University of Alberta

Simulation-Aided Framework for Assessing the Effect of Project Quality Management on Construction Performance

by

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ABSTRACT

Construction managers usually find it difficult to understand the implications of quality management initiatives on the performance of construction projects and, therefore, to manage the performance improvement process. On the other hand, while the reliance on quantitative parameters has characterized construction simulation, the consideration of quality management factors in the simulation modeling of construction operations has been limited.

This research work was aimed at developing a framework for integrating the appropriate modeling techniques in order to estimate the effect of project quality management (PQM) factors on the performance of construction operations. The proposed framework takes advantage of the information and knowledge available in construction organizations to model the variables involved in the assessment of the effect of PQM practices on the performance of construction operations. As a result, this thesis presents the design, development, and application of the Project Quality Management Assessment Framework (PQMAF). This framework includes fuzzy-logic and discrete event simulation modeling in order to simulate the effect of PQM practices on the performance goals of construction operations.

The application of the PQMAF is illustrated through a case study, in which the effect of the PQM practices on the completion time of open cut construction projects is simulated. The estimates obtained through this simulation approach are expected to support decision making in the implementation of quality management and related performance improvement actions in construction projects.

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CHAPTER 1

INTRODUCTION

Construction organizations have always been faced with the risk and uncertainty related to the achievement of the goals that are established for each of the projects they carry out. Several reports have acknowledged that the unique characteristics of every project, in terms of organization, management, design, location, supply chain, resources, and interested parties make project goals difficult to achieve as initially planned [Winch 1987; Tay 1994; Gidado 1996; Low and Tan 1996; Kumaraswamy and Dissanayaka 2000; and others]. Construction projects have also been identified as among the most complex of undertakings, with continuous-ly increasing complexity and, therefore, continuous increases in the amount of risks and uncertainties implicit in such undertakings [McCabe 1998; Shammas-Thoma *et al.* 1998]. Meanwhile, a traditional approach in assessing the success or failure of project organizations has been to evaluate performance regarding the extent to which client objectives, like quality, time, and cost of delivery are achieved [Ward *et al.* 1991; Mohsini and Davidson 1992]. When aiming at achieving the project performance goals, construction organizations often implement project quality management (PQM) [Kumar and Wolf 1992; Willis and Willis 1996; Battikha and Russell 1998; Sharma and Gadenne 2002; Bassioni *et al.* 2004; and several others]. However, this approach is a source of uncertainty itself, as it is difficult to determine and understand the impact of PQM practices on project goals. Integrating modelling techniques that have been proven on systems involving uncertainty, this research proposes a framework to model and evaluate the impact of PQM initiatives on construction operations.

1.1 Problem description

Quality management (QM) initiatives are usually implemented at the corporate level in construction organizations and deployed as PQM practices at the project level. This way, the influence of such QM initiatives is propagated up to the operational process level. Moreover, this makes the performance of construction operations dependant on the effectiveness of such QM initiatives. However, the assessment and measuring of QM performance has been a complex subject shrouded in uncertainty and vagueness due primarily to:

i) The complex nature of management processes, as they comprise diverse factors such as human, organizational, and resource considerations [Aghaie & Popplewell 1997]. This complexity is deemed greater in the management of construction projects, due to their unique characteristics [Aoieong *et al.* 2002; Tang *et al.* 2004].

ii) The predominance of subjective variables in management systems, as opposed to objective variables that are preferred by construction managers because they can be measured in quantitative terms. This is especially true regarding QM systems in which the definition of the involved variables is naturally more subjective [Eldabi *et al.* 2002; Yasamis *et al.* 2002; Crawford and Vogl 2006] and, therefore, managers believe QM practices have an effect on performance though this cannot be verified by examining the objective measures [Sharma and Gadenne 2002].

Under these conditions, managers in construction organizations usually evaluate the implementation of quality initiatives in projects based on their judgment and experience, as limited information is a common situation in such decision-making processes. Here, the vague terms are unavoidable since project managers find it easier to assess QM factors by using qualitative linguistic terms. It is difficult to understand the implications of quality initiatives on project performance and, therefore, to manage the performance improvement process.

Probability-based modelling, such as discrete-event simulation, has been an effective technique used to deal with the uncertainty associated with the parameters of construction operations. Discrete-event simulation models have been used to predict the time and cost performance of construction operations, as well as to improve productivity in projects by experimenting with different production strategies [Sobotka 2000; Hajjar and AbouRizk 2002; Fernando *et al.* 2003; and others]. Nevertheless, few efforts have been made towards the incorporation of the uncertainties associated with the management aspects of construction projects or in terms of applying experiment management strategies in construction processes. The reason for this is certainly related to the aforementioned issues regarding the assessment and measuring of QM performance, the complexity of construction processes, and the subjectivity of the variables in QM systems. These issues limit the availability of data; whereas, in any analysis-using simulation, probability distributions have to be determined for each of the state variables involved in the system under consideration. This is deemed the most difficult and controversial part in the generation of simulation models incorporating management factors, in the sense that the modelling process would have to rely on subjectively-derived probabilities. Subjective probabilities for the likely values of the variable under consideration would have to be elicited from suitable experts due to the limited amount of quantitative data available. However, in spite of substantial evidence that it is possible to produce meaningful distributions by using subjective opinions, some authors still doubt the authenticity of such assessments [Byrne 1997; Shaheen 2005]. The difficulty in approximating a probability distribution is that experts do not think in probability values, but rather in linguistic terms [Fishwick and Modjeski 1991; Fishwick 1992]. Therefore, it is thought that more modelling techniques should be integrated within probability-based models in order to overcome the modelling demands of simulation models of this nature and to enhance the modelling capabilities of discrete-event simulation.

Fuzzy sets and fuzzy logic are currently considered the best-adapted formalism to integrate probability uncertainties, vague information, and subjective evaluations [Bojadziev and Bojadziev 1997]. Fuzzy logic provides a methodology with which to handle linguistic variables and describing modifiers like very, fairly, not, etc. whereas fuzzy logic facilitates common sense reasoning with imprecise and vague propositions dealing with natural language and serves as a basis for decision analysis and control actions. Imprecise, complex systems can be described with fuzzy sets that can be used to obtain a conclusion through fuzzy logic operations [Zadeh 1996]. Fuzzy sets and fuzzy logic have been effective techniques for modelling complex systems, such as management systems, in the absence of complete and precise information [Bojadziev and Bojadziev 1997; Gien and Jacqmart 2005]. There have been, as well, a number of attempts to exploit fuzzy logic within the construction engineering and management domain. For example, risk assessment [Tah and Carr 2000; Baloi and Price 2003; Choi *et al.* 2004], safety performance [Lee and Halpin 2003], bid/no-bid evaluation [Lin and Chen 2004], project planning and scheduling [Ayyub and Haldar 1984; Abourizk and Sawhney 1993; Liberatore 2002; Marzouk and Moselhi 2004; Ordoñez and Fayek 2005], cost estimating [Mason and Kahn 1997; Knight and Fayek 2002], productivity performance [Zayed and Halpin 2004], and supplier/contractor performance evaluation [Lam *et al.* 2001; Ng *et al.* 2002; Singh and Tiong 2005], among other topics. Based on the aforementioned advantages of these techniques, fuzzy sets and fuzzy logic were deemed appropriate methods to overcome the modelling demands of this research project.

1.2 Research objectives

This research project targeted the development of a simulation modelling approach to estimate and evaluate the effect of PQM on the performance of construction operations. This modelling approach should be capable of supporting the evaluation of quality improvement strategies in construction projects. The approach towards the achievement of this objective included:

1. Identifying and modelling the factors and interactions within the PQM systems implemented in construction organizations to manage the quality performance of construction operations.
2. Developing an approach through which to model and incorporate the effect of PQM factors that affect the performance of construction operations in construction simulation models.
3. Formulating a framework with which to implement the proposed simulation modelling approach in the evaluation of the effect of PQM systems on the performance of specific construction operations.

4. Carrying out a case study in order to test the simulation modelling approach and validate its capability for supporting decision-making on the improvement of QM strategies in construction projects.

The contributions to the development of the construction engineering and management body of knowledge, expected after the conclusion of this research, include the provision of the following:

1. A modelling approach that is capable of incorporating the effect of project management aspects into stochastic simulation models, which would enhance the potential of the computer simulation techniques used for construction operations. The outputs obtained from such enhanced simulation models are intended to be useful for decision-making on the implementation and improvement of project management processes.
2. A simulation-aided framework with which to evaluate the effect of PQM practices on the performance of construction operations, which would enhance the understanding of the influence of quality systems on construction projects. The use of the proposed assessment approach on specific projects is expected to allow construction managers to make more intelligent, reliable, and timely decisions about the implementation and improvement of project quality management.

1.3 Underlying premises

The following three underlying premises motivated the approach used in this research project:

1. Knowledge-based assessments can be a powerful problem-solving and research tool when dealing with problems where empirical data is not available or difficult to obtain. Regarding this statement, Alarcón and Ashley [1992] pointed out that individuals have a significant amount of relevant information which can be elicited from them toward a problem solution. By identifying relevant information about a problem, an accurate solution estimate can be obtained. This relevant information may exist in one or more persons and needs to be gathered and structured in a way that is useful for decision-making.

2. The quality of the information and the quality of the decision can be improved by taking advantage of both the probability theory and the possibility theory. Moreover, the integration of both methods can be integrated into a modelling approach with which to make the most of the aforementioned kinds of information, and provide valuable feedback on the mechanisms, the interactions, and the most effective ways of achieving project quality objectives.

3. Knowledge-based models can facilitate the learning of new lessons from theoretical models, such as QM standard models. Knowledge-based models rely on the effective pairing of knowledge management and knowledge creation. Knowledge management emphasizes efficiency in using what is known, whereas knowledge creation focuses on generating new knowledge [Lin and Wu 2005]. Two approaches can be applied when generating new knowledge from existing knowledge [Simon 1981]:

i) It is possible to achieve understanding and predict the behavior of systems by integrating partial, sparse knowledge of their subsystems; and

ii) When the basics of a system are poorly understood, it is also possible to gain understanding and predict behavior of the system by using simplified models. Such knowledge is deemed critical to the management of quality performance in construction projects.

Further discussion on these premises is included in Chapters 4 and 5. All three suggest that the procedure or method used to structure or approach the problem is at least as important as, or perhaps more important than, the knowledge about the problem itself.

1.4 Research overview

Figure 1.1 approximates the interrelationships among the research tasks in the way in which they were developed in this research. The initial part of the research effort was focused on the exploration of potential supporting areas for the research. The literature review covered quality performance in construction projects with an emphasis on modelling and assessment, as well as other technical aspects that were expected to provide support to the research. Some of the topics in the literature review included: decision-making under uncertainty, quantitative and qualitative modelling methods and computer simulation in management science, fuzzy sets and fuzzy logic applications, knowledge representation and acquisition, and software alternatives for computer analysis.

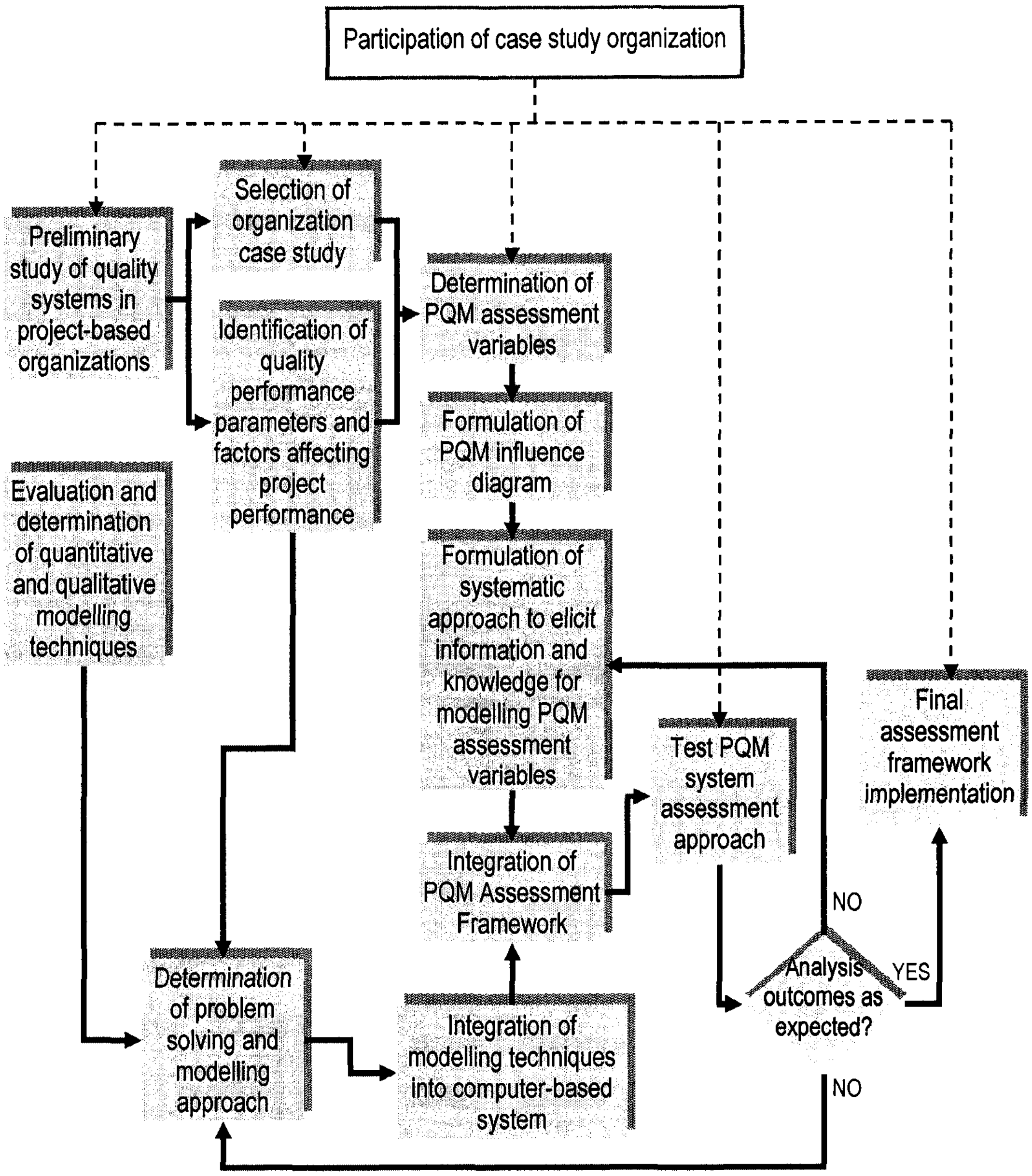


Figure 1.1: Interrelationship among tasks of research methodology

A systematic knowledge acquisition process was established and followed in the research activities. The quality systems of project-based organizations were surveyed early in this research in order to select a case study that would make further development of this research project possible. The parameters to evaluate quality performance and the factors affecting quality performance in construction projects were identified from the aforementioned early study. The most important research activities involved either the participation or validation of managers in the construction organization on which the development of this research project was based. The activities shown in Figure 1.1, as subjected to the organization case study validation, required special meetings for evaluation. The determination of the variables to assess the quality performance factors in construction projects and the formulation of an influence diagram depicting the interrelationship among such variables, were accomplished with the information and knowledge collected from the organization case study.

Quantitative and qualitative modelling techniques for the modelling of hard and soft variables were also explored in order to determine the appropriate techniques to use in the assessment approach. The capacity of computer-based modelling methods, which had been proven on the analysis of construction systems including uncertainty, was evaluated to model the variables identified construction PQM systems. A computer-based system was formulated in order to integrate the different variables and modelling techniques.

Furthermore, a systematic approach was established in order to collect the information and knowledge required in the modelling of the PQM assessment variables and, then, in the application of the integrated computer-based system. This approach was based on the minimal information that should be available in ISO 9001 certified organizations, which includes the nonconformance and causal analysis records. After that, a framework to model and assess the effect of the PQM systems on construction performance was formulated by integrating the information and knowledge elicitation approach and the integrated computer-based system.

A computer prototype was then established with which to test the analysis capabilities of the models generated through the proposed assessment framework. A hypothetical test project, which was based on a typical construction process carried out by the organization case study, was formulated and used for this test. The aforementioned systematic approach used to collect the information and knowledge was also used to accomplish the modelling of the assessment variables of the model under analysis. Several analyses were carried out for different performance levels of the PQM system implemented for the undertaking of projects in the organization case study. Analysis examples, output reports, tables, and graphics were generated in order to display the information in a way useful for research and decision-making.

It is also important to note in Figure 1.1 that the entire development of this research work was entirely based on the study of a single organization. The reason for this was the interpretative nature of this research. The interpretative type of research looks for fitting the findings and experience to a theoretical framework or model [Fellows and Liu 2003]. Since in-depth investigation of the particular experience of this organization was required in this interpretative approach, the data collection was limited to this organization. However, as explained in Section 4.3, the selection of this case study sought the selected organization to be a representative sample of construction organizations with extensive experience on the implementation of quality management systems. This means that the model resulting of this research work may be easy to adapt to the requirements of similar construction organizations.

1.5 Thesis Report Overview

This report consists of seven chapters, including this introductory chapter. Chapter 2 discusses the motivation for developing quality performance models for construction projects, introduces basic concepts, and reviews the current quality performance assessment models in construction. Advantages and limitations of the current models are discussed and shortcomings common to the modelling approaches are also highlighted.

Chapter 3 provides basic background on the modelling techniques adopted in this research: influence diagramming, fuzzy logic, and discrete-event simulation analysis. It discusses problem solving, identifying how the selected techniques support decision-making.

Chapter 4 introduces the Project Quality Management Assessment Framework (PQMAF) that this research work proposes for use in evaluating the effect of PQM systems on the performance of construction processes. The chapter emphasizes the description of a Project Nonconformance Assessment Approach (PNAA), which addresses the elicitation of information and knowledge available in a construction organization as well as the modelling of quality performance assessment variables involved in a PQM system. The participation of the construction organization that supported the development of this assessment framework was also described in this chapter.

Chapter 5 presents the knowledge acquisition and representation methods and discusses the way they are used in the research. This includes the description of the knowledge elicitation tools, as well as the development of the membership functions and inference rules that the fuzzy logic models involved in the modeling approach proposed in this research.

Chapter 6 presents the results of the analyses conducted with the modelling methodology applied to the test project. The initial sections discuss computational issues, such as the simulation steps required in the calculations. Sample analyses are used to illustrate the application of the assessment framework and the features of the modelling approach. An evaluation of the computer simulation prototype and recommendations for final implementation are also included in this chapter.

Chapter 7 summarizes the research accomplishments, identifying and discussing research contributions. It identifies potential applications of the methodology and provides suggestions for future research.

1.6 Summary and conclusions

The inappropriateness of the probability theory-based techniques for systems, in which the information available is vague, was discussed in this chapter. This is the case when the performance of PQM systems is to be evaluated, as variables that are difficult to measure in quantitative terms are involved. Therefore, modelling techniques such as the fuzzy set theory and fuzzy logic were thought to be useful approaches in modelling the variables and interactions involved in the assessment of the effect of the performance of PQM systems on construction processes outcomes. Moreover, this research contention is that the quality of the information and, in that case, the quality of the decision, can be improved by taking advantage of both the probability theory and the possibility theory, which can be integrated into a modelling framework.

Therefore, this research project targeted the development of a simulation-aided framework that takes advantage of the information and knowledge available in construction organizations, in order to support the modelling and evaluation of the effects of PQM processes on the performance of construction operations. This objective involved some underlying premises, such as:

i) The tacit knowledge of construction managers and workers involved in a PQM system can be elicited and used to model the assessment variables involved in the effect of PQM practices implemented in construction projects;

ii) A hybrid modelling approach involving heuristic modelling techniques, such as fuzzy logic and discrete-event simulation, can be used to incorporate the effect of PQM processes in simulation models of construction operations; and

iii)The behavior of complex systems can be better understood, and even predicted, when the implicit knowledge is simplified and integrated into a knowledge-based system.

Furthermore, the expected contributions of this research included the development of a knowledge-based approach through which to evaluate the effect of PQM practices on the performance of construction operations, which would enhance the understanding of the influence of quality systems on construction projects. At the same time, the potential of computer simulation techniques used in construction could be enhanced, as this modelling approach would permit the incorporation of the effects of project management aspects into stochastic simulation models.

CHAPTER 2

QUALITY PERFORMANCE MODELLING – BACKGROUND AND MOTIVATION

This section defines key concepts related to quality performance in construction in order to provide a better understanding of the fundamental aspects involved in the modelling of quality initiatives in construction. The understanding of the concepts discussed in this chapter is essential for the development of the modelling framework proposed in this research. Finally, the reasons and motivation for attempting this research are revealed in this chapter as well.

2.1 Quality performance in construction

Performance represents the results of activities performed in a system. Traditionally, systems are evaluated and analyzed with two major performance measures: *effectiveness* (which represents the degree to which goals are achieved, e.g., time and cost of construction); and *efficiency* (which corresponds to the use of inputs or resources in achieving outputs, e.g., how many man-hours are used to place a ton of concrete) [Turban and Aronson 2001].

However, the meaning of performance may vary depending on the context in which it is used. Performance in the construction context, as applied to on-site activities, is usually evaluated based on the extent to which client objectives like productivity, schedule, safety and quality are achieved [Oglesby *et al.* 1989; Ward *et al.* 1991; Mohsini and Davidson 1992; Brown and Adams 2000; Kagioglou *et al.* 2001; Lee *et al.* 2006; and others]. Whereas, when off-site activities are considered, construction performance involves additional aspects on which management should focus its efforts; for example, customer satisfaction, profitability, flexibility, growth, innovation, quality of work life, and others [Milakovich 1995; Bassioni *et al.* 2004]. Many of these dimensions can be interpreted as functions of the others, which adds complexity to the definition of performance.

Quality can be defined in terms of (i) conformance to the agreed requirements of the customer and (ii) a product or service free of deficiencies [Juran 1988; Crosby 1992, ASQ 2006]. In addition, one should also differentiate between "product quality" (i.e., the quality of elements directly related to the physical product itself), and "process quality" (i.e., the quality of the process that causes the product to be either acceptable or not) [Nagasaku and Oda 1965]. For example, product quality in the construction industry may refer to achieving a level of quality in the materials, equipment and technology, which will endure in the constructed facility; whereas process quality may refer to achieving quality in the way the project is organized and managed during the three phases of planning and design, construction, and operation and maintenance.

The construction industry tends to define quality as the ability of products and/or processes to conform to established requirements. Requirements are the established characteristics of a product, process, or service as specified in the contractual agreement. They are initially determined by the owner or client and then translated into a conceptual design by the designer during the preplanning stage. Next, the requirements are specified in the design documentation, which include plans, drawings, and other specifications. Also during this period, the procurement of materials begins along with the fabrication of basic components. Construction commences when the necessary components of design and procurement are available at the site for erection and installation. After construction is completed, facility start-up can begin. It should be acknowledged that quality is a pervasive concern throughout the entire project process, as the performance of each phase (i.e., achievement of established objectives) in the process will affect the performance of the subsequent phases [Willis and Willis 1996].

According to the process previously described, quality in construction can be defined in terms of meeting the requirements of the following parties [ASCE 1990]:

- *Owner/Client*, in terms of adequate function and appearance; completion on time and within budget; lifecycle costs; operation and maintainability; impacts on environment, health, safety, people, and other features.
- *Designer*, in terms of the provision of a well-defined scope of work; a budget adequate enough to assemble and deploy a qualified, trained, and experienced staff; a budget for obtaining adequate field information prior to design; the provisions for timely decisions by the owner; a realistic schedule in which to perform work; interesting work for staff; realistic risk sharing; a reasonable profit; a satisfied client; and a finished project that results in positive recognition and recommendations for future work.
- *Constructor*, in terms of the provision of a set of contract plans, specifications, and other documents prepared in sufficient detail to permit the constructor to prepare a priced proposal or competitive bid; timely decisions by the owner and the designer on the authorization and processing of change orders; fair and timely interpretation of contract requirements from field design and inspection staff; a realistic risk sharing; an allowance for work performance to take place on a reasonable schedule that permits a reasonable profit; and the positive recognition and recommendations for future work.

- *Regulatory agencies*, in terms of public safety and health; environmental considerations; protection of public property including utilities; and conformance with applicable laws, regulations, codes, and policies.

In addition, other interested parties may include customers and users (of the project's products), partners (e.g., as in joint-venture projects), funders (e.g., financial institutions), suppliers and subcontractors (e.g., organizations supplying products and services to the project), society (e.g., the public at large), and internal personnel (i.e., members of the project organization). Therefore, quality can be defined as well from the point of view of function; for example, a high quality construction project can be described by terms such as ease in understanding drawings, level of agreement in drawings and specifications, economics of construction, ease of operation, ease of maintenance, and energy efficiency [Arditi and Gunaydin 1999].

Based on the previous arguments, the following facts should be taken into account in defining quality performance in construction:

1. The basic project team consists of the owner, the design professional, and the constructor [ASCE 1990]. When members of the project team are competent and work together, chances for quality greatly increase. These three team members, individually and collectively, control quality and are also the direct beneficiaries of quality in the project's product. It is important to say as well that, though the constructor is not responsible for the design, the earlier the contractor gets involved in the design process the higher the quality that can be expected for the project.

2. Quality performance in construction organizations is defined at three levels:

i) The *corporate organization* or originating organization is the level that decides to undertake the project that is eventually assigned to a project organization. The corporate organization may be undertaking multiple projects, each of which may be assigned to a different project organization. The corporate organization may be constituted as a single organization, joint-venture, consortium, etc. [ISO 10006:2003]

ii) The *project organization* carries out the project processes in order to produce a physical facility and provide a contracting service. The project organization may be part of the corporate organization [ISO 10006:2003].

iii)The *operation-level* refers to the multiple construction operations carried out within the project (e.g., pipe installation, trench excavation, or backfilling). Each operation usually involves multiple and different activities, tasks, and resources, by which performance defines the outcome of the operation. The level of quality awareness at the project-level influences to some extent the quality performance at the operation-level. Therefore, quality performance of operations can be evaluated based on the availability and implementation of certain quality improvement techniques that will support the achievement of the operations' goals. This fact is further discussed throughout this chapter and in Chapter 4.

3. Quality performance should be assessed for two categories of processes carried out by project organizations [ISO 10006:2003]:

i) The *project management process* includes all activities that are needed to manage the project and achieve the project objectives on a continual basis (e.g., planning, controlling, and improving).

ii) The *processes related to the project's product* include the activities for realizing the project's product (e.g., design/engineering, procurement, construction).

4. Quality performance in construction is defined over the long term in order to determine its permanence [Yasamis *et al.* 2002]. Construction projects are usually complex systems involving the performance of several activities undertaken at different phases of the project lifecycle (e.g., planning and design, construction, operation and maintenance). Such activities may fail at any time during the development of the project. Failure to take appropriate and opportune corrective actions at any stage during these processes may lead to higher construction costs and time delays later. In such cases, the outcome of the project would be permanently affected as the budget and schedule of processes may not be met.

5. The quality of construction projects is primarily determined during the design and the construction phases of the project. In fact, the major sources of quality deviation are usually identified during the undertaking of these two project phases [Burati *et al.* 1992]. This means corrective actions made in these stages of the project will have a significant influence on the quality of the project's product.

6. Quality performance in construction is result oriented, and thus seeks evidence of quality awareness within the operations and outputs of a project organization [Yasamis *et al.* 2002]. For example, cost overruns and time delays of construction activities are often used to measure the impact of rework occurring during the process.

7. The output of a construction project includes the finished facility and the contracting service. A complete description of project quality requires the consideration of both

these elements [Yasamis *et al.* 2002]. The constructed facility constitutes the product of the construction project. The contracting service refers to the process of transplanting resources to the constructed facility. The level of customer satisfaction experienced with the constructed facility and the contracting service defines the quality of the project.

8. The quality of the project design also significantly affects the quality performance of the constructed facility. Hence quality performance in construction projects not only requires the constructed facility to be reliable, the contracting service to be competent, and the contractor organization to be quality-conscious, but also the design to be reliable, the designing service to be competent, and the designer organization to be quality-conscious.

Nonetheless, the achievement of any performance goal is the result of a systematic effort. In order to plan, control, and improve the performance of processes carried out in an organization, a management system must be implemented [Karapetrovic and Willborn 1998]. The following section introduces the general concepts involved in the management systems implemented in construction organizations for managing the performance of projects and especially quality performance.

2.2 Managing the quality of construction projects

The performance management process is briefly introduced in this section in order to get a better understanding of the role of a QM system in construction projects. Next, the implementation of quality systems in construction organizations to manage the quality of projects is discussed.

2.2.1 Performance management

The performance management process involves a system by which the performance of processes is accomplished. Its objective is to provide a proactive closed-loop control system by which (i) the corporate and functional policies and strategies are deployed to all business processes, activities, tasks, and personnel; and (ii) feedback is obtained from various levels through the performance measurement system to facilitate appropriate management decisions [Bititci *et al.* 1997]. The performance management system makes this possible by incorporating the following processes [Katz and Green 1997]:

i) *Performance awareness* is the process that assigns responsibility for performance management, defines key processes and desired outcomes, and educates the responsible parties about their roles in the performance management system.

ii) *Performance measurement* is the process of determining how successful organizations or individuals have been in attaining their objectives and strategies [Evangelidisz 1992] by means of collecting performance data and comparing the actual results with projections to determine process/outcome variance.

iii)*Performance improvement* is the process that includes the plan to improve the dimensions of performance, the implementation of the improvement plan, and the communication of the results of the plan's implementation.

Concerning construction organizations, when the project processes fail to achieve the project objectives (e.g., quality, time, and cost), the performance management process should improve the effectiveness and efficiency of such processes. In order to manage this, the performance measurement system should be supported by an information management system (IMS) in the identification, collection, storage, updating, and retrieval of [Ayyub 2001]:

- *Objective* or empirical information based on experimental results, or observations; and
- *Subjective* information based on experience, intuition, other previous problems that are similar to the one under consideration, or the physics of the problem.

Such information should be gained during the performance of a project in order to identify the opportunities for improvement [ISO 10006:2003]. Using information derived from the IMS that is relevant to past projects, managers should be able to make fact-based decisions on such opportunities. Figure 2.1 depicts the performance management process.

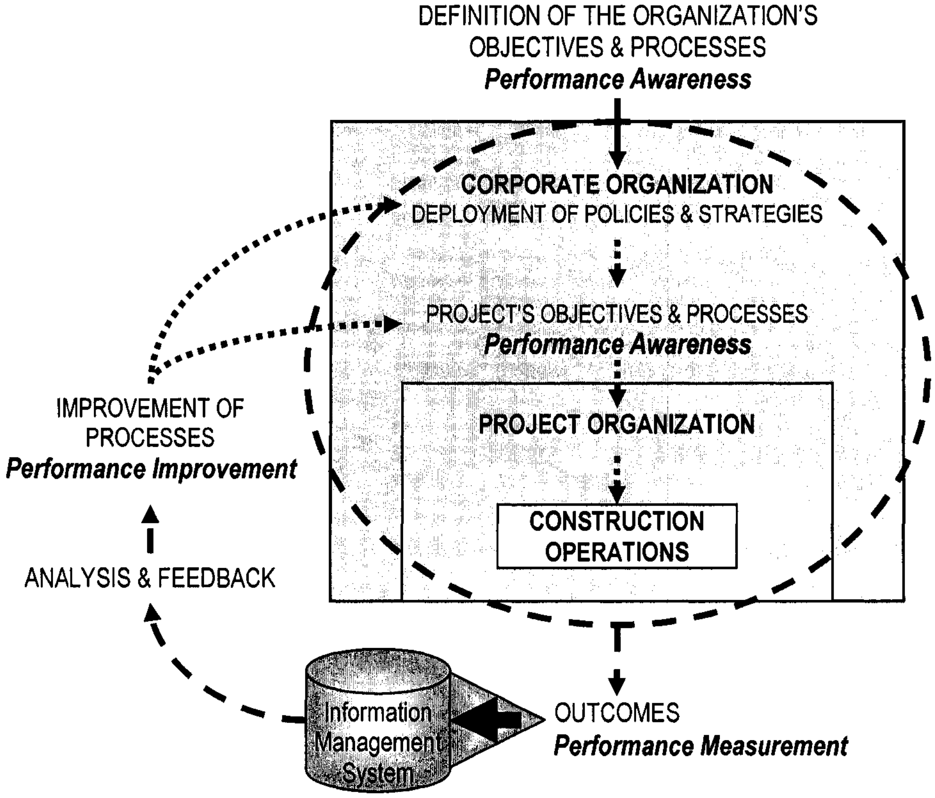


Figure 2.1: Performance management process in project-based organizations

2.2.2 Quality systems in construction

A quality system, as defined by the American National Standard Institute (ANSI), is "the organizational structure, responsibilities, procedures, processes, and resources for implementing quality management" [Arnold 1994]. Quality systems implemented in an organization for ensuring that the requirements for quality will be met can be as basic as the application of inspection procedures or quality control (QC) techniques in key processes. However, more comprehensive quality systems like the ones used for quality assurance (QA) and quality management (QM) provide a higher level of confidence related to product quality to the customers. According to ISO 9000:2005, QM is defined as coordinated activities for directing and controlling an organization with regard to quality; and QA is the part of QM that focuses on providing confidence that quality requirements will be fulfilled. Moreover, the International Organization for Standardization (ISO) provides conceptual guidelines to structure and implement the elements of a quality system. The current ISO standards that are relevant to this research are the following:

- *ISO 9004:2000, Quality management systems – Guidelines for performance improvement* provides guidelines beyond the requirements given in ISO 9001 in order to consider both the effectiveness and efficiency of a quality management system, and consequently the potential for improvement of the performance of an organization. The objectives of customer satisfaction and product quality are extended to account for the satisfaction of interested parties and the performance of the organization.
- *ISO 10006:2003, Quality management systems – Guidelines for quality management in projects* provides guidance on the application of quality management in projects of varying complexity, duration, environments, and the kind of product or process involved. This standard is not a guide to project management itself, but to quality in project management processes; it is not intended for use in certification/registration.

The generic approach offered by these standards allows an organization to develop its quality system in accordance with its specific needs, objectives, products, and services [Battikha and Russell 1998]. These standards present models for quality assurance by fostering the structure through which to implement the total quality management (TQM) business philosophy [Arnold 1994]. TQM is a framework that engages the entire organization in a system for the purpose of satisfying internal and external customers through continuous improvement [Drummond 1992]. The most utilized TQM-based models are the European Foundation for Quality Management (EFQM) Excellence model in Europe, the Malcolm Baldrige National Quality Award (MBNQA) in the United States, and the Deming Prize in Japan.

As part of an organization's management system, the QM system focuses on the attainment of the objectives related to quality in the organization (ISO 9000:2005). A QM system consists of: (i) a framework for guiding quality-related actions by all employees, and (ii) a means for assessing how well these actions are carried out [Yasamis *et al.* 2002]. Moreover, the QM system includes the following processes [Karapetrovic and Willborn 1998; Juran 1988; ISO 9000:2005]:

i) *Quality planning* involves the identification of the customer's requirements and objectives for quality, as well as the design of the quality system and the allocation of resources required to perform the project.

ii) *Quality control* ensures that the requirements for quality are met. Quality planning predetermines the quality control system to implement in a project.

iii) *Quality improvement* targets the increase of the effectiveness and efficiency of the quality system.

The similarity between these QM sub-processes and those of the performance management system is evident at this point. In fact, a QM system can be defined as a performance management system focused on the meeting of objectives of quality established for the processes carried out within an organization. QM involves the optimization of quality activities performed in producing a product, process, or service, and encompasses prevention and appraisal [Burati *el al.* 1992]. Over the last few decades, many QM models have evolved from the classic total quality concept (management of quality) to a more business excellence (quality of management) approach [Adebanjo 2001]. Moreover, QM system represents a tool to effectively manage and improve the performance of processes, and not only the objectives related to quality. Figure 2.2 depicts this idea.

