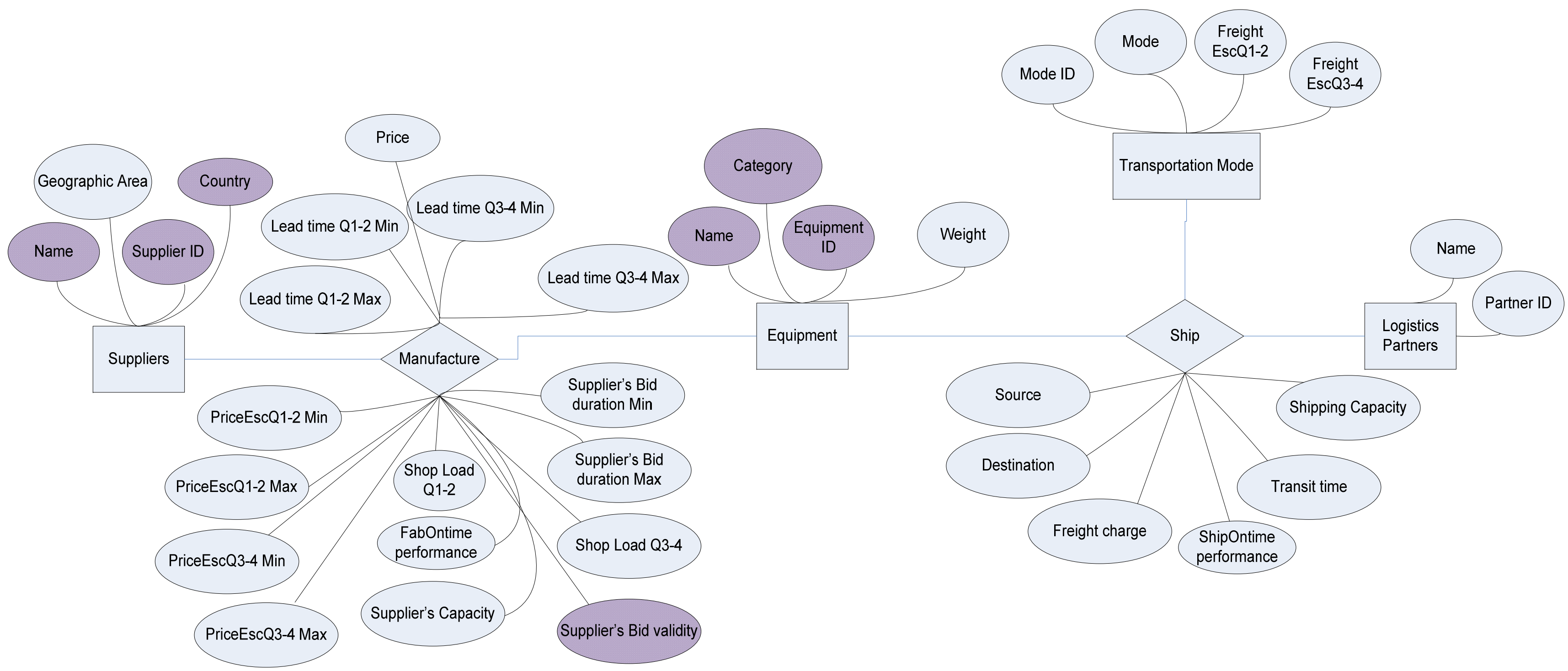
This page automatically populates all the results, so every change in the criteria is updated instantaneously in the schedule analysis