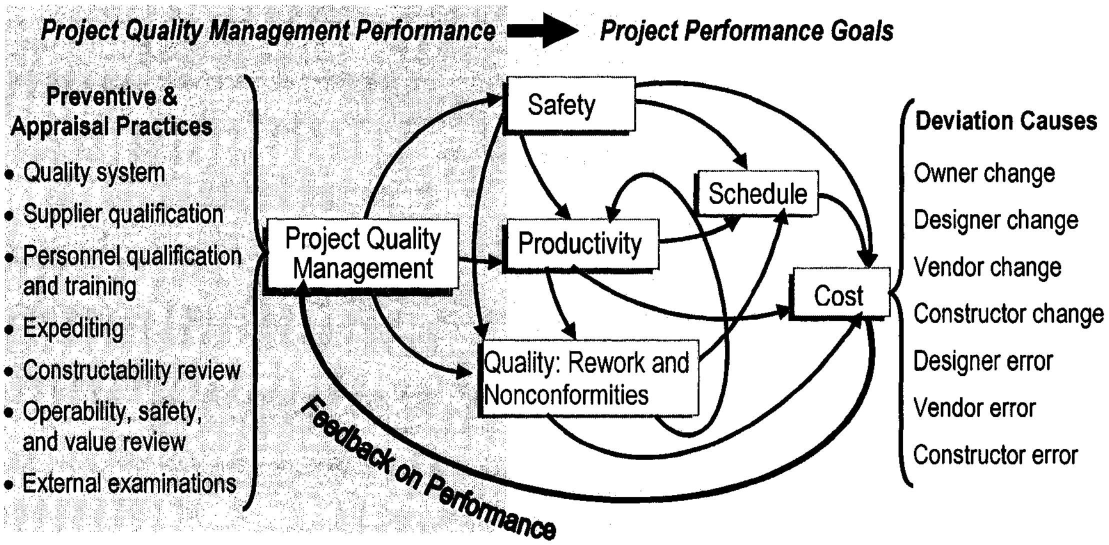


Figure 2.2: Influence of quality management on project performance

However, few construction organizations have any systematic program for ensuring and improving the experience that internal and external customers have with the organization [Shammas-Toma *et al.* 1998; Tam *et al.* 2000]. Moreover, clients have been urging construction organizations to consider the use of formal QM systems as a means of achieving improved conformance to established requirements [Battikha and Russell 1998]. Assuring conformance to specified project requirements involves a series of QM activities during the various phases of the project. Battikha and Russell [1998] provide an overview of the quality assurance process throughout these phases of construction projects as follows:

i) In the design phase, quality requirements for the end-products and/or their performance are specified in order to meet the customer and/or user's needs.

ii) Depending on whether the specifications are method-type, end-result, or performance-related, construction methods are chosen to permit achievement of these requirements, and QM procedures are developed to ensure compliance with the specifications.

iii) Once construction is underway, nonconformance may be detected in terms of quality process, end-products, and/or other characteristics, with its source being derived from a myriad of factors, such as environmental, managerial, and operational factors, or deficiencies in the design itself.

iv) Appropriate actions must then be taken to rectify nonconforming situations and, if possible, a diagnosis of the causes of nonconformances, followed by their elimination, in order to avoid similar situations arising during the remainder of the project or future projects.

v) Finally, and as an extension of the current practice, knowledge gained during the construction process pertaining to the quality requirements and factors (and their values) that resulted in nonconformance should be documented in the post-construction phase in a form that assists in the quality management function of future work.

More about project quality management is discussed throughout the next section.

2.2.3 Project quality management and continuous improvement

In order to codify project management in construction, the Project Management Institute (PMI) has published a Construction Extension to the Project Management Body of Knowledge (PMBOK) Guide. The sixteen knowledge areas outlined in the guide include Project Quality Management (PQM), which describes the processes required to ensure that the project will satisfy the needs for which it was undertaken [PMI 2003]. As shown in Table 2.1, the Construction Extension of the PMBOK Guide and ISO 10006:2003 standard propose comparable approaches to support the management of projects.

However, it should be acknowledged that the ISO 10006 standard proposes a more comprehensive approach to QM, as it takes account of an imperative practice within the QM philosophy: the implementation of improvement-related processes. In fact, project management appears to be in conflict with the principle of continuous improvement. Because of the temporary nature of projects and the uniqueness of their results, the implementation of continuous improvement in projects is thought as impossible [Orwig and Brennan 2000]. In addition, Owen and Brennan [2000] also point out that the short-term approach to measure project performance undermines the long-term emphasis of QM on continuous improvement. Nevertheless, it is until the PM is seen as an ongoing and repetitive process in an organization, to which at least some of the QM practices could apply, that the implementation of continuous improvement in projects is thought possible [Orwig and Brennan, 2000].

Table 2.1: Project Management Knowledge Areas and Processes

PMBOK Guide – 2000 Edition		ISO 10006:2003	
Knowledge areas	**Sub-processes**	**Quality Processes**	**Sub-processes**
4. Project Integration Management	4.1 Project plan development 4.2 Project plan execution 4.3 Integrated change control	7.2 Interdependency-related processes	7.2.2 Project initiation and project management plan development 7.2.3 Interaction management 7.2.4 Change management 7.2.5 Project and process closure
5. Project Scope Management	5.1 Initiation 5.2 Scope planning 5.3 Scope definition 5.4 Scope verification 5.5 Scope change control	7.3 Scope-related processes	7.3.2 Concept development 7.3.3 Scope development and control 7.3.4 Definition of activities 7.3.5 Control of activities
6. Project Time Management	6.1 Activity definition 6.2 Activity sequencing 6.3 Activity duration estimating 6.4 Schedule development 6.5 Schedule control	7.4 Time-related processes	7.4.2 Planning activity dependencies 7.4.3 Estimation of duration 7.4.4 Schedule development 7.4.5 Schedule control
7. Project Cost Management	7.1 Resource planning 7.2 Cost estimating 7.3 Cost budgeting 7.4 Cost Control	6.1 Resource-related processes 7.5 Cost-related processes	6.1.2 Resource planning 6.1.3 Resource control 7.5.2 Cost estimation 7.5.3 Budgeting 7.5.4 Cost control
8. Project Quality Management	8.1 Quality planning 8.2 Quality Assurance 8.3 Quality Control	Function integrated to all the project management processes incorporated to the ISO 10006 standard model.	
9. Project Human Resource Management	9.1 Organizational planning 9.2 Staff acquisition 9.3 Team development	6.2 Personnel-related processes	6.2.2 Establishment of the project organizational structure 6.2.3 Allocation of personnel 6.2.4 Team development
10. Project Communications Management	10.1 Communications planning 10.2 Information distribution 10.3 Performance reporting 10.4 Administrative closure	7.6 Communication-related processes	7.6.2 Communication planning 7.6.3 Information management 7.6.4 Communication control
11. Project Risk Management	11.1 Risk mangmnt. planning 11.2 Risk identification 11.3 Qualitative risk analysis 11.4 Quantitative risk analysis 11.5 Risk response planning 11.6 Risk monitoring & control	7.7 Risk-related processes	7.7.2 Risk identification 7.7.3 Risk assessment 7.7.4 Risk treatment 7.7.5 Risk control
12. Project Procurement Management	12.1 Procurement planning 12.2 Solicitation planning 12.3 Solicitation 12.4 Source selection 12.5 Contract administration 12.6 Contract closeout	7.8 Purchasing-related processes	7.8.2 Purchasing planning and control 7.8.3 Doc. of purchasing requirements 7.8.4 Supplier evaluation 7.8.5 Contracting 7.8.6 Contract control
13. Project Safety Management	13.1 Safety planning 13.2 Safety plan execution 13.3 Administration & reporting	Not highlighted in ISO 10006 standard model	
14. Project Environmental Management	14.1 Environmental planning 14.2 Environmental assurance 14.3 Environmental Control	Defined in ISO 14001:1996 Environmental management systems – Specification with guidance for use	
Not highlighted in PMBOK model		8.1 Improvement-related processes	8.1.1 Measurement and analysis 8.1.2 Corrective & preventive actions
15. Project Financial Management	15.1 Financial planning 15.2 Financial control 15.3 Financial administration	Not highlighted in ISO 10006 standard model	
16. Project Claim Management	16.1 Claim identification 16.2 Claim quantification 16.3 Claim prevention 16.4 Claim resolution	Not highlighted in ISO 10006 standard model	

2.2.4 Quality management practices in construction organizations

The foundations of the quality orientation of a company are defined at the corporate level, and corporate-level quality is achieved through the corporate quality culture. The corporate quality culture is the organizational value system that encourages a quality-conscious work environment; and quality-conscious companies adopt QM systems [Yasamis *et al.* 1996]. Studies have identified certain requirements as the critical success factors of a QM system [Saraph *et al.* 1989; Black and Porter 1996]. Black and Porter [1996] provide a particularly thorough listing of critical success factors. Table 2.2 shows these factors as adapted by Yasamis [*et al.* 2002] for construction organizations. As the focus of this research is on the assessment of PQM processes, the effect of the aforementioned factors was assumed to be implicit with regard to the quality performance of projects. Project management processes that have been identified as recommended practices for managing quality performance at the project level are introduced in the following section.

2.2.5 Recommended quality practices in construction projects

Specific management practices have been identified as strong supporters of the successful achievement of performance objectives for construction projects. Anderson [1992] confirmed through an empirical study that as the percentage use of key principles and recommendations on projects increases, this causes a corresponding increase in the percentage of projects that meet cost, schedule, quality, technical, profit, and safety targets. Moreover, management practices based on TQM principles have been especially emphasized as a means to meet objectives related to quality in project processes.

Table 2.2: Quality management success factors at the corporate level

Factors	Description
1) *People and customer management*	• Human resource management in line with company performance plans • Employee recognition/measurement to support quality performance plans • Management of customer relations
2) *Supplier partnership*	• Assurance of supplier quality • Action to assist and improve the quality and responsiveness of suppliers • Strategic management of suppliers
3) *Communication of improvement information*	• Determination of quality costs • Assessment of needs for quality training and subsequent delivery and review • Benchmarking of processes in no-competing organizations • Promotion of quality improvement with outside groups
4) *Customer satisfaction orientation*	• Commitments to customers through strengthening of warranties/policies, etc. • Comparisons of customer satisfaction with competitors and internal indicators • Determination of improvements in customer satisfaction • Benchmarking of direct competitors' products and policies
5) *External interface management*	• Recognition of responsibilities for public health and safety, and the environment • Determination of customers' future requirements • Integration of the design process with customer and operational requirements
6) *Strategic quality management*	• Process control and improvement of core processes in accordance with design • Active leadership by managers in quality issues • Inclusion of employee well-being considerations in improvement activities • Senior executive commitment to quality through involvement & communications • Development/implementation of long-term plans/strategies focused on quality • Analysis of performance and cost data to support improvement priorities
7) *Teamwork structures form improvement*	• Use of specific organizational structures to support quality improvement • Use of techniques to identify key processes, customers and suppliers
8) *Operational quality planning*	• Development/implementation of short-term plans/strategies focused on quality • Consideration of performance requirements in developing short-term goals
9) *Quality improvement measurement systems*	• Assessment and improvement of processes, practices and products/services • Management of data/information to support quality improvement efforts • Procedures to ensure reliability and improvement of data gathering
10) *Corporate quality culture*	• Consideration of performance requirements in developing long-term goals • Encouragement of a company wide culture committed to quality improvement

The literature reports several studies that have contributed to the identification of project QM practices implemented in construction organizations. The following are the most significant efforts pursuing such a purpose:

i) Davis and Ledbetter [1987] identify a comprehensive list of QM activities usually implemented in the design and construction phases. As seen in Table 2.3, these activities are primarily related to the prevention and appraisal efforts in the PM function.

ii) The Construction Industry Institute (CII) and the Business Roundtable's Construction Industry Cost Effectiveness (CICE) [Anderson-Tucker 1990a, 1990b] have articulated that the key principles and recommended practices having the strongest effect on project performance are those included in the eight PM categories shown in Table 2.4.

iii)The CII has also proposed eight types of prevention and appraisal activities, which depict how quality improvement efforts occur within an organization's QM system [Neese & Ledbetter 1991; Ledbetter 1994]. Table 2.5 shows a classification of such activities.

For the purposes of this research, all of the PM processes, activities and procedures implemented at the project level in order to manage quality objectives are identified as PQM practices. They are the elements under evaluation in the modelling approach proposed in this research and represent specific alternatives to PQM derived from the corporate QM strategy. This research's contention is that the quality performance of construction operations depends on the performance of such PQM practices. Chapter 4 further clarifies this assumption.

Table 2.3: Representative QM activities for design and construction

Design	• Design requirement verification • Quality program development – Responsibility allocation – Budget setting – Specification input • Design validation • Design review – Bases and assumptions – Calculations	• Constructability review • Specification review • Design checks • Drafting control – Review, release • Change control – Design – Specifications – Drawings	• Documentation control – Drawings – Engineering records – Job history • Standard documentation preparation – Design methods – Specifications • Engineering process audit • Contractor inspection • Post project review
Construction	• Quality program development • Quality circles • Quality plan development • Constructability review • Supplier evaluation • Contractor and subcontractor evaluation • Inspection of materials	• Quality audits • Inspection of off-site fabrication • Inspection of construction • Testing and evaluation of equipment • Resolution of noncompliance reports • Training and skill deployment of workers • Record keeping – Rework documentation	

Table 2.4: Project management recommended practices by CII/CICE [*]

Management category	Scope statement
Strategic project organizing	This category focuses on principles/recommendations related to project organization, establishing objectives, scope definition control, establishing communications/information processes, and constructability planning.
Contracting practices	This category focuses on principles/recommendations related to contracting strategy (planning, packaging, etc.) and the use of specific contract provisions and/or clauses for contracts controlled by the initiating party.
Design effectiveness	This category covers principles/recommendations related to the evaluation of the design effort, incorporating constructability concepts into design, and control of design activities.
Project controls	This category focuses on principles/recommendations related to control integration, decision-making, scope control, control techniques, and estimating practices.
Management of quality	This category is concerned with principles/recommendations related to the implementation of quality assurance/quality control and the documentation of quality effectiveness.
Materials management	This category focuses on principles/recommendations related to planning and use of materials management on projects.
Human resource management	This category is concerned with principles/recommendations related to the quality of site supervision, field work force motivation, training, and site labor practices (substance abuse, overtime, etc.).
Safety	This category covers principles/recommendations related to safety communications, specific practices, and management attitude toward safety.

* Table taken from Anderson [1992].

Table 2.5: Project quality management activities proposed by the CII

Activities	Description
Quality system	• Developing quality improvement programs, standards and goals. • Indoctrination and training. • Data collection, analysis, and reporting.
Supplier qualification	• Evaluating the ability of suppliers, vendors, contractors and subcontractors to perform capability. • Developing a certification system and compiling rating scores to measure supplier performance.
Personnel qualification, testing and training	• Testing personnel's ability to perform work according to specified standards. • Craft certification and training for quality assurance/control activities.
Expediting	• Activities prior to delivery to ensure on-schedule delivery of all purchased materials, equipment, services and third-party engineering information.
Constructability review	• Activities to ensure that the most efficient design and planned construction methods are used to maximize the chance of constructing perfect utilities. • Construction site layout studies, dewatering studies, prefabrication studies, etc.
Operability, safety, and value review	• Determining if the design is in compliance with client, industry and government requirements in terms of operability, safety analysis, process hazards and operability reviews, value engineering studies, etc.
Internal examinations	• Reviewing, checking, inspecting, testing and observing services/products produced internally in the organization. • Reviewing designs, drafting and documentation. • Soil testing, concrete testing, hydro-testing piping, etc.
External examinations	• Reviewing, checking, inspecting, testing and observing services/products produced externally by others. • Inspection of material/equipment received, vendor document reviews, etc.

2.3 Measuring quality performance in construction projects

The construction industry is a project-oriented industry in which each project is unique and may be considered as a prototype, although a similar set of process stages is involved in every project [Love and Holt 2000; Kagioglou *et al.* 2001]. There are two traditional approaches to measure the performance of construction projects: (i) in relation to the product as a facility, i.e., if the requirements of the customer and the specifications of the design for the facility have been met; and (ii) in relation to the creation of the product as a process, i.e., in terms of the achievement of the requirements or objectives established for the project management processes, as well as for the processes related to the project's product. In particular, the former has been the primary performance assessment (in terms of success or failure) of construction projects [Kagioglou *et al.* 2001]. However, from a QM system viewpoint, it is the assessment of the performance of processes used to accomplish the project objectives that should be emphasized. In other words, it is the effectiveness and efficiency of project processes that should be improved in order to obtain an improvement in the project's product.

This research work seeks to develop a framework for the assessment of the effect of QM practices in construction projects on operation-level goals; therefore, performance assessment should concentrate on measuring the quality performance of processes carried out at the project-level. The following sections introduce the quality performance measurement of both the project quality management processes and the processes related to the project's product, (e.g., design and construction activities).

2.3.1 Measuring the performance of PQM systems

Measuring the performance of QM systems can be challenging for organizations and researchers looking to assess the benefits of their implementation in order to make appropriate decisions with regard to their control and improvement. This endeavor is usually difficult because of the subjectivity involved in the assessment of two key aspects to be considered when measuring the performance of QM systems: (i) the maturity or implementation stage of QM initiatives and practices in the organizations, and (ii) the impact of such initiatives and practices on performance goals of the organizations. Attempts to assess these aspects are briefly introduced throughout the following sections.

2.3.1.1 Measuring the maturity of quality management initiatives

Subjective performance measures are widely accepted in organizational research [Lawrence and Lorsch 1967; Dess 1987; Powell 1992;] and are usually applied to measuring maturity and/or use management strategies and initiatives. Regarding the assessment of the maturity level of QM systems, several models have been proposed to deal with this kind of evaluation [Crosby 1979; Williams and Bertsch 1989; Calingo 1996; ISO 9004:2000]. These models assume that organizations pass through different stages of QM integration, each one associated with unique QM practices. They offer conceptual bases for the development of the assessment framework proposed in this research work. A brief review of these models is summarized in Table 2.6.

Moreover, the measurement of the maturity of QM systems has been preferably based on self-assessment approaches. Self-assessment is accepted as a comprehensive, systematic, and regular review of an organization's activities, these results of which are referenced against a specific model [Ahmed *et al.* 2003]. It is deemed a powerful tool to measure performance, highlighting areas that require immediate action, and involving people at the strategic, tactical, and operational levels in the development of a process improvement approach to quality [ISO 9004:2000; EFQM, 1999]. In addition, self-assessments usually involve the collection of managers' perceptions through the application of Likert scales. The following are examples of studies that have subjectively measured the implementation and/or use of QM practices in construction:

Table 2.6: Quality system maturity typologies

Model	Stages	Description
Crosby: quality management maturity [Crosby, 1979]	• *Uncertainty*	The cost of quality is about 20 per cent of sales and management has no comprehension of quality as a management tool.
	• *Awakening* • *Enlightenment* • *Wisdom*	Transformation in management understanding and attitude towards quality, how quality appears within and organization, how organizational problems are handled, the cost of quality as a percentage of sales, quality improvement actions taken by management, and how management summarizes the organization's quality problems.
	• *Certainty*	The cost of quality (reported and actual) falls to about 2.5 percent and management considers TQM as an essential part of the company system.
Erasmus University: quality maturity [Williams and Bertsch, 1989]	• *Top management consensus*	Top management wholeheartedly embraces quality management as the appropriate means to improve productivity, achieve customer satisfaction and enhance market performance.
	• *Company-wide education* • *Problem solving* • *Quality improvement*	Phased introduction of company-wide education, the use of TQM tools and techniques, the adoption of quality improvement strategies and the institutionalization of TQM in the organization.
	• *Total control*	The organization achieves total integration of quality management and business strategy.
Calingo's strategy-quality integration [Calingo, 1996]	• *Annual budgeting*	– Specific quality values and goals are non-existent. – Quality assurance is done by inspection and quality data is scarce. – Customer needs, beyond mere conformance to specifications, are not explicitly considered in setting product and service requirements. – Human resource management (HRM) plans do not reflect quality requirements, and little quality training is provided.
	• *Long-range planning*	– Long-range plans make random references to quality and other non-financial performance initiatives. – Top management embraces quality management as the appropriate strategy to improve profitability, achieve customer satisfaction and enhance performance in the market. – Quality initiatives focus on improving product reliability. – A QM system that meets ISO 9000 standards is developed and implemented. – A company-wide education process is initiated in which everyone learns to use problem-solving methods and fundamental concepts of TQM.
	• *Strategic quality planning*	– Strategic planning process is implemented to explicitly address quality goals, consider customer needs, and incorporate competitive benchmarking. – Good system documentation is undertaken. – Company-wide quality control training is virtually complete, with most managers and an increasing number of employees already trained in TQM. – Problem-solving tools are actually applied to problems within departments, allowing participants to build experience and refine their problem-solving skills. – Quality circles or work improvement teams are formed, and quality assurance shifts in emphasis from product reliability to a focus on the quality of all business activities, from strategy to operations. – A high degree of error prevention is attained through process control. – Customer needs shape product/service requirements.

Table 2.6 (Continuation)

(Continuation) *Calingo's strategy-quality integration* [Calingo, 1996]	• *Management by policy*	– Explicit use of quality as a strategy in which it is involved the management and co-ordination of quality improvement across the entire organization. – Quality improvement is viewed in terms of breakthrough projects. – Principles of policy deployment are implemented to progress towards integrating quality within the entire strategic plan of the business. – Prevention-based design processes are implemented. – HRM plans reflect TQM priorities. Most managers and many employees are trained in TQM. – Quality requirements are communicated to suppliers.
	• *Strategic quality management*	– Total integration of strategic management and TQM, which leads to a free flow of information between strategic planners and quality planners. – A disciplined customer-driven, process-oriented approach to quality planning is demonstrated. – Quality awards such as Malcolm Baldrige National Quality Award, Japan's Deming Prize, or the European Quality Award are pursued. – Incremental quality improvement plans are increasingly being replaced by bold initiatives such as cycle-time reduction, optimization experiments and business process re-engineering. – HRM planning integrated with quality planning. Participative management and high level of employee empowerment. All employees have comprehensive TQM training. – Cooperation with suppliers is pursued to meet quality standards.
Model for the Evolution of a Quality System [Montgomery, 1996]	This model defines the maturity of a quality system based on the predominant tools used. Montgomery related this evolution to the systematic reduction in process variation.	
	• *Immature quality system*	Extensive use of acceptance sampling is made.
	• *Maturing quality system*	Acceptance sampling is displaced by process control.
	• *Mature quality system*	Design of experiments and process control are the primary tools used.
ISO 9004:2000 Performance maturity levels [ISO 9004: 2000]	• *No formal approach*	No systematic approach evident, no results, poor results or unpredictable results.
	• *Reactive approach*	Problem- or corrective-based systematic approach; minimum data on improvement results available.
	• *Stable formal system approach*	Systematic process-based approach, early stage of systematic improvements; data available on conformance to objectives and existence of improvement trends.
	• *Continual improvement emphasized*	Improvement process in use; good results and sustained improvement trends.
	• *Best-in-class performance*	Strongly integrated improvement process; best-in-class benchmarked results demonstrated.

i) Anderson [1992] proposed a subjective scale to measure the level of perceived use on projects of key project management practices, such as those listed in Table 2.3. The scale was an 11-point ratio scale where 0 = "not used on any project" and 10 = "100% use on projects".

ii) Kumar and Wolf [1992] developed a self-assessment model, which enables a project manager to determine the extent to which QM practices are in place and to identify any problem areas detrimental to the overall quality of the project. They focused on the assessment of three basic aspects of QM that recapitulate the assets of the MBNQA model: customer needs and expecta-tions, organizational and management aspects, quality assurance practices. The self-assessment model includes a series of questions related to the aforementioned aspects. Project managers should evaluate each question subjectively by checking one of the five possible rankings, each of which is associated with a score (i.e., 0 = Not at all, 1 = Inadequate, 2 = Adequate, 3 = Good, and 4 = Superior) in order to quantify the evaluation and calculate a process quality index (PQI) according to Equation 2.1.

$$Process\ Quality\ Index = \frac{Total\ Rating\ Score}{Maximum\ Score} \times 100 \qquad \textbf{(2.1)}$$

Next, the maturity of the QM practices in place can be appraised according to the QI obtained and the criteria proposed by Kumar and Wolf, as shown in Table 2.7.

Table 2.7: Criteria to appraise the maturity of QM practices

Scale	Remarks
0 – 20	Absence of any quality program
20 – 40	Minimal presence of quality
40 – 60	Acceptable levels of quality, but sufficient for competitiveness
60 – 80	High degree of quality level in all areas of the project
80 – 100	Quality level reflects long term commitment to fulfilling the customer's needs

iii)Powell [1995] assessed the organizational implementation of several TQM-based quality features using a subjective zero to five scale in which 5 = highly advanced in implementation, 1 = have not begun implementation but intend to, and 0 = do not intend to implement. Respondents were asked to use such a scale to assess the implementation of quality features such as executive commitment, philosophy adoption, closeness to customers, closeness to suppliers, benchmarking, training, organizational openness, employee empowerment, zero defects mentality, flexible manufacturing, process improvement, and measurement.

The data obtained from studies similar to those previously described have been used to perform quantitative analyses based primarily on statistical techniques. Such techniques have been used to determine the impact of QM initiatives on project performance, as explained throughout the following section.

2.3.1.2 Measuring the impact of quality management

The effectiveness of QM systems is evaluated in terms of the improvements that result from their implementation and use [Sower *et al.* 2002]. The measurement of such improvements has commonly focused on the degree to which performance targets (e.g., productivity, profitability, cost, schedule, etc.) of projects have been met; and again, subjective assessments have been involved in this kind of endeavor. The following are examples of studies, reported within the construction industry, which included a measurement of the effects of the implementation of QM systems:

i) Anderson [1992] uses an 11-point subjective scale to measure the perceived frequency of meeting cost, schedule, quality, technical, profit, and safety performance targets in projects where specific key project management practices had been implemented. In the scale, 0 = "project performance target is never met" and 10 = "project performance target is always met". Anderson uses these subjective measures to determine whether or not the level of use of such PM practices on projects have had a positive impact on the percentage of projects that meet cost, schedule, quality, technical, profit, and safety targets. A correlation analysis confirms this hypothesis.

ii) Powell [1995] measures the impact of TQM on performance targets such as productivity, competitive position, profitability, and revenues. He proposes an agree-disagree scale (5 = "agree strongly", 1 = "disagree strongly") which respondents should use to indicate their perception on statements such as "our quality program has dramatically increased our organization's productivity", for example.

iii)Karim *et al.* [2005] elicit information about various positive and negative outcomes resulting from the implementation of ISO 9000-based QA systems in construction organizations. They design different sets of questions intended to assess performance outcomes regarding project-related benefits, customer relations, marketing advantage, communication, supplier relations, and drawbacks, which must be responded to on a Likert scale: strongly agree, agree, disagree, and strongly disagree.

However, a common approach to assessing the impact of the implementation and use of QM practices in construction organizations has been the measurement of quality costs. A further introduction to the measurement of quality costs in construction is provided throughout the following sections.

2.3.2 Measuring quality performance of construction processes

Construction organizations traditionally employ "hard" measures such as cost, schedule, and safety in order to determine a project's quality performance on projects [Stevens *et al.* 1994; Chung 1999]. This point of view is related to the degree of compliance with stipulations in the contract, which serves to assess the quality of the supplier in terms of not only meeting the technical specifications of the project but also the contract sum and the contract period. However, it has also been pointed out that the cost, time, and quality of a construction project do not, in isolation, provide a balanced view of the project's performance and that, therefore, they are not sufficient to comprehensively assess the performance of construction projects [Kagioglou *et al.* 2001]. Hence, other performance indicators such as customer satisfaction, profitability, flexibility, growth, innovation, quality of work life, organizational capability, and others have been suggested [Sink 1985; Milakovich 1995; Bassioni *et al.* 2004; Ward *et al.* 1991; Kagioglou *et al.* 2001]. However, such indicators are better suited to evaluating the performance of the entire project, whereas if one is to focus on the evaluation of the performance of processes at the operation-level, then looking at cost, time, and quality may be sufficient [Oglesby *et al.* 1989].

However, a common approach to quantifying the quality performance of construction processes has to do with the measurement of quality costs. Within quality costs, quality failures can have an especially adverse effect on the performance and productivity of design and construction processes, as they are a major contributing factor to time and cost overruns [Chan and Kumaraswamy, 1997; Love, 2001]. The measurement of the quality costs incurred in construction projects is briefly introduced in the next section.

2.3.2.1 Issues on the measuring of quality costs in construction

Organizational quality performance measurement in construction has traditionally relied on quality costs [Bassioni *et al.* 2004]. Measuring the cost of quality is deemed the first step towards the implementation of process improvement as it permits to monitor performance trends [Clark and Tannock 1999; Aoieong *et al.* 2002]. The most widely accepted method in construction is the traditional prevention-appraisal-failure (PAF) model, which classifies costs as prevention, appraisal, internal failures, and external failures [De Ruyter *et al.* 2002; Love and Irani 2003]. Nevertheless, the implementation of the PAF model has been reported as difficult to achieve in construction projects [Barber et al. 2000], whereas the process cost model (PCM) has been deemed a more feasible approach to measuring quality costs in construction due to its simpler classification as cost of conformance, cost of nonconformance, and process cost [Aoieong *et al.* 2002].

On the other hand, the literature also reveals that the systematic tracking of quality costs has not been widely developed in construction organizations [Tang *et al.* 2004]. In fact, most studies on the assessment of quality costs in construction have been limited to measuring rework, which is merely one aspect of the lack of quality management [Davis and Ledbetter 1987; Hall and Tomkins 2001]. Furthermore, the absence of rework does not mean that there is no risk of nonconformances or good performance of the organization's quality system.

2.3.2.2 Causes of quality failures in construction projects

Terms such as rework, quality deviation, non-conformances, quality failures, and defects have been used interchangeably in previous studies in the construction context [Love and Edwards, 2005]. Whatever the term used to identify the lack of quality in a process or product, all of them have been deemed significant factors contributing to time and cost overruns in construction projects [Love 2002]. Having acknowledged this, academics and practitioners have attempted to identify the causes [e.g., Burati *et al.* 1992; Willis and Willis 1996; Barber *et al.* 2000, Josephson *et al.* 2002; Love and Smith 2003; Love *et al.* 2003] in which the changes, errors, and omissions occurring during the performance of the different project phases are implicitly involved [Farrington 1987]. In fact, the classification of causes of quality deviations proposed by the Construction Industry Institute [CII 1990] includes the changes and errors/omissions associated with key participants in construction projects, as seen in Table 2.8. Further specific factors affecting quality performance of construction projects have been documented as well. For example, Table 2.9 includes other relevant studies identifying the factors that contribute to the occurrence of quality failures in construction projects.

Table 2.8: CII's classification of causes of quality deviations in construction

Causes	Description
Owner change	Changes authorized by the owner-client during design, construction, or start-up.
Designer change	Changes made by the designer to improve the value or operability of the process.
Vendor change	Changes made to a purchased product or to its interface to the project by the vendor.
Constructor change	Changes made by the constructor on a product or process system.
Designer error	Changes made by the designer to correct an error/omission during design, construction or start-up
Vendor error	Changes made by the vendor to correct an error or omission to a furnished product or process.
Constructor error	An error or omission made by the constructor.

On the other hand, Hall and Tomkins [2001] have recommended caution when analyzing the causes of quality failures arising during a project, as the identification of root causes may not be straightforward. The complex, interwoven array of factors (and variables within factors) which contributes to the occurrence of quality failures obscures any specific cause-and-effect relationship that may exist [Love and Edwards 2004]. For example, the root cause of suppliers' errors may in fact have been poor selection of specific suppliers in the first place, or poor coordination of the various trades. In fact, a drawback of previous studies has been their failure to take into account the hierarchical relationships of the factors involved in project organization in order to identify the root causes of quality failures. What such studies have set out to do in their analyses of the causes of quality failures is to factorize the different types of occurrences into categories that may not clearly identify the root causes of the problem and, especially, the PM processes requiring improvement.

Accurate identification of the causes of quality failures is critical to performance improvement, as the purpose of analyzing the causes of poor quality is to provide an overview of the issues, indicate the direction for corrective measures, and change management [Hall and Tomkins 2001]. Furthermore, such efforts provide information that serves three purposes [Willis and Willis, 1990]: (i) the identification of the nature of quality problems; (ii) the determination of the effectiveness of the prevention and appraisal efforts and the need for improvement actions; and (iii) the provision of a baseline measure for evaluating quality improvement efforts in future projects. This was an important point taken into account in the design of the assessment framework proposed here.

According to the literature review described in this section, the systematic assessment of quality performance has been quite limited in construction organizations. Moreover, there is also a need for an assessment of quality performance in its broadest context, as most of the current assessment frameworks used in construction focus on partial assessments of quality performance, such as the quantification of rework costs. As an alternative, analysis of the consequences of nonconformities on the entire construction management process rather than merely on the physical construction of the product should be pursued [Burgess 1996; Foster 1996]. In addition, Hall and Tomkins [2001] have pointed out that what should be assessed is any disruption to the construction of the product, in order to focus such analysis on the flow of value to the client. For example, where the process is interrupted or goes awry in some way, non-value adding activities will be incorporated into the given process.

Furthermore, the aforementioned approach to measuring quality performance in terms of the consequences of nonconformities on a project outcomes agrees with ISO guidelines, which suggests that nonconformities affecting the product realization and management processes should be tracked and analyzed in order to assist learning and provide data for improvement [ISO 9004:2000; ISO 10006:2003].

Therefore, for the purposes of this research, quality performance was assessed in terms of the duration of delays caused by disruptions associated with nonconformances occurring during the performance of construction activities. This approach was deemed appropriate as this research targeted the simulation of the effect of PQM factors on construction operations using discrete-event simulation (DES) models. This is further discussed in Chapters 3 and 4.

Table 2.9: Factors affecting quality performance in construction

Authors	Classification of Causes
Burati *et al.* [1992] (Based on CII, 1990)	• *Construction change,* i.e., change in the method of construction • *Construction error/omission,* i.e., error or omission made during construction • *Design change/improvement,* i.e., design revision, modifications, improvements • *Design change/construction,* i.e., design change initiated by construction • *Design change/field,* i.e., design change required to field conditions • *Design change/owner,* i.e., design change initiated by the owner • *Design change/process,* i.e., design change initiated by operations or processes • *Design change/fabrication,* i.e., design change initiated by the fabricator • *Design change/unknown,* i.e., design change with an unknown source of initiation • *Design error/omission,* i.e., error or omission made during design • *Operability change,* i.e., change made to improve operability • *Fabrication change,* i.e., change made during fabrication • *Fabrication error/omission,* i.e., error or omission made during fabrication • *Transportation change,* i.e., change made to method of transportation • *Transportation error/omission,* i.e., error or omission made in transportation
Hall and Tomkins [2001] (Based on Barber *et al.* 2000)	• *Communications*, e.g., poor information control, misunderstandings. • *Plant and equipment*, e.g., breakdowns, punctures. • *Personnel*, e.g., carelessness, lack of training, poor workmanship, sickness. • *Design*, e.g., mistakes that get on to the construction site. • *Management*, e.g., lack of planning, errors, poor organization. • *Suppliers* (including subcontractors), e.g., poor selection, errors and mistakes. • "*Force majeure*", e.g., third parties, weather, ground conditions.
Love and Edwards [2004]	• Lack of understanding for end-user requirements. • Poor contract documentation and low consultant fees. • Poor standard of workmanship. • Lack of quality focus. • Poor supervision and inspection.
Robinson Fayek *et al.* [2004]	• *Engineering and reviews*, e.g., late design changes, poor document control, scope changes, errors and omissions. • *Construction planning and scheduling,* e.g., late designer input, constructability problems, unrealistic schedules, insufficient turnover & resource commissioning. • *Leadership and communications*, e.g., ineffective management of project team, lack of operations persons buy-in, lack of safety and QA-QC commitment, poor communications. • *Material and equipment supply*, e.g., untimely deliveries, prefabrication and construction not meeting requirements, noncompliance with specification, materials not in the right place when needed. • *Human resource capability*, e.g., unclear instruction to workers, inadequate supervision and job planning, excessive overtime.

2.3.3 Quality performance measurement systems in construction

A performance measurement system refers to the measurement system implemented by a company, while a performance measurement framework is a general theoretical framework developed in research that can act as the basis for a company's performance measurement system [Bassioni *et al.* 2004]. Effective quality-performance measurement frameworks must provide guidelines on the elicitation of the appropriate information required to assess the quality performance of a system (e.g., a project management system). Table 2.10 includes the most relevant frameworks that have been developed to respond to the specific requirements of construction organizations for measuring quality performance in construction projects. This review was significant for the purposes of this research, as it permitted the appropriate formulation of the project quality-management assessment framework (PQMAF) proposed here. Based on the review of the systems in Table 2.10, it was possible to identify the different facets of performance within a construction organization.

However, according to the focus of this research, only those models encompassing performance factors at the project- and operation-levels were deemed relevant to this research. This is to say that the QPMS and the PROMQACS were particularly useful in formulating a quality-performance assessment approach, based on the tracking of nonconforming events, which should provide the information related to quality performance that the PQMAF requires. The project nonconformance assessment approach (PNAA) would overcome the limited information that performance measurement systems in construction organizations usually have regarding the performance of PM processes. The PNAA is detailed in Chapter 4.