APPENDIX C – Database ER model and queries

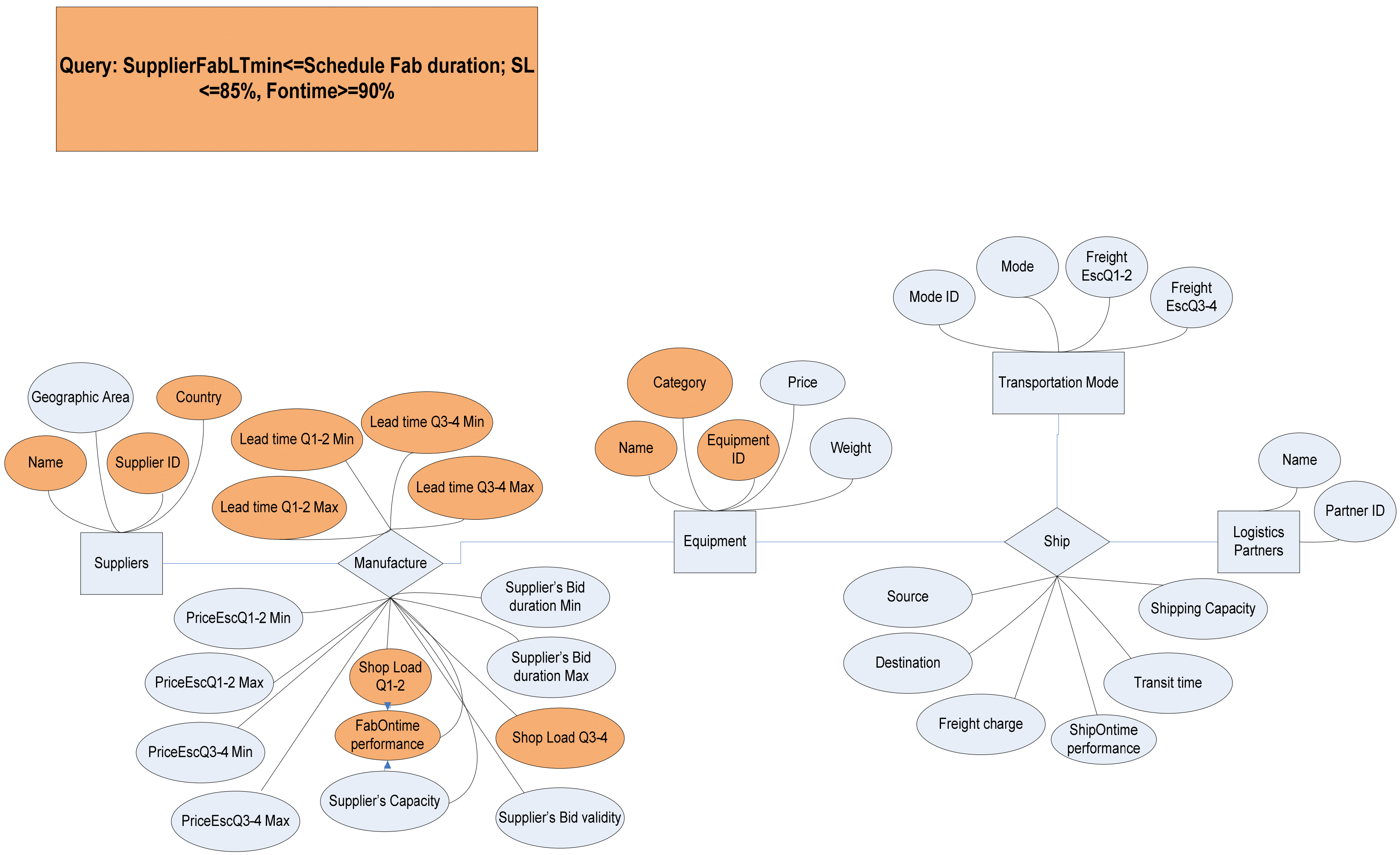


Querying bid information from database

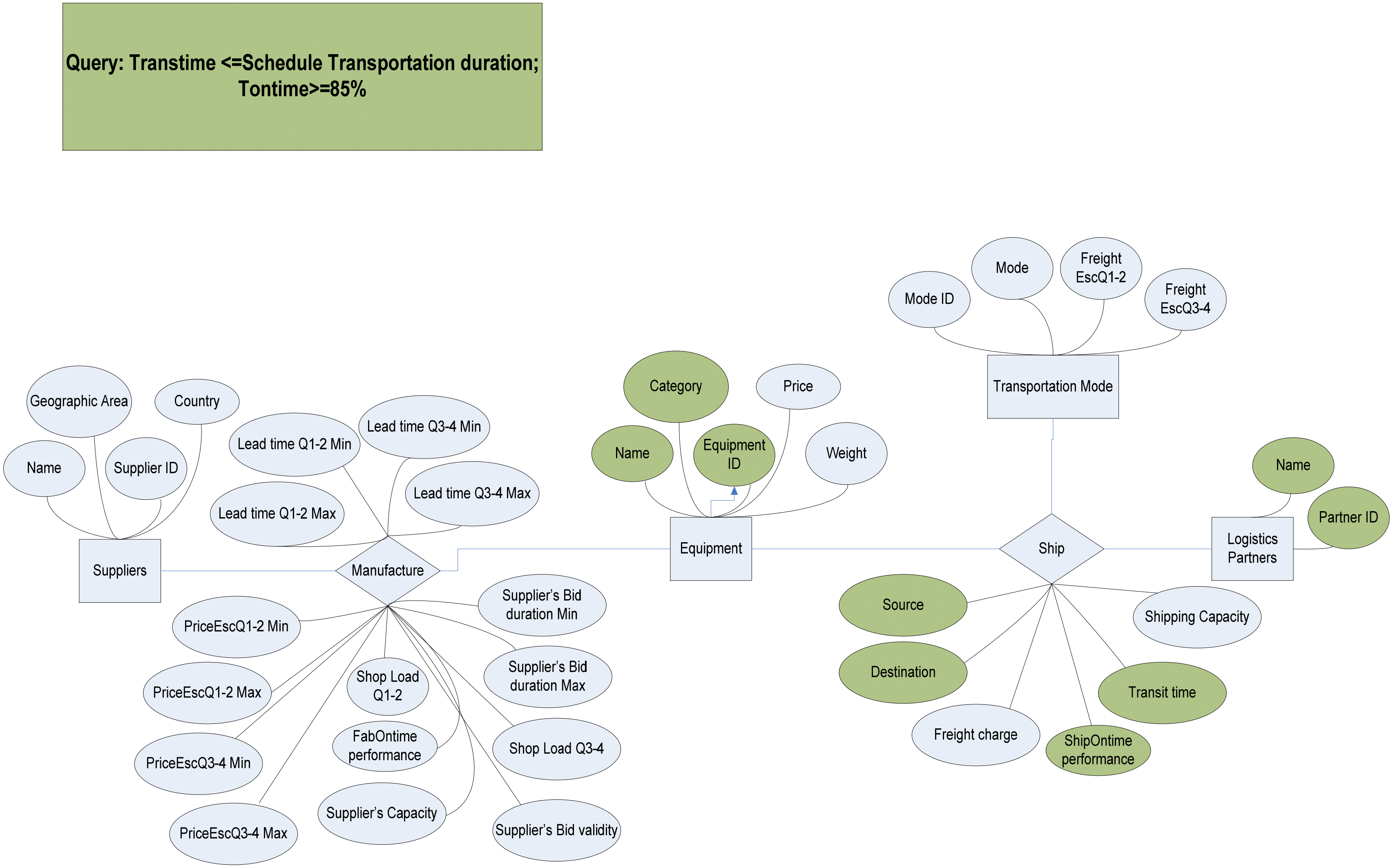
Query: Bid Validity>=Schedule BidCondDur