Table 2.10: Performance measurement systems for construction

Model	Description
Quality Performance Tracking System (QTPS) [Davis & Ledbetter, 1987]	Management tool to systematically collect and classify the quality costs involved in design and construction. The QTPS was based on the concept of quality costs as developed in the manufacturing industry, which was adapted to be compatible with QM practices and cost and schedule systems used in the construction industry. QM activities in design and construction (exhibited in Table 2.3) were identified for cost tracking. Meanwhile, deviations were categorized by cause (owner, designer, vendor, transportation, constructor, other), type (change, omission, error), and time of detection (design, construction, start-up); though their tracking was limited to rework costs. The QTPS also identifies information for analysis pertaining to the task associated with the deviation, activity involved, response, and degree of severity.
Quality Performance Management System (QPMS) [Ledbetter & Wolter, 1990]	It is a refined version of the QPTS to provide management with information on where improvements can be made. It was designed as a self-measurement system to track the personnel time invested in three main endeavors: (i) normal work, (ii) quality management work (prevention and appraisal activities in Table 2.5); and (iii) rework (deviation corrections in Table 2.8). QPMS requires three pieces of information when tracking rework: (i) the root cause of the rework, (ii) the instigating discipline, and (iii) the phase in which the rework was detected. The QPMS framework has been adopted by several construction organizations that have indicated its usefulness for identifying quality issues and their impact costs, deciding about their rectification, as well as reducing the projects costs [Willis & Willis, 1996].
Balanced Scorecard (BSC) [Kagioglou *et al.* 2001]	The original BSC proposed by Kaplan and Norton [1993] is a performance management system that incorporates four main measurement categories (perspectives): (i) customer perspective, (ii) internal business processes, (iii) learning and growth, and (iv) financial perspective, in order to evaluate whether a business is moving towards its strategic goals. However, Kagioglou et al. [2001] added two perspectives important to the construction industry: project and supplier perspectives. Each of these six perspectives may include a wide range of potential submeasures, depending on the organization's needs. The framework rationalizes the relationships between performance measures and goals derived from strategy to indicate potential areas for improvement, trough a process-performance measurement relationship matrix.
Project Management Quality Cost System (PROMQACS) [Love and Irani, 2005]	It was developed to determine quality costs in construction projects. The systems supports the tracking of quality costs from two different sources: (i) prevention and appraisal work, and (ii) quality failures, though it focuses on quality failures. The information regarding quality failures is collected in six data modules: (i) the description of the problem, (ii) the originator of the failure (client, contractor, consultants, suppliers), (iii) the class of failure (error, change, omission, damage), (iv) the subcontract trade (piling, excavation, reinforcement, etc.), (v) the affectation on time (ineffective work, inactivity, critical/non-critical activities), and (vi) the affectation on cost (direct, overhead, impact). PROMQACS can be used as a decision support system by clients, contractors, etc., as it is able to evaluate their performance, as well as the factors that contribute to rework. Furthermore, it can be used to identify poor organizational management practices and specific parts of the procurement process that have induced error to occur.
Framework for Measuring Business Performance in Construction [Bassioni *et al.* 2005]	A conceptual framework for measuring the business performance of construction organizations was formulated based on the principles of the balanced scorecard and Business excellence models. The framework is divided into performance driving factors (i.e., leadership; customer and other stakeholder focus; strategic management; information and analysis; people management; partnerships and suppliers management; resources management; intellectual capital management; risk management; work culture; and process management) and performance results factors (i.e., people, partnership and supplier results, project results, customer and society results, and organizational business results).

2.4 Performance assessment models in construction

For the purposes of this research, a performance assessment model can be seen as a framework that provides a methodology for predicting the behavior of a system and which is based on the assessment of the impact of different factors affecting the system. Several authors have attempted to build conceptual models to evaluate and predict the construction process by explaining different aspects of project performance. Most of these efforts have been related to construction productivity [Thomas and Yiakounis 1987; Sanvido 1988; Alarcón and Ashley 1992; Rodrigues and Williams 1998; Hajjar and AbouRizk 2002; and others], and different modelling techniques such as cross-impact analysis, system dynamics, and DES have been used. Moreover, although some models have been developed to specifically evaluate construction quality performance [Love *et al.* 2002; Yasamis *et al.* 2002; Ling 2005] none of these models focuses on quality performance at the operation-level, which is the target of the model proposed in this research work. From the models reviewed in the literature, only those that were relevant to this project are introduced:

Alarcón and Ashley [1992] develop a modelling methodology to support management decision-making for application to individual projects. The model combines experience captured from experts with assessments from the project team. The methodology consists of a conceptual, qualitative model structure and a mathematical model structure. The conceptual model structure, called the general performance model (shown in Figure 2.3), is a simplified model of the variables and interactions that influence project performance. The modular structure of the model permits the collection of judgments and knowledge from experts that are accurately concerned with the subject being assessed at four different levels of variables [Alarcón & Ashley 1996; Venegas & Alarcón 1997]:

i) *Strategies* represent the elements under evaluation in the model.

ii) *Drivers* are the variables directly impacted by the implementation of strategy alternatives, and which propagate their effects to the rest of the model. A driver usually has a performance element associated with it, such as productivity of quality, which reflects the potential of the driver to perform.

iii) *Processes* describe the key function of construction projects and are useful in identifying key information and resources within a project.

iv) *Performance outcomes* are useful to reflect the impact of strategies on project performance: for example, cost, schedule, effectiveness, etc.

Moreover, the mathematical model involved in the Alarcón and Ashley's modelling methodology uses concepts of cross-impact analysis and probabilistic inference to capture the uncertainties and interactions among project variables. The model allows management personnel to test different combinations of project-execution strategies through the prediction of project cost, schedule, and other performance outcomes. Several studies have been carried out with this modelling methodology to support decision problems, such as the analysis of owner-contractor relationships [Alarcón *et al.* 1994], strategy implementation at the corporate- and project-level in construction organizations [Venegas and Alarcón 1997; Ashley *et al.* 1996; Alarcón and Bastias 2000], environmental policy impacts [O'Ryan *et al.* 1997], and contractor selection [Alarcón and Morgues 2002].

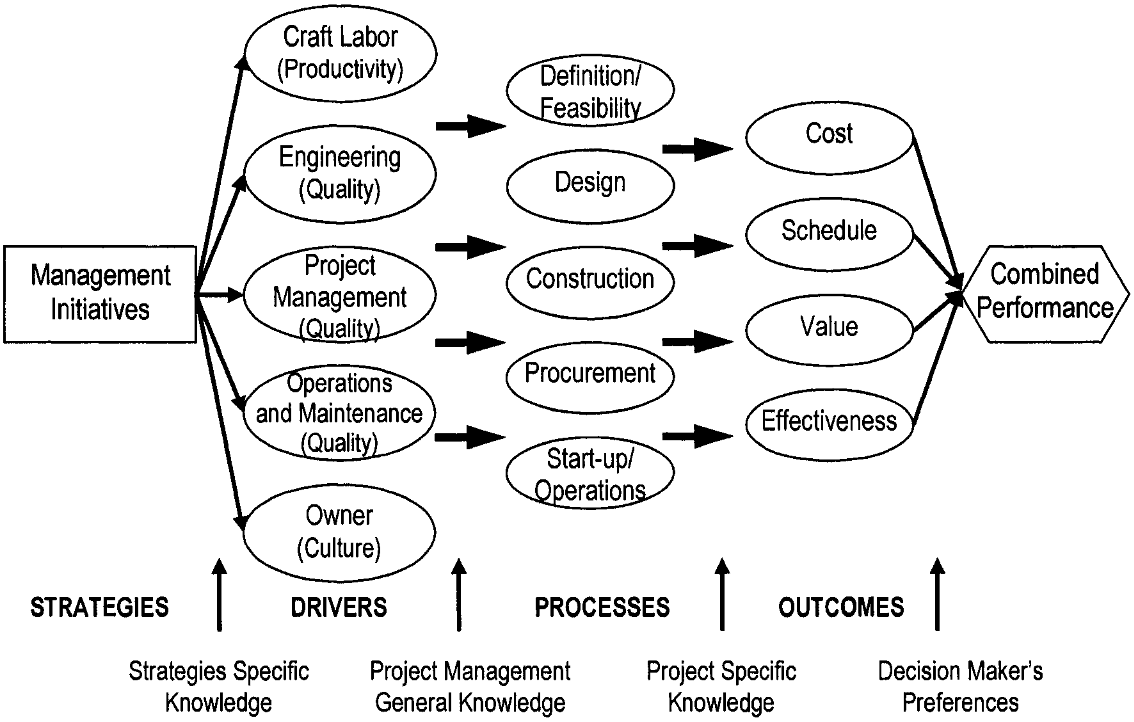


Figure 2.3: Alarcón & Ashley's General Performance Model structure and knowledge inputs

On the other hand, Yasamis *et al.* [2002] proposed a contractor quality performance (CQP) evaluation model, which uses the set of factors called CQP indicators to facilitate quality-based evaluations of contractors. The CQP evaluation model considers that the quality performance of a contractor is defined at the corporate level and the project level, as made explicit in the framework shown in Figure 2.4. Therefore, the model includes the following indicators:

- *Corporate CQP indicators* are the processes an organization uses to achieve corporate quality attributes such as leadership, employee empowerment, partnerships development, information and analysis, continuous improvement, and client focus. The corporate CQP indicators adopted for the CQP evaluation model are those identified by Black and Porter [1996] and shown in Table 2.2.

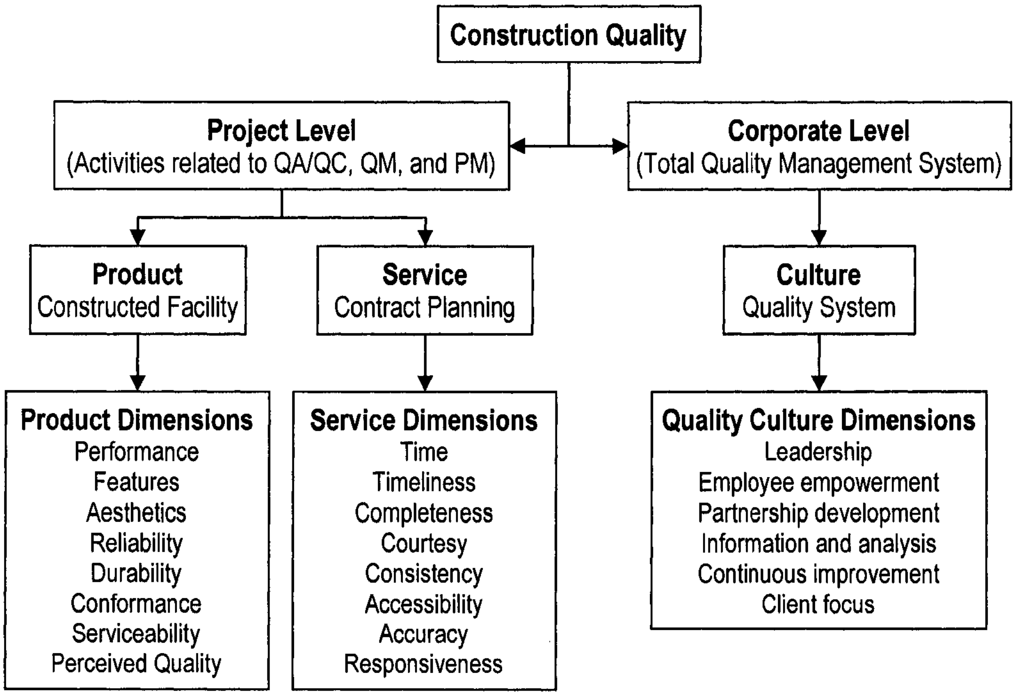


Figure 2.4 Yasamis *et al.*'s alternative framework to construction quality

- *Project CQP indicators* are the tools, techniques, and processes an organization uses to achieve the project quality attributes that define product quality (e.g., performance, features, reliability, conformance, reliability, serviceability, aesthetics, and perceived quality) and the service quality (e.g., time, timeliness, completeness, courtesy, consistency, accessibility and convenience, accuracy, responsiveness) delivered by a construction organization. The first set of indicators at this level consists of the most common QA/QC tools used in project management today, such as inspection, control charts, Pareto diagrams, statistical sampling, flowcharting, cause-and-effect diagramming, checklisting, and metrics development. The second set of indicators includes the QM activities proposed by the CII as listed in Table 2.5, while the third set comprises the remaining PM functions (shown in Table 2.1) which facilitate achieving some or all of the project quality attributes.

The evaluation of the CQP indicators in this model includes their subjective weighting by owners and end-users in order to assess the quality orientation of a contracting company and identify those business practices geared towards the construction of a higher quality facility and provision of a higher quality service.

The aforementioned assessment models were relevant to the development of the project quality management assessment framework (PQMAF) proposed in this research, as they offered some guidelines for the modelling of assessment variables involved in quality performance and project management systems in construction. According to this, the models generated from the PQMAF should feature the following:

i) Permit the evaluation of the effect of quality management on the performance of construction operations; hence, the need for a conceptual structure that clearly represents the propagation of such effect up to the operation level was identified.
ii) Comprise the evaluation of the quality performance of the QM factors involved at different levels of a project organization.
iii) Estimate the performance outcomes of construction operations based on the assessment of the performance level of QM factors.
iv) Comprise an appropriate performance assessment approach in order to facilitate the acquisition of the information required for the development and application of models for estimating the impact of QM on the performance of construction operations.

Further details on the aforementioned features are discussed in Chapter 4.

2.5 Motivation

Most experts agree that quality, in its broadest sense, is the dominant factor involved in the success of organizations [e.g., Dale 1999; Feigenbaum 1999]. However, the problems that construction firms may face during the implementation phase of QM systems have been reported in the literature [Low and Teo 2004], and may include the following:

- Managers fail to understand the concept and philosophy behind QM systems.
- QM has yet to be proven to work in the construction industry, and organizations may be waiting for it to become a more tested and common practice in the industry.
- Construction organizations are usually more inclined towards profit generation rather than quality improvements, especially if they have already met the minimum requirements for quality.
- In addition to the above, costs of implementing QM systems are perceived to be high, although these may be offset by lower quality costs in the long run.
- It may be more difficult to implement a QM system on a construction site (i.e., at the operation-level) than within the organization because the other parties in the project team may resist the process.
- Employees within the organization may be resistant to change, which will render education and awareness related to quality management more difficult.

In conclusion, these problems illustrate the need that construction managers at all levels still have for getting a better understanding of the impact of PQM practices on project goals. This is especially true with respect to managers participating at the project level, as they focus on practice within the organization and usually find the understanding exercise too "theoretical" [Szilagyi and Wallace 1990]. However, Szilagyi and Wallace

[1990] point out that though managers have little interest in testing theories or models, they are often still interested in knowing if such theories and models have been tested in order to determine how much confidence to place on its predictions. The aforementioned authors also add that accurate prediction is the practical outcome of using scientifically-based theory and models and, therefore, is the rationale for developing logically deduced theories and testable models. This means that theories and models resulting in reasonably accurate predictions would also be useful as guidelines to understanding organizational behavior. Moreover, additional research is needed to test organizational behavior theories. Specifically, managers need scientific procedures such as theory formation and model building in order to predict the results of their policies and decisions. In addition, there is a need to structure and classify the knowledge related to quality performance that is available in construction organizations.

The development of computer technologies has allowed existing construction management tools, such as simulation, to be applied in the performance forecasting of construction operations. In addition, tools have been developed based on improved computer modelling techniques for construction projects. Of particular importance is research on the development of database management systems, knowledge-based expert systems, fuzzy sets theory, and their integration to DES. Taking advantage of these tools is imperative to the development of models that improve the decision-making process undertaken by managers in the construction industry.

2.6 Summary and conclusions

The literature review reported in this chapter made possible the recognition of important aspects related to the assessment of quality performance in construction organizations, which were taken into account in the development of the assessment framework proposed. Such aspects include the following:

i) Measurement and assessment models are needed for enhancing the quality of the information available in construction organizations for decision-making on the continuous improvement of quality performance management in projects. There is also a need to test out QM models in order to assist managers in determining how much confidence to place on their predictions.

ii) Continuous improvement in construction projects is possible when the improvement efforts focus on the assessment of PM processes implemented in the organization, as PM is an ongoing process in the organization. QM in construction projects can itself be regarded as a repetitive operation.

iii) The effectiveness of QM processes implemented at any organizational level should be evaluated in terms of the improvements that result from its implementation. At the project-level, the assessment of the impact of PQM practices on the performance of construction operations is deemed an appropriate approach to realize such an attempt.

iv) There is also a need to assess quality performance in its broadest context, as most of the current assessment frameworks used in construction focus on partial assessments of quality performance, such as the quantification of costs of rework. As an alternative, the analysis of the consequences of nonconformities on the entire construction management process rather than merely on the physical construction of the product should be pursued. For example, quality performance could be assessed in terms of the duration of delays caused by disruptions related to nonconforming events occurring during the performance of construction activities.

v) Quality-performance assessment models should comprise the performance assessment of the different PQM factors involved in construction projects in order to make clear the effect that they have on the performance of the construction activities.

CHAPTER 3

PROBLEM SOLVING AND MODELLING BACKGROUND

This chapter includes three major sections. The first section discusses the modelling approach used for the development of a knowledge-based system for supporting the assessment of the performance of quality management systems in construction projects. The second section reviews the theoretical foundations of computer-based modelling techniques that were relevant to this research, including fuzzy-logic based and simulation modelling, and clarifies how the techniques were adapted for the purposes of this research. Meanwhile, the third section clarifies how the proposed modelling techniques could interact as a computer-based system for estimating the effect of a project quality management (PQM) system on the performance of a construction operation.

3.1 Problem solving and modelling approach

Project managers usually have to decide on the implementation and improvement of project quality management (PQM) initiatives under a degree of uncertainty. Modelling management factors in construction organizations requires a modelling technique that considers the complexity of human, organizational, and resource aspects involved in management processes and activities [Aoieong *et al.* 2002; Tang *et al.* 2004]. Moreover, traditional or classical modelling techniques often do not capture the nature of complex systems, especially when humans are involved [Bezdek 1995]. For example, it is difficult to model the cause-effect relationship between uncertainty variables and project performance directly using a simulation model or an analytic model due to the complex nature of these variables; thus, in construction organizations, the assessment of such cause-effect relationships mostly relies on analogies to experience [Song *et al.* 2005]. However, relevant and explicit historical data regarding the interactions of factors in QM systems are usually unavailable. In fact, limited information is a common problematic situation in such decision-making processes, due primarily to the subjectivity of the variables involved in those systems, making them difficult to measure quantitatively [Eldabi *et al.* 2002]. The vague terms may be unavoidable, since project managers find it easier to assess quality in qualitative linguistic terms. For example, the maturity of a given PQM process and the significance of such a maturity level to the performance of each of the construction resources involved in the system, and then, the consequences of the resulting quality levels of such resources on the performance of a given construction operation. In addition, the performance of a project depends on the combined effect of the alternative levels of quality of the construction resources, e.g.: (i) high quality of labor, average quality of supervision, and low quality of supplying; or (ii) low quality of labor, high quality of supervision, and average quality of supplying; and so on. An engineer or manager may not have any mathematical tools available to estimate that combined effect on the quality performance of construction operations.

From the previous argument, the requirement of a tool to support decision-making under the aforementioned conditions is made clear. It is also clear that such a tool should have the capacity to work with qualitative knowledge rather than with explicit information. Therefore, a knowledge-based system was deemed an appropriate approach through which to model the uncertainty prevailing within the interaction of QM factors.

A knowledge-based system is an artificial intelligence (AI) application the goal of which is to transfer, utilize, and extend common-sense knowledge [Negoita and Ralescu 1987].

Furthermore, several previous studies have demonstrated how stochastic simulation can cope with the weaknesses associated with qualitative methods and be used as an effective research strategy [Eldabi *et al.* 2002]. However, simulation has been mostly used as a quantitative tool and, in fact, very little effort has been made on simulation models towards analyzing, designing, or developing management systems [Aghaie and Popplewell 1997]. The literature reveals that this is due to the complexity of most management systems, which are comprised of diverse factors; such as human, organizational, and resource considerations. Therefore, the capability of simulation modelling can also be improved by incorporating more modelling techniques in order to be able to model uncertainty in an explicit and effective manner. The enhancement of simulation modelling should take advantage of the knowledge that construction experts have on QM systems as an alternative to the limited information.

Though AI and simulation are both modelling techniques developed independently using different problem solving concepts, the integration of these two approaches, combining qualitative knowledge representation in a quantitative simulation model, has been attempted in the past [Fishwick and Modjeski 1991, quoted by Chang and Chen 2006]. The development of modern software engineering has made it easier to integrate the two techniques, so they can benefit each other. So-called knowledge-based simulations or hybrid expert simulations are usual monikers in the literature for identifying such combined systems [Chang and Chen 2006]. A variety of successful applications are described in various domains, including the steel fabrication operations

[Stirling and Sevinec 1991], the study chemical processes [Eisenberg 1991], resource planning in service and manufacturing industries [Lee *et al.* 1996; Chang and Chen 2006], emergency management systems [Hernández *et al.* 2001], and construction operations [Mohamed and AbouRizk 2006], among others.

Moreover, fuzzy sets and fuzzy logic were identified as the most appropriate techniques to develop a knowledge-based system that could deal with the abovementioned problem, as they have been proven as effective tools for modelling complex systems, such as management systems, in the absence of complete and precise information [Bojadziev and Bojadziev 1997]. Currently, the fuzzy theory is deemed the best-adapted formalism that permits to integrate probability uncertainties, vague information, and subjective evaluations [Gien and Jacqmart 2005].

However, before producing a model (and thus a computer program), it is necessary to identify the main elements involved in the system to be modeled. In doing so, Pidd [1984] has pointed out two aspects that should be taken into account. The first is the nature of the system to be simulated, which implies the model needs to be a good representation of the system; this includes selecting the modelling approaches that better suit the problem. The second aspect is the nature of the study to be carried out; which means it is necessary to identify the objectives of the study, the point of the simulation, and the results expected. The following section clarifies the answers to these questions and how the abovementioned modelling techniques were used for accomplishing the objective of this research.

3.1.1 Modelling approach to simulate the effect of PQM on the performance of the construction operations

The objective of this research was identified as the development of a framework to facilitate evaluating a PQM system. Figure 3.1 represents the scope of influencing factors that need to be modeled in order to measure the effectiveness of PQM in a quantitative manner. In particular, to measure the impact of PQM on construction operation productivity we need to model the construction operation and explicitly include in these models all influencing factors shown in Figure 3.1. To achieve this, it is necessary to consider the statistical parameters depicting the effect of the performance of the PQM system. These are required as inputs to the discrete-event simulation model. As shown in Figure 3.1, the effect of a PQM system on the performance of a construction operation can be measured in terms of the disruptions due to the nonconformities observed during the undertaking of the operation. Therefore, these disruption measures were modeled with two statistical parameters:

i) The number of nonconformities in each of the construction activities included in the operation, and
ii) The duration of the delays associated with each of these nonconformities.

Moreover, the selection of the modelling technique for estimating these statistical parameters was constrained by the availability of data for appropriate quantitative input modeling. Therefore, fuzzy logic was used in order to incorporate subjective assessments in such estimation. Based on the PQM factors included in the diagram shown in Figure 3.1, the implementation of two different fuzzy logic-based applications was required:

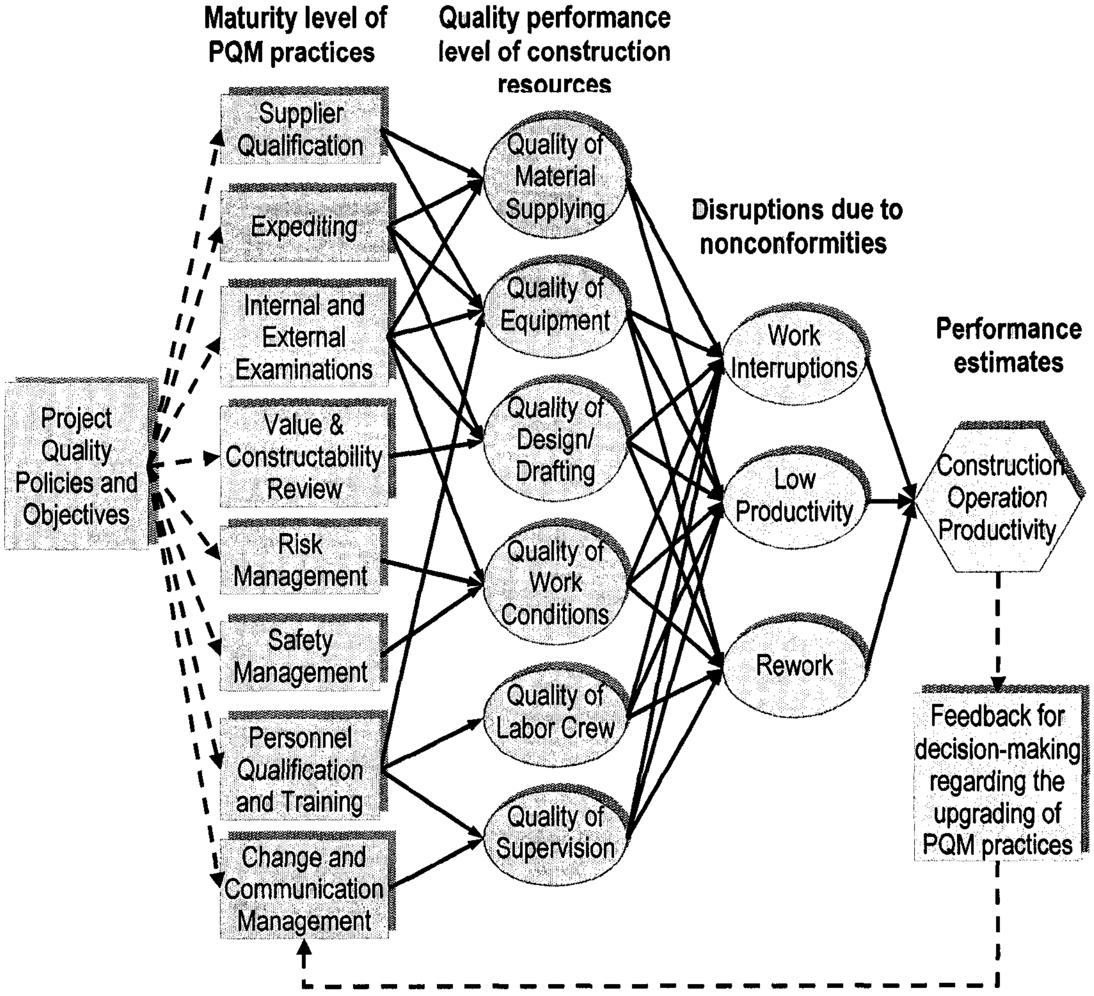


Figure 3.1: Influence diagram of the PQM factors affecting the performance of construction operations

i) A fuzzy expert system to deduce the quality level of the construction resources taking part in the operation, given the maturity level of the PQM practices, and

ii) A fuzzy logic-based procedure to estimate the statistical parameters based on the effect of the quality levels of the construction resources. The model proposed by Ayyub and Eldukair [1989] was applied for the implementation of this procedure.

A background of the modelling techniques applied on the development of the simulation of the effect of the PQM practices on the performance of a construction operation is included in the following section. Moreover, a further clarification of the development and implementation of the proposed modelling approach has been included en Chapters 4 and 6.

3.2 Background of the modelling techniques

The background of the modelling techniques applied in the formulation of the abovementioned modelling approach is included in this section, according to the following:

1. The concepts involved in the fuzzy set theory and fuzzy logic are first introduced in order to understand their application on the abovementioned fuzzy logic-based applications.
2. The procedure and elements involved in the estimation of the statistical parameters required as inputs to the simulation project models for estimating the effect of PQM practices on construction operations are then explained.
3. The procedure and elements involved in the development of the fuzzy expert systems implemented for inferring the quality level of the construction resources are examined.
4. The development of simulation project models incorporating the uncertainty of the effect of PQM practices on construction operations is finally clarified.

The following sections include the abovementioned points.

3.2.1 Fuzzy sets and fuzzy logic definitions

i) Fuzzy sets were first introduced by Zadeh [1965] to elucidate the concept of fuzziness. Fuzzy sets represent linguistic variables whose values are not numbers, as for numerical variables, but are words or sentences in a natural or artificial language. For instance, the performance maturity level of PQM practices in an organization is a subjective variable that can be assessed in linguistic terms such as *No Formal Approach*, *Reactive Approach*, *Stable Formal System Approach*, *Continual Improvement Emphasized*, and *Best-in-Class Performance*. Moreover, the universe of discourse Process Quality Index (PQI) is a set of elements x from zero to 100%, which can be used to describe the maturity level variable in a more objective way. However, there is uncertainty as to what PQI values (x) should define each of the aforementioned linguistic terms. The fuzzy sets theory can be applied in order to reformulate and evaluate the qualitative measures into mathematical terms. As shown in Figure 3.2, a fuzzy set A can be defined mathematically by assigning to each possible element in the universe of discourse a value representing its degree of membership in the fuzzy set. This means that, contrary to the classical sets theory in which an element either belongs to or does not belong to a set (i.e. its membership to that set is crisp), in fuzzy sets theory the belonging of an element x (e.g. a PQI value) to a set A (e.g. "No Formal Approach") is defined by a degree of membership indicated by a number in the interval [0,1]. Hence, the fuzzy set A can be defined by a set of ordered pairs, a binary relation, as follows [Bojadziev and Bojadziev 1997]:

$$A = \{(x, \mu_A(x)) \mid x \in A, \mu_A(x) \in [0,1]\} \qquad \textbf{(3.1)}$$

where $\mu_A(x)$ is the membership function that specifies the degree to which any element x in A belongs to the fuzzy set A. Definition (3.1) associates with each element in A a real number $\mu_A(x)$ in the interval [0,1] which is assigned to x. Larger values of $\mu_A(x)$ indicate higher degrees of membership. In general, the fuzzy set A can be expressed by m discrete values, $\mu_A(x)$ as follows:

$$A = \left[x_1|\mu_A(x_1), x_2|\mu_A(x_2), x_3|\mu_A(x_3), \cdots, x_m|\mu_A(x_m)\right] \qquad \textbf{(3.2)}$$

For example, "No Formal Approach", as a linguistic variable can be defined as:

$$A_1 = (0|1.0, 5|1.0, 10|1.0, 15|0.6, 20|0.3, 25|0.1)$$

Similarly, "Reactive Approach" as a fuzzy set A_1, and "Best-in-Class Performance" as fuzzy set A_3 can be represented, respectively, as follows:

$$A_2 = (10|0.1, 15|0.35, 20|0.6, 25|1.0, 30|0.8, 35|0.4, 40|0.1)$$

$$A_3 = (35|0.1, 40|0.6, 45|1.0, 50|1.0, 55|1.0, 60|1.0, 65|1.0, 70|0.6, 80|0.1)$$

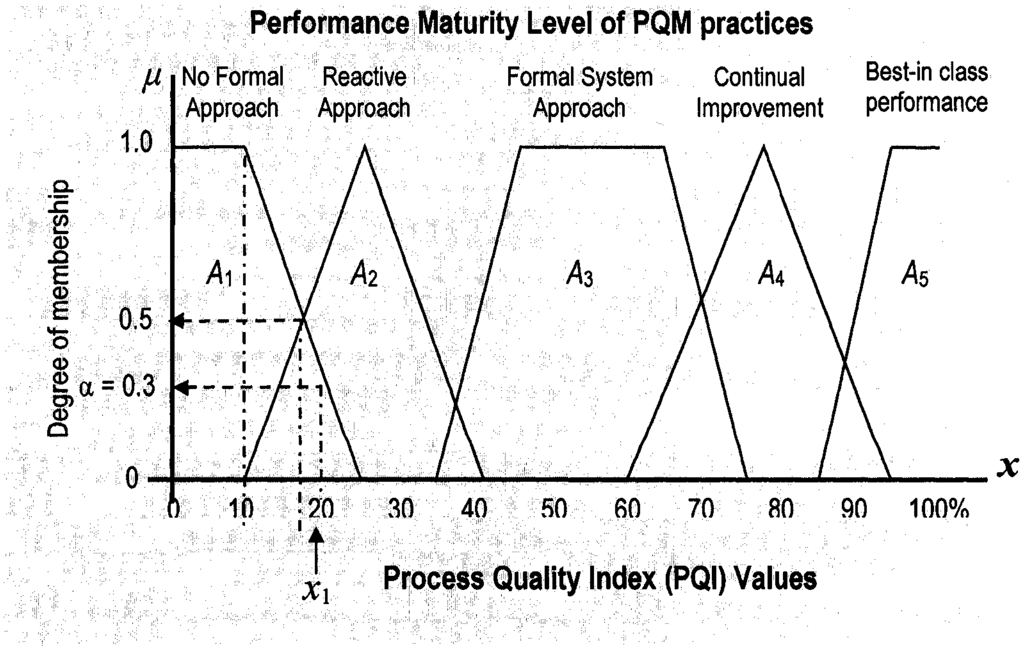


Figure 3.2 Sample membership functions for evaluating the PQM practices

ii) Properties of fuzzy sets are briefly introduced as follows:

- A *normalized* fuzzy set is one that includes at least one element x_0 in the universe of discourse that attains the maximum degree of membership, that is, $\mu_A(x_0)=1$; otherwise the fuzzy set is called *non-normalized.* For example, all fuzzy sets in Figure 3.2 are normal as they have at least one element x with a degree of membership equal to 1.
- *α-level interval* or *α-cut*, denoted by A_α, is defined as the crisp set of elements x which belong to A at least to the degree α. It gives a threshold that provides a level of confidence α in a decision or concept modeled by a fuzzy set. The threshold may be used to discard from consideration those element x in A with degrees of membership $\mu_A(x)<\alpha$. This can be expressed as:

$$A_\alpha = \{x | x \in R, \mu_A(x) \geq \alpha\}, \quad x \in [0,1] \qquad \textbf{(3.3)}$$

  For example, in Figure 3.2, $A_{0.3}$ = {0, 1, 2, 3, ... 20}; hence, elements from 21 to 25 are not included in $A_{0.3}$.

- A fuzzy set A, where the universe $U = R$, is *convex* if and only if the α-level intervals A_α are convex for all α in the interval (0, 1]. Otherwise, the set is *non-convex.* In this case, all fuzzy sets in Figure 3.2 are convex.

iii) Operations on fuzzy sets, which are relevant to this research work, include the *intersection* and *union* of two or more fuzzy sets. The operations with fuzzy sets A and B in the universe U are introduced via operations on their membership functions $\mu_A(x)$ and $\mu_B(\mathrm{x})$, as follows:

a) *Intersection* of fuzzy sets A and B denoted as $A \cap B$ is defined by

$$\mu_{A \cap B}(x) = \min(\mu_A(x), \mu_B(x)), \quad x \in U \tag{3.4}$$

The *intersection* of two fuzzy sets is related to the conjunction (logical operator *AND*) in fuzzy logic. For instance, if $a_1 < a_2$, min $(a_1, a_2) = a_1$; this is, min (0.5,0.7)= 0.5.

b) *Union* of A and B denoted as $A \cup B$ is defined by

$$\mu_{A \cup B}(x) = \max(\mu_A(x), \mu_B(x)), \quad x \in U \tag{3.5}$$

The *union* of two fuzzy sets is related to the logical operation of disjunction (*OR*) in fuzzy logic. For instance, if $a_1 < a_2$, $\max(a_1, a_2) = a_2$; that is, max(0.5, 0.7) = 0.7

c) *Complementation* of the fuzzy set A is $\bar{A}$ if the following condition is true:

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x) \quad \text{or} \quad \mu_A(x) + \mu_{\bar{A}}(x) = 1 \tag{3.6}$$

The *complement* of a fuzzy set is related to the logical operator *NOT* in fuzzy logic and its membership function $\mu_{\bar{A}}(x)$ is symmetrical to $\mu_A(x)$ with respect to $\mu = 0.5$.

iv) Fuzzy numbers are defined in the universe R as a convex and normalized fuzzy set. Therefore, all fuzzy sets in Figure 3.2 are fuzzy numbers. Membership functions of fuzzy numbers are assumed to be able to take any kind of shape; however, *triangular* and *trapezoidal* membership functions are the most common shapes for fuzzy numbers used in management, as they can be constructed based on little information [Bojadziev and Bojadziev 1997]. Fuzzy sets A, C, and E, in Fig. 3.2, are fuzzy numbers with trapezoidal membership functions, while fuzzy sets B and D are fuzzy numbers with triangular membership functions. Triangular fuzzy numbers are used when the experts can precisely identify one, and only one, value to totally represent the corresponding linguistic term.

Meanwhile, in trapezoidal fuzzy numbers a range of values are thought to totally represent the linguistic term, which may mean that there is a higher uncertainty on defining the membership function in a trapezoidal fuzzy number than in a triangular one.

The development of the membership functions, established to represent the fuzzy numbers of the variables involved in the proposed model, is introduced in Chapter 5.

v) Fuzzy relations possess the computational potency and significance that functions possess in conventional approaches [Tsoukalas and Uhrig 1997]. Fuzzy if/then rules and their aggregations, known as fuzzy algorithms, both of central importance in engineering applications, are *fuzzy relations* in linguistic terms. A relation implies the presence of an association between elements of different sets. In crisp relations the degree of association can be indicated by either 0 or 1; while in fuzzy relations a number between 0 and 1 is taken to indicate partial absence or presence of association. Fuzzy relations are fuzzy sets defined in Cartesian products [Tsoukalas and Uhrig 1997]. Whereas the fuzzy sets introduced in the previous section were defined on a single universe of discourse (e.g. X = *PQI of PQM initiatives*), fuzzy relations are defined on higher-dimensional universes of discourse (e.g. $X \times Y$ or $X \times Y \times Z$).

For example, consider the Cartesian product $A \times B = \{(x,y) \mid x \in A, y \in B\}$, where A and B are subsets of the universes U_1 and U_2, respectively. A fuzzy relation on $A \times B$ denoted by R or $R(x,y)$ is defined as the set [Bojadziev and Bojadziev 1997]:

$$R = \{((x,y), \mu_R(x,y)) \mid (x,y) \in A \times B, \mu_R(x,y) \in [0,1]\} \qquad \textbf{(3.7)}$$

where $\mu_R(x,y)$ is a function in two variables called *membership function* (MF). It gives the degree of membership of the ordered pair (x,y) in R associating with each pair (x,y) in $A \times B$ a real number in the interval [0,1]. This degree of membership indicates the degree to which x is in relation with y.

There are some basic operations on fuzzy relations that are relevant to this research. The operations with fuzzy relations R_1 and R_2 on A×B are introduced via operations on their MFs $\mu_{R1}(x,y)$ and $\mu_{R2}(x,y)$, as follows:

a) *Intersection* of fuzzy relations R_1 and R_2 denoted as $R_1 \cap R_2$ is defined by

$$\mu_{R_1 \cap R_2}(x,y) = \min\{\mu_{R_1}(x,y), \mu_{R_2}(x,y)\}, \quad (x,y) \in A \times B \qquad \textbf{(3.8)}$$

b) *Union* of R_1 and R_2 denoted as $R_1 \cup R_2$ is defined by

$$\mu_{R_1 \cup R_2}(x,y) = \max\{\mu_{R_1}(x,y), \mu_{R_2}(x,y)\}, \quad (x,y) \in A \times B \qquad \textbf{(3.9)}$$

c) *Direct products* of fuzzy sets $A = \{(x, \mu_A(x))\}$ and $B = \{(y, \mu_B(y))\}$ defined on $x \in A \subset U_1$ and $y \in B \subset U_2$, correspondingly, are:

- *Direct min product*, denoted $A \underset{\bullet}{\times} B$ with MF $\mu_{A \underset{\bullet}{\times} B}$ is a fuzzy relation

$$A \underset{\bullet}{\times} B = \{(x,y), \min(\mu_A(x), \mu_B(y)), (x,y) \in A \times B\}, \qquad \textbf{(3.10)}$$

which means it is necessary to perform the Cartesian product A×B and at each pair (x,y) to attach as a membership value the smaller of the two $\mu_A(x)$ and $\mu_B(y)$.

- *Direct max product*, denoted $A \overset{\bullet}{\times} B$ with MF $\mu_{A \overset{\bullet}{\times} B}$ is a fuzzy relation

$$A \dot{\times} B = \{(x,y), \max(\mu_A(x), \mu_B(y)), (x,y) \in A \times B\}, \qquad \textbf{(3.11)}$$

in which the larger between $\mu_A(x)$ and $\mu_B(y)$ is attached as the membership value at each pair (x,y) within the Cartesian product A×B.

vi) Fuzzy logic provides a framework for decision analysis and control actions through the facilitation of common sense reasoning with imprecise and vague propositions dealing with linguistic variables [Bojadziev and Bojadziev 1997]. Linguistic variables are those whose values are words or sentences in natural or artificial languages. Figure 3.3 depicts the linguistic variable 'quality of labor' in a natural language, as it cannot be characterized precisely. The 'quality of labor' can be described approximately with values such as *very poor*, *poor*, *average*, *good*, and *very good*, which are called terms or labels of the linguistic variable 'quality of labor' and are expressed by fuzzy numbers on a universal set $U \subset R$, measured in average years of experience of labor.

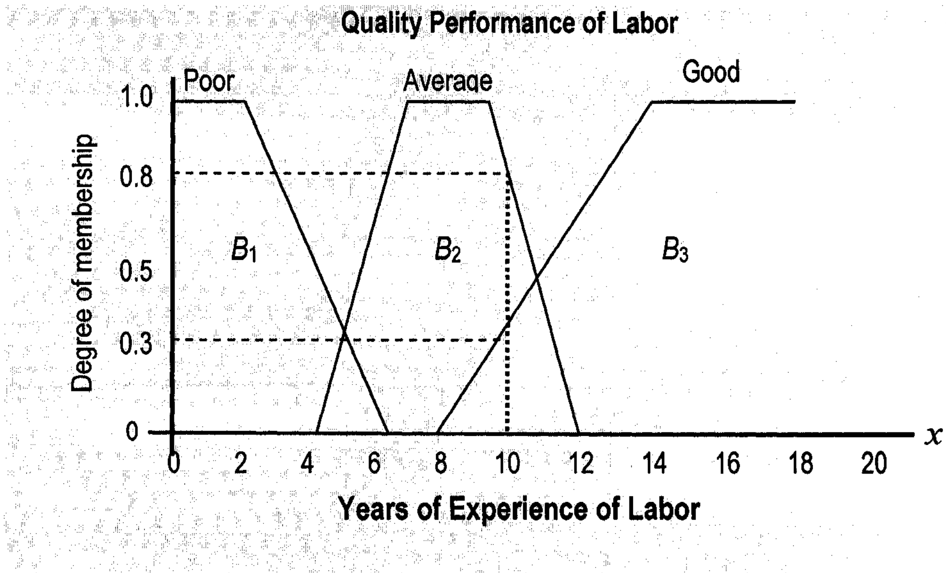


Figure 3.3 Example of membership functions for evaluating the quality of labor

Fuzzy logic uses the fuzzy sets theory as a major tool [Bojadziev and Bojadziev 1997]. Fuzzy sets and fuzzy numbers can be used to assess the "degree of truth" of propositions such as "*quality of labor* is *good*". In fuzzy logic a proposition is true to a degree in the interval [0,1]. This degree of truth is expressed by a membership function; for instance, Figure 3.3 shows that the labor in a project whose average years of experience is 10 years is good quality to the degree 0.30 and average quality to the degree 0.80.

vii) Fuzzy composition uses fuzzy relations to evaluate the degree of truth of composite propositions. *Composition* is very important for inference procedures used in linguistic descriptions of systems and is particularly useful in fuzzy controller and expert systems [Klir and Folger 1988]. Fuzzy relations defined on different Cartesian products can also be combined with each other in a number of different ways through *composition*. Though there are several types of composition for fuzzy relations, such as the max-min, max-star, max-product, and max-average, Tsoukalas and Uhrig [1997] consider the *max-min composition* the most common in engineering. The max-min composition of two fuzzy relations uses the familiar operators of fuzzy sets, max ($\vee$), and min ($\wedge$) as previously introduced. Given two fuzzy relations $R_1(x,y)$ and $R_2(y,z)$ defined over the Cartesian products A×B and B×C, respectively, the max-min composition of R_1 and R_2 is a new relation $R_1 \circ R_2$ defined on A×C as

$$R_1 \circ R_2 \equiv \int_{A\times C} \bigvee_{y} \left[\mu_{R_1}(x,y) \wedge \mu_{R_2}(y,z) \right] / (x,z) \qquad \textbf{(3.12)}$$

and in which the degree of membership of each (x,z) is

$$\mu_{R_1 \circ R_2}(x,z) = \bigvee_{y} \left[\mu_{R_1}(x,y) \wedge \mu_{R_2}(y,z) \right] \qquad \textbf{(3.13)}$$

where the outer maximum is taken with respect to the elements y of the common boundary. This is similar to matrix multiplication, with the max ($\vee$) being analogous to summation (+) and min ($\wedge$) being analogous to multiplication (•) [Tsoukalas and Uhrig 1997].

3.2.2 Fuzzy-logic based models to estimate the probability of events

Probability is essentially a measure of the frequency of occurrence of an event. However, the accurate estimation of the failure rate actually requires a large amount of data, which, in practice, is often not possible to obtain. In such cases, the failure rate can be estimated based on the knowledge and judgment of experts, which can be modeled as fuzzy probabilities in a flexible and efficient way [Onisawa 1990]. Zadeh [1968] introduced the concept of fuzzy probability as a tool to determine risk measures from subjective information. Ayyub and Haldar [1984] further adapted the concept of fuzzy probability of events to assess the reliability of construction operations. Now, this research applies the methodology proposed by Ayyub and Eldukair [1989] in order to estimate the statistical parameters of (a) the number of nonconformities in each construction activity included in a construction operation and (b) the duration of delays associated with each of these nonconformities. This methodology permits to obtain the probability mass function, normally distributed, (i.e. defined by the mean and standard deviation), of the occurrence of a given event, based on the subjectively assessed state of the factors affecting such event. For example, it is possible to generate the number of nonconformities occurring during a given construction activity as a random variable for use in any simulation technique. The following section details the application of this methodology for within the proposed modeling approach.

3.2.2.1 Fuzzy-logic approach to estimate the number of nonconformities

This methodology, used to estimate subjectively the number of nonconformities resulting from the state or quality level of the resources involved in the construction activities under analysis, concerns the following variables:

i) Q = state (i.e. quality performance level) of the factors (i.e. construction resources) involved in the undertaking of a given construction activity. The linguistic terms used to assess the quality level of such factors are *very poor*, *poor*, *average*, *good*, and *very good.*

ii) F = frequency of occurrence of the state of the factors (i.e. the quality level of the resources); which is assessed as *very unusual*, *unusual*, *often*, *usual*, and *very usual.*

iii) C = level of adverse consequences that the construction activity under analysis may be exposed to. This variable determines the sensitivity level of the construction activity to the combined effect of the quality level of the resources and the frequency of the occurrence of such state. The linguistic terms used to assess the adverse consequences are *very mild*, *mild*, *medium*, *severe*, and *very severe.*

iv) N = expected number of nonconformities observed during the performance of a given construction activity. This variable represents the sensitivity level of the activity resulting from the combined effect of the state of the factors involved in the activity and the frequency of occurrence of such a factor state. It is assessed as *very small*, *small*, *medium*, *large*, and *very large*.

Construction managers often assess these variables qualitatively rather than quantitatively. Therefore, they can only use their intuition to evaluate the combined effect of the quality of inputs affecting the construction activities; e.g.: (i) good quality of labor, average quality of supervision, and poor quality of supplying; or (ii) poor quality of labor, good quality of supervision, and average quality of supplying; etc.

Following the method proposed by Ayyub and Eldukair [1989], the subjective estimation of an average of the expected number of nonconformities is based on the following fuzzy relations:

1. The MF resulting from the fuzzy relation of the effect that the quality level of each operation resource has on the performance of a given activity, which combines the quality level of the construction resources (*Q*) and the adverse consequences (*C*), can be determined by adapting Equation 3.10 as follows:

$$\mu_{Q\times C}(x_i, y_j) = \min[\mu_Q(x_i), \mu_C(y_j)] \qquad \textbf{(3.14)}$$

where $\mu_{Q\times C}(x_i,y_j)$ is the MF of the ordered pairs (x_i, y_j), while $\mu_Q(x_i)$ and $\mu_C(y_j)$ are the membership values of the quality level of a construction resource and the adverse consequences on the activity under analysis, respectively. Furthermore, the MF of the total effect (T_1) of the quality level of all construction resources in the system on the performance of the activity can be determined by adapting Equation (3.8) to get the fuzzy union (U) of the Cartesian relations obtained with Equation (3.14), as follows:

$$T_1 = \left(Q_1 \underset{\bullet}{\times} C_1\right) \bigcup \left(Q_2 \underset{\bullet}{\times} C_2\right) \bigcup \cdots\cdots \bigcup \left(Q_n \underset{\bullet}{\times} C_n\right) = \bigcup_{i=1}^{n} \left[\mu_{Q \underset{\bullet}{\times} C}\left(x_i, y_j\right)\right] \qquad \mathbf{(3.15)}$$

where n = the number of construction resources involved in the analysis.

2. Similarly, the effect of the frequency of occurrence of the quality level of each construction resource on the performance of the activity can be developed by combining the frequency of the factor (F) and the number of nonconformities (N) by the following fuzzy Cartesian product relation:

$$\mu_{F \underset{\bullet}{\times} N}\left(f_j, r_k\right) = \min\left[\mu_F\left(f_j\right), \mu_N\left(r_k\right)\right] \qquad \mathbf{(3.16)}$$

where $\mu_{F\times N}\,(f_j, r_k)$ is the MF of the ordered pairs (f_j, r_k), while $\mu_F(f_j)$ and $\mu_N(r_k)$ are the membership values of the frequency of occurrence of the factor and the number of nonconformities in the activity, respectively. Furthermore, the MF of the total effect (T_2) of the frequency of occurrence of the state (i.e. quality levels) of the factors (construction resources) on the number of nonconformities, can be determined by adapting Equation (3.8) to get the fuzzy union (⋃) of the Cartesian relations obtained with Equation (3.16), as follows:

$$T_2 = \left(F_1 \underset{\bullet}{\times} N_1\right) \bigcup \left(F_2 \underset{\bullet}{\times} N_2\right) \bigcup \cdots\cdots \bigcup \left(F_n \underset{\bullet}{\times} N_n\right) = \bigcup_{i=1}^{n} \left[\mu_{F \underset{\bullet}{\times} N}\left(f_j, r_k\right)\right] \qquad \mathbf{(3.17)}$$

where n = the number of construction resources involved in the analysis.

3. The standard fuzzy relation $R(y, r)$ is developed by assessing, in linguistic, terms the relationship between each level of adverse consequence (C) and the expected number of nonconformities (N) for the given construction activity, in order to establish fuzzy condition statements represented by rules (Ayyub and Haldar, 1985), e.g.:

Rule 1 (R_1): N_1 is large, if C_1 is severe = $C_1 \times N_1$

Rule 2 (R_2): N_2 is average, if C_2 is medium = $C_2 \times N_2$

Rule 3 (R_3): N_3 is small, if C_3 is mild = $C_3 \times N_3$

Using Equation (3.9), a matrix representing the relation R_N is obtained, as follows:

$$R_N = R_1 \cup R_2 \cup R_3 = \max\left[(C_1 \times N_1),(C_2 \times N_2),(C_3 \times N_3)\right] \qquad \textbf{(3.18)}$$

4. Then, a combination process between the total effect of the quality level of the resources and the expected number of nonconformities in the activity under analysis needs to be obtained by a fuzzy composition relation, M, between T_1 and R_N which are given in Equations (3.15) and (3.18), respectively. The MF of the composition relation, M, can be presented as:

$$\mathrm{M} = T_1 \circ R_N(x_i, r_k) = \max_{\mathrm{y_j}}\left\{\min\left[\mu_{T_1}(x_i, y_j), \mu_{R_N}(y_j, r_k)\right]\right\} \qquad \textbf{(3.19)}$$

5. Finally, a subjective quantitative estimate of the expected number of nonconformities in a given activity can be determined by developing the joint effect of the state (Q) and the frequency of occurrence of the factors (F) on the level of expected number of nonconformities. The MF of this fuzzy joint effect, can be developed as:

$$\mu_{M,T_2}(x_i, y_j)(r_k) = \min\left[\mu_M(x_i, r_k), \mu_{T_2}(f_j, r_k)\right] \qquad \textbf{(3.20)}$$

where $\mu_{M,T_2}(x_i, y_j)(r_k)$ is the joint MF of the state (i.e. quality level) and frequency of occurrence of such state of the construction resources, $[\mu_M(x_i, r_k)]$ is the MF of the effect of the state of the construction resources on the expected number of nonconformities in the activity, obtained with Equation (3.19), while $[\mu_{T_2}(f_j, r_k)]$ is the MF of the effect of the frequency of occurrence of the state of the construction resources on the on the expected number of nonconformities in the activity, obtained with Equation (3.17).

6. The MF of the subjective measure for each element N can be determined by calculating the ratio of the maximum sum of the products of the joint MF and the state or quality levels, x_i and the maximum sum of the products of the joint MF and the frequency levels, f_j.

Subsequently, according to Zadeh [1968], the probability of occurrence for each element N in a construction activity for a given combination of quality levels of the construction resources participating in such activity can be calculated as follows:

$$P(N = r_k) = \frac{\mu_{S_N}(r_k)}{\sum_{k=1}^{m} \mu_{S_N}(r_k)} \qquad \textbf{(3.21)}$$

Meanwhile, using the probability mass function of N, the mean value of the number of nonconformities ($\overline{N}$) can be calculated as follows:

$$\overline{N} = \sum_{k=1}^{m} (r_k) \times P(N = r_k) \qquad \textbf{(3.22)}$$

where N = expected number of nonconformities; r_k = discrete element within the universe of discourse N; $P(N = r_k)$ = probability of occurrence of a given number of nonconformities to be element r_k; $\mu_S(r_k)$ = membership value of element r_k in the normalized fuzzy probability function (subset S_N) obtained with Equation (3.20); and m = number of elements in the universe of discourse N in subset S_N.

An example of the application of this procedure has been included within the case study described in Chapter 6, in order to clarify the subjective estimation of the number of nonconformities in the given construction activities.

3.2.2.2 Fuzzy logic approach to estimate the duration of delays

The subjective estimating of the statistical parameters that define the duration of delays in a given construction activity follows the same procedure explained in Section 3.2.2.1. However, in this case, the expected duration of delays (D) in hours or days is assessed instead of the number of nonconformities (N). D represents the sensitivity level of the performance of the activity to the combined effect of both the state of the factors and the frequency of occurrence. The duration of delays is evaluated with the same linguistic terms as N, i.e. *very small*, *small*, *medium*, *large*, and *very large*.

In this case, the same value T_1 obtained with Equations (3.14) and (3.15) is used to represent the total effect of the quality level of construction resources on the activity duration. However, Equations 3.16) and (3.17) must be adapted to combine the frequency of the factor (F) and the expected duration of delays (D) and, then, obtain the total effect (T_2) of the frequency of occurrence of the state of the factors on the duration of delays in the activity, as follows:

$$\mu_{F \underset{\bullet}{\times} D}(f_j, r_k) = \min[\mu_F(f_j), \mu_D(r_k)] \qquad \textbf{(3.23)}$$

$$T_2 = \left(F_1 \underset{\bullet}{\times} D_1\right) \bigcup \left(F_2 \underset{\bullet}{\times} D_2\right) \bigcup \cdots\cdots \bigcup \left(F_n \underset{\bullet}{\times} D_n\right) = \bigcup_{i=1}^{n} \left[\mu_{F \underset{\bullet}{\times} D}(f_j, r_k)\right] \qquad \textbf{(3.24)}$$

On the other hand, the fuzzy relation $R(y,r)$ given in Equation 3.18 must be adapted to assess the relationship between each level of adverse consequence (C) and the expected duration of delays (D) for the given construction activity, e.g.,:

$$R_D = R_1 \cup R_2 \cup R_3 = \max\left[(C_1 \times D_1), (C_2 \times D_2), (C_3 \times D_3)\right] \qquad \mathbf{(3.25)}$$

given that, in this case, the fuzzy rules are:

Rule 1 (R_1): D_1 is large, if C_1 is severe = $C_1 \times D_1$

Rule 2 (R_2): D_2 is medium, if C_2 is medium = $C_2 \times D_2$

Rule 3 (R_3): D_3 is small, if C_3 is mild = $C_3 \times D_3$

Then, Equation 3.19 can also be adapted to combine the total effect of the quality level of the resources and the duration of delays in the activity, as follows:

$$\mathrm{M} = T_1 \circ R_D(x_i, r_k) = \max_{y_j}\left\{\min\left[\mu_{T_1}(x_i, y_j), \mu_{R_D}(y_j, r_k)\right]\right\} \qquad \mathbf{(3.26)}$$

From here, the same procedure is followed up to the point of determining the probability of occurrence for each element D, the mean value ($\overline{D}$) and the standard deviation (σ_D) of the duration of delays in the activity, which, respectively, should be calculated as follows:

$$P(D = r_k) = \frac{\mu_{S_D}(r_k)}{\sum_{k=1}^{m} \mu_{S_D}(r_k)} \qquad \mathbf{(3.27)}$$

$$\overline{D} = \sum_{k=1}^{m} (r_k) \times P(D = r_k) \qquad \mathbf{(3.28)}$$

$$\sigma_D = \sqrt{\left[\sum_{k=1}^{m} (r_k)^2 \times P(D = r_k)\right] - \left(\overline{D}\right)^2} \qquad \mathbf{(3.29)}$$

where D = duration of the delay; r_k = discrete element within the universe of discourse D; $P(D = r_k)$ = probability of occurrence of the duration of delay to be element r_k; $\mu_S(z_k)$ = membership value of element r_k in subset S_D; and m = number of elements universe of discourse D in subset S_D.

It is possible to generate the delay duration of each activity as a random variable from the probability mass function calculated by the proposed technique for use in any simulation model for project scheduling. An example of the application of the proposed technique and the use of its outputs in a simulation project model has been included within the case study described in Chapter 6.

3.2.3 Fuzzy expert system to predict the effect of PQM practices

The assessment framework proposed in this research requires estimating the effect of PQM practices on the quality performance of the resources directly involved in the performance of construction activities. However, there is a lot of uncertainty and subjectivity embedded within this kind of estimation because there are many factors that can affect the quality of the resources used in a construction project. In order to reduce the problem, it can be assumed that the quality of such resources is mostly defined by the quality of the management in the project. For example, the supplier qualification process, the expediting process, and the internal and external examinations may define the quality of material supplying, as shown in Figure 3.4. Most of those factors are subjective in nature and they are difficult to account for. Even experienced managers find it difficult to account for the effect of all possible management processes that will define the performance of resources employed in the construction operations.

A successful and reliable model should be able to structure the factors involved in a PQM system in order to facilitate the systematizing of the knowledge that experts have on management systems in construction projects. It was deemed appropriate to attempt the application of fuzzy expert systems (FES) to achieve this, as they are able to integrate more objective variables into the relatively accurate estimating of a state of output variables with a high degree of subjectivity, such as the quality level of construction resources. The FES developed to test the application of such a modelling approach is further introduced in Chapter 6. The following sections introduce the concepts involved in the development of an FES, as well as their application in the building of an FES to predict the effect of PQM practices on the quality performance of resources involved in construction operations.

3.2.3.1 Definition of fuzzy expert systems

Expert systems, as defined by Chang and Chen [2006], are ‘intelligent computer programs’ that posses knowledge and inference mechanisms. They describe the main features of expert systems as follows:

i) Use symbolic logic and heuristic algorithms to emulate the reasoning process of human experts or to perform in an expert manner in a domain for which no human expert exists. Practical expert systems typically reason with uncertain and imprecise information.

ii) Are designed to manipulate knowledge, unlike conventional programs that process only data. The knowledge they embody is often not exact in the same way that a human's knowledge is imperfect. They use this knowledge and employ rules to function intelligently.

iii)Rules provide a systematic way of emulating strategies and procedures developed from years of problems-solving experience. The 'IF *premise*, THEN *conclusion*' statement is the general expression used in a knowledge-based system, representing a context where, when the premise is satisfied, the conclusion takes effect.

In addition, fuzzy reasoning techniques can provide the basis for representing the imprecision inherent in an expert system. Therefore, an FES can be described as an expert system that incorporates fuzzy sets and/or fuzzy logic into its reasoning process and/or knowledge representation scheme [Wong and So 1995]. Mason and Kahn [1997] have pointed out two main differences between an FES and a traditional expert systems:

i) The conditions contained in the antecedent (IF premise) and consequent (THEN conclusion) clauses of the rules may be expressed as fuzzy sets. In that case, the rules are identified as fuzzy rules.

ii) The reasoning process used to reach conclusions is not based on the assessment of the antecedent portion of the rules as true or false. In an FES, both the condition and the conclusion of each rule are expressed in linguistic terms, represented by membership functions. This approach represents better the imprecise knowledge humans have on the behavior of conditions involved in a system.

The structure of a fuzzy inference system includes four main components as shown in Figure 3.4. Wong and So [1995] define these components as follows:

i) *Knowledge base*: contains the database that defines the MFs of the fuzzy sets representing the input and output variables involved in the system under consideration. In addition, the knowledge base should also contain the fuzzy rules that the inference engine requires to perform the inference operations.

ii) *Fuzzification interface*: performs a procedure that converts *input readings* into degrees of membership. An input reading is an estimate the user obtains by the measurement, observation, or estimation of a given variable to evaluate specific conditions of the factors or input variables in the system [Bojadziev and Bojadziev 1997]. This is done by matching a given input reading against the appropriate membership functions representing terms of the linguistic variable. Input readings can be crisp values or linguistic terms within the universe of discourse of the respective input variable.

iii) *Inference engine*: is a program that executes the inference operations on the fuzzy rules. The inference engine makes use of the membership functions and the inference rules contained in the knowledge base of the system in order to obtain the membership functions of the output variables after manipulation, in accordance with the standard fuzzy logic operations.

iv) *Defuzzification interface*: performs a procedure that transforms the outputs of the fuzzy system, modelled as membership functions, back into crisp values such that they define a meaningful solution to the user. This stage is optional, depending on the need for crisp values as the outputs of the system; otherwise, there is no need for defuzzification.

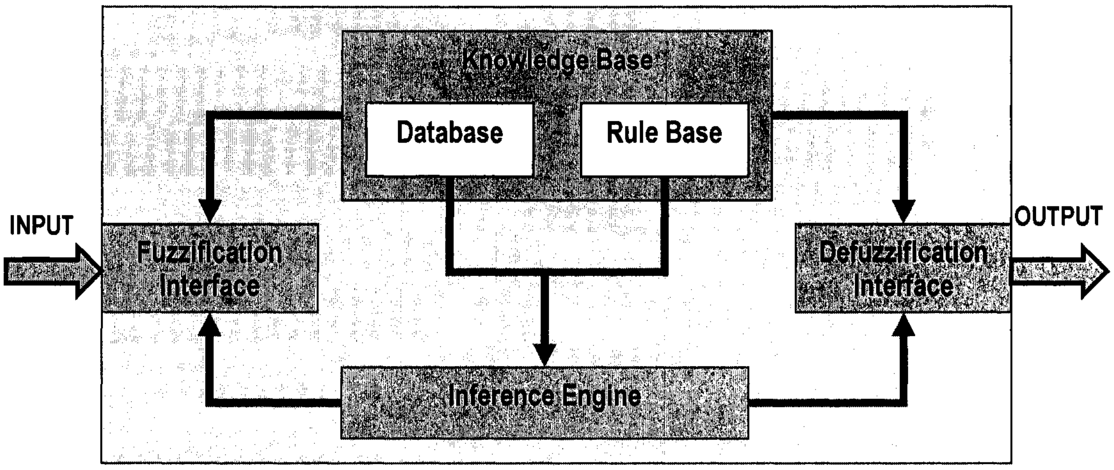


Figure 3.4: Components of a fuzzy expert system [Jang, 1993]

3.2.3.2 The fuzzy inference process

The design of a fuzzy expert system has to take into account the inference process that is required in order to infer the output expected from the system. The inference engine carries out the inference process using fuzzy logic operations. Figure 3.5 indicates several steps are involved in the performance of the inference process. The steps of the inference process have been explained as follows:

1. The first step is the *fuzzification* of the various input readings to the system, in order to determine their corresponding degrees of membership within the membership functions of each input variable. Depending on the precision with which the user is able to estimate the input readings, the fuzzification can be done as follows [Mason and Kahn 1997]:

   a) The user's knowledge is relatively precise, which means a crisp value (e.g. $x_1 = 20\%$ in Figure 3.2) can be provided to evaluate the input variable (e.g. A_1, in Figure 3.5) throughout the fuzzy inference process. The crisp input readings (x_1, x_2 . . . x_n, in Figure 3.5) are compared with the membership functions to get the degree of membership (e.g. $\mu_{A1}(x_1)$, $\mu_{A2}(x_1)$, $\mu_{A3}(x_2)$, $\mu_{A2}(x_n)$, in Figure 3.5) of each linguistic term of the respective input variable.

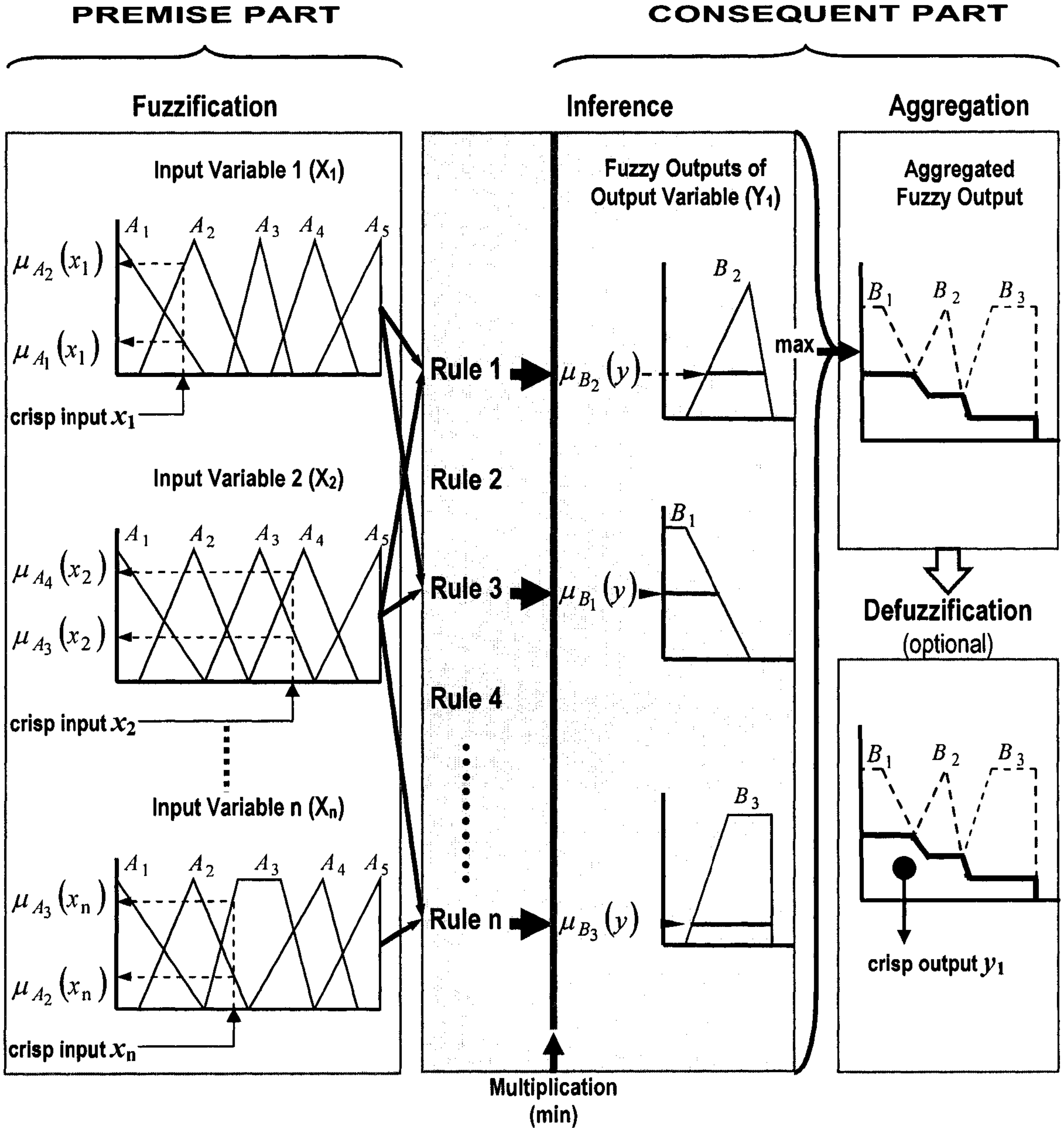


Figure 3.5: Sample structure of a fuzzy expert system

b) The user states a premise using a known linguistic expression, For example, when the user evaluates the *maturity level* of a given PQM practice as *no formal approach*. This means that the respective MF must be considered entirely to evaluate the input variable. Accordingly, a FES that accepts the inputs as linguistic terms should be implemented.

c) The user states a premise using an unknown linguistic expression, meaning the user makes an assertion about the input variable not defined within its respective membership functions. For example, *maturity level* is *not reactive approach.* In such an example, *not reactive approach* is not defined in Figure 3.2 and neither is included in the rule base. In this case, it is necessary to infer a membership function for the linguistic term *not reactive approach* by subtracting the membership function of reactive approach over the entire universe of discourse (Equation 3.6)

Using any of these three methods, the corresponding truth-values or degrees of membership of each input variable in the system are calculated. The membership functions used from each input variable will determine which rules will be fired.

2. The second step is actually when the inference engine starts. This step, which is called *implication* or *input aggregation*, determines the degree to which the premise part of the fired inference rule is fulfilled. The rules of inference, also called fuzzy production rules, can be denoted as follows:

$$\textbf{IF } X_1 \text{ is } A_1 \textbf{ AND } X_2 \text{ is } A_4 \textbf{ AND} \ldots X_n \text{ is } A_m, \textbf{THEN } Y_1 \text{ is } B_3 \textbf{ AND} \ldots X_n \text{ is } B_k \quad \textbf{(3.27)}$$

where x_1, $x_2 \ldots x_n$ and $y_1 \ldots y_n$ are respectively the input and output variables of the system. Meanwhile A_1, $A_4 \ldots A_m$ and $B_3 \ldots B_k$ are the MFs representing the linguistic terms of each input and output variable, respectively. For example, in Figure 3.5 each input variable (x_1, x_2 . . .x_n) has five membership functions (m = 5) and the output variable (y_1) has three MFs (k = 3). In addition, as seen in Equation (3.27), fuzzy operators are used if the premise part of the rule contains more than one input variable. As stated in Equations (3.4) and (3.5), *AND* and *OR* are the two main fuzzy operators in fuzzy logic and the operations produced with them are called *T*-norms and *S*-norms, respectively. Table 3.1 contains common *T*-norm and *S*-norm operations.

Fuzzy operators combine the calculated membership values of all the input variables, involved in a fired rule, in order to obtain one single value that represents the result of the premise part of that given rule. The most common methods that the implication process uses to obtain such combined, single truth-vale are the 'min' and the 'prod' operations. Next, that single truth-value obtained from the premise part of the rule is applied to the respective MF of the output variable in the consequent part of the rule. The 'min' operation truncates the MF such output variable of the rule, while the 'prod' operation scales it. For example, Figure 3.5 illustrates the 'min' implication method with the truncation of the MFs that define the output variable.

Table 3.1: Common operations with *T*-norms and *S*-norms

***T*-norm (*AND*) operations**	
min (*a*, *b*)	Minimum of all membership values. Refer to Equation 3.10.
prod (*a*•*b*)	Product of all membership values (e.g. product of *a* and *b*).
***S*-norm (*OR*) operations**	
max (*a*, *b*)	Maximum of all membership values. Refer to Equation 3.11.
probor (*a*, *b*) = (*a* + *b* – *ab*) = 1 – (1-*a*) (1-*b*) probor (*a*, *b*, *c*) = 1 – (1-*a*) (1-*b*) (1-*c*)	Probabilistic OR = algebraic sum of all truth-values.

∗ *a*, *b* and *c* are degrees of membership or truth values ∈ [0,1].

Robinson [2006] provided some guidelines to use the aforementioned operations in the firing of the inference rules, as follows:

- Use *AND* for independent input variables; use *OR* for correlated input variables.
- Use max or min when no interaction between input variables exists.
- Use product or probor when interaction between input variables exists.

3. The *aggregation* operation combines all membership functions of the partial fuzzy outputs resulting from the fired rules, into a single MF or fuzzy set. This way, an aggregated fuzzy output is generated for the output variable. The commonly used result aggregation methods are: max (takes the maximum value of each output set generated with the implication procedure, from each rule, for a given output variable), probor (probabilistic OR, which implies the algebraic sum of all the fuzzy outputs generated by the fired rules), and sum (simply the sum of each rule's output set). For example, Figure 3.5 illustrates an aggregated fuzzy output obtained with the max method.

4. The *defuzzification* or *decoding of the aggregated fuzzy output* obtained from the aggregation step is an optional step to produce a nonfuzzy or crisp value that adequately represents the membership function of such aggregated fuzzy output. There is no unique method to perform the operation defuzzification. The most accurate and, therefore, commonly used method for defuzzification is the Center of Area, which involves the calculation of the centroid or center of gravity of the membership function for the aggregated fuzzy output [Bojadziev and Bojadziev 1997]. However, if a fuzzy value, instead of a crisp value, is required as the output of the system, there is no need for the defuzzification of the aggregated fuzzy output.

Moreover, it is also necessary to go through the actual process involved in the development of an FES, which is explained throughout the following section.

3.2.3.3 Development of fuzzy expert systems

The development of an FES involves several steps. Figure 3.6 shows the basic steps involved in such attempt and that are briefly explained in this section:

1. *Identify the factors influencing the system.* Three classes of factors taking part in the system must be identified [Robinson and Sun 2001]:

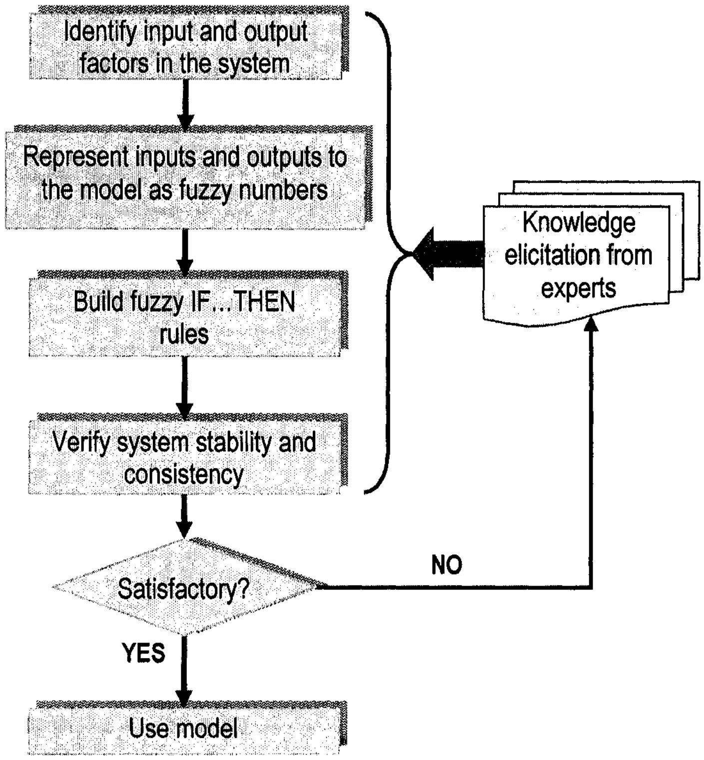


Figure 3.6: Development of a fuzzy expert system [Shaheen 2005]

i) *Context variables* are used to describe the context in which the system being studied is involved. They can be used to classify systems into similar groups given its characteristics and external conditions affecting; for example size, environment, weather, etc. They are not the elements under evaluation in the model, which means the study of their effect on the output of the system is not emphasized in this research. These variables are qualitative in nature.

ii) *Input factors* describe the elements under evaluation in the model, which means the study of their effect on the output of the system is emphasized. For example, for the assessment framework proposed in this research, the focus is on the PQM initiatives implemented in a construction project system, hence, they are the input factors to the system. Each of these factors is variable, e.g. they can vary from project to project in a fixed context. Their assessment also involves subjective variables that can be described using linguistic terms (e.g. the maturity level of a given PQM initiative, as shown in Figure 3.2). Each input factor can be further broken down into a number of factors, which are easier to quantify, thereby reducing the subjectivity associated with describing the input factors.

iii) *Output factors* are used to measure the performance of the system under study. For example, as for the FES proposed within the computer-based system, the outputs are the quality of the construction resources employed in a given construction operation. A number of subfactors could be included in the system in order to determine more objectively the output factors. Chapter 4 includes an explanation of this, along with a further clarification of the input and output factors included in the proposed modeling approach.