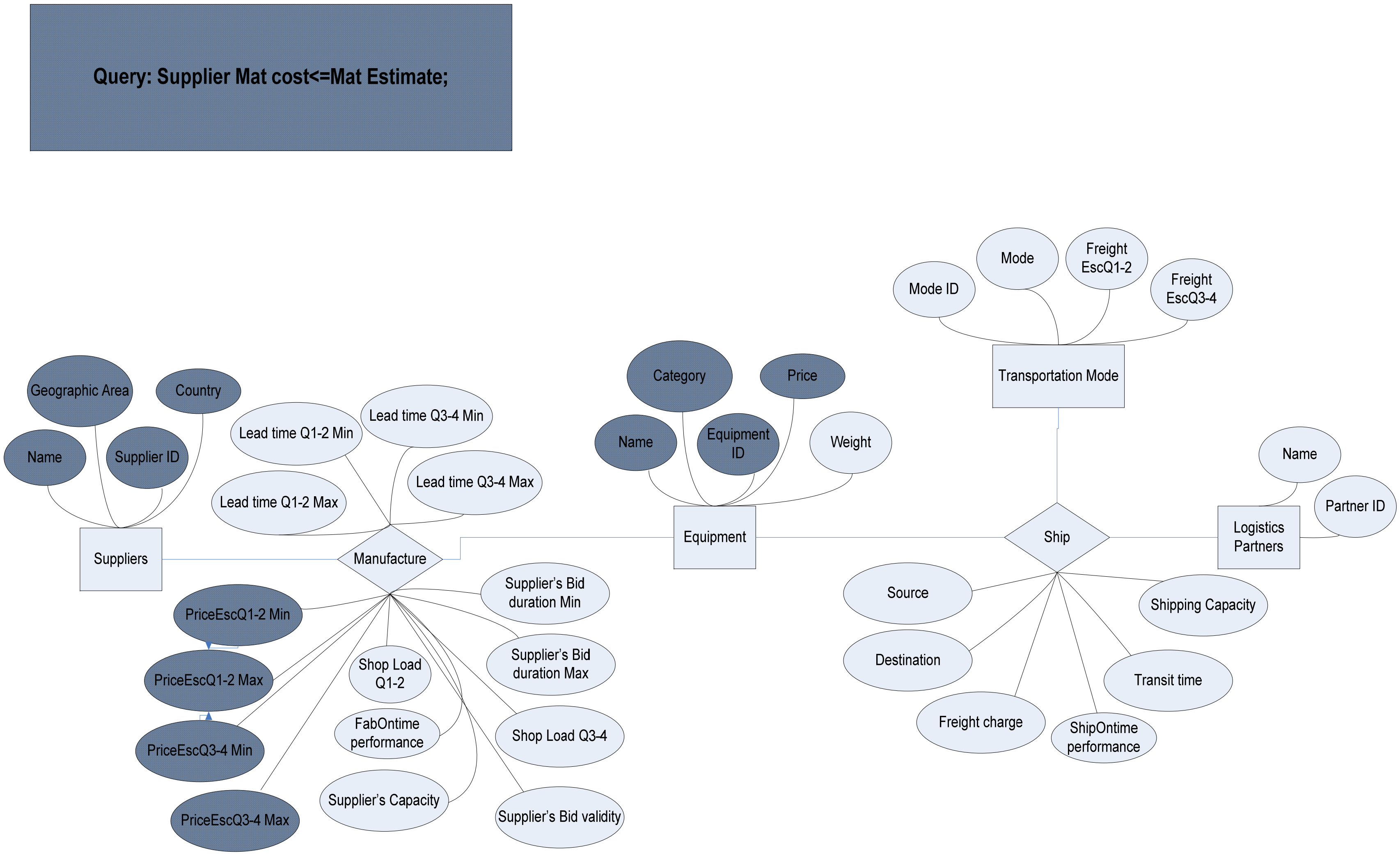
Querying bid conditioning information from database



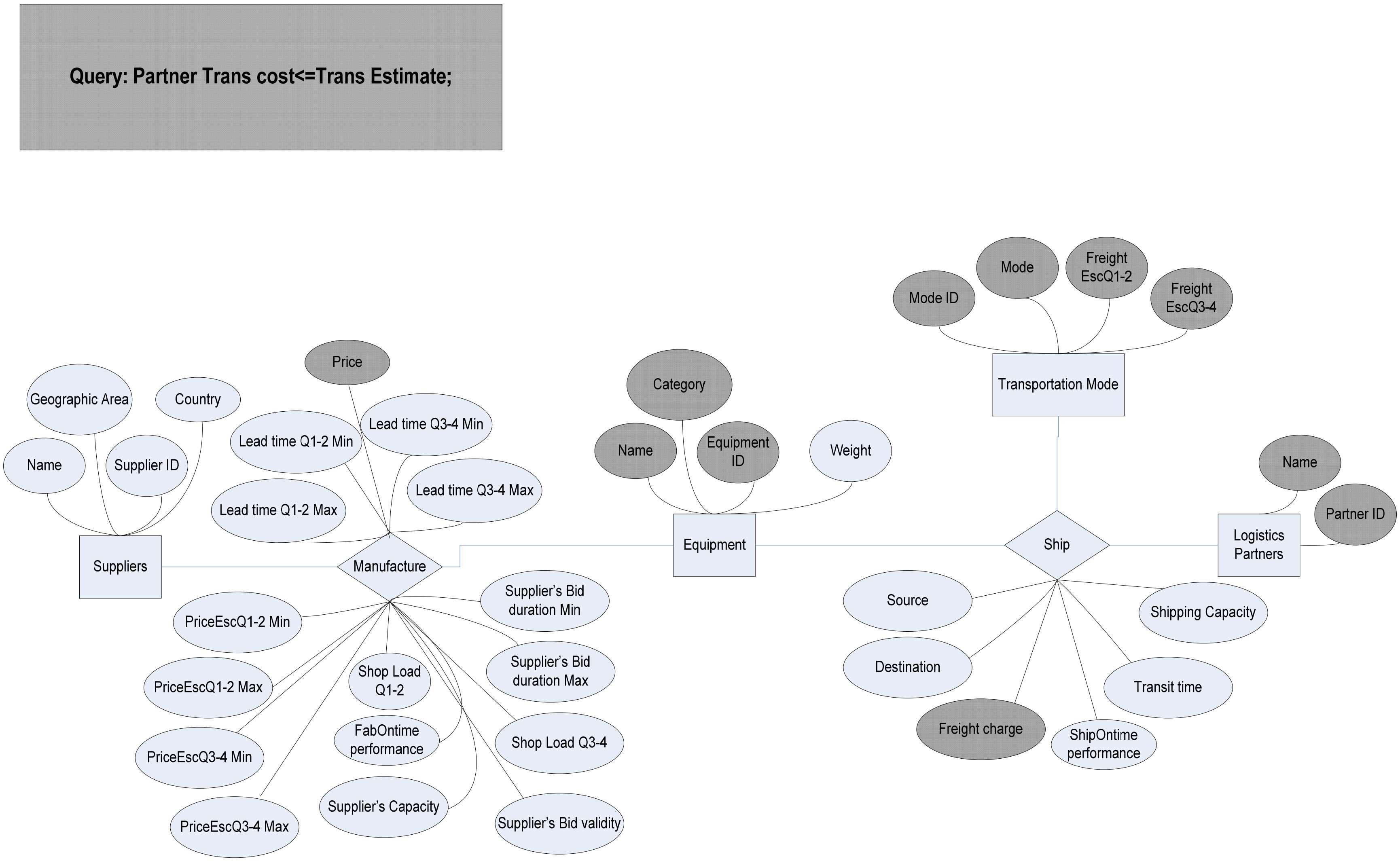
Querying fabrication information from database



Querying transportation information from database

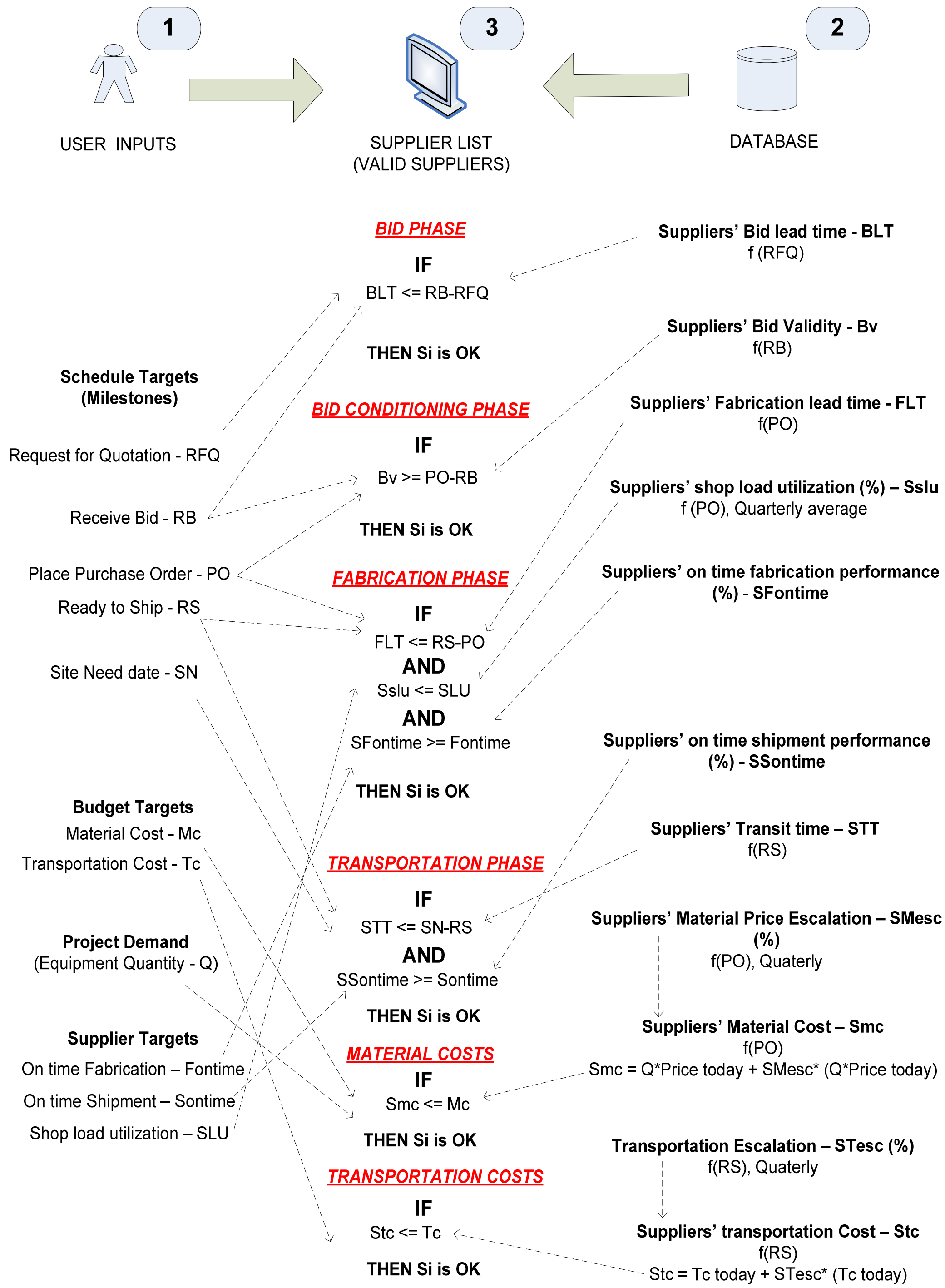


Querying equipment cost information from database

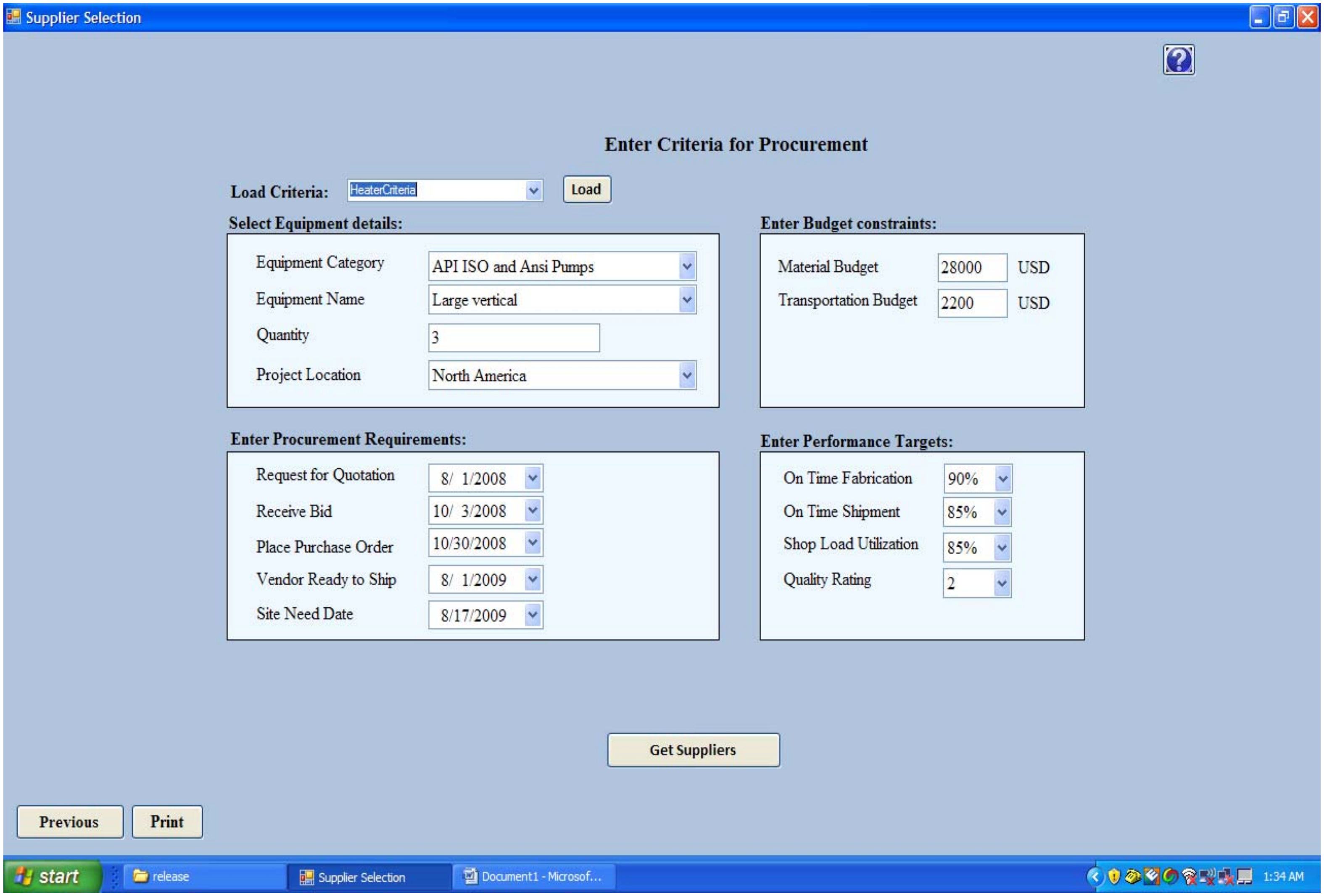