2. *Represent inputs and outputs to the model as fuzzy numbers.* The linguistic terms used to assess the context, input, and output variables in the system can be represented, if required, in the form of membership functions (e.g., see MFs A_1 to A_5 in Figure 3.2), in order to model the uncertainty caused by their fuzziness and subjectivity. Experts tend to provide their estimates in the form of most possible ranges for the assessment of uncertain and/or subjective terms, such as low quality of labor, consequence is large, delays are medium, etc. There are four main methods for establishing the fuzzy membership functions: (i) the horizontal approach [Bharathi-Devi and Sarma 1985], (ii) the vertical approach [Civanlar and Trussel 1986], (iii) the pairwise comparison method [Saaty 1980], and (iv) the membership function estimation approach with the aid of probabilistic characteristics (Dubois and Prade 1983). The method used to develop the membership functions of the variables involved in the modelling approach proposed in this research has been introduced in Chapter 5.

3. *Build inference rules.* Developing the inference rules is one of the most important steps because the rule base triggers the inference engine of the system. Experts with knowledge and experience on the system to model may be able to determine the rule base subjectively. However, an approach proposed by Shaheen [2005] to determine such rule base more objectively was adapted for the purposes of this research and has been detailed in Section 5.1.2. Such an approach includes determining the premises of the rules in the system by calculating the total number of possible combinations of the linguistic terms of the input variables, as follows:

$$\text{Number of rules} = [\text{Number of input terms}]^{(\text{Number of input variables})} \qquad \textbf{(3.28)}$$

When several input variables are involved in the definition of an output variable, it is possible to control the exponential growth of rules generated by grouping the related input variables into different rule blocks based on their class commonalities [Shaheen 2005]. After grouping the input factors, the inference rules can be generated using the rule blocks and their consequents on output factors must be evaluated.

Another method to reduce the number of rules in a system involves determining the correlation between input factors and output factors in order to identify what input and output factors should be included into each rule [Robinson and Sun 2001]. The drawback of the correlation analysis is that a significant amount of data points are required, which it is difficult to obtain in this case.

On the other hand, it is also possible to reduce the number of system factors by identifying, from the nonconformance reports and root cause analyses that are kept in the records of the organization's QMS, the most significant input factors affecting the output factor in the system. Such an approach would also facilitate the identification of causes of the specific PQM practices requiring improvement actions that may reduce nonconformities in the system under analysis. For example, Figure 3.7 shows that the most significant intermediate output factors that define the quality of material supplying (i.e. the output factor) are the number of delayed deliveries and the number of inadequate material deliveries. On the other hand, the PQM practices (i.e. the input factors) that are associated to the delayed deliveries and inadequate material deliveries are the supplier qualification, the expediting, and the internal/external examination processes. In fact, this approach was implemented within the assessment framework proposed in this research project, as it is further detailed in Sections 4.1.2 and 4.1.3.

After identifying the input and output factors to include in the system under analysis, the premise part of the rules can be established and the consequent part must be defined for each premise. Samples of the rules that could be generated for the system illustrated in Figure 3.7 are:

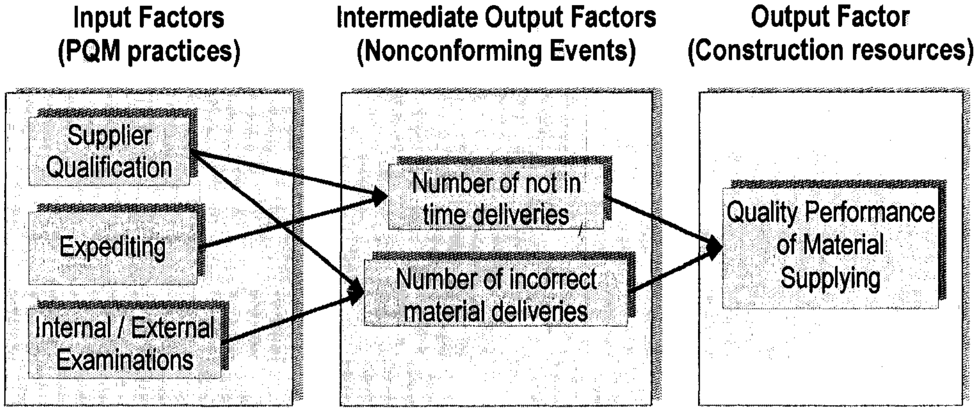


Figure 3.7: Example of the relation between input and output factors in the proposed FES to infer the quality level of the construction resources

i) IF (*maturity level of Supplier Qualification* is *No formal approach*) AND (*maturity level of Expediting* is *Reactive approach*), THEN (*Number of not on time deliveries expected* is *High*).

ii) IF (*Number of not in time deliveries* is *Low*) AND (*Number of incorrect deliveries* is *Very Low*), THEN (*Quality of material supplying* is *High*).

The consequent part of the rules is usually determined with the subjective opinion elicited from experts. The methods used in this research to determine the consequents of rules for the proposed fuzzy expert system, is further explained in Section 5.1.2.

4. *Verify system stability and consistency.* After an FES is built, the system needs to be tested by checking its stability and consistency. One way of verifying the stability of

the system is to study the behavior of the system under different model parameters (i.e. implication and defuzzification parameters) and different input variations [Shaheen 2005]. This approach to the verification of the system is expected to show whether each of the factors is behaving as expected or not, as well as to help on the selection of the model parameters under which the model is behaving reasonably.

It is important to clarify at this point, that the final output that will be required from the system is a fuzzy value of the quality level of the construction resources, (i.e. expressed in linguistic terms such as low, medium, or high). Therefore, it was expected that the testing of the stability and consistency of the system was made possible by performing different trials of different scenarios of the maturity of the PQM system under analysis and submitting the outcomes to the opinion of experienced managers within the case study organization. Further clarification of the methodology used to verify the stability of the FES is provided in Chapter 6, in which the application of the proposed modelling approach has been documented.

As seen in Figure 3.6 a key process involved in every one of the four steps described previously is the experts' knowledge elicitation. This includes the acquisition of the knowledge and its representation in a manner that facilitate its manipulation to make inferences. The knowledge acquisition and knowledge representation methods, proposed for the modelling approach developed in this research, are introduced in Chapter 5. Other important point for the development of a FES is the establishment of the assumptions that were required to simplify the complexity of the system under study, as well as to identify the limitations of the proposed model. The following section clarifies such assumptions.

3.2.3.4 Assumptions for the FES to infer the quality performance level of the construction resources

It was necessary to establish some assumptions and limitations in order to emphasize the purpose of the FES proposed here. Such an FES attempts to determine the quality level of the construction resources that results from the maturity level of the PQM system implemented in an organization. Therefore, as articulated in the last section and exemplified in Figure 3.7, the quality level of such resources is the final output of the FES application. For example, the proposed FES attempts to determine what is the quality level of the material supply, (expressed as *very poor*, *poor*, *average*, *good*, or *very good*), given that the maturity levels of the supplier qualification, expediting, and examination practices (i.e. the input variables) are respectively assumed to be *reactive approach*, *continual improvement emphasis*, and *best-in-class performance*. Then, the following limitations were established for the development of the FES:

i) The FES proposed in this research is limited to the modelling of the influence of PQM practices. Therefore, the fuzzy model of the system under study does only attempt to account for the main and specific factors affecting the quality performance of construction resources, other than for all the factors affecting the quality of a construction operation. Hence, it was assumed that the system affecting each specific output (operation resource) could be reduced subjectively with the support of experts and records related to the quality system in an organization.

ii) A drawback of a FES is that its capacity to make inferences is limited to the context in which it was developed. In fact, the main difficulty in using heuristic models is that they are not as general as algorithms [Turban and Aronson 2001]. Therefore, they can only be used for the specific situation for which they were intended. This means that the entire set of membership functions and inference rules must be checked and adjusted if any factor (input or output) has to be introduced to or taken from the system, or if the FES is to be adapted in another organization. For example, if a new PQM process is to be evaluated within a given system, it is necessary to check how the outputs and the other already existing PQM practices would be affected. The adjustment of the FES is also required when it is to be used in a different construction operation, as the experts' assessments may seriously vary from operation to operation and, thus, lead to different simulation results.

iii) The quality of construction resources was defined, in this research, as the capacity of the given resource to contribute to the performing of construction activities with no nonconformities associated to that resource during its participation in the project. Meanwhile, nonconformity was defined as the occurrence of any disruption during the undertaking of construction activities, caused by any of the resources utilized in the performance. Moreover, it was assumed that the performance of the construction resources entirely depends on the performance of the PQM practices implemented in the organization; whereas other factors affecting the performance of such resources were not taken into account. For example, a delay on the supplying of materials should not be considered a nonconformance if the delay was due to the weather conditions on the work-site; but, instead, it should be considered a nonconformance if the delay was due to the capacity of the supplier or vendor. In that case, the supplier qualification and the expediting processes should assure that the supplier has the capacity to supply the material on time. Other example is the occurrence of nonconformities due to the soil conditions, which may affect the work conditions. In that case, the procedures implemented for internal examinations should warn of such soil conditions in order to take the appropriate actions that could avoid unexpected work conditions. Hence, it must be clear that only nonconformities associated to the performance of PQM practices were appointed to evaluate the quality of resources.

iv) On the same way, the influence of context variables was not directly included in the proposed system, though it was considered for the appropriate assessment of the output sub-factors. The context variables that should be taken into account in this case are the project type (i.e. water system, sewer system, oil and gas pipeline system, multiple utility system, etc.), the construction method (i.e. open cut or tunnelling), and the size of the project (i.e. small, medium, or large). For example, the number of not on time deliveries, in Figure 3.7, is influenced by the size of the project as it is expected that a large project will have more chances to experiment delayed deliveries than a small one. It must be noticed, though, that the size of the project or the project type should not be considered as factors influencing the final output, but it would be an auxiliary factor to determine what membership functions should be used to assess a project of a given size or type.

v) Though at least some degree of interaction is expected among all processes carried out into a PQM system, it was assumed, for the development of the FES in this research, that the interaction exists only among those PQM practices which have a key contribution in the definition of the quality level of a given output sub-factor or final output. For example, in the case of the system shown in Figure 3.7, the interaction exists between the supplier qualification and the expediting practices, but not with the internal and external examinations, when assessing the factors influencing the number of delayed deliveries. While, on the other hand, it would be assumed that the interaction exists between the supplier qualification and the internal/external examination processes, but not with the expediting process, when assessing the factors influencing the number of inadequate material deliveries.

These and other assumptions have been further clarified in Chapters 5 and 6.

3.2.4 Simulation modelling to estimate the effect of PQM on the performance of construction operations

System simulation is a powerful tool for analysis and design, which can help in conducting experiments, identifying system behavior, and evaluating system performance by establishing a set of structural and procedural elements that represent real systems [O'Reilly and Lilegdon 1999, as quoted by Chang and Chen 2006]. Computer simulation is used for conducting experiments (such as what-if analyses) on a computer-based model of some system, often in a 'trial and error' way, to demonstrate the likely effects of various policies [Pidd 1984]. Hence, those that produce the best results in the model would be implemented in the real system. Such an approach represents a typical use of system simulation to support decision-making. However, Pidd [1984] also pointed out that when a manager needs to make a decision on a particular problem other modes of approach are possible, such as experimenting directly on the real system or constructing a mathematical model or a logic model of the system of interest. On the other hand, Pidd also considers that simulation has the following advantages against real experimentation:

- *Cost*: Though simulation can be time consuming and therefore expensive in terms of skilled work force, real experiments may also turn out to be expensive, particularly if something goes wrong.
- *Time*: Though it may take a significant amount of time, once a computer simulation model is completed an attractive opportunity presents itself; namely, it is possible to simulate weeks, months or even years in seconds of computer time. Hence, a whole range of policies could be properly compared.
- *Replication*: The real world is rarely kind enough to allow precise replication of an experiment. Simulations are precisely repeatable.
- *Safety*: One of the objectives of a simulation study may be to estimate the effect of extreme conditions and to do this in real life may be dangerous or even illegal.

Moreover, though realistic simulation may require long computer programs of some complexity, there are already special purpose simulation languages and packaged systems available to ease this task [Pidd, 2003]. As well, because there is some randomness in real decision-making situations many times simulation may be the only way of tackling some problems in management and engineering systems. For example, optimization or other models may not represent appropriately the complexity of reality, which involves semi-structured or unstructured situations. Simulation can often handle such situations, though an optimal solution cannot be guaranteed. [Turban and Aronson, 2001].

Simulation can be classified into two categories: continuous or discrete. In discrete simulation, the state of the system changes discretely, only after the occurrence of programmed events. On the other hand, in continuous simulation models the state of the system is represented by dependent variables that change continuously over time. For its simplicity, most of the work in construction simulation falls into the discrete sector [Shi and AbouRizk 1998]. On the other hand, simulation can also be stochastic, in which the state of the system changes randomly over the time based on probabilistic functions, or deterministic, in which the state of the system does not change over the time and, therefore, the behavior of the system is entirely predictable. Stochastic simulation based on statistical data has been deemed more suitable for modelling systems in construction projects, which are very susceptible to variation and interruption [AbouRizk and Halpin 1990]. In fact, simulation models based on discrete-event and stochastic simulation modelling have already been put into practice successfully to improve productivity in projects by experimenting different production strategies [Sobotka 2000; Hajjar and AbouRizk 2002; Fernando *et al.* 2003; Zayed and Halpin 2004; and others].

However, probability-based modelling is very effective in dealing with uncertainty only when enough data describing the uncertainty are available. In fact, that would be a major drawback of simulation because, in case of data limitation, selecting the probability distribution that best represents the missing data is not effective and straightforward [Shaheen 2005]. The difficulty in approximating a probability distribution is that experts think in linguistic terms such as low, high, etc., rather than thinking in probability values [Fishwick and Luker 1991]. For example, very little effort has been made on simulation modelling to analyze, design, or develop management systems. The literature reveals that this is due to the complexity of most management systems, as they comprise diverse factors such as human, organizational, and resource considerations, which are difficult to model in a probabilistic approach [Aghaie and Popplewell 1997]. Therefore, in agreement with Shaheen's opinion [2005], the modelling capabilities of discrete event simulation (DES) need to be enhanced by incorporating more modelling techniques, in order to be able to model uncertainty in an explicit and effective manner.

3.2.4.1 Discrete-event simulation and fuzzy-logic models

Several authors have attempted to incorporate the effect of the uncertainty related to subjective or vaguely defined factors into construction simulation models [Abourizk and Sawhney 1992; Zhang *et al.* 2003; Shaheen 2005; Lee *et al.* 2006, Chang and Chen 2006]. According to Abourizk and Sawhney [1992], there are two different approaches to include uncertainties in simulation experiments of specific activity parameters:

i) The *aggregated input-process method* (AIM), which incorporates all past knowledge with similar activities and all uncertainty elements into the parameter statistical distribution. In this case, a single statistical distribution models the activity parameter.

ii) The *separate input-process method* (SIM), which models based on knowledge and historical records, the influences of external and uncertainty elements and factors separately as mathematical functions, elemental data, and other statistical distributions and random input processes. After that, the effect of such elements and factors can be incorporated in the statistical distribution of the activity parameter.

The SIM approach can be more accurate than the AIM when sufficient records are available to categorize and specify all aspects of the various input factors. Though it is rather computationally expensive, as it requires numerous manipulations of the activity duration during the simulation experiment, this method was deemed more appropriate for accurately incorporating the effect of the uncertainty of highly complex factors, such as those involved in a QM system, into a construction simulation model. Such approach was thought would provide more transparency to the model, as the way the knowledge was represented and manipulated would be easier to comprehend to the end user.

i) On the other hand, fuzzy logic theory has been a recurrent alternative to model the uncertainty of subjective or vaguely defined factors that are difficult to integrate to simulation models. However, fuzzy logic modelling, as a technique based on qualitative methods, can also be better off with its interaction with simulation modelling. Authors of simulation literature have revealed how DES can cope with the weaknesses associated with qualitative methods and be used as an effective research strategy [Eldabi *et al.* 2002]. Table 3.2 shows how DES can deal with the weaknesses associated with qualitative methods.

Table 3.2: The use of DES to deal with the weaknesses of qualitative methods*

Qualitative Methods	Discrete Event Simulation
The collection and analysis of data are time-consuming and demanding because many types of data are collected. Large variety of data may inhibit data analysis.	Can be used to identify key variables to avoid unnecessary data collection
The inability of the researcher to interpret events from the subjects' point of view without biases	Capable of giving independent picture of the situation by dynamic mimicking
The relationship between theory and research can be weak, as qualitative research approaches are criticized for not instilling theoretical elements	Offers facility for adding or removing any theoretical assumptions whilst examining their impacts
The extent to which qualitative research can be generalized beyond the confines of a particular case, is questioned	It is possible to examine as many hypothetical situations (what-if-scenarios) expanded from the base cases
Unstructured research is endangered of being to be meaningless	The research may start as unstructured yet it becomes more refined and structured in later stages as more understanding is gained from the process
It is possible to loose detachment of the researcher	Researcher is able to experiment a simulated environment without risking to loose detachment
Potentially poor reliability, as qualitative research often involves a single event being observed by a single researcher	It is possible to produce reliable qualitative analysis, as model could be replicated and observed by different researchers

*** Based on the table included in Eldabi *et al.* 2002.**

In the case of this research work, basing the development of the fuzzy models on the fact that they were required to provide the inputs for DES models facilitated the following:

ii) The identification of key variables involved in the system under analysis, which may avoid unnecessary data collection for decision-making. This also leads to figuring out the structure representing the interaction of the variables.

iii)The increase of objectivity in the approach to evaluating soft variables influencing the performance of a given system. For instance, the decision to model the effect of the quality performance of PQM practices on operations in terms of delays in the construction activities was because DES models work better for time-based variables.

The incorporation of randomness to the estimation of the effect of PQM practices on the performance of construction operations, which is more appropriate when dealing with a system with uncertain behavior.

In the construction context, Lee [2001] has already used the SIM approach to integrate a model for evaluating the productivity variation due to the occurrence of accidents. Based on the approach used by Lee [2001], this research work proposes to separately obtain the different outputs, from different model components, that will be required to evaluate a PQM system. The following section explains the integration of the components of the modeling techniques proposed in this research.

3.3 Interactive-computer-based system to estimate construction quality

The system that integrates the computer-based modelling techniques previously described is an essential component of the PQM assessment framework proposed in this research work. This interactive-computer-based system attempts to make an organization's explicit and tacit knowledge on QM systems, useful for decision-making. At the same time, the system combines four components based on sequential partitioning of system flow, as seen in Figure 3.8, which have been clarified as follows:

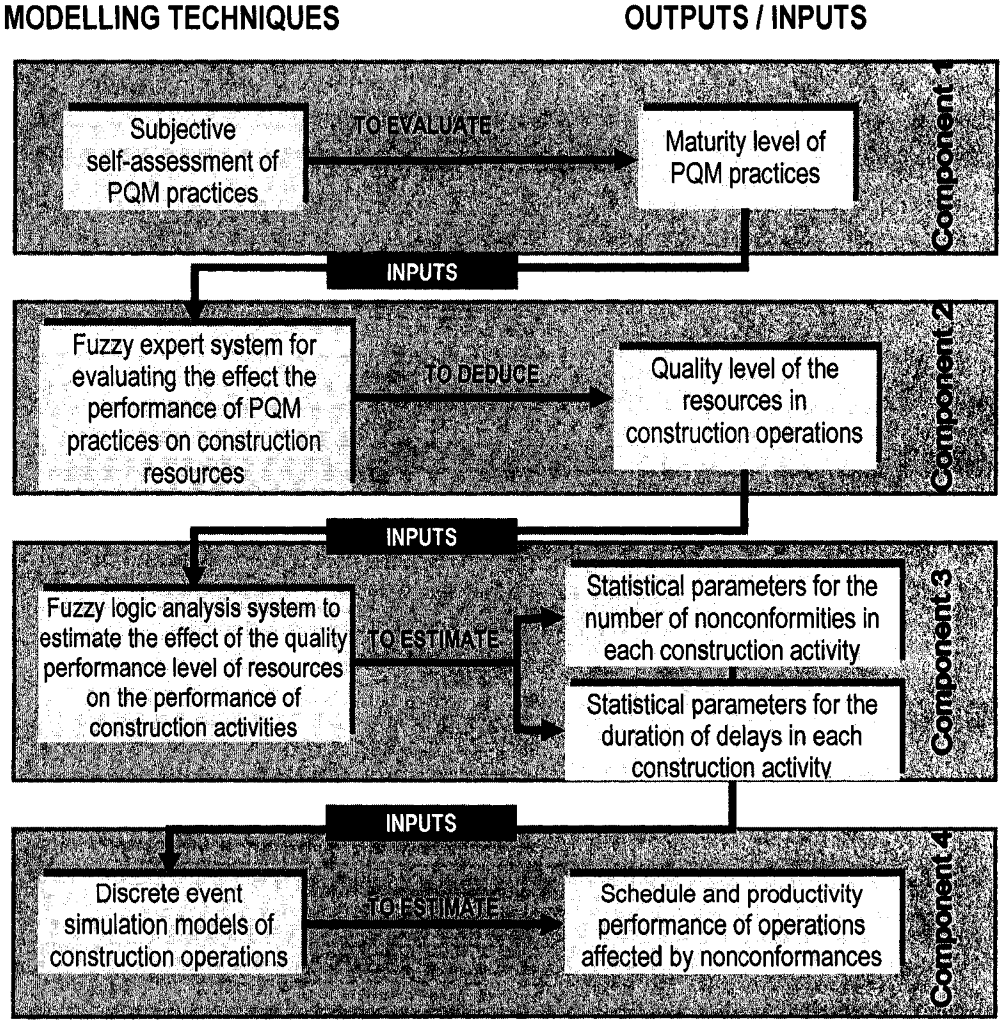


Figure 3.8: Interactive-computer-based system

i) The first component evaluates the maturity level of each of the PQM practices that are included in the system being appraised. There are two approaches to determine the maturity level of PQM practices. One is determining the maturity level with the answers given to self-assessment questionnaires formulated to evaluate each specific PQM process with which a process quality index (PQI) score can be obtained, as proposed by Kumar and Wolf [1992] (refer to Section 2.3.1.1.ii). The other approach is to base the determination of the maturity level on the subjective assessment that the user can assert about the given PQM process; for example, a knowledgeable manager could assert the implementation of a given PQM process is in the *reactive approach* stage. Using the first approach a crisp value would be the input to the FES; while if using the second approach, a linguistic term (e.g. *reactive approach*) would be input.

ii) In the second component, the FES then takes the information transferred from the first module to perform the fuzzy inference process, explained in Section 3.2.3.2, in order to infer the output. As pointed out before, the maturity levels, given as a crisp value or a linguistic term, of each of the different PQM practices in the system being analyzed are the input variables in the proposed FES. Meanwhile, the output variables are the quality levels of the different resources required in the performance of a given construction operation. However, the outputs of the FES are only deemed intermediate outputs within the integrated model, as they still have to be delivered, in linguistic terms (e.g. poor for the quality of material supplying, average for labor crew, etc.), as inputs to the fuzzy logic models adapted to estimate the occurrence of nonconformities.

iii)The purpose of the third component, the fuzzy-logic-based models, is to estimate the quality performance of construction activities. This includes obtaining both the average number of nonconformities and the statistical parameters of the duration of delays, which would be obtained in the different construction activities based on the quality performance level of resources. The procedures to obtain these estimates are explained in Sections 3.2.2.1 and 3.2.2.2, respectively. The statistical parameters of delay durations include the mean value and the standard deviation of the estimated probability mass function for a given construction activity. This would allow for the generation of random variables that would be used in a simulation model accounting for the duration of the activities involved in the operation.

iv) In the fourth component, a discrete-event simulation model of a specific construction operation estimates the impact of the performance of PQM practices on the construction operation by using the inputs generated from the fuzzy-logic-based models in the third component. A discrete-event simulation model is usually expressed in the form of a network diagram where entities flow through interconnected modelling elements. With the Common template, a general-purpose simulation tool available in the Simphony.NET platform, a simulation project can be formulated by using pre-defined elements of the Common template or creating new modelling elements to graphically represent network activities involved in the construction operation under study.

Simulation models of construction operations usually include the uncertainty of factors involved in the performance of activities by using the AIM modelling approach. That is to say that the influence of nonconformities in construction activities (interruptions, disruptions, and rework) is usually integrated to the probability distributions representing the activity durations. The assessment framework proposed in this research, attempted to measure separately such influence (i.e. in terms of the impact on the completion time and productivity of construction operations), in order to get a more clear understanding on how the PQM practices affect the performance of construction.

Moreover, it is important to notice that the estimates obtained with the simulation analysis are not expected to provide an accurate prediction of the operation's productivity and completion time, but only a reference of how the implementation or improvement of PQM practices would affect the performance of the given operation. The simulation project for the case study was documented in Chapter 6.

3.4 Summary and conclusions

This chapter introduced the modelling approach that was followed for the development of the computer-based system included within the PQM assessment framework proposed in this research. The major challenge in this development was the selection and adaptation of the appropriate techniques to model greatly subjective factors, such as the influence of the PQM practices on construction operations, for simulation purposes. Therefore, special attention was put to the background of the modelling techniques that were applied in this research. The following points should be highlighted from this review:

i) Influence diagrams are appropriate tools to structure the elements within a system under study. They also can offer an initial conceptual model that could facilitate the knowledge flow within a project organization regarding the quality of management processes, as well as further improve the organization's knowledge management systems. An influence diagram was used as a conceptual model to structure the way the influence of PQM practices permeates through the elements within a construction project system. This allowed identifying what information is significant for the decision-making problem stated in last section. The proposed structure was also the basis to the development of the fuzzy-logic modelling approach.

ii) The modelling of linguistic variables is one possible approach for dealing with the problem of experts describing influences in qualitative terms and, therefore, to overcome the limited amount of data that is available as to simulate such influences. Applying fuzzy logic may enhance confidence in the validity of a model which purpose is to evaluate the influence of the quality of project management processes on the performance of a given operation.

iii) Fuzzy logic modelling was identified as an appropriate alternative to developing a knowledge-based system with the capability to infer the influence of PQM practices on construction performance goals such as the completion time of a given operation. The knowledge-based system included two different fuzzy-logic-based applications:

a) A fuzzy expert system proposed to infer, based on the maturity level of PQM practices, the quality of resources used in a given construction operation. The development of an FES was deemed an appropriate approach for the aforementioned purpose as it would permit to integrate more objective variables into the inferring of the state of output variables with a high degree of subjectivity, such as the quality level of construction resources.

b) A fuzzy logic-based procedure proposed to analyze the effect that the qualities of the construction resources have on the performance goals of the construction operation (i.e. the operation's completion time and productivity). Two fuzzy-logic-based procedures were adapted in order to determine the statistical parameters of the number of nonconformities and the duration of delays expected in specific construction activities. This approach was deemed appropriate for the aforementioned purpose as the procedure includes the assessment of variables that could lead to more accurate estimates needed as input to a given simulation model. In addition, it may be easier to include a larger number of the resources into the system under study.

iv) Simulation modelling was proposed to evaluate the impact of the quality of PM processes on the completion time of construction operations, based on the inputs provided by the fuzzy-logic-based models. The inclusion of discrete-event simulation within the proposed modelling approach was a fact that also supported the development of the fuzzy models, as the following was facilitated:

a) The identification of key variables involved in the system under analysis, which may avoid unnecessary data collection for decision-making;

b) The increase of objectivity in the approach to evaluating soft variables influencing the performance of the given system (e.g. the effect of the PQM system on a construction operation);

c) The integration of randomness into the estimation of the effect of PQM practices on the performance of construction operations, which is wanted when dealing with systems with uncertain behavior.

The interaction of the aforementioned modelling techniques would allow taking advantage of the construction experts' knowledge and the limited information available on the assessment of project quality systems and, then, facilitating the decision-making process on the implementation of management initiatives.

CHAPTER 4

THE PROJECT QUALITY MANAGEMENT ASSESSMENT FRAMEWORK – DESCRIPTION AND CASE STUDY

This chapter introduces the Project Quality Management Assessment Framework (PQMAF) that this research work has proposed in order to evaluate the effect of PQM systems on the performance of construction processes. A major requirement for the development of the PQMAF was the integration of a Project Nonconformity Assessment Approach (PNAA), which addresses the elicitation of information and knowledge available in a construction organization for modelling the quality performance assessment variables involved in a PQM system. The development of the proposed PNAA was based on the study of the project management (PM) processes of an organization dedicated to the design and construction of underground utilities; thus, this case study is also referenced throughout the chapter.

4.1 Description of the Project Quality Management Assessment Framework

Leading and operating an organization successfully requires the management of its performance attributes in a systematic and visible manner. Success should result from implementing and maintaining a management system that is designed to continually improve the effectiveness and efficiency of the organization's performance [ISO 9004: 2000]. The PQMAF is intended to facilitate an assessment of the effect of project quality management (PQM) practices on construction operations.

As shown in Figure 4.1, the framework includes two main components, the Project Nonconformity Assessment Approach (PNAA), which is further detailed in Section 4.1.2, and the Interactive-Computer-based System (ICBS), which was introduced in Section 3.3. The PNAA is intended to provide the basic quality-related information and knowledge required for the development and application of the simulation models proposed by the PQMAF. For instance, the ICBS requires the information and knowledge obtained through the PNAA for developing and applying the fuzzy logic models incorporated into such system.

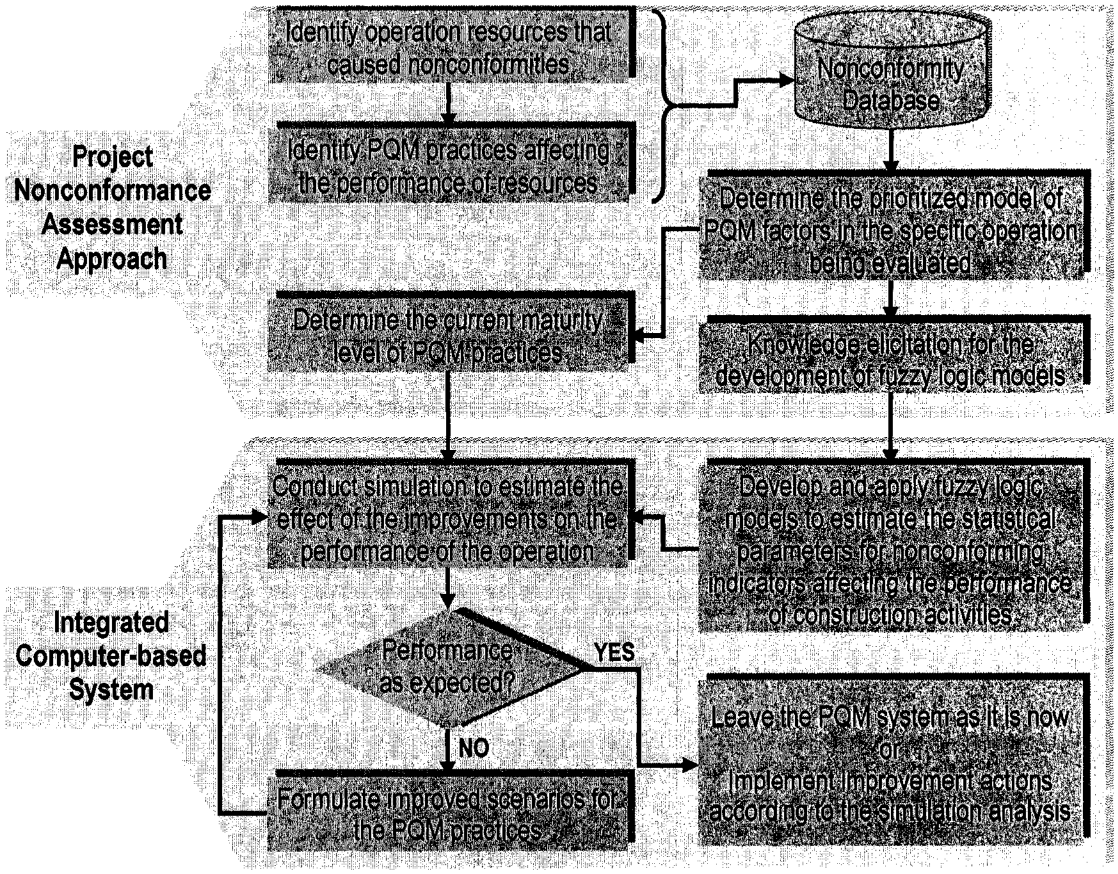


Figure 4.1: Project Quality Management Assessment Framework

4.1.1 Considerations for the development of the PQMAF

The general framework for the assessment of performance in any given context requires the following [Szilagyi and Wallace 1990]: (i) a combination of criteria, i.e. not a single measurement; (ii) a level of analysis, e.g. corporate level, project level, operation level, etc.; (iii) a certain focus, i.e. the kind of performance desired; (iv) a time frame, e.g. short- or long-range; and (v) a measurement system, e.g. quantitative vs. qualitative or objective vs. subjective. Such requirements were taken into account in the development of the proposed PQMAF as follows:

i) *Measurement criteria*: the PQMAF focused on the evaluation of the effect of the quality of PQM practices on construction operations; accordingly, quality was deemed the main criteria to measure performance in the proposed framework. However, since the evaluation was simulation-aided, time was also thought an appropriate performance indicator to facilitate the use of simulation modelling. In fact, the PQMAF proposes that such an evaluation be based on a comparison of the completion time and productivity estimates obtained through the simulation of a given construction operation affected by PQM practices, in which maturity is represented with alternative improved scenarios.

ii) *Level of analysis*: two organizational levels were taken into account in order to model the performance of a PQM system: the project-level and operation-level. The performance of the system is explained at the project-level, through the maturity of the PQM practices and, at the operational-level, with the quality of the construction resources involved in the operation being analyzed.

iii) *Focus*: the proposed framework focused on the effect, with respect to PQM practices, of performance level on the performance outcomes (e.g. schedule or cost) in construction operations.

iv) *Time frame*: though QM initiatives are steadily implemented in an organization during a typically long period of time, their effect on the performance of a construction operation is determined by the state of PQM practices at the point in time at which the construction operation is actually carried out. Therefore, the time frame in which the influence of the performance of such practices is evaluated is determined by the period of time required for undertaking the construction operation under analysis. This implies the need for a self-assessment of the state of the PQM system in place when its impact on a construction operation is to be appraised.

v) *Measurement system*: the proposed modelling framework combines a qualitative and quantitative approach in its assessment of the impact of PQM processes on the completion time and productivity of construction operations. In one respect, assessment of the performance level of PQM practices and their effect on the performance level of the construction resources uses subjective assessments of experts. However, the incorporation of simulation modelling within the framework suggests an approach that estimates in quantitative terms the effect of PQM processes on the completion time and productivity of construction operations.

In addition, the formulation of the PQMAF considers that the usefulness of any quality assessment framework for decision-makers in the industry depends on the extent to which it enables the identification of the underlying drivers of quality. This requires an approach that formally describes the quality of the construction process and explains as much as possible the construction output in terms of the quality of the inputs used to generate it. While it is generally accepted that data requirements are a major constraint to such an approach, it is suggested that through the establishment of a robust assessment framework, data deficiencies can be overcome more easily. As such, the integration of an approach to overcome such issue was a key requirement for the application of the PQMAF. The PNAA intends to support the achievement of such a requirement, as is made clear throughout the following Section.

4.1.2 Nonconformity Assessment Approach for construction projects

Formulation of the PNAA is based on previous approaches to the measurement of quality performance in construction projects. However, the PNAA attempts to overcome their limitations in supporting the assessment and improvement of the PM processes. Such limitations include:

- Focusing on only one aspect of quality failures (rework during the physical construction of the product), rather than covering their broadest context as nonconformities occurring throughout the construction process [Foster 1996].
- Failure to recognize PM processes as the root causes of nonconformities occurring at the operational level and, therefore, affecting the identification of unambiguous link between the performance of PM and construction.
- Total reliance on the memory of project participants interviewed to measure quality failures in construction. For example, after-the-event and post-project interviews have been the primary sources of data for decision-making about the improvement of project quality [Hall and Tomkins 2001].