Querying transportation cost information from database

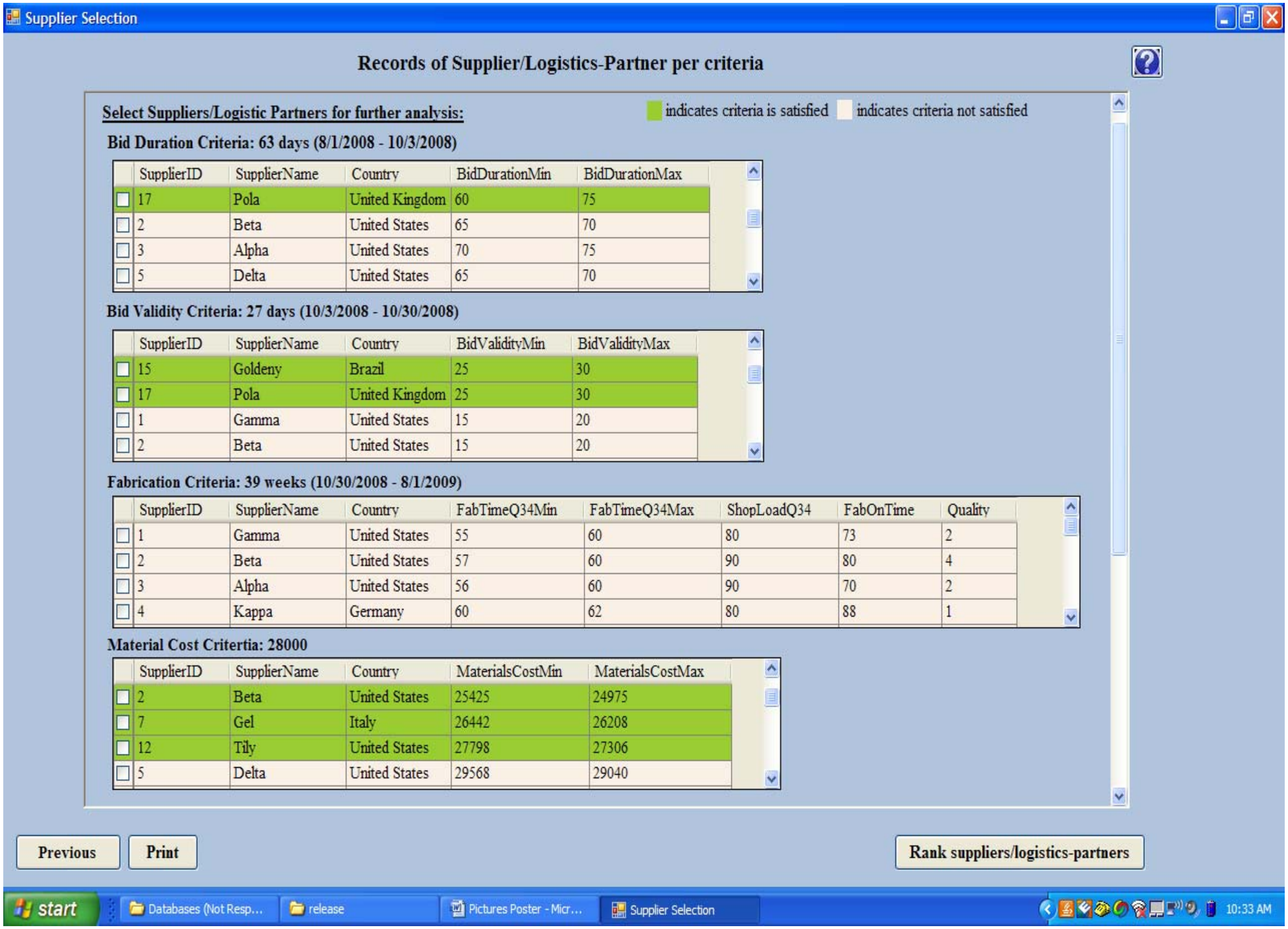
APPENDIX D – Identifying valid suppliers from database