In order to overcome the above-mentioned limitations, the following features were included in the PNAA:

- Quality performance assessment based on an analysis of the nonconformities reported during the undertaking of construction operations. This approach takes advantage of the quality-related information that ISO 9001 certified organizations are required to record. Moreover, this also agrees with ISO 10006:2003 and ISO 9004:2000, which persuade the management of project organizations to ensure that the records of nonconformities, in terms of the project's product and processes, are analyzed to assist learning and to provide data for improvement. In this case, the analysis of nonconformities focused on any disruption that affected the performance of the activities involved.
- Emphasis on the assessment of PQM processes, which are deemed the root drivers of quality in construction projects. This includes identifying the way in which the effect of PQM processes propagates up to the performance of construction operations.
- Knowledge-based assessment both of the performance level and of the interactive effect of the factors involved in a given PQM system, as a means to complement the factual, albeit limited in quality, performance-related information available in construction organizations. This condition serves to highlight that the quantitative measuring of quality performance is usually minimal in construction organizations; therefore, these subjective assessments attempt to provide the missing information that the proposed simulation-aided framework requires.
- Disaggregated elicitation of knowledge according to a causal structure depicting the way in which the effect of PQM factors propagates up to the operational level. This

means that the elicitation of the knowledge required by the PQMAF should be conducted through two independent knowledge modules: the specific-PQM-system knowledge and the knowledge related to the performance specific operations. This feature encompasses important implications for the quality and practical application of the modelling approach. Such modularization allows for independent knowledge elicitation from the most competent personnel at different organizational levels within a project organization. Moreover, both modules can be integrated into a permanent knowledge-base that may eventually support the application of other techniques that aid decision-making. Chapter 5 includes further clarification concerning both knowledge elicitation modules.

The role of the PNAA within the PQMAF is further detailed in Figure 4.2, which shows the sequence of activities to be undertaken in the application of the PQMAF. This is detailed throughout the following Section.

4.1.3 The process involved in the PQMAF

As seen in Figure 4.2, there are four phases grouping the tasks involved in the PQMAF. The first three phases, surrounded by dashed lines, integrate the tasks to be undertaken as part of the PNAA. The fourth phase is dedicated to the tasks required for the development and application of the ICBS. These four phases are further explained below.

1. The first phase includes the activities involved in the basic information elicitation process to be carried out by the personnel participating in the execution of the construction projects. These activities should be carried out at two different stages:

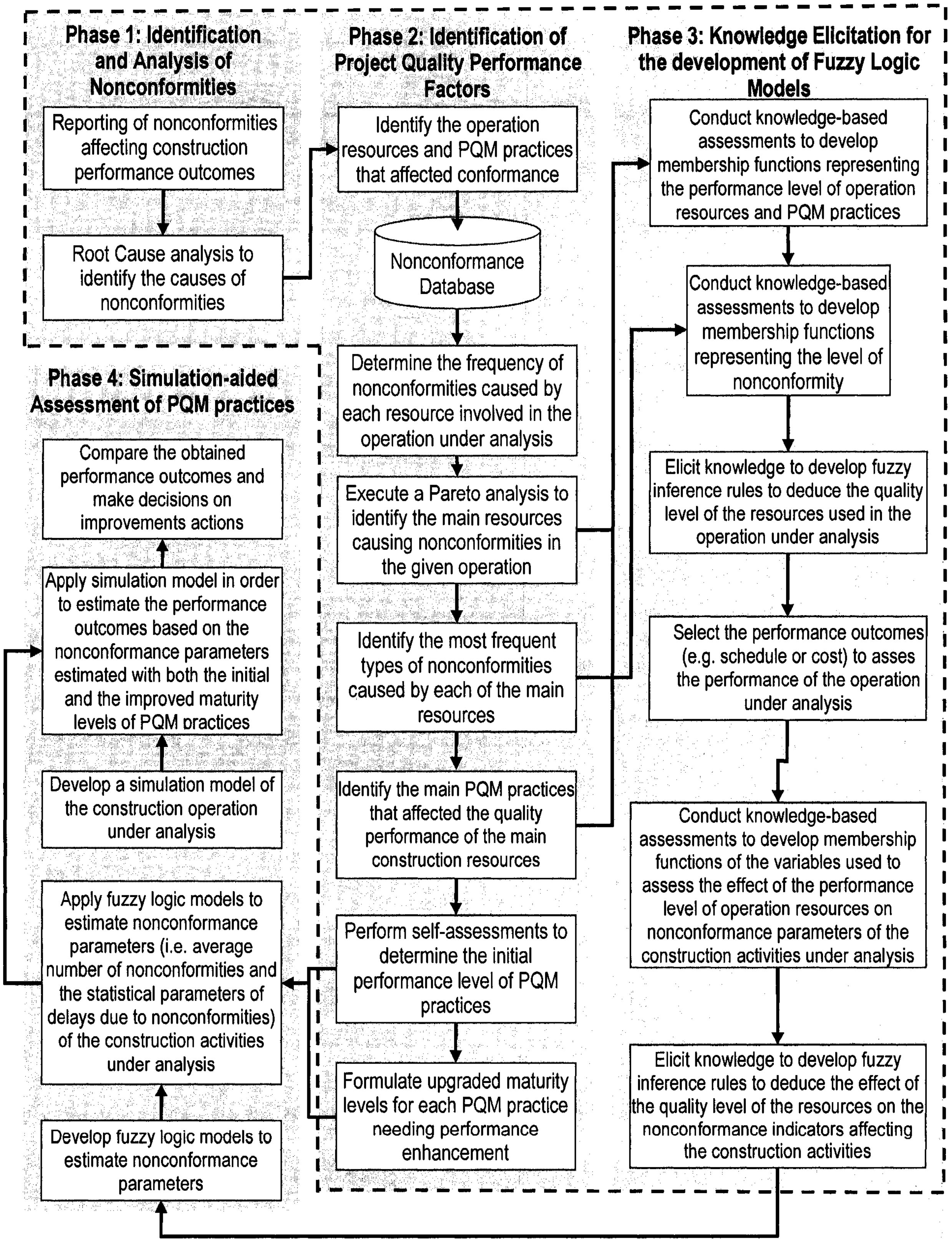


Figure 4.2: Integration of the activities involved into the PQMAF

i) At the time in which the nonconformity is detected: the personnel directly involved in it should report the consequences of the nonconformities occurring during the execution of a construction activity. This primarily includes a description of the nonconformities, on which further analysis can be based. The reporting of nonconformities can be done in a Nonconformity Report form like the one shown in Figure A.1 in Appendix A, which is used as part of the QA program implemented in the construction organization referenced as a case study in this research. As they arise, all nonconformities should be recorded, along with their effects on the construction activities, by the site-based staff. In the spirit of inclusiveness, all employees within the organization should be encouraged to monitor any quality failures or nonconformities that seem relevant to the exercise, whether related to their own activities or to those of other parties in the supply chain (e.g., suppliers, subcontractors, designers, and clients). The organization used as a case-study put into practice the recording of nonconformities following the implementation of a QA program into its business processes.

ii)During the after-the-event analysis of the nonconformity: At this stage, the factors that caused the nonconformities should be identified and assessed. This analysis can be formalized as a root cause analysis, which is recommended to be performed by supervisors and other personnel knowledgeable about the performance of the given activity, even if they had not been present when the nonconformities were detected. This analysis should be based on the description of the nonconformities formulated at the time of the detection, (as pointed out in the previous stage). The information obtained from the analysis can be used to further analyze the behavior of quality performance factors within construction projects, as is clarified in the following block of activities in Figure 4.2. Moreover, Figure A.2 in Appendix A shows a sample of the Root Cause Analysis forms used in the case study organization, as part of its QA program.

Although, in this case the PNAA takes advantage of the limited information provided by the basic nonconformity tracking procedure, it was noted that simple adjustments could largely improve its usefulness in other decision support systems. For example, the quantification of the effects of nonconformities on the schedule and cost of the affected activities and the explicit identification of the causes associated with the nonconformities could be easily included in the nonconformity reporting and the root cause analysis, respectively. Such adjustments were proposed to the case-study organization, although the implementation was in its early stage by the time this research was concluded. Figures A.3 and A.4 in Appendix A show the Nonconformity Report and Root Cause Analysis forms adjusted to obtain more comprehensive information regarding the nonconformities occurring during daily work in the case-study organization.

Moreover, Table A.1, also in Appendix A, includes examples for the measurement of the consequences of nonconformities pertaining to the schedule and cost of a given construction activity. Schedule delays and cost overruns due to waste were thought as appropriate indicators for measuring the effect of nonconformities on the performance of the construction activity.

2. The second phase is dedicated to the identification of the quality performance factors involved in the project being analyzed. The factors in the system may vary depending on the construction operation under analysis, and include:

   i) Nonconformities that affect the performance outcomes of the construction activities under analysis (e.g. delays in the supplication of resources, rework, accidents, etc.);
   ii) Construction resources (e.g. labor, supervision, materials, etc.) required to perform the construction operation. The number of nonconformities associated with a given construction resource define is further translated into the quality level of such resource.
   iii) PQM practices (e.g. supplier qualification, risk management, etc.) involved in the management of quality performance of the operation resources. PQM practices are regarded as the factors affecting the number of nonconforming events associated with of the construction resources.

Further detailed definitions of these factors are included in Section 4.2. Moreover, the identification of the main PQM factors affecting the performance of specific construction operations has the following purposes:

i) Reducing the number of factors included in the PQM system model, which affect the operation under analysis. A Pareto analysis is proposed in order to identify the construction resources most frequently affecting the given operation. An example of the application of Pareto analysis intended to reduce the amount of PQM factors is described in Section 4.3.2. A prioritized model of the PQM factors affecting the operation being analyzed was obtained through this process in order to make more efficient the development of the fuzzy logic models involved in the PQMAF.

ii) Determining specific PQM practices to be assessed and upgraded based on the number of nonconformities caused by each of them. Moreover, the efforts associated with conducting the self-assessment of PQM practices would be reduced as well. Self-assessment procedures are required in order to determine the current or initial maturity level of PQM practices and, then, to decide on the actions that should be taken to improve the system. The self-assessment of PQM practices is discussed in Section 4.2.3.1.

The information generated in this phase can be useful to carry out basic analyses such as those based on descriptive statistics, which may still support the assessment and improvement of PQM practices. However, the development of more advanced tools to assess and improve such practices necessitates comprehensive information in order to facilitate the application of modelling techniques such as discrete event-simulation. Because of the vague information that construction organizations usually have regarding the quality of processes, the tacit knowledge that experts have within an organization concerning the performance of project quality factors should be integrated in order to overcome such need. The knowledge elicitation having to do with this issue is explained in phase three.

3. The third phase in Figure 4.2 shows how a knowledge elicitation process should complement the information obtained within the second phase in order to support the development of fuzzy logic models for the assessment of specific construction operations. The purpose of this phase is to conduct knowledge assessments that would provide the knowledge required for the development of the membership functions of

the variables and the fuzzy inference rules that make up the fuzzy logic models described in Chapter 3.

As mentioned above, knowledge elicitation should be undertaken through two different modules:

i) The *specific-PQM-system knowledge elicitation* (SPQMSKE) module, which should provide the assessments required to develop a fuzzy expert system useful for inferring the performance level of the main construction resources involved in the operation under analysis, (as described in Section 3.2.3). The variables that should be represented as membership functions in such a model are:

  a) The performance maturity levels of the PQM practices affecting the performance of the construction resources.
  b) The quality performance level of the construction resources involved in the operation under analysis.
  c) The frequency of occurrence (*F*) of the quality performance levels of the construction resources.
  d) The adverse consequences (*C*) of the combined effect of the quality level of the construction resources on the performance of construction activities.

On the other hand, the fuzzy inference rules that should be determined include the following:

a) The effect of the performance maturity levels of PQM practices on the number of specific nonconforming events associated to the resources.

b) The effect of the number of the specific nonconforming events on the quality performance level of the respective construction resources.

ii) The *specific-operation knowledge elicitation* (SOKE) module, which should provide the assessments required to develop the fuzzy logic models used in the estimation of the statistical parameters of both the number of nonconformities and the duration of delays resulting from the quality level of the resources involved in the construction activities under analysis, (as described in Section 3.2.2). The variables that should be represented as membership functions in those models are:

a) The number of nonconformities (*N*) during a given construction activity, based on the appraisal of adverse consequences.

b) The duration of delays (*D*) caused by the level of adverse consequences.

Meanwhile, the fuzzy inference rules that should be determined for these fuzzy models include:

a) The effect of the quality level of construction resources involved in the activity under analysis and the frequency of occurrence of such quality levels on the level of adverse consequences tied to the performance of the activity;

b) The effect of the level of adverse consequences on the number of nonconformities in the activity under analysis; and

c) The effect of the level of adverse consequences on the duration (delays) of the activity under analysis.

Chapter 5 includes further clarification about the development of the membership functions and the inference rules used to illustrate the application of the PQMAF. However, it is imperative to highlight at this point that this research focuses on the analysis of nonconformities whose effect on the performance of construction activities (e.g. trenching, utility installation, backfilling, etc.) is considerable. On the other hand, the PNAA is also applicable to activities carried out at the operational level to support the undertaking of the construction activities, such as the storage and inspection of material, the dispatching of approvals, the maintenance of the equipment, etc. Furthermore, accounting for such supporting activities would permit a more comprehensive assessment and improved performance throughout the entire organization.

4. The fourth phase includes activities concerning the development and application of the ICBS introduced in 3.3. As seen in Figure 4.2, there are five main activities involved in this phase, which are briefly explained as follows:

   i) The development of the fuzzy logic-based applications introduced in Sections 3.2.2 and 3.2.3. Such a development is based on the knowledge-based assessments obtained in the previous phase. The fuzzy logic-based models are intended to estimate the statistical parameters of the NIs, which have been defined in Section 4.2.1.iii. For instance, the NIs estimated as part of the sample application of the PQMAF, (see Chapter 6), are the number of nonconformities, and the durations of delay, which should be obtained for each of the construction activities under analysis. This process is further clarified in Chapters 5 and 6.

ii) The application of the fuzzy logic-based models for estimating the above-mentioned NIs for two different states of the PQM practices, including:

   a) The initial performance or maturity level of PQM practices, determined with a self-assessment procedure based on a questionnaire method. The application of the self-assessment procedure must provide the maturity levels expressed as quality indices (see Section 2.3.1.1) reflecting the current state of management practices implemented in order to assure the quality of projects. Further clarification on the self-assessment procedure is included in Section 4.2.3.1.

   b) The improved performance level of the PQM practices that the organization may decide to pursue based on the reference given by the initial or current maturity level previously obtained. The improved performance levels of PQM practices can be determined using the above-mentioned self-assessment procedure to obtain an improved quality index, or simply selecting the enhanced maturity levels in linguistic terms. The integration of a simulation approach to the PQMAF permits that a number of performance levels be evaluated.

   The statistical parameters of the NIs obtained in this stage are the inputs to the simulation model developed to estimate the completion time and productivity of the operation under analysis.

iii)The development of the discrete-event simulation model that represents the process carried out in the performance of a specific construction operation. The Common template, a general-purpose simulation tool embedded in the Simphony.NET platform, was deemed an appropriate instrument to formulate a simulation model that serves to estimate the completion time and productivity of the construction operation under analysis. The discrete-event simulation model used to test the application of the PQMAF is described in more detail in Chapter 6.

iv) The application of the discrete-event simulation model to estimate the performance outcomes (i.e. the duration or cost) of the operation under analysis, affected by the NIs (i.e. delays or cost overruns) obtained from the fuzzy logic-based models. The estimates of the number of nonconformities and the duration of delays are the inputs to the simulation model, by which the impact of PQM practices on the completion time and productivity of the operation can be estimated. As is mentioned above, at least two different estimates should be obtained from the simulation: the duration of the operation with the initial or current maturity level of PQM practices, and one or more with the improved maturity levels determined by the user.

v) The comparison of the outcomes obtained from the applications of the simulation model, which may further elucidate the effect of PQM practices on the performance of the construction operation and inform decisions regarding the specific improvement actions required in order for implementation within the management system of the organization. This is further clarified in the application described in Chapter 6.

It should be clarified at this point that the estimate obtained from the ICBS need not be deemed an accurate predictor of the operation's performance, but only a useful reference for assessing the effect that improvement actions implemented in PQM processes would have on the performance of the operations. This means that construction managers could obtain a better understanding of the behavior of the PQM system and thus make appropriate decisions about the improvement of the system. The focus of the PQMAF is on the proactive role that simulation can play in designing management systems.

4.2 Definition and assessment of PQM factors

For the purposes of this research, and according to the findings from the case-study described in Section 4.3.1, three PQM factors are involved in the determination of the quality performance of construction operations: the nonconforming events occurring during construction, the resources needed to execute the construction operations, and the PQM processes required to manage the quality performance of such resources. This suggests, as shown in Figure 4.3, that the performance maturity of PQM practices affects the quality performance of the resources, which eventually may cause nonconforming events that affect the achievement of the performance goals of construction operations. A knowledge-based assessment of the effect of PQM practices on the performance of the resources was facilitated through the assessment of the number of nonconforming events associated to the construction resources being analyzed. This is further discussed in the following sections.

4.2.1 Nonconformities and construction performance outcomes

Nonconformity is defined, for the purposes of this research, as any incident that impedes the construction process and which, consequently, results in a negative impact on the performance outcomes of construction activities. In addition, only those nonconformities which the project management is able to prevent and control, were accounted for the purposes of this research. Work conditions affected by weather for instance, should not be deemed nonconformities. Moreover, there are three key concepts related to the assessment of nonconformities:

i) The *specific nonconformities* associated with each construction resource involved in the operation under analysis should be identified in order to determine the quality level of such resources. The number of times a specific nonconformity associated with a given construction resource occurs during the performance of a construction project is expressed in linguistic terms, such as *very low*, *low*, *average*, *high*, or *very high*, in order to evaluate the contribution of such nonconformity to the quality of the respective resource. This number of occurrences of a specific nonconformity associated with a given construction resource is deemed an intermediate variable within the fuzzy expert system included in the PQMAF (see Section 3.2.3), as illustrated in Figure 4.3. Moreover, it should be noted that the assessment of this variable depends on context variables, such as project type, project size, and the construction method used. The number of nonconformities associated with the construction resources is a variable that should be assessed within the specific PQM system knowledge elicitation module described above.

ii) The *operation performance outcomes* are useful for describing the type of results of interest to the decision-maker in order to assess the performance of a construction operation. In this case, the performance outcomes are the simulation estimates obtained with different scenarios of the PQM system, and should assist an evaluation of the effect of the PQM practices on the performance of construction operations. The time and/or cost performance parameters of construction operations were thought to be appropriate alternatives to carry out this evaluation, as they are objective performance measures that would facilitate the application of simulation modelling in the PQMAF. Completion time evaluates the total duration of the operation under analysis, while Cost evaluates the total expenditures involved in the operation. However, this report focused on time performance parameters in order to illustrate the application of the PQMAF.

iii)The *nonconforming indicators* (NIs) represent the effect of the performance level of the PQM factors, (i.e., the PQM practices and the construction resources), on the performance outcomes for a given construction activity. The magnitude of such effect is expressed using linguistic terms like very small, small, medium, large, or very large. For example, the consequences for the completion time of construction operations can be assessed with the delays resulting from occurrences of nonconforming events, while the consequences for the cost of the operation can be assessed through the cost overruns incurred. Nevertheless, it is important to recall that the PQMAF proposes knowledge-based assessments of the nonconformity consequences as a means of overcoming the lack of empirical data. Such assessments should be elicited as part of the specific operation knowledge elicitation module previously introduced. Moreover,

Table A.1 in Appendix A shows sample approaches so as to report the consequences of nonconformities. On the other hand, a more detailed definition of the proposed NIs was formulated in order to reduce the subjectivity of the judgments, as follows:

a) *Delays* can be attributed on the work-site to one of three types of disruptions:

- *Interruptions*: when an activity is temporarily discontinued due to nonconformities related either to delay and inaccuracies with the supply of resources (labor, material, equipment, information, etc.) or to unforeseen work conditions.
- *Low-productivity periods*: when work is observed to progress at a slower pace than in normal or average workdays. This could be caused by nonconformities concerning delays on the supply of resources, unforeseen work conditions, and/or poor performance of labor or equipment.
- *Reworks*: when work already executed needs to be redone as the result of a failure to meet specifications or requirements.

b) *Cost overruns* can be accounted for with respect to the waste of the resources required to perform a construction activity (e.g. materials, labor, equipment, and corporate overhead), due to disruptions such as rework, inadequacies to do with the supply, inaccurate planning, etc.

It is important to note that both types of NIs are intended to assess the potential magnitude of the effect (i.e. duration of delays or amount of cost overruns) that a single given nonconforming event has on an activity performance outcome (i.e. schedule or budget). Nevertheless, the total effect on the performance outcome should include into the equation the number of times that any nonconformity affects the activity under analysis. Therefore, the proposed modelling approach takes as well into account the assessment of the number of nonconforming events expected in a given activity under analysis, as shown in Figure 4.3.

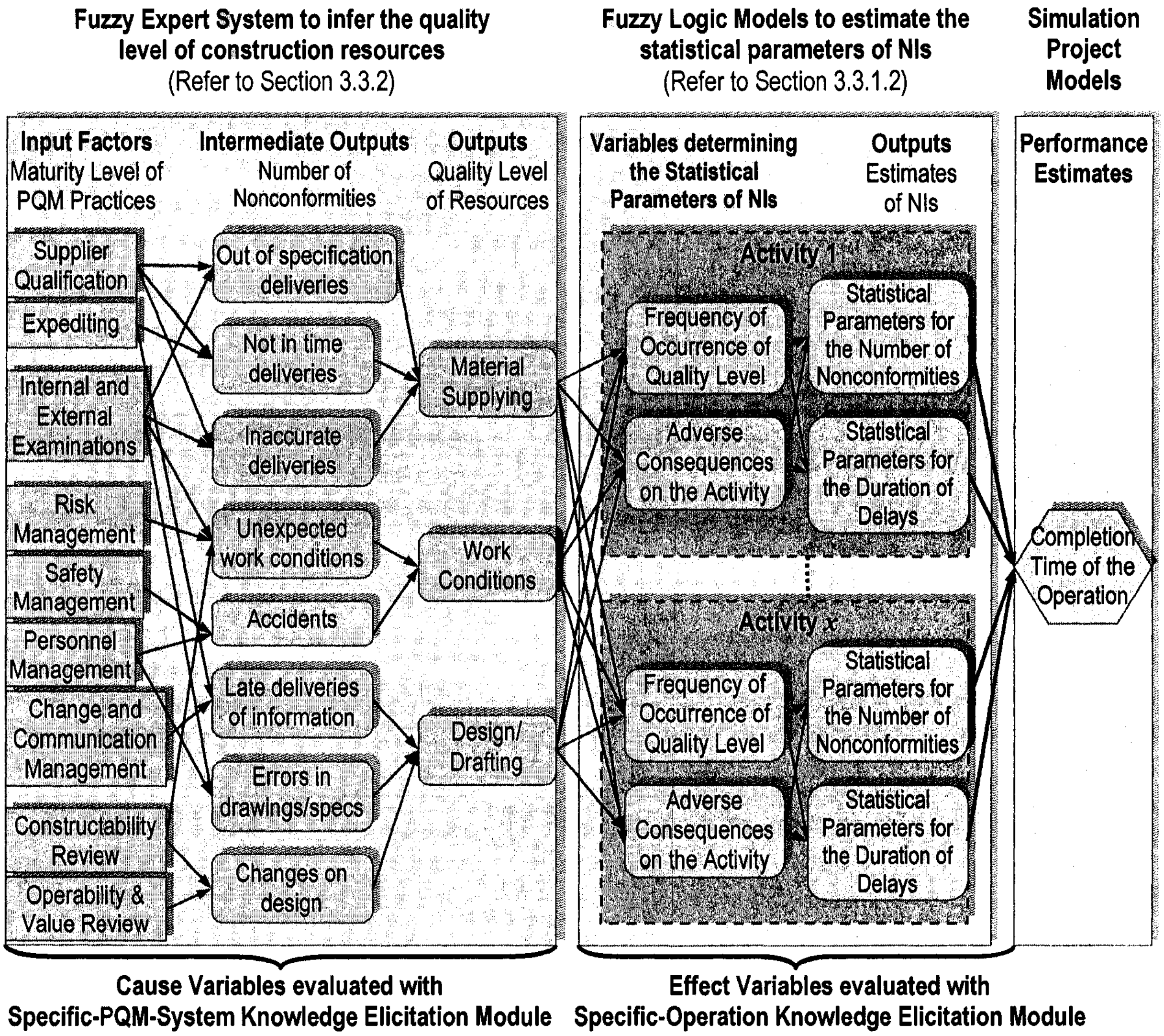


Figure 4.3: Integration of variables involved in the model causal structure

In addition, it is also important to notice that the assessment of NIs should take into account the context variables implicit in the system under analysis, such as the project type, the project size, the construction method used in the operation, and the specific activity under analysis. Chapter 5 further discusses the assessment of NIs such as the number of nonconforming events and the duration of delays.

4.2.2 The performance of resources in construction operations

Operation resources are the elements that are required to carry out the activities included in a construction operation. It is assumed that the performance of operation resources depends on the quality performance level of the management system implemented in the organization and, on the other hand, they are deemed the intermediate drivers that propagate the effect of the organization's QM efforts up to the performance of construction operations. Therefore, it is necessary to determine the quality performance level of the resources in order to be able to estimate their influence on the performance outcomes of the operations. This explains the significance of the operation resources within the proposed model.

As mentioned before, on one hand the quality level of the construction resources is inferred through the FES described in Section 3.2.3, while the influence of the quality of such resources on the performance of the operations is estimated through the fuzzy logic procedure detailed in Section 3.3.2. In addition, Figure 4.3 looks to clarify the assessment of the variables associated to the quality level of the construction resources.

The identification of the construction resources to include in the PQM system of a given construction operation plays a major role in the definition of the model. As stated in the description of the PNAA, such identification should be accomplished by means of a root cause analysis procedure. In order to facilitate this analysis, standard lists of construction resources used in specific operations under analysis could be provided along with a comprehensive listing of nonconformities associated to each resource. For example, the list of nonconformities that the 'material supplying' resource might be associated to, would include 'not in time deliveries', 'inaccurate deliveries', and 'out of specification deliveries'. In addition, the tracking of the root cause of the nonconformity should be done through the backward detection of the sequence with which the resources involved in the failure were affecting one to other. For example, the vendor supplying may be at first glance the cause of an inaccurate material delivery; though, further analysis may point towards an incorrect requisition submitted by the estimating staff due to erroneous design specifications provided by the designer. In this case, it would be concluded that the design/drafting information was the root cause of the nonconformity.

Moreover, Table B.1 in Appendix B contains the definition of a number of the resources used in construction operations undertaken by the organization used as case study, as well as some directions on how to appraise such resources for a root cause analysis and the meaning of quality performance for each resource.

4.2.3 The performance of project quality management practices

PQM practices represent the factors under evaluation in the model and are elements derived from the project quality policies and objectives, as illustrated in Figure 3.1. Hence, for the purposes of this research, they include all the project management initiatives, programs, and processes that are implemented at the project level to manage the objectives for quality in construction operations.

As mentioned before, the contention of this research is that the effect of the performance of such PQM practices is propagated throughout the PQM system and determines the performance of construction operations, which assumes two assessments are required:

i) The determination of the performance maturity level of the PQM practices, which is made by means of the Process Quality Indexes (PQIs) obtained with a self-assessment procedure of the PQM practices under evaluation, such as explained in Section 3.2.3.2 (stage 1.b). The self-assessment of PQM practices and the estimation of their PQIs are further clarified in Section 4.2.3.1.

ii) The assessment of the effect of the performance of PQM practices on the performance of the operations in the project, which is initiated from the appraisal of their effect on the quality of the construction resources involved in the construction operation being analyzed, as seen in Figure 4.3. Therefore, the identification of the main PQM practices affecting specific construction resources is a key requirement for modelling a PQM system. As it was previously stated, PQM processes are deemed the root causes of nonconformities in construction activities and they should be identified through the root cause analyses executed by managers and supervisors within the project organization. For example, Figure 4.3 shows that the 'Expediting', the 'Internal & External Examinations', and the 'Value Engineering and Constructability Reviews' mainly determine the quality level of 'Design'. Regarding this, Figure A.4 in Appendix A shows a Root Cause Analysis form that was suggested to facilitate the tracking of the root causes of nonconformities, i.e. the PQM practices.

In addition, these two kinds of assessment require the elicitation of knowledge-based assessments that will allow the development of the membership functions of the variables involved in the model and the inference rules that will control the inference engines within the fuzzy logic-based models.

Furthermore, Table B.2 in Appendix B describes a number of the PQM practices that were identified with the literature review developed in Chapter 2 and which implementation was corroborated within the PM system of the case study organization. The table also includes some examples of activities or requirements included in each of the PQM practices described there.

4.2.3.1 The performance assessment of PQM practices

A self-assessment approach is proposed for evaluating the performance maturity level of specific PQM practices implemented in an organization. This assumes a collection of questionnaires, one for each specific PQM practice, can be formulated in order to facilitate such evaluations. In order to increase the objectivity in the assessment of the maturity level of PQM practices the estimate of Process Quality Indexes (PQIs), which was defined in Section 2.3.1.1(ii), should be included in the self-assessment procedure. Based on the subjective responses of knowledgeable managers within the organization an initial state of PQM practices or baseline performance of the system under study can be obtained. It is assumed that the analysis of the given system would permit to identify the PQM practices that should be improved in order to obtain better project outcomes. Moreover, the decision on the improvement of PQM processes would be facilitated with the application of the PQMAF, as it intends the simulation of the effect of different improved states of performance of the PQM practices affecting the project outcomes. In fact, as it was clarified in Sections 3.3 and 4.1.3, the ICBS requires the PQIs of the different PQM processes to perform such simulation process.

Appendix C includes a sample of the kind of questionnaire that should be applied to undertake the self-assessment of a given PQM practice and the respective computation of the PQI. The sample evaluates the maturity level of the safety management program implemented in a construction organization, which PQI results to be 76.8%. However, if the concerned managers decide that the safety management program needs to be improved, they have two options to determine an upgraded maturity level to be analyzed:

i) Based on the initial rating of the questions, a subsequent assessment using the same questionnaire can be done in order to re-rate specific aspects of the safety program that should be enhanced and, then, calculate the improved PQI value for the safety management program. This upgraded PQI value could be used for analyzing the effects that such improvement action would have on the performance of the construction operations, in order to make a more appropriate decision.

ii) A simple linguistic term representing the performance level towards which the program should be leaded. For example, Figure 4.4 shows that the current performance maturity level of the above-evaluated safety program could be identified as *continual improvement approach*, given that this is the membership function where the corresponding PQI (x = 76.8%) attains the highest membership value ($\mu_{76.8\%}$ = 0.82). This way, the decision-makers could decide to analyze the effects of implementing a *best-in-class performance* approach in the safety management program in order to make a decision about the pursuing of this upgraded maturity level.

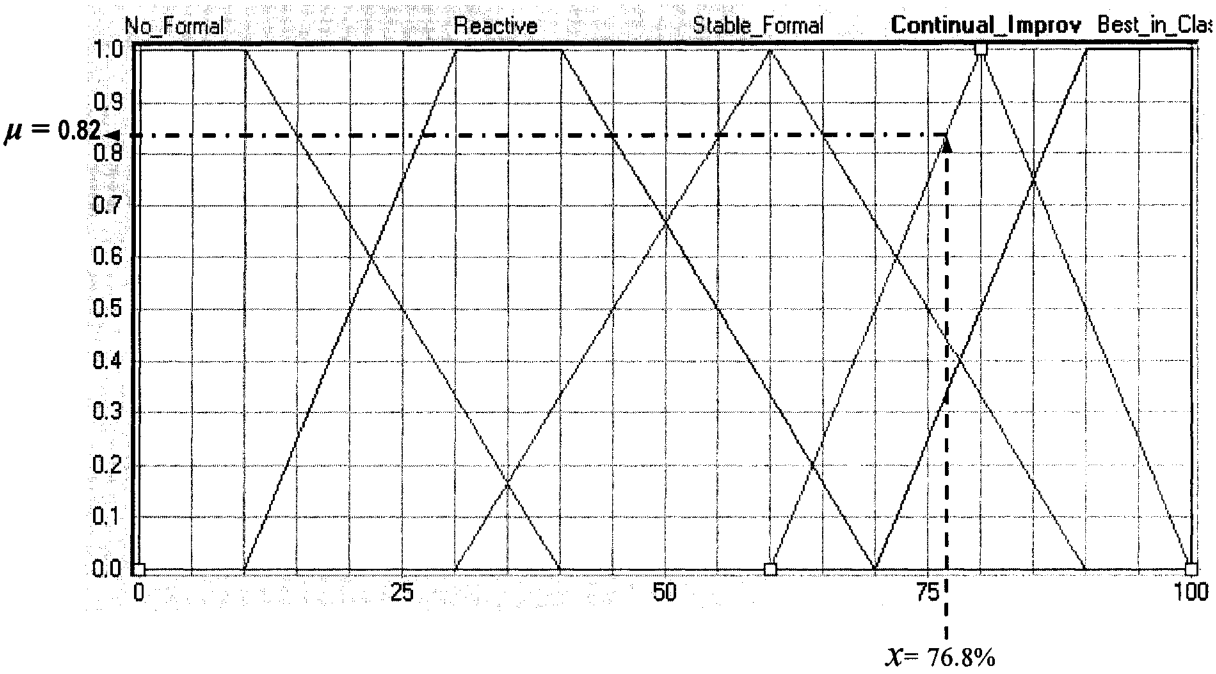


Figure 4.4 Sample of the evaluation of the membership degrees of PQI values

It should be noted that in order to analyze the effects of upgraded maturity levels of PQM practices expressed as PQI values, (i.e. like in the first approach explained above), an FES accepting crisp values as inputs is required. On the other hand, an FES accepting fuzzy values as inputs is required for analyzing the effects of maturity levels given as linguistic terms, (i.e., like in the second approach explained above). This was considered for undertaking the analyses that demonstrated the application of the PQMAF, included in Chapter 6.

4.3 Case study: Surveying a construction PQM system

A construction organization was selected as a case study on which the development of the PQMAF could be based. Preference was given to an organization that had a formal and mature quality system for the execution of projects and that was dedicated to carry out projects in which standard construction processes were employed. The Design and Construction (D&C) Section of the Drainage Services, Asset Management and Public Works Department of the City of Edmonton was selected for surveying the PQM factors that are involved in the performance of construction projects. A preliminary survey (Form D.1 in Appendix D), was conducted to learn more about the organization's business and project quality management system. The organization of D&C is devoted to project management, drainage engineering and design, drainage and water construction, and fabrication services. This organization fulfilled the requirements of this research project, as follows:

i) All design and construction processes are developed under a quality assurance system and have been ISO 9001 certified since 1997. It was found that the organization had a stable formal system approach to the improvement of processes by the time this study was conducted.

ii) The organization specializes on the performance of two different types of processes, open cut and tunnel construction. Most of the activities within D&C are related to either of these two construction processes.

Both of these features promised a high standardization of the management and execution of construction processes along with a significant amount of information and knowledge regarding the quality performance of the processes. The availability of information was an asset, as the investigation of different approaches to the assessment of quality performance in construction processes would be facilitated. In fact, a significant amount of information was available in the Quality Information Management System (QIMS) that D&C has put into operation for managing all the information related to the requirements of the ISO 9001 standard, such as quality audits, quality policies, nonconformity reports, root cause analysis, improvement action reports, and customer feedback. It is worth highlighting that any kind of statistical method was being applied to analyze the data available in the QIMS by the time this research work was carried out.

4.3.1 Examination of the Quality Information Management System

The examination of the QIMS reveled that the recording of data and information related to project quality performance was limited to the reporting of nonconformities describing deviations from: (i) the quality system, (ii) proper safety, loss or environmental control practices, (iii) project or service requirements, (iv) inspection acceptance criteria, (v) purchasing requirements, (vi) equipment reliability, and (vii) stakeholder satisfaction. However, nonconformity reports included a mere description of the deviations while the quantitative effects on the performance of the activities are overlooked. Consequently, the analysis of these records was reduced to identifying the root causes of the deviations, which was reserved to relevant cases determined by the project management. In fact, there are no procedures defined in the organization's system procedures to use statistical techniques in the analysis and improvement of performance. This made the organization's quality system geared toward short-term improvements rather than long-term strategic goals.

Nevertheless, a significant amount of nonconformity reports were available in the QIMS that would support the identification of PQM factors. Further examinations of the records of nonconformities and root cause analyses shaped the modelling approach that would make possible the assessment of PQM factors in construction projects. More than one thousand nonconformity records dated from 1997 to 2005 were examined and classified according to the context where the nonconformity was observed (i.e. construction sites, workshops, warehouses, and managerial center) and the affected performance goals (i.e. schedule, cost, and quality). It is should be noted that according to the scope of this research project, the study focused on the nonconformities occurred in the construction sites. The main construction resources that were identified as causes of nonconformities have been described in Table B.1, while Figures E.1, E.2 and E.3 in Appendix E show the frequency of nonconformities caused by each of the resources and that affected the cost, schedule, and quality of the project, respectively. Moreover, the following are the main conclusions attained through these examinations:

i) It is straightforward, for the personnel reporting nonconformities, to identify the resources that are involved in the causes of performance deviations. However, the records of root cause analyses revealed that most of the improvement actions accorded to avoid future nonconformities of the same kind, addressed the PM processes. Moreover, construction resources were identified as the drivers that propagate the effect of the PQM system up to the performance of the construction operations.

ii) The necessity to assess the effect of the PQM practices on the performance of the construction resources was recognized. Though a set of aspects were discerned in order to assess the performance level of each resource, they were quite subjective in nature, while according to feedback from the project managers, allowing for the faulty performance of resources would facilitate the cognitive process in the appraisal of the performance level of the resources. Therefore, the number of a nonconformity associated with a given resource, was thought a more appropriate approach to evaluate such variable. Moreover, this variable is intended to be an intermediate variable, which purpose is to increase the objectivity in the assessment of the effect of the performance maturity level of the PQM practices on the quality performance level of the construction resources. Further clarification of the number of the nonconformities associated with the construction resources was included in Section 4.2.1.

iii) The need for an appropriate approach to assess the effect of the PQM factors (i.e. project resources and PQM practices) on the performance outcomes of construction operations was also acknowledged. Again, such an assessment should be a knowledge-based approach, as quantitative measures were not available. The fuzzy logic-based model developed by Ayyub and Eldukair [1989] and introduced in Section 4.1.3 (phase 3.ii), was found an appropriate approach to accomplish such endeavor.