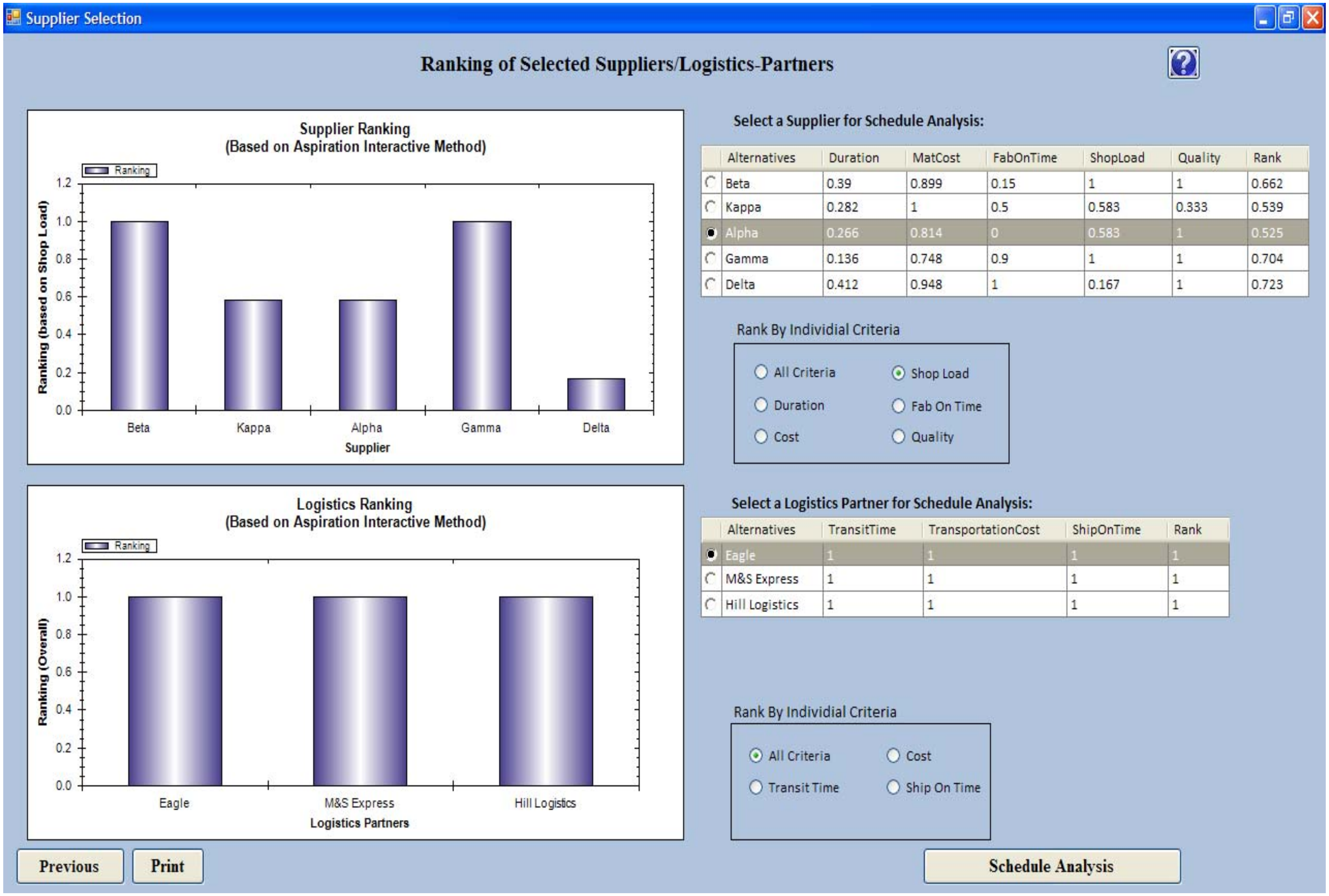
APPENDIX E – SOFTWARE (ENLARGED SCREENS)



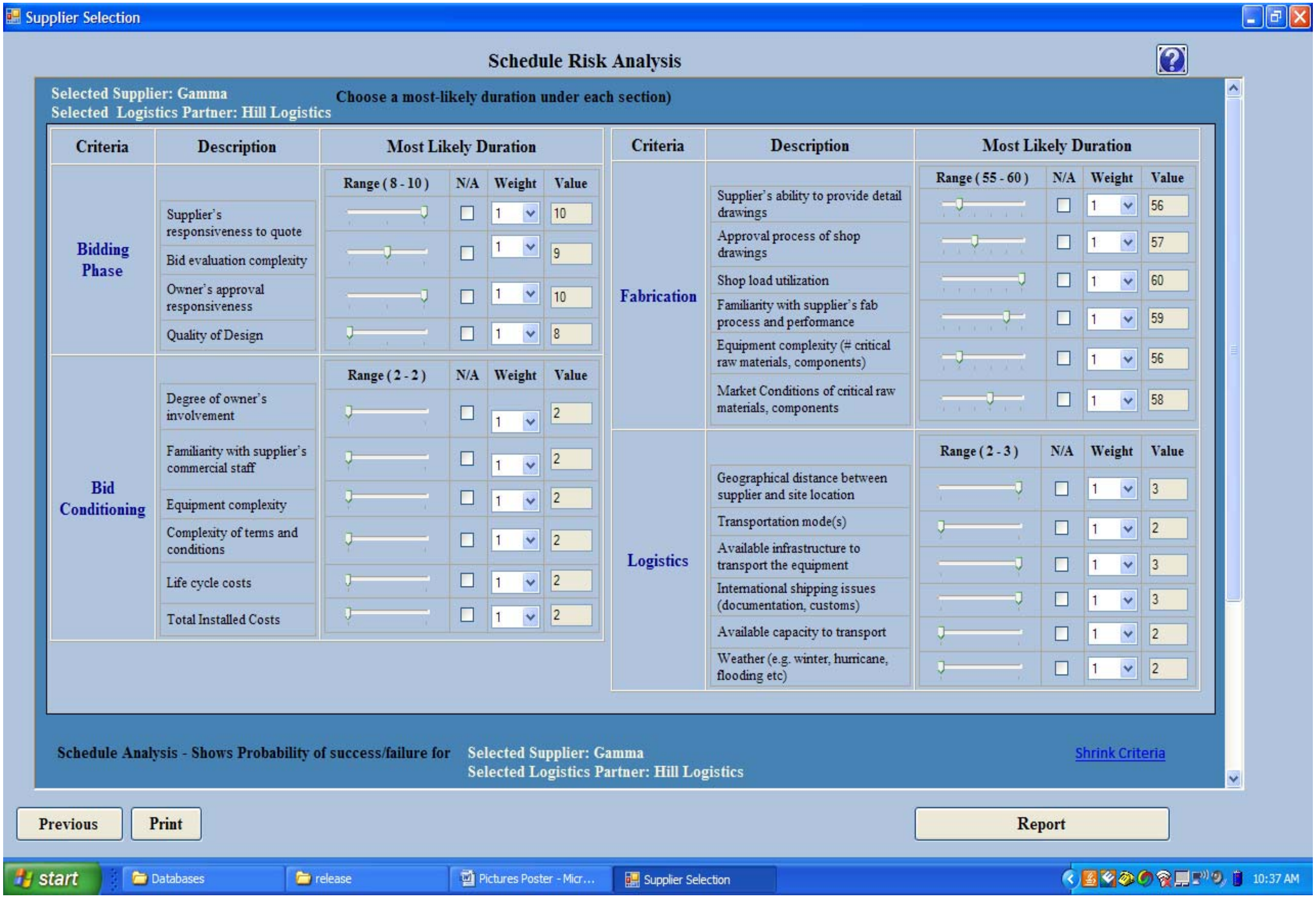
Entering data (aspirations) to start evaluation