These findings supported the development of the PNAA, introduced in Section 4.1.2, and the organization of the PQM factors into the configuration shown in Fig. 4.3.

4.3.2 Prioritized PQM factors model for open cut construction projects

In order to perform the efficient assessments of a system, it is necessary to reduce the system to a model integrating the key factors of the system. The systematic reduction of complex QM systems implemented in construction projects to the PQM Practices – Construction Resources – Performance Outcome structure pro-vides a powerful means of representing the most important cause-and-effect linkages while minimizing the requirements for expert assessment and computational effort. Furthermore, the focus of the model on the effect on a specific construction operation permits to further reduce the modelling effort. Therefore, advance surveying of the PQM factors in D&C focused on a specific construction operation in order to demonstrate the application of the PQMAF. In this case, the open-cut construction process was thought an appropriate operation to perform such undertaking as it is the most common construction process carried out in D&C.

Open-cut construction is widely used in construction projects for the reason that it is economic. This construction method involves the excavation of trenches for placing a diversity of utilities such as power and communications service lines, commercial and irrigation systems, water and sewer mains, cross-country pipelines, and just about any kind of pipeline [Griffin 2004]. The construction of a pipeline usually include numerous challenges that may affect the performance of work, including phased design and construction, varied terrain, deep open cuts, other existing parallel pipelines (e.g. high-voltages power lines), river crossings, road and railroad crossings, contaminated groundwater, and stringent scheduling and sequencing requirements [Eskridge *et al.* 2003]. These issues define the complexity of the project and should be addressed by the project management in order to anticipate any difficulties and minimize the risks during construction.

The procedures established in D&C's manual of procedures and the records in the QIMS related to open-cut construction projects were further studied in order to identify the main PQM system involved in such an operation. The procedures involved in open-cut construction projects have been integrated in Figure F.1 in Appendix F. On the other hand, one hundred ninety one records related to nonconformities affecting the performance of activities in open-cut construction projects were further analyzed. In this case, performance is mainly explained by the disruptions, defined in Section 4.2.1(iii.a), that were reported as nonconformities during the undertaking of the construction activities, which means nonconformities involving no more than waste of resources (i.e. cost overruns) were not accounted in such analysis. Following the procedures detailed in Section 4.1.3, the PQM factors affecting the performance of the activities in open-cut construction projects were identified. In addition, a Pareto analysis, shown in Figure E.4 in Appendix E, was carried out to identify the construction resources having a significant effect on the performance of open-cut operations, which permitted the reduction of the number of factors. After that, it was possible to build the prioritized model of the PQM factors affecting the quality performance of the open-cut process, shown in Figure 4.5.

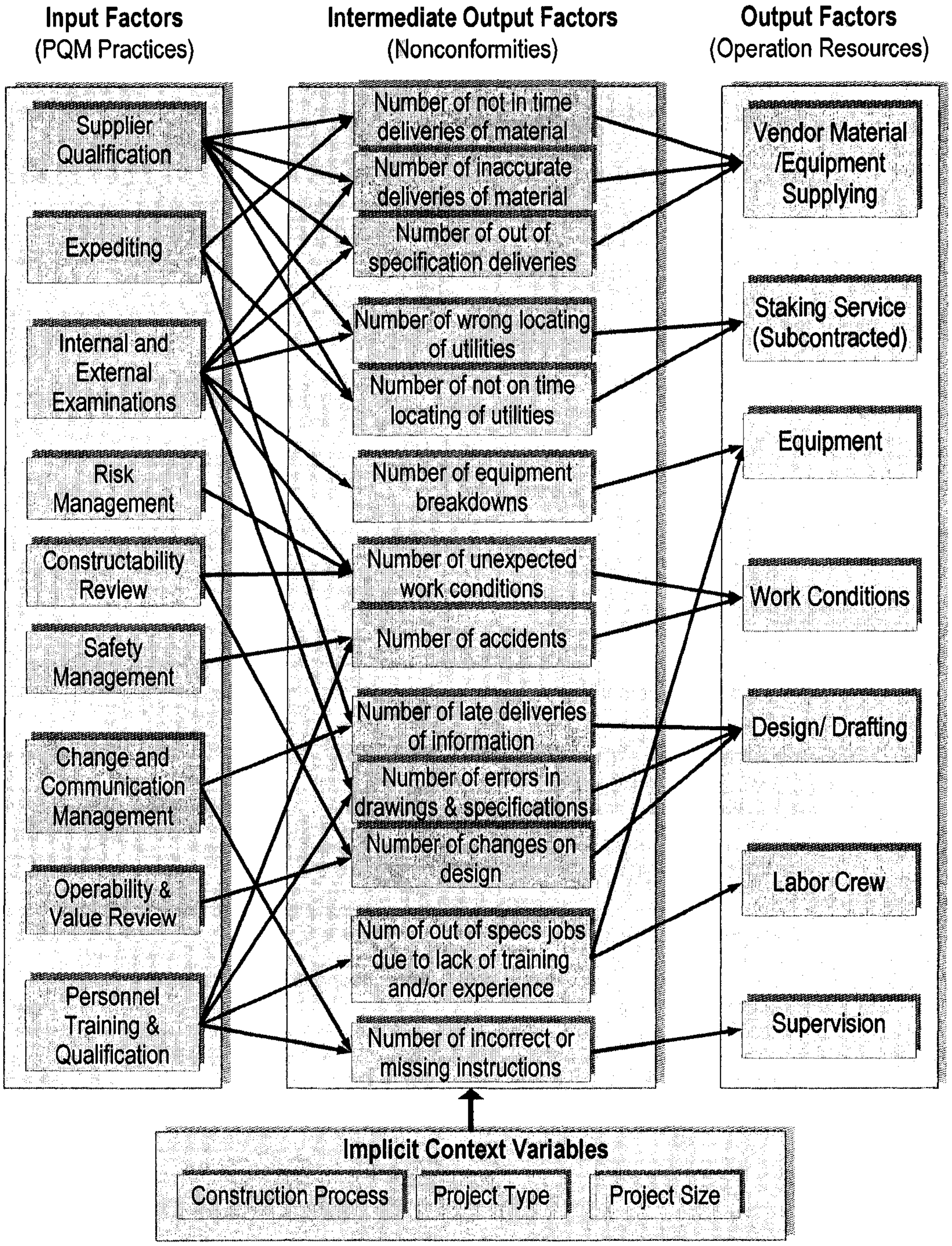


Figure 4.5: Prioritized model of PQM factors affecting the quality performance of an open-cut construction operation

It is also important to notice from the aforementioned open-cut PQM model, that, as the concern in this modelling approach is the effect of the performance of the PQM system, only the PQM practices should be included as input factors, as seen in Figure 4.5. However, the effect of context variables such as the construction process (e.g. open-cut or tunnel), the project type (e.g. water or sewer projects), and the project size (e.g. very small, small, medium, large, or very large) should be implicitly reflected on the model when defining the membership functions developed to assess the nonconformity variables affecting the quality performance of the construction resources. As clarified in Section 4.1.3 (phase 3.i), this prioritized model is required to build the FES for inferring the quality level of the resources involved in the open-cut construction activities.

Furthermore, in order to further facilitate the evaluation of the entire PQM system under analysis and the development of the respective FES, it is necessary to identify and independently assess the subsystems involved in the entire system. Accordingly, such subsystems should be assumed as submodels within the PQM model. For example, as seen in Figure 4.5, three nonconformities were taken into account for defining the quality performance level of design/drafting, the number of late deliveries of information, the number of errors in drawings and specifications, and the number of design changes. These four factors (i.e. three output subfactors and one output factor) were integrated as a submodel. Further illustration on the development of the FES for the case shown in Figure 4.5 was included in Chapters 5 and 6.

4.4 Summary and conclusions

This chapter clarifies the factors and procedures involved in the project-quality-management assessment framework (PQMAF), which is proposed to evaluate the PQM practices implemented to deal with the quality performance of construction operations. The main features of the modelling approach proposed by the PQMAF include the following:

i) Emphasis on the assessment of PQM practices, which are deemed the root drivers of quality in construction projects. In fact, the focus is on the impact that PQM systems have on the performance of construction projects. Moreover, the PQMAF then assumes that the PQM system implemented in the organization should respond for constrains that every construction project may include. This means that, for example, project factors such as the space constraints, public considerations, or ground condition should not be deemed excuses for nonconformities as the project management is assumed to be able to implement the appropriate quality practices in order to avoid any nonconformity due to such project factors. Therefore, project models generated through the proposed PQMAF assume that PQM practices of the nonconformity affecting the performance goals of the project.

ii) Quality performance assessment based on the analysis of nonconformities occurred during the undertaking of construction operations, which promises that advantage is taken from basic quality-related records required to ISO 9001 certified organizations.

iii) Knowledge-based assessment of the performance level and interactive effect of factors involved in a given PQM system, as a means to complement the factual, but limited quality-related information that is typically available in construction organizations.

iv) Disaggregated elicitation of knowledge through two independent modules: the PQM general knowledge and the knowledge related to the performance of specific operations, which allows for independent knowledge elicitation from the most competent personnel at different organizational levels within a project organization.

v) Incorporation of discrete-event simulation, which:

- Increases the objectivity in the evaluation of soft variables affecting the performance of a given system (e.g. the effect of the PQM system on the performance of a construction operation);
- Enables focusing on key variables involved in the system under analysis, which may avoid unnecessary data collection for decision-making;
- Integrates a stochastic process into the estimate of the effects of subjective factors, which is desired when dealing with uncertainty quantification.
- Facilitates the experimentation with different states of a given PQM system, in order to support decision-making related to the system improvement.

These features are incorporated throughout the two main components of the framework, the Project Nonconformity Assessment Approach (PNAA) and the Interactive-Computer-based System (ICBS). On one hand, the PNAA provides the information and knowledge that is required for the development of the fuzzy logic-based models, while the ICBS computes the performance outcomes (e.g. completion time and productivity) of construction operations affected by the PQM system through the fuzzy logic and simulation applications integrated in the system.

Although the estimates obtained from PQMAF should not be deemed useful for estimating purposes, they could be used as reference for evaluating the effect of a PQM system on the performance of construction operations. Construction managers could have a better understanding of the behavior of the PQM system and make appropriate decisions on the improvement of the system. The focus here is on the proactive role that simulation can play in designing management systems.

CHAPTER 5

ELICITATION AND REPRESENTATION OF KNOWLEDGE-BASED ASSESSMENTS FOR CONSTRUCTION QUALITY PERFORMANCE

This chapter is dedicated to the implementation of the PNAA. Therefore, it describes the methods and procedures that were adopted to elicit and represent the knowledge existing in the personnel of the construction organization used as case study for the development of the fuzzy logic applications proposed within the PQMAF to estimate the statistical parameters of the nonconforming indicators (refer to Sections 3.2.2 and 3.2.3). This includes the development of the membership functions (MFs) and the inference rules (IRs) within two independent modules, the specific-PQM-system knowledge elicitation (SPQMSKE) module, and the specific-operation knowledge elicitation (SOKE) module. The procedures involved in each of the two modules are explained throughout the sections included in this chapter. Since the proposed PQMAF concentrates on the analysis of PQM systems affecting the execution of specific construction operations, the explanations provided in this chapter are based on the case study introduced in Section 4.3.2.

5.1 Assumptions for the development of membership functions

The implementation of the methods used to develop the MFs in a given system depends on the availability of data required for such a purpose. In this case, the amount and quality of data was constrained by the fact that the knowledge elicitation was entirely based on the surveying of only one construction organization and no information related to the assessment of the variables in the model had ever been recorded. Therefore, though several different approaches have been proposed to develop MFs, adjustments to previous methodologies were required in order to overcome the particular conditions of information availability encountered during this research attempt. A comprehensive anthology of methods developed to generate MFs can be found in Sun [2000] and Oduba [2002]. Moreover, the method used for generating the MFs in this case study was based on that proposed by Lee [2001] and Oduba [2002]. The following assumptions were applied in order to facilitate the development of the MFs of the variables involved in the SPQMSKE and the SOKE modules:

i) Only triangular and trapezoidal MFs were generated in order to represent the assessment terms of the variables involved in the model. This is associated to the fact that triangular and trapezoidal MFs can be constructed easily on the basis of little information.

ii) Factors of a similar kind shared the same set of triangular or trapezoidal MFs, as this facilitated the elicitation process and the analysis itself. This was the case when representing the maturity level of PQM practices, the quality performance level of construction resources, the frequency of occurrence of such resources, and the adverse consequences of the states of construction resources. For example, a single set of MFs was used to represent the maturity levels of all the PQM practices being evaluated in the model. Moreover, the frequency of occurrence and the adverse consequences of the states of construction resources shared the same MFs though they are meant to be two different variables.

iii) Variables that were represented with exclusive sets of MFs included the number of nonconforming events (*N*), and the duration of delays due to nonconforming events (*D*). The reason for this is the singular nature that each of these variables has and is affected in a particular way by the context variables implicit in the system such as the construction process used, the type of the project, and the size of the project. Regarding this, the development of MFs evaluating the Nonconforming Indicators (NIs), i.e. the number of nonconforming events and the duration of delays, took into account the specific activity under analysis. For instance, two different sets of MFs were developed to respectively represent the number of nonconforming events (*N*) in the excavation activity and in the pipe installation activity, as seen in Table G.3(a) in Appendix G.

Further clarification of these and other assumptions, relevant to the development of MFs in both the SPQMSKE and the SOKE modules, was included in Sections 5.2.1 and 5.3.1 respectively.

5.2 Specific-PQM-system knowledge elicitation procedures

The SPQMSKE module concentrates on the development of the MFs and IRs relating to the variables involved in the fuzzy expert system (FES) that was formulated to infer the performance level of the construction resources involved in the operation under analysis. Such an FES must be based on a prioritized model of PQM factors affecting the performance of the construction operation being analyzed and which should be deduced through the procedure introduced in Section 4.1.3. According to the modelling approach proposed by the PQMAF, these variables, (identified as *cause variables* in Figure 4.3), were modelled as follows:

1. The maturity level of the PQM practices was modelled as an *input interface*. This variable was able to be expressed as one of two, a crisp value or a linguistic (fuzzy) values (see Section 4.2.3.1). Therefore, the input interfaces were implemented in such a way that both crisp values and linguistic terms can be used as inputs to the FES. Moreover, the FES in which crisp input values were used required the implementation of the MFs whose development is explained in Section 5.2.1.

2. The number of nonconformities, respectively associated with the quality level of the construction resources, was modelled as an *intermediate variable*. Intermediate variables attain values during the inference process, which are not needed as outputs of the model and, therefore, they are only intended for passing information from one rule block to another. This information is in the form of linguistic (fuzzy) values, which means that that MFs of the variable terms, (i.e. the linguistic terms established for evaluating the number of each of the nonconformities respectively associated with the construction resources), are not needed to achieve this stage within the inference process.

3. The quality level of the construction resources, which were modelled as *output interfaces*. Since the outputs to be obtained from the FES are required as linguistic (fuzzy) terms, no defuzzification was involved within the inference process and, therefore, no MFs were neither required. However, as the MFs of the quality levels of the construction resources are still required in the procedure for estimating the

statistical parameters of the NIs (refer to Section 3.2.2), they were also generated within the SPQMSKE module.

Therefore, the MFs developed within the SPQMSKE module include those of the following variables:

a) The performance maturity level of the PQM practices affecting the quality of the construction resources.

b) The quality performance level of the construction resources (*Q*) used in the operation under analysis.

Section 5.2.1 clarifies the procedure carried out to develop such MFs. In addition, the MFs of the following variables, which belong to the *effect variables* though (see Figure 4.3), were also generated within the SPQMSKE module:

c) The frequency of occurrence (*F*) of the quality performance levels of the construction resources involved in the operation under analysis.

d) The adverse consequences (*C*) of the combined effect of the quality level of the construction resources and the frequency of occurrence of such quality level, on the performance of construction activities.

On the other hand, the procedure used to develop the IRs is detailed in Section 5.2.2 and includes the determination of two groups of rules:

a) The effect of the performance maturity levels of PQM practices on the number of specific nonconforming events associated to the construction resources being analyzed.

b) The effect of the number of the specific nonconforming events on the quality performance level of the respective construction resources.

Moreover, the explanation of the SPQMSKE procedures was based on the development of the MFs and IRs for the variables assessing the factors included in the case study model introduced in Section 4.3.2 and illustrated in Figure 4.5. In addition, this effort was based on the assessments and opinions of managers who were especially involved in the management of projects in the organization of D&C. For example, in this case eight top-level managers including four general supervisors, three program managers, and the principal manager within the organization, participated in this work. The average experience of these participants was 17.4 years at the date the study began.

5.2.1 Development of membership functions for the SPQMSKE module

This research adapted the procedures proposed by Lee [2001], Sun [2001], and Oduba [2002] to generate the MFs of the assessment variables involved in the case study model. This procedure included the following steps:

1. The linguistic terms commonly used by managers to assess the performance level of the variables involved in the model were determined, as seen in Table 5.1. Three terms were established to evaluate the maturity level of PQM practices: *No Formal Approach, Reactive Approach*, *Stable–Formal System Approach*, *Continual Improvement Emphasized*, and *Best-in-Class Performance*. These terms were derived from the ISO 9004 performance scale for the self-assessment of management systems, which was explained in Table 2.6. On the other hand, five terms were established for

assessing the number of the nonconforming events associated with the construction resources as well as the quality level of these resources, which ranged from *very low* to *very high* and from *very poor* to *very good* respectively. In addition, the terms used to evaluate the frequency of occurrence of the quality levels of these resources were *very unusual*, *unusual*, *often*, *usual*, and *very usual*; while the terms for the adverse consequences resulting of the effect of the quality levels of construction resources were *very mild*, *mild*, *medium*, *severe*, and *very severe*.

Table 5.1: Linguistic terms and domains for the assessment of variables in the model

Variables	Domain	Domain Range	Linguistic terms for assessment of variables				
Maturity level of PQM practices	Process Quality Index	0 – 100%	No Formal Approach	Reactive Approach	Stable-Formal System	Continual Improvement Emphasized	Best-in-Class Performance
Number of nonconforming events associated with the construction resources	Fuzzy	NA	Very Low	Low	Average	High	Very High
Quality performance level of the construction resources (*Q*)	Fuzzy	NA	Very Poor	Poor	Average	Good	Very Good
Frequency level of occurrence of the quality level (*F*)	Psychometric	0 – 10	Very Unusual	Unusual	Often	Usual	Very Usual
Adverse consequence resulting of the quality level (*C*)	Psychometric	0 – 10	Very Mild	Mild	Medium	Severe	Very Severe
Number of nonconforming events (*N*)	Number of nonconforming events	0 – + ∞	Very Small	Small	Medium	Large	Very Large
Duration of Delays due to nonconformities (*D*)	Duration of delay in hours	0 – + ∞	Very Small	Small	Medium	Large	Very Large

2. The domains or universes of discourse and their respective ranges of values were determined for each of the aforementioned variables, as seen in Table 5.1. In order to establish a general numerical guideline for the assessment of the variables, it was assumed that the extreme value of *No Formal Approach*, *very poor*, *very mild*, and *very*

unusual was zero. On the other hand, it was assumed that the extreme value for *Best-in-Class Performance* is 100% for assessing the maturity level for PQM practices, and *very good*, *very severe*, and *very usual* is ten for assessing the quality level of resources (*Q*), the adverse consequences (*C*), and the frequency of occurrence (*F*) respectively.

Moreover, it is important to highlight that in this case the preliminary meetings with quality managers in the organization used in the case study permitted a significant amount of discussion that gave relevant advice regarding the assessment of the variables involved in the PQM systems of construction organizations.

3. A questionnaire was developed in order to conduct the elicitation of the knowledge-based assessments needed for the development of the MFs. The format asked the interviewees to assign the appropriate numerical values for each of the linguistic variables in Table 5.1. For example, a sample question formulated to determine the numerical values for the linguistic terms assessing the maturity levels of the PQM practices is illustrated in Table 5.2(a); while a sample question assessing the quality level of construction resources is shown in Table 5.2(b).

   Form D.2 included in Appendix D illustrates the full questionnaire used for acquiring the data required for the development of MFs of the variables involved in the SPQMSKE module. However, it should also be noted that two variables of the SOKE module were assessed within this questionnaire; the frequency of occurrence (*F*) of the quality performance levels of the construction resources and the adverse consequences (*C*) of such levels on the performance of construction activities under analysis. It was thought that better assessments on these subjective variables could be obtained from personnel at the managerial level of the organization.

The questionnaire was applied during a meeting with the eight D&C managers participating in the SPQMSKE module. It is important to highlight that though an assessment of the linguistic terms for generating the MFs of the maturity levels of each of the PQM practices was originally required in the first version of the questionnaire, the respondents agreed that the same set of MFs would represent well the maturity levels of all the different PQM practices.

Table 5.2(a): Sample question to assign numerical values to linguistic terms assessing the maturity level of PQM practices

Questions	Answers	
1. For the performance maturity level of the **Supplier Qualification** practice		
a. From zero to what value would you consider as ***No Formal Approach***?	From *Zero*	To
b. What range of values as ***Reactive Approach***?	From	To
c. What range of values as ***Stable Formal System***?	From	To
d. What range of values as ***Continual Improvement***?	From	To
e. From what value to 100 as ***Best-in-Class Performance***?	From	To *100%*
f. Other level (specify please):	From	To

Table 5.2(b): Sample question to assign numerical values to linguistic terms assessing the quality performance of construction resources

Questions	Answers	
1. For the quality performance level of the **Material/Equipment Supplying**		
a. From zero to what value would you consider it as ***Very Poor***?	From *Zero*	To
b. For ***Poor***?	From	To
c. For ***Average***?	From	To
d. For ***Good***?	From	To
e. From what value to 10 for ***Very Good***?	From	To *Ten*

4. The assessments of all survey respondents were accumulated for the development of the MFs of the respective variables. The development of MFs was based on the frequency with which each value, within the respective x-axis domain, was favoured by the interviewees participating in the survey. A preliminary membership value $\mu(x_i)$ was determined by the average degree of belief that the respondents had regarding the belonging of a value or range of values to each the linguistic terms used to evaluate the respective variables. This approach is illustrated in Table 5.3, which shows the ranges of values within the proposed subjective scale (from 0 to 100%) that each of the eight interviewees believed should correspond to the linguistic term 'No Formal Approach' for the maturity level of PQM practices. The opinions favouring each value were summed and the result was standardized by dividing them by the total number of interviewees in order to obtain the preliminary MF for the linguistic term, which can be expressed in its $x_i | \mu(x_i)$ form as: [0% | 1.0, 10% | 1.0, 20% | 0.67, 30% | 0.33, 40% | 0.00]. Likewise, all the opinions expressed for the other variables were developed into preliminary fuzzy MFs.

Table 5.3: Example of the calculations for the development of MFs

Opinions for ***No Formal Approach***	**Elements within the subjective scale (in %)**										
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100%**
Interviewee A	X	X	X								
Interviewee B	X	X	X								
Interviewee C	X	X	X	X							
Interviewee D	X	X									
Interviewee E	X	X	X	X							
Interviewee F	X	X	X								
Interviewee G	X	X									
Interviewee H	X	X	X	X							
Sum of opinions	8	8	6	3	3	1	0	0	0	0	0
Standardized frequency	1.0	1.0	0.75	0.38	0.00	0.00	0.0	0.0	0.0	0.0	0.0

5. The preliminary MFs obtained with the previous procedure were adjusted in order to obtain triangular or trapezoidal shaped MFs. Triangular and trapezoidal MFs were preferred in this case, because of the clarity they can provide to the analysis. Rules for generating the triangular and trapezoidal MFs were established, and are as follows:

    i) The determination of the shape of the MFs was based on the number of peak values included in the preliminary MFs. Peak values refer to the values with the highest frequency of responses and were identified with the corresponding standardized frequencies previously calculated. Values with the highest standardized frequency were deemed peak values and were assigned a degree of membership of 1.0 to the MF being evaluated. For example, as seen in Table 5.3, the peak values for the *No Formal Approach* MF were the zero, 10, and 20% values, as all of them obtained the maximum standardized frequency, i.e. 1.0. Based on this, the following rules were applied to determine the shape of the MFs:

        a. If there was only one peak value, the MF was triangular.

        b. If there were two or more peak values (i.e. two or more values tie with the highest frequency of responses, as in the case shown in Table 5.3), then the MF was trapezoidal.

        c. If two or more peak values were not contiguous then the intermediate values were considered peak values as well, which in that case resulted in a trapezoidal shaped MF as well.

    ii) The determination of the supporting intervals of the MFs was based on the range of values that, according to the beliefs of the interviewees, should belong to the linguistic term being assessed, and that were identified with the preliminary MFs previously obtained. Once the peak values of the corresponding MF had been identified, the supporting intervals to the left and right of the peak values were determined as follows:

a. Every value to the left of the peak values and with a standardized frequency equal to or higher than 0.20 was assigned a degree of membership in an ascending manner, meaning that the closer to the peak values the higher its membership.

b. Likewise, every value to the right of the peak values and with a standardized frequency equal or higher than 0.20 was assigned a degree of membership in a descending manner, as well, the closer to the peak values the higher its membership value.

c. If a value with a standardized frequency lower than 0.20 was located between two values with a standardized frequency equal or higher than 0.20, then such a value was also included within the corresponding MF.

d. The assigned degrees of membership depended on the number of values to the left or to the right of the peak values. For example, as seen in Table 5.3, the 30, 40, and 50% values, to the right of the peak values, were assigned a degree of membership to the *No Formal Approach* MF of 0.67, 0.33, and 0.0 respectively, as seen in Table 5.4(a). Moreover, Figure 4.4 illustrates the MFs developed to represent the performance maturity level of the PQM practices included in the case study model generated to illustrate the application of the proposed framework.

Likewise, all the preliminary MFs obtained with the raw data were adjusted and developed into triangular or trapezoidal MFs. The MFs generated for each of the variables involved in the SPQMSKE module are shown in Tables G.1(a), G.1(b), G.1(c), and G.1(d) in Appendix G.

Table 5.4(a): Sample of the fuzzy membership functions for the performance maturity level of PQM practices

Linguistic Terms	Fuzzy Membership Functions											
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	Shape
No Formal Approach =	1.00	1.00	0.67	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Trap
Reactive Approach =	0.00	0.00	0.50	1.00	1.00	0.67	0.33	0.00	0.00	0.00	0.00	Trap
Stable Formal System =	0.00	0.00	0.00	0.00	0.33	0.67	1.00	0.67	0.33	0.00	0.00	Triang
Continual Improvement =	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00	0.50	0.00	Triang
Best-in-Class Performance =	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00	1.00	Trap

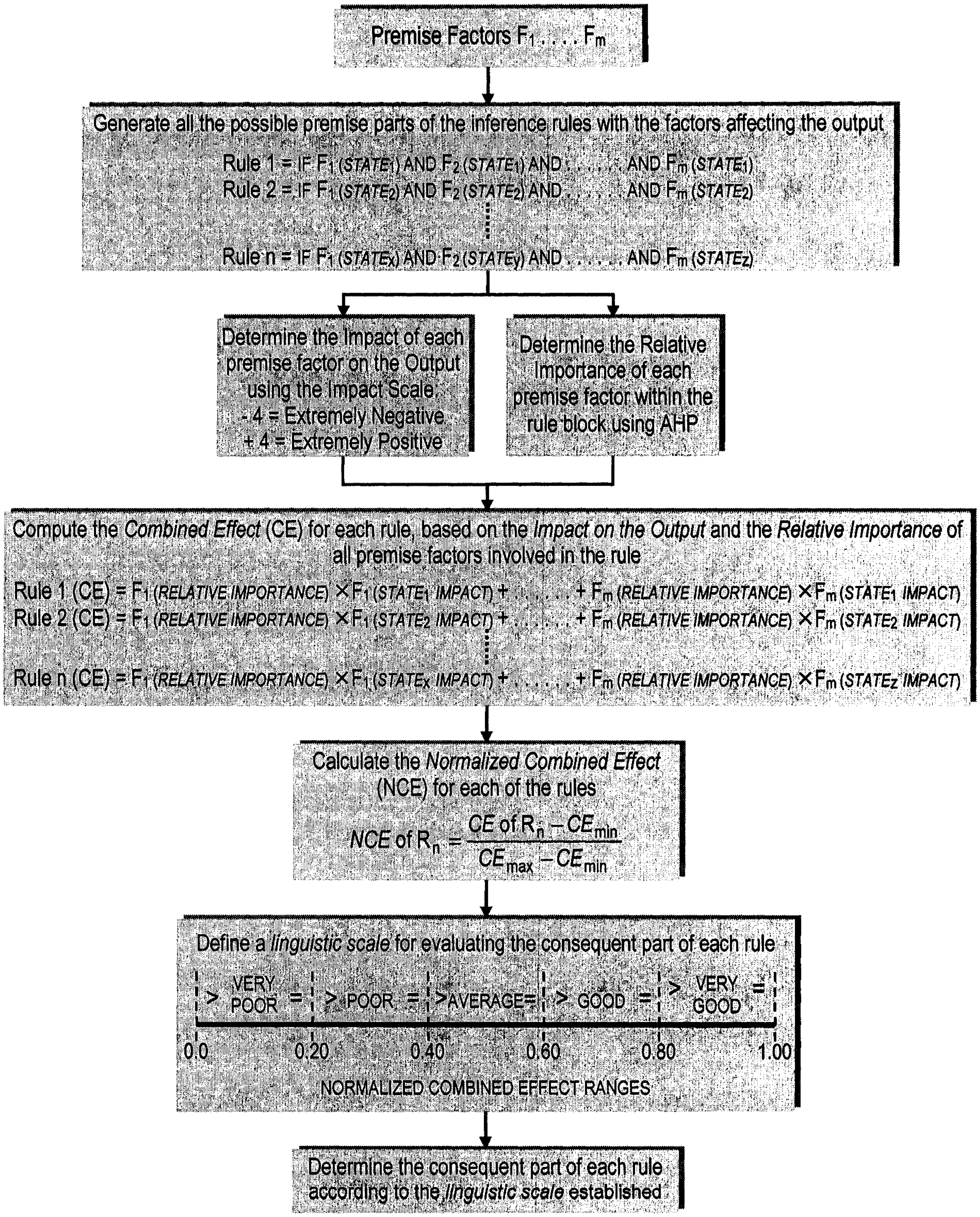
In addition, it is necessary to point out that the author of this research project was available in the knowledge elicitation meeting for discussing and clarifying the assumptions involved in the assessment of the model variables. This was especially true for the assessment of the maturity level of the PQM practices, as a discussion with the interviewees was required in order to generate appropriately their MFs.

5.2.2 Development of inference rules for the SPQMSKE module

Developing the inference rules is one of the most important steps in the integration of an FES because the rule base represents the reasoning and logic mechanism of the system [Shaheen 2005]. Experts can establish subjectively the inference rules involved in the assessment of a system. However, a more systematic approach proposed by Shaheen [2005] to develop the rule base of a system under analysis was adapted and applied for this development. The main feature of the methodology is the incorporation of the effect of the factors' *relative importance* within the corresponding rule block as well as the *impact* of the specific states (i.e. quality levels in this case) of the factors (i.e. construction resources) *on the output*. This feature makes this methodology an objective approach to defining the consequent part of the inference rules generated in the system. The methodology is shown in Figure 5.1 and is explained through the following steps:

1. The antecedent parts of rules were determined by calculating the total number of combinations of the linguistic terms used to assess the input factors. The number of rules generated was determined using Equation 3.28 introduced in Section 3.2.3.3. For example, as seen in Figure 4.5, there are three kinds of nonconformities affecting the quality level of Design Information, the number of late deliveries of information, the number of errors in drawings and specifications, and the number of design changes. In addition, the number of those three nonconforming events was assessed by using five linguistic terms, (see Table 5.1), which results in the following number of rules:

$$\text{Number of rules} = [\text{Num of input terms}]^{(\text{Num of input variables})} = (5)^3 = 125$$



Premise Factors $F_1 \ldots F_m$

Generate all the possible premise parts of the inference rules with the factors affecting the output

Rule 1 = IF F_1 (*STATE*$_1$) AND F_2 (*STATE*$_1$) AND . . . . . . AND F_m (*STATE*$_1$)
Rule 2 = IF F_1 (*STATE*$_2$) AND F_2 (*STATE*$_2$) AND . . . . . . AND F_m (*STATE*$_2$)
⋮
Rule n = IF F_1 (*STATE*$_x$) AND F_2 (*STATE*$_y$) AND . . . . . . AND F_m (*STATE*$_z$)

Determine the Impact of each premise factor on the Output using the Impact Scale:
- 4 = Extremely Negative
+ 4 = Extremely Positive

Determine the Relative Importance of each premise factor within the rule block using AHP

Compute the *Combined Effect* (CE) for each rule, based on the *Impact on the Output* and the *Relative Importance* of all premise factors involved in the rule

Rule 1 (CE) = F_1 (*RELATIVE IMPORTANCE*) × F_1 (*STATE*$_1$ *IMPACT*) + ... + F_m (*RELATIVE IMPORTANCE*) × F_m (*STATE*$_1$ *IMPACT*)
Rule 2 (CE) = F_1 (*RELATIVE IMPORTANCE*) × F_1 (*STATE*$_2$ *IMPACT*) + ... + F_m (*RELATIVE IMPORTANCE*) × F_m (*STATE*$_2$ *IMPACT*)
⋮
Rule n (CE) = F_1 (*RELATIVE IMPORTANCE*) × F_1 (*STATE*$_x$ *IMPACT*) + ... + F_m (*RELATIVE IMPORTANCE*) × F_m (*STATE*$_z$ *IMPACT*)

Calculate the *Normalized Combined Effect* (NCE) for each of the rules

$$NCE \text{ of } R_n = \frac{CE \text{ of } R_n - CE_{min}}{CE_{max} - CE_{min}}$$

Define a *linguistic scale* for evaluating the consequent part of each rule

Determine the consequent part of each rule according to the *linguistic scale* established

Figure 5.1: Methodology to evaluate consequent part of inference rules

Therefore, it can be assumed that, in general, the total number of rules for m input factors, each of which is assessed with a given number of linguistic terms, is R_n.

R_1 = IF F_1 ($STATE_1$) AND F_2 ($STATE_1$) AND . . . . . . AND F_m ($STATE_1$)
R_2 = IF F_1 ($STATE_2$) AND F_2 ($STATE_2$) AND . . . . . . AND F_m ($STATE_2$)
⋮
R_n = IF F_1 ($STATE_x$) AND F_2 ($STATE_y$) AND . . . . . . AND F_m ($STATE_z$)

For example, Table H.1(a) in Appendix H contains the entire rule base that resulted from combining all the input factors and terms involved in the assessment of the number of late deliveries of information, the number of errors in drawings and specifications, and the number of design changes, respectively.

Moreover, in this case study the input variables were considered independent and the AND operator was used to develop the rules. However, the interaction between such input variables was assumed and the PROD operation was used for the aggregation process implemented in the fuzzy inference process (refer to Section 3.2.3.2) of the fuzzy expert system built to illustrate the application of the PQMAF.

2. The relative importance or "contribution to the output" of each factor relative to the other factors involved in the same rule was evaluated. The method used to evaluate the relative importance of a multi-attribute problem was the Analytic Hierarchy Process (AHP), which was developed by Saaty [1980]. In Saaty's approach, the multi-attribute problem is structured into a hierarchy of interrelated factors, and then a pairwise comparison of the factors is conducted in terms of their dominance. For the purposes of this case study, the AHP comparison process was possible with the feedback obtained from the quality manager in the case study organization. Two different sets of matrices

were created. The first set compared the input factors affecting each of the intermediate output factors. For example, as seen in Figure 4.5, the Supplier Qualification and the Expediting practices had to be compared in order to obtain their relative importance on the number of not in time deliveries of material. On the other hand, the second set compared the intermediate output factors affecting the output factors. For example, Table 5.5(a) shows the matrix obtained with the pairwise comparison of the factors in the submodel that evaluates the contribution of such factors to the quality performance level of the design/drafting. Such a submodel comprises the number of late deliveries of information, the number of errors in drawings & specifications, and the number of design changes. The comparison was based on a ratio scale between 1 and 9 that represents the level of preference for the most valuable of two alternatives or factors. A ratio equal to one means that the significance of the two factors being compared is equivalent, which was the case when comparing factor 2 to factor 3. Meanwhile, a ratio 2 means that factor 2 is considered twice as important as factor 1. Otherwise, if factor 1 is compared to factor 2 then a ratio ½ must be obtained. Once the matrix of ratios between each of the factors was obtained with the pairwise comparisons, the problem now was to infer from this table the relative weights of the three factors. As shown in Table 5.5(b), this is done by normalizing the columns and, then averaging the normalized column values. The relative weights representing the relative importance of the three factors are also included in Table 5.5(b).