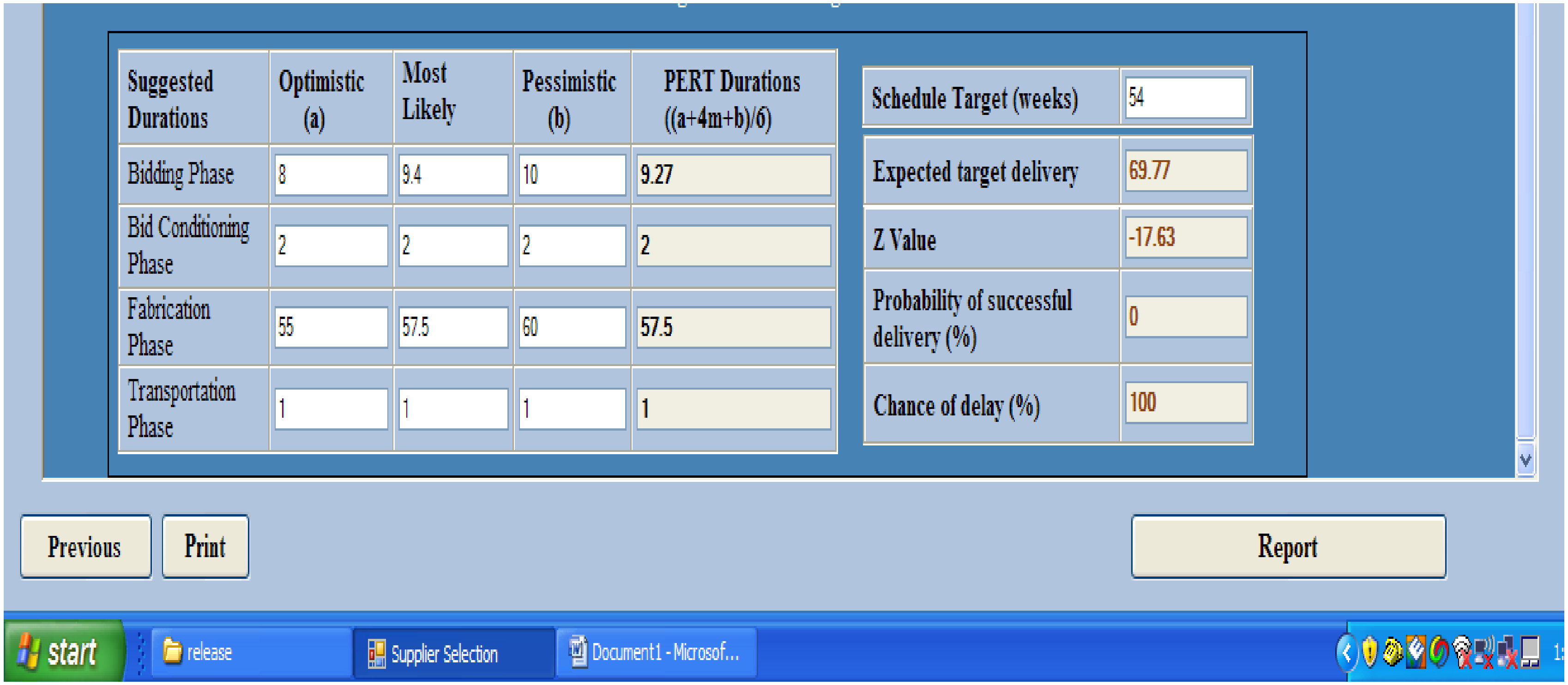
Identifying and selecting valid suppliers for AIM analysis



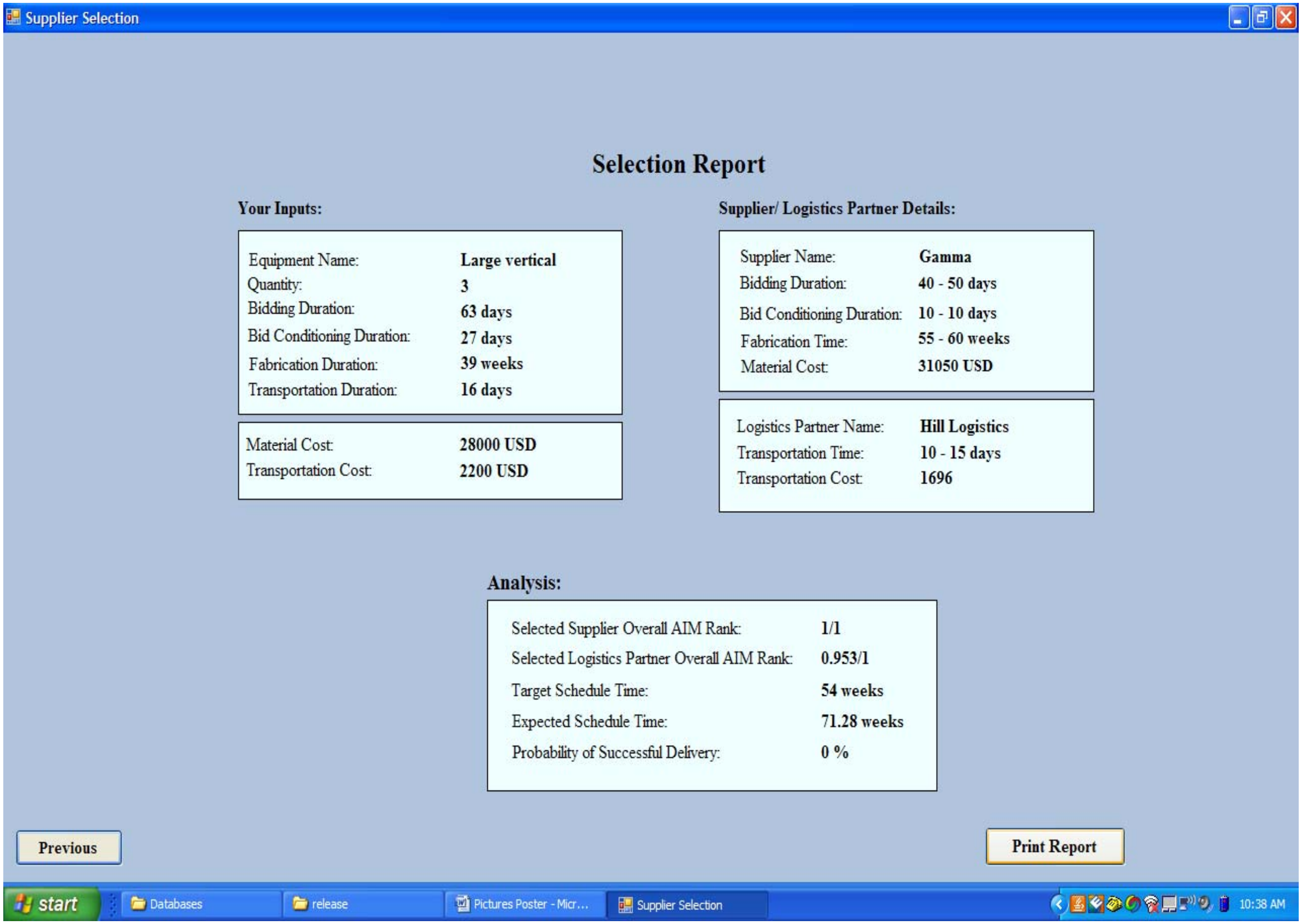
AIM ranking, visualization of tradeoffs, and selection of preferred supplier for schedule analysis



Choosing and weighting most likely durations based on project and supplier's characteristics



Automatic results of PERT analysis after assessment of most likely durations



Final report of equipment supplier evaluation – inputs, selected suppliers, and AIM/PERT results

APPENDIX F – Interview guide for Decision Support validation

1. Please describe your current supplier decision process
2. How does my software fit into this process?
3. How can my software aid/support you in this decision process?
4. What recommendations do you have for improvement of this software?
5. What do you feel could be added to the software to make it more useful for you?
6. How much has your market forecast varied over the last few months?
7. How much do you trust your data for supplier selection decision-making?
8. At what point during the project is the data required to run my software available to you?

APPENDIX G – Commercial Bid Tab

RFQ NUMBER	REV. NO.	GENERAL DESCRIPTION		BUDGET
Recycle Compressor	0	Recycle Gas Compressor		$9,075,465.00

BIDDER			
DATE OF QUOTATION	28-Nov-07	05-Dec-07	18-May-07
BIDDER'S QUOTATION REFERENCE NUMBER	Rev.2	Rev. 2	
QUOTATION VALIDITY DATE	30-Dec-07	05-Mar-08	18-Jun-07
MANUFACTURER			
LOCATION OF MANUFACTURER			
CURRENCY QUOTED	USD / CAN	USD	USD
ACCEPTS TERMS & CONDITIONS	Yes with Exceptions		Yes With Exceptions
SUPPLIER RATING	87.25	N/A	N/A
TECHNICALLY ACCEPTABLE	Further clarifications Required	NO	TBD
TOTAL MATERIAL COST [see BOM]	$9,587,738.00	5,242,369.00	$0.00
CONVERTED TO USD @ (1.466) TO 1 USD		$7,685,312.95	
FAS POINT / SHIPPING POINT	FCA Manufactures Facility	FAS Nearest Port	FCA Manufactures Facility
TERMS OF PAYMENT	Net 30	Net 30	Net 30 W/LOC
TRUCKING COST FOR MOTOR	$5,200.00	$5,200	
OCEAN FREIGHT FOR COMPRESSOR SKID	N/A	$350,000	
TRUCKING COSTS FOR COMPRESSOR SKID	$25,000	N/A	
TRUCKING COSTS FOR AUXILLARY SYSTEMS	$2,500	$2,500	
DOCUMENTATION COSTS	Included	Included	
TAGGING COST	Included	Included	
TOTAL EVALUATED COST	$9,620,438.00	$8,043,012.95	
VERTED TO USD @ (EXCHANGE RATE) TO 1 USD			
RECOMMENDED BIDDER			
ESTIMATED SHIPPING WEIGHT	100,000 LBS	62,000 LBS	
DELIVERY OF DRAWINGS (ARO) - WEEKS	16 Weeks	13 Weeks	
DELIVERY OF EQUIPMENT	15 Months	16Months	23 Months
WARRANTY (MONTHS)	12/18 Months	12/18 Months	12/18 Months
PRICE ADJ. TERMS (FIRM/MAX. ESC.)	Firm	Firm	Budgetary

BASIS FOR RECOMMENDATION AND COMMENTS:	BIDDERS NOT EVALUATED / REASON	APPROVALS:
		Buyer:

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