Table 5.5(a) Example of an AHP application: Matrix of pairwise comparisons

Factors	**Factor 1** Number of late deliveries of information	**Factor 2** Number of errors in drawings & specs	**Factor 3** Number of changes on design
Factor 1 Number of late deliveries of information	1	1/2	1/2
Factor 2 Number of errors in drawings & specifications	2	1	1
Factor 3 Number of changes on design	2	1	1

Table 5.5(b) Example of an AHP application: Normalized columns and relative weights

Factors	**Factor 1** Number of late deliveries of information	**Factor 2** Number of errors in drawings & specs	**Factor 3** Number of changes on design	**Relative Importance (Weights)**
Factor 1: Number of late deliveries of information	0.20	0.20	0.20	0.20
Factor 2: Number of errors in drawings & specs	0.40	0.40	0.40	0.40
Factor 3: Number of changes on design	0.40	0.40	0.40	0.40

3. The next step includes the evaluation of the impact of a factor being at a specific state (e.g. *Stable-Formal System* when the maturity level of PQM practices was evaluated or *very good* when the quality performance level of construction resources was being evaluated) on the output factor. For example, if the number of errors in drawings and specifications were *very high,* what would the impact of that state be on the definition of the quality performance level of design/drafting? The measurement of such an impact is based on a scale ranging from -4 (extremely negative impact) to +4 (extremely positive impact). Figure 5.2 shows the full scale adopted for this purpose.

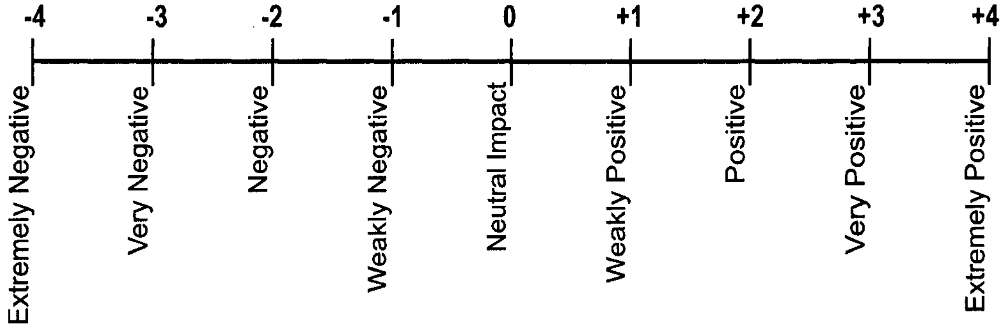


Figure 5.2: Scale to evaluate the impact of factors on output factors

The use of the proposed scale can be illustrated with the assessment of the impact of the factors mentioned in Table 5.5, which affect the quality level of design/drafting. Moreover, experts with knowledge of the system under analysis were commended to evaluate the impact of each of the five linguistic terms (i.e. *very low*, *low*, *average*, *high*, and *very high*) on the quality performance of design, as follows:

a) Number of late deliveries of design information (F1)

IF F1 is VERY LOW → Impact on quality of design = VERY POSITIVE (+3)

IF F1 is LOW → Impact on quality of design = POSITIVE (+2)

IF F1 is AVERAGE → Impact on quality of design = WEAKLY NEGATIVE (-1)

IF F1 is HIGH → Impact on quality of design = NEGATIVE (-2)

IF F1 is VERY HIGH → Impact on quality of design = EXTREMELY NEGATIVE (-4)

b) Number of errors in drawings and specifications (F2)

IF F2 is VERY LOW → Impact on quality of design = EXTREMELY POSITIVE (+4)

IF F2 is LOW → Impact on quality of design = VERY POSITIVE (+3)

IF F2 is AVERAGE → Impact on quality of design = WEAKLY NEGATIVE (-1)

IF F2 is HIGH → Impact on quality of design = VERY NEGATIVE (-3)

IF F2 is VERY HIGH → Impact on quality of design = EXTREMELY NEGATIVE (-4)

c) Number of changes on design (F3)

IF F3 is VERY LOW → Impact on quality of design = VERY POSITIVE (+3)

IF F3 is LOW → Impact on quality of design = POSITIVE (+2)

IF F3 is AVERAGE → Impact on quality of design = WEAKLY NEGATIVE (-1)

IF F3 is HIGH → Impact on quality of design = NEGATIVE (-2)

IF F3 is VERY LOW → Impact on quality of design = VERY NEGATIVE (-3)

4. Once the relative importance of all factors involved in the rule block and the impact of their states on the given output have been evaluated, the consequences of the rules and their degrees of support can be determined. The combined effect (CE) of the relative importance and the impact of the factors in the different rules, generated as explained in step 1, can be calculated as follows:

$$R_1(CE)=F_1\ (\text{RELATIVE IMPORTANCE}) \times F_1\ (\text{STATE}_1\ \text{IMPACT}) + \ldots F_m\ (\text{RELATIVE IMPORTANCE}) \times F_m(\text{STATE}_1\ \text{IMPACT})$$

$$R_2(CE)=F_1\ (\text{RELATIVE IMPORTANCE}) \times F_1\ (\text{STATE}_2\ \text{IMPACT}) + \ldots F_m\ (\text{RELATIVE IMPORTANCE}) \times F_m(\text{STATE}_2\ \text{IMPACT})$$

$$\vdots$$

$$R_n(CE)=F_1\ (\text{RELATIVE IMPORTANCE}) \times F_1\ (\text{STATE}_X\ \text{IMPACT}) + \ldots F_m\ (\text{RELATIVE IMPORTANCE}) \times F_m(\text{STATE}_Z\ \text{IMPACT})$$

For example, Table 5.6 shows some samples of the calculations of the combined effect for some of the rules generated from the example previously described.

Table 5.6: Samples of the calculations for determining the rule consequents

	A	R.I.	I.O	CE	B	R.I.	I.O	CE	C	R.I.	I.O	CE	Total CE	Norm CE	Cons
R1	No Formal Approach	0.33	-4	-1.32	No Formal Approach	0.33	-3	-0.99	No Formal Approach	0.33	-3	-0.99	-3.3	0.00	Very High
R2	No Formal Approach	0.33	-4	-1.32	No Formal Approach	0.33	-3	-0.99	Reactive Approach	0.33	0	0	-2.31	0.14	Very High
R3	No Formal Approach	0.33	-4	-1.32	No Formal Approach	0.33	-3	-0.99	Formal System	0.33	2	0.66	-1.65	0.23	High
R4	No Formal Approach	0.33	-4	-1.32	No Formal Approach	0.33	-3	-0.99	Continual Improve	0.33	3	0.99	-1.32	0.27	High
R5	No Formal Approach	0.33	-4	-1.32	No Formal Approach	0.33	-3	-0.99	Best-in-Class	0.33	4	1.32	-0.99	0.32	High

A = Constructability Review
B = Internal and External Examinations
C = Risk Management

5. Based on the combined effect of all the rules included in the given rule base developed to determine the output of the submodel (e.g. the 125 rules for the abovementioned example), the combined effect of each of the rules must be normalized between 0 and 1 using Equation 5.1:

$$\text{Normalized}\,CE\text{ of Rn} = \frac{CE\text{ of Rn} - CE_{\min}}{CE_{\max} - CE_{\min}} \qquad \textbf{[5.1]}$$

Table 5.6 contains some examples of the normalized CE values that were calculated with the CE values of all the inference rules established to assess the quality level of design/drafting. Furthermore, Table H.1(b) in Appendix H contains the CEs of the entire rule base on which such calculation was based, as well as the resulting normalized values for each of the 125 rules.

6. The next step was to determine the consequents of the rules based on a scale ranging from 0 to 1.0 that was segmented into zones representing the different linguistic terms

used to assess the output of the submodel under analysis. The intention of this scale was to cluster the normalized combined effect values, obtained with the previous steps, into the linguistic terms. For example, Figure 5.3 illustrates the five term scale ranging from very poor to very good that was established to determine the quality performance level of construction resources (e.g. design/drafting).

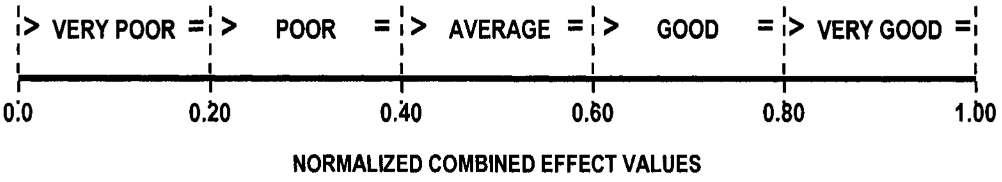


Figure 5.3: Example of the linguistic scale used to determine the consequents of rules developed to assess the quality level of construction resources

In order to illustrate the use of the scale, Table 5.3 shows some samples of the consequents that were determined for the given rules. For example, according to the scale shown in Fig. 5.3 and given that the normalized CE value resulted in 1.0 for Rule 1 (R1), *very good* was the linguistic term assigned as consequent of such rule, while *good* was assigned to R3 given that its respective normalized CE value was 0.77.

7. Finally, once the rule base for each of the sub-models integrated into the PQM system under analysis was developed, the weights or degrees of support for each of the rules in the rule bases were determined. The weight of a rule (a number between 0 and 1) represents the relative significance of the given rule, in comparison to the others in the rule base, on the evaluation of the output. The effect of these weights is applied during the implication process implemented within the fuzzy inference process (refer to Section 3.2.3.2, step 2). According to the observations made by the experts involved in

this knowledge-based assessment effort, all the rules were assigned weights equal to 1 which means the weighting had no effect at all on the implication process.

Moreover, Tables H.1, H.2, and H.3 in Appendix H contain the rule bases that were generated for the case study analyzed to illustrate the application of the proposed modelling framework.

5.3 Specific-operation knowledge elicitation procedures

The *specific-operation knowledge elicitation module*, which should provide the knowledge required to develop the fuzzy logic models used to estimate the statistical parameters of the NIs, such as described in Section 3.2.2. Therefore, the variables whose MFs should be generated as part of the SOKE module include:

a) The number of nonconforming events (N) during the undertaking of a specific construction activity. In this case, different MFs representing the number of nonconformities that could occur for each specific construction activity being analyzed in the model should be generated.

b) The duration of a delay (D) due to a nonconformance occurred during the undertaking of any construction activity. In this case, it was assumed that a single MF would represent appropriately the duration of delays due to any kind of nonconformance occurred in any construction activity.

Meanwhile, the fuzzy inference rules that should be assessed for these fuzzy models include:

a) The frequency of occurrence of each of the quality performance levels of the construction resources in the activity under analysis,

b) The combined effect of the quality levels of construction resources and the frequency of occurrence of such quality levels on the level of adverse consequences on the performance of the activity under analysis,

c) The effect of the level of adverse consequences on the level of the NIs, i.e. the number of nonconformities and the duration of delays in the activity under analysis,

d) The combined effect of the quality levels of construction resources and the frequency of occurrence of such quality levels on the number of nonconformities and the duration of delays in the activity under analysis.

Moreover, the MFs and IRs developed within the SOKE module should be based on the assessments of personnel available in the organization under study and who are directly involved in the undertaking of open-cut construction projects. For example, in this case nine employees within the open-cut section in the D&C organization, including four open-cut supervisors, four foremen, and the open-cut general supervisor, participated in this effort. The average experience of the participants was 15.22 years.

5.3.1 Development of membership functions for the SOKE module

The procedure to generate the membership functions related to the SOKE module included the following steps:

1. The appropriate linguistic terms to assess the number of nonconformities and the duration of delays due to nonconformities were determined, as seen in Table 5.1. Five terms were established to evaluate these variables: *very small*, *small*, *medium*, *large*, and *very large*.
2. The x-axis domains and their respective ranges of values were determined for both variables, as seen in Table 5.1. On one hand, the number of nonconformities was evaluated in terms of the quantity of nonconforming events, while the duration of delays was evaluated in terms of the hours that the delay may last. In order to establish a general numerical guideline for the assessment of the variables, it was assumed that the extreme value of the *very small* term was zero. On the other hand, no extreme value was established for *very large* as the bound varied according to the opinions of the personnel participating in this module of the knowledge elicitation effort. However, in order to facilitate the assessment process, interviewees were asked to first decide on the maximum value for the very large number of nonconformities and the duration of delays, and from there to evaluate the values for the other linguistic terms. This decision should be made by considering the size of the project that is being surveyed. For the purposes of this study the size of the sanitary sewer projects tracked in the QIMS were classified according to their length as very small (i.e. $L<20$ ft), small (i.e. $20<L<100$ ft), medium (i.e.$100<L<500$ ft), large (i.e. $500<L<1500$ ft), and very large (i.e. $L>1500$ ft). In this case, the elicitation of these knowledge-based assessments was

demonstrated with the evaluation of a medium sanitary sewer project, which served to illustrate the application of the PQMAF in Chapter 6.

3. A questionnaire was developed in order to conduct the elicitation of the knowledge-based assessments needed for the development of these MFs. The format asked the interviewees (i.e. experienced personnel directly involved in the undertaking of open-cut construction projects) to assign the appropriate numerical values for each of the linguistic terms. For example, the question formulated to determine the numerical values for the linguistic terms assessing the number of nonconformities is illustrated in Table 5.7(a); while for those assessing the duration of delays due to nonconforming events is shown in Table 5.7(b). Moreover, Form D.3 included in Appendix D illustrates the full questionnaire used for acquiring the data required for the development of MFs of the variables involved in the SOKE module.

Table 5.7(a): Sample question to assign numerical values to linguistic terms assessing the number of nonconformities

1. In the **Excavation**, what **number of nonconformities** would you consider as													**Skip?**
a. ***Very Small***?	0	1	2	3	4	5	6	7	8	9	10	> 10	
b. ***Small***?	0	1	2	3	4	5	6	7	8	9	10	> 10	
c. ***Medium***?	0	1	2	3	4	5	6	7	8	9	10	> 10	
d. ***Large***?	0	1	2	3	4	5	6	7	8	9	10	> 10	
e. ***Very Large***?	0	1	2	3	4	5	6	7	8	9	10	> 10	

Table 5.7(b): Sample question to assign numerical values to linguistic terms assessing the duration of delays due to nonconformities

For the **duration of a delay event due to a nonconformance**, what number of **hours** would you consider as													**Skip?**
a. ***Very Small***?	< 1.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	> 10.0	
b. ***Small***?	< 1.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	> 10.0	
c. ***Medium***?	< 1.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	> 10.0	
d. ***Large***?	< 1.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	> 10.0	
e. ***Very Large***?	< 1.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	> 10.0	

The questionnaire was applied individually to each of the nine D&C employees directly involved in open-cut construction projects while the author of this research was available to clarify any issue related to the questions. Moreover, it is important to highlight that the application procedure took care of interviewing the participants when they had been appointed to an open-cut construction project similar to the one that was taken as case study for illustrating the application of the proposed framework. In addition, because of the length of the questionnaire, which included the knowledge elicitation for both the development of MFs and the generation of the IRs in the SOKE module, more than one session with some of the interviewees were required.

4. The assessments of all survey respondents were accumulated for the development of the MFs of the respective variables. In addition to the rules implemented for the variables in the SPQMSKE module, (refer to Section 5.2.1), other assumptions were applied on the development of the MFs of both the number of nonconformities and the duration of delays, including:

a. If more than 50% of interviewees decided to skip the assessment of a given linguistic term, then the term was not used to evaluate the corresponding nonconformance. Otherwise, the MFs of the linguistic terms that were evaluated by at least the 50% of interviewees were generated by using the opinions of such majority of interviewees. In this case, any of the linguistic terms was skipped.

b. The last or highest value of the *very large* term was assumed the peak value of the given MF, to which a degree of membership of 1.0 was eventually assigned. Moreover, all the values to the right of the peak values of the *very large* MFs were dismissed. For example, as seen in Table 5.8(a), the peak value and last value in the *very large* MF representing the number of nonconformities in the excavation activity is 5, and no right supporting interval was considered for such MF.

Tables G.2(a) and G.2(b) in Appendix G contains all the MFs that were generated within the SOKE module.

Table 5.8(a): MFs of the number of nonconformities in the excavation

Open-cut Construction Activity	Linguistic Terms	Fuzzy Membership Functions											
		0.0	1.0	2.0	3.0	4.0	5.0						Shape
EXCAVATION	Very Small =	1.0	0.67	0.33	0.00	0.00	0.00						Triang
	Small =	0.00	1.00	0.67	0.33	0.00	0.00						Triang
	Medium =	0.00	0.50	1.00	0.67	0.33	0.00						Triang
	Large =	0.00	0.00	0.00	0.50	1.00	0.00						Triang
	Very Large =	0.00	0.00	0.00	0.33	0.67	1.00						Triang

5.3.2 Development of inference rules for the SOKE module

The generation of the rules that infer the level of the NIs (i.e. the number of nonconformities and the duration of delays due to nonconformities) due to the effect of the quality performance levels of the construction resources involved in the operation under analysis (refer to Figure 4.3), included the following steps:

1. The SOKE questionnaire included a section in which the interviewees had to identify the linguistic values that, in their opinion, describe appropriately the effect of each of the quality performance levels of the construction resources on the state level of the variables that explain the performance of the construction activity under analysis. Therefore, the interviewees were asked to check the appropriate linguistic values for assessing the effect of a specific quality level of a given resource on a given construction activity, keeping in mind the following questions as a guide for making the assessments:
    a. What is the *Frequency of the Occurrence* of the *x* performance level of resource *A* in the construction activity under analysis?
    b. Then, what is the *Adverse Consequence* of the *x* performance level of resource *A* on the completion time of the construction activity under analysis?
    c. Then, what is the expected *Number of Nonconformities* to occur during the construction activity under analysis, given the level of adverse consequences?
    d. In addition, what is the expected *Duration of a Delay* due to the occurrence of a non-conformance during the construction activity under analysis, given the level of adverse consequences?

Moreover, interviewees were asked to articulate their assessments using matrices with the linguistic values of the variables involved, such as illustrated in Figure 5.4. Likewise, the assessments about the effect of all five quality levels of each resource involved in the construction activities under analysis were required from the participants. The construction activities analyzed in this case study included the excavation, pipe installation, bedding, and backfilling, in each of which the effect of the material/equipment supplying, the stacking service, the equipment, the work conditions, and the design/drafting information was evaluated. Form D.3 in Appendix D, includes the questionnaire used to elicit the knowledge required to generate the rules.

2. All the data acquired from the previously introduced survey were summarized to obtain the percentage of the interviewees that favoured each of the linguistic values of the assessed variables. For example, Table 5.9 shows the percentages of responses given to the linguistic terms of the variables in the assessment of the effect of each quality level of the work conditions.

1. Evaluation of the effect of the performance of construction resources on EXCAVATION

	Performance Level of ***Material/Equipment Supplying***	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformities*	*Duration of Delays due to Nonconformities*
a.Evaluate the effect of the performance of the **Material/ Equipment Supplying (from Vendors) on Excavation**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		[✓ **Unusual**]	Mild	[✓ **Small**]	[✓ **Small**]
		Often	[✓ **Medium**]	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		[✓ **Unusual**]	[✓ **Mild**]	[✓ **Small**]	[✓ **Small**]
		Often	Medium	Medium	Medium
		Usual	Large	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	[✓ **Mild**]	[✓ **Small**]	[✓ **Small**]
		Often	Medium	Medium	Medium
		[✓ **Usual**]	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	[✓ **Very Mild**]	[✓ **Very Small**]	[✓ **Very Small**]
		Unusual	Mild	Small	Small
		[✓ **Often**]	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	[✓ **Very Mild**]	[✓ **Very Small**]	[✓ **Very Small**]
		[✓ **Unusual**]	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

Figure 5.4: Sample of the linguistic matrices used to generate the inference rules in the SOKE module

Table 5.9: Sample analysis for generating the inference rules of the effect of the quality levels of resources on the open-cut construction activities

Assessment of the Work Conditions on the Excavation activity								
Quality Level (Q)	**Frequency of Occurrence (F)**		**Adverse Consequences (C)**		**Number of Nonconformities (N)**		**Duration of Delays (D)**	
Very Poor	Very Unusual	11%	Very Mild	11%	Very Small	0%	Very Small	0%
	Unusual	56%	Mild	11%	Small	11%	Small	0%
	Often	22%	Medium	22%	Medium	11%	Medium	11%
	Usual	11%	Severe	22%	Large	33%	Large	56%
	Very Usual	0%	Very Severe	33%	Very Large	44%	Very Large	33%
Poor	Very Unusual	11%	Very Mild	0%	Very Small	0%	Very Small	0%
	Unusual	22%	Mild	11%	Small	11%	Small	0%
	Often	44%	Medium	22%	Medium	22%	Medium	22%
	Usual	11%	Severe	44%	Large	33%	Large	56%
	Very Usual	11%	Very Severe	22%	Very Large	33%	Very Large	22%
Average	Very Unusual	0%	Very Mild	11%	Very Small	0%	Very Small	11%
	Unusual	0%	Mild	33%	Small	22%	Small	11%
	Often	67%	Medium	56%	Medium	56%	Medium	33%
	Usual	22%	Severe	0%	Large	22%	Large	44%
	Very Usual	11%	Very Severe	0%	Very Large	0%	Very Large	0%
Good	Very Unusual	11%	Very Mild	22%	Very Small	33%	Very Small	33%
	Unusual	0%	Mild	33%	Small	22%	Small	56%
	Often	44%	Medium	44%	Medium	44%	Medium	11%
	Usual	33%	Severe	0%	Large	0%	Large	0%
	Very Usual	11%	Very Severe	0%	Very Large	0%	Very Large	0%
Very Good	Very Unusual	33%	Very Mild	44%	Very Small	44%	Very Small	44%
	Unusual	22%	Mild	44%	Small	56%	Small	44%
	Often	22%	Medium	11%	Medium	0%	Medium	11%
	Usual	11%	Severe	0%	Large	0%	Large	0%
	Very Usual	11%	Very Severe	0%	Very Large	0%	Very Large	0%

3. Based on the linguistic terms with the highest percentages of responses, the inference rules were established. For example, Table 5.9 shows that for the effect of the *very poor quality level* of the work conditions on the excavation activity 56% of interviewees considered that the *frequency of occurrence* of such quality level was

unusual. While 56% was the highest percentage of responses given to a linguistic value in the assessment of the frequency of occurrence variable, the *unusual* linguistic value was picked to generate the corresponding inference rule. Likewise, the level of *adverse consequences* was *very severe* as this linguistic value received 33% of responses, the *number of nonconformities* was *very large* as it got 44% of responses, and the *duration of delays* was *large* as it obtained 56% of responses. Therefore, the resultant inference rules for the quality levels of the work conditions in the excavation activity are shown in Table 5.10, which were generated based on the results shown in Table 5.9.

Table 5.10: Sample of the fuzzy IRs generated in the SOKE module

Fuzzy Inference Rules for the Excavation Activity					
Construction Resource	**Quality Level (Q)**	**Frequency of Occurrence (F)**	**Adverse Consequences (C)**	**Number of Nonconformities (N)**	**Duration of Delays (D)**
Work Conditions	Very Poor	Unusual	Very Severe	Very Large	Large
	Poor	Often	Severe	Large	Large
	Average	Often	Medium	Medium	Large
	Good	Often	Medium	Medium	Small
	Very Good	Unusual	Mild	Small	Very Small

Moreover, Table H.4 in Appendix H contains the fuzzy inference rules that were generated as part of the SOKE module for the analysis of the different activities included in the case study.

5.4 Summary and conclusions

This chapter introduces the procedures that were implemented to elicit the knowledge-based assessments required to generate the fuzzy MFs and IRs that integrate the fuzzy logic models involved in the proposed PQMAF. The following are the main approaches that were implemented towards the accomplishment of these goals:

1. Suitable elicitation procedures were implemented to facilitate the assessment of the variables involved in the fuzzy logic models. Two different knowledge elicitation modules were formulated, the specific-PQM-system knowledge elicitation module and the specific-operation knowledge elicitation module. The former one is concerned with the procedures to develop the fuzzy expert system that infers the quality level of the construction resources being analyzed. Meanwhile, the second one is focused on the development of the fuzzy logic model that estimates the statistical parameters of the nonconforming indicators (i.e. the number of nonconformities and the duration of delays due to these nonconformities) for the different construction activities being evaluated. This approach intended to address the different required assessments to the suitable experienced personnel available in the organization being studied. This way, though the assessment of the model variables was unusual to the participants, the procedures implemented for the knowledge elicitation seemed to facilitate the process.
2. Procedures and assumptions to generate the fuzzy MFs and IRs were adapted from methods that had been proved appropriate to overcome the limited size of data available. In this case, as only one organization participated in the development of this research the amount of data was limited by the availability of experienced personnel involved in the organization's management and operational processes under evaluation.

However, though the assumptions implemented were suitable for the purposes of this research, it is necessary to elicit this kind of assessment from other organizations in order to apply other methods that may improve the consistency of MFs and IRs used in the proposed model. This would also develop a more comprehensive knowledge base that may facilitate the undertaking of more reliable analyses.

Moreover, the illustration of the knowledge elicitation procedures was based on the development of the MFs and IRs of a medium size sanitary sewer project that was used as case study. The obtained MFs and IRs were further used in Chapter 6 to demonstrate the application of the modelling framework proposed in this research work.

CHAPTER 6

APPLICATION OF THE ASSESSMENT FRAMEWORK AND ANALYSIS OF RESULTS

This chapter details the implementation of the components included in the Interactive-Computer-Based System (ICBS), which is part of the modelling approach proposed within the PQMAF (refer to Section 3.3). This includes the implementation of the fuzzy logic and the discrete-event simulation applications, previously introduced in Section 3.2, for estimating the effect of PQM practices on the performance of the operation being analyzed, i.e. the open-cut construction process in this case. In fact, a sensitivity analysis based on the simulation of different scenarios representing alternative maturity levels of the PQM system, was conducted to evaluate the variation of the operation's completion time and productivity estimates due to the effect of the delays resulting of the occurrence of nonconforming events. The magnitude of this effect is assumed associated with the maturity level of the PQM system.

6.1 Description of the case study project

A medium size sanitary sewer project developed by the Design and Construction (D&C) section of the Drainage Services, in the City of Edmonton, was used as a case study to validate the modelling techniques detailed in Chapter 3. The case study includes a section of a new sanitary sewer that was constructed in a residential area that was developed in Edmonton by the time this research work was conducted. This involved the construction of 1320 feet (402.3 meters) of 24-inch sewer pipeline. Concrete sewer pipe pieces with a standard length of 3.0 meters were installed in the project section under analysis. The activities and resources involved in the construction operation of the sanitary sewer project are shown in Table 6.1. Given that the project was constructed in open country, the sloping of the sides of the trench for earth stability was possible. This eliminated the placing, maintaining, and removing of temporary sheeting and bracing that may otherwise be necessary to hold the sides of the excavation.

Table 6.1: Durations and resources of the activities included in the case study

Activity	Resources	Advance Rate (min/m)	Distance Buffer (m)
Excavation	1 Backhoe 1 Survey crew	T(2.9, 4.2, 6.1)	20
Detailing Excavation	6 Laborers 1 Survey crew (shared with excavation)	T(3.1, 4.0, 5.2)	40
Bedding	1 Loader 2 Vibratory equipment 6 Laborers (shared with excavation)	T(1.9, 3.8, 4.7)	20
Pipe Installation	1 Loader (shared with bedding) 2 Pipeman 1 Laborer	T(3.2, 4.5, 5.5)	20
Finishing of Bedding	1 Loader (shared with bedding) 2 Vibratory equipment (shared with bedding) 6 Laborers (shared with bedding)	T(2.5, 3.9, 5.2)	40
Backfilling	1 Dozer (shared with finish bedding) 1 Compaction equipment	T(2.7, 3.6, 4.8)	

While the availability of records related to the durations of the activities was limited, the advance rates of each activity were elicited from the open-cut supervisor who, based on his experience, provided estimations of the advance rates for each of the activities. During the interview the supervisor was asked how many meters per hour of each given activity could be completed if no nonconformity would occur during the process. Moreover, the most optimistic, most pessimistic, and most likely estimates were required to the interviewee in order to model the advance rates as triangular distributions. Because of the nature of the simulation model developed for case study analysis, the advance rates are given in meters per minutes, as shown in Table 6.1. The required distance buffer between each activity and the subsequent one is also included in Table 6.1.

6.2 Implementation of the Interactive-Computer-Based System

The modelling approach proposed within the ICBS included the development and implementation of the following computer-based applications:

1. A fuzzy expert system (FES) to infer the quality performance level of specific construction resources involved in the open-cut construction operation that was used as case study.
2. A fuzzy logic-based procedure to estimate the statistical parameters of the NIs, i.e. the number of nonconformities and the duration of delays due to the occurrence of nonconformity events in each of the activities, given the quality performance levels of the construction resources.
3. A simulation project model that estimated the effect of alternative performance maturity levels of the PQM system on the completion time and the productivity of the case study operation. The uncertainty of such an effect on the operation's performance outcomes was modeled through the inclusion of the statistical parameters of the NIs as inputs to the simulation project model.

It is important to highlight that the first fuzzy logic application (the fuzzy expert system) analyzes the PQM system at the project level, while the second fuzzy logic application analyzes the effect of the PQM system on the operation level and specifically, on each of the activities involved in the operation being analyzed. Meanwhile, the simulation application estimates the performance of the entire operation affected by the performance of the PQM system.

6.2.1 Implementation of the FES to infer the quality level of the construction resources

By applying the membership functions (MFs) and inference rules (IRs) developed with the SPQMSKE module, (see Section 5.2), a fuzzy expert system (FES) was implemented to infer the quality performance level of the construction resources involved in the prioritized PQM factors model for large size open-cut projects, which was introduced in Section 4.3.2. The implementation of the FES for this case study used Fuzzytech, a software development tool for fuzzy logic analyzes. Notice that in order to simplify the exemplification of the modelling approach, three construction resources were analyzed in the implemented sample model, the material supply, the design information, and the work condition, instead of the seven included in the prioritized PQM factors model (refer to Figure 4.5). Figure 6.1 shows that the FES implemented in Fuzzytech include the following variables:

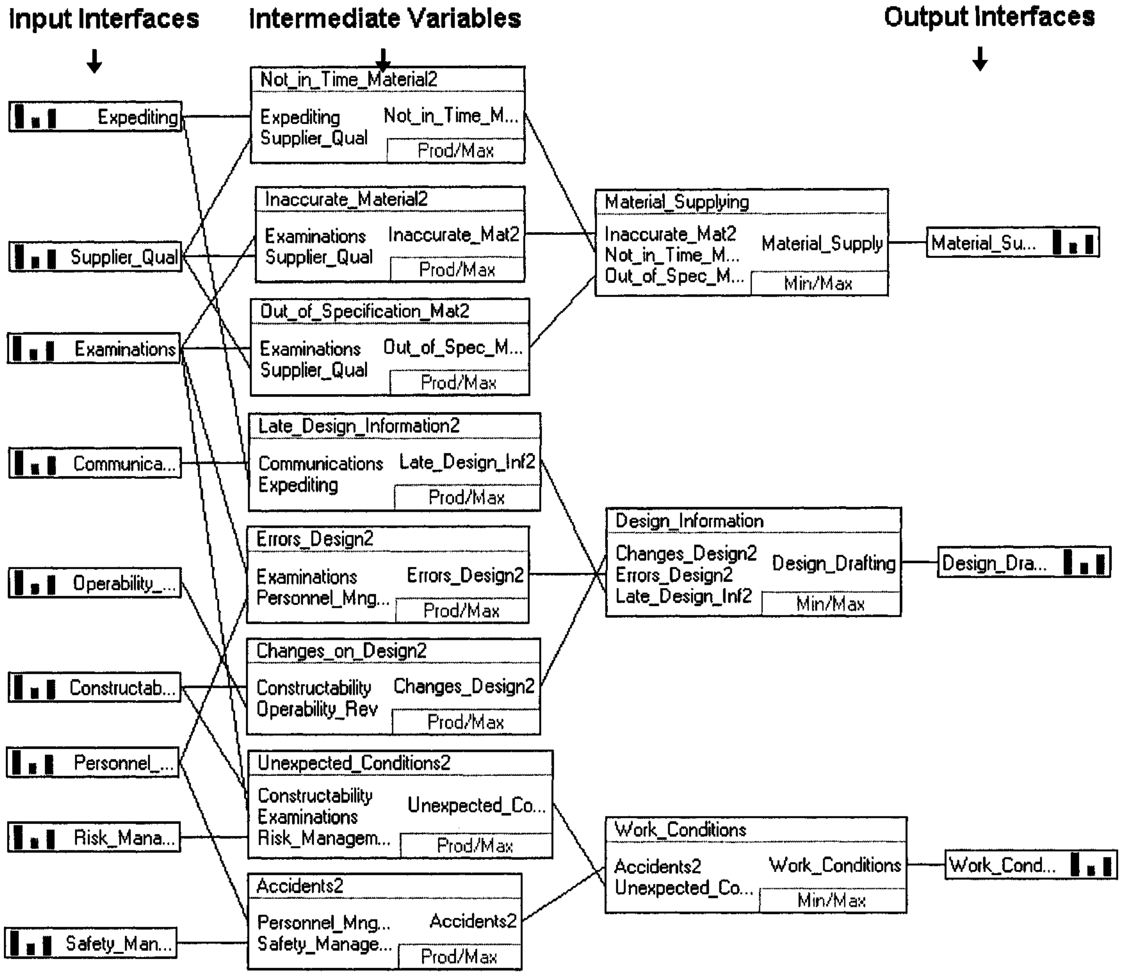


Figure 6.1: Fuzzy expert system, as implemented in Fuzzytech, for inferring the quality level of construction resources with linguistic terms as inputs

1. The maturity level of the PQM practices, which was modelled as an *input interface*. This variable was able to be expressed as one of two, a crisp value or a linguistic (fuzzy) values (see Section 4.2.3.1). Therefore, the input interfaces were implemented in such a way that both crisp values and linguistic terms can be used as inputs to the FES. Moreover, the FES in which crisp input values were used required the implementation of the MFs shown in Figure 6.2, which represent the different linguistic terms established for evaluating the maturity level of the PQM practices (see

Section 5.2.1). On the contrary, these MFs were not implemented when fuzzy values were inputs to the FES because no fuzzification was involved within the inference process.

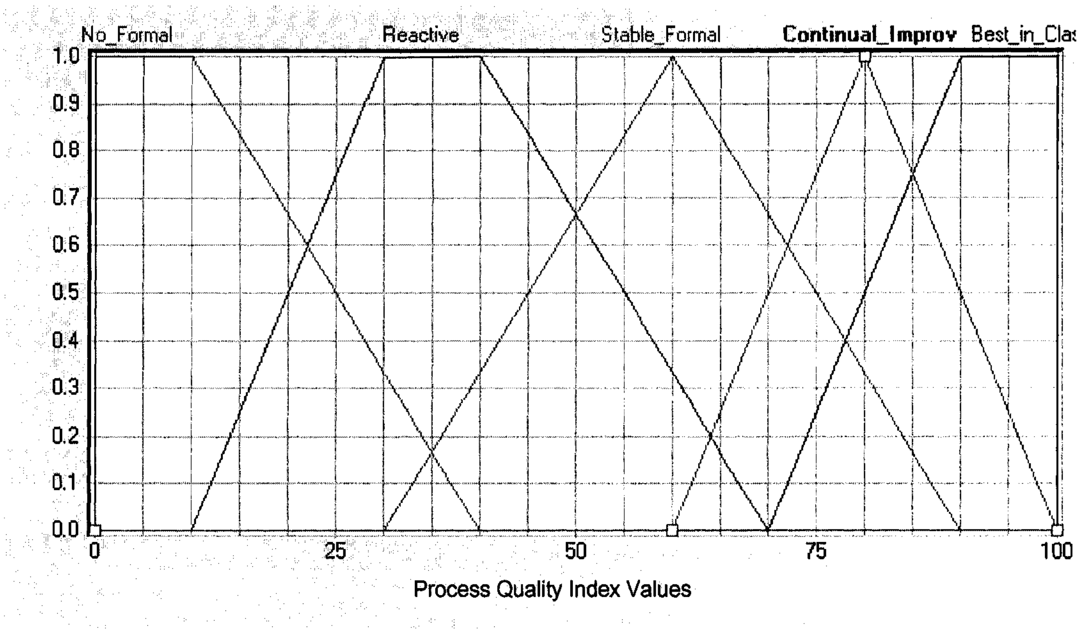


Figure 6.2: Fuzzy membership functions representing the linguistic terms for evaluating the maturity level of PQM practices

2. The number of nonconformities respectively associated with the quality level of the construction resources, which was modelled as an *intermediate variable*. Intermediate variables attain values during the inference process, which are not needed as outputs of the model and, therefore, they are only intended for passing information from one rule block to another. This information is in the form of linguistic (fuzzy) values, which means that that MFs of the variable terms, (i.e. the linguistic terms established for evaluating the number of each of the nonconformities respectively associated with the construction resources), are not needed to achieve this stage within the inference process.

3. The quality level of the construction resources, which were modelled as *output interfaces*. Since the outputs to be obtained from the FES are required as linguistic (fuzzy) terms, no defuzzification was involved within the inference process and, therefore, no MFs were required for representing the linguistic terms established for evaluating the quality level of the construction resources.

Moreover, since the independency among the input variables (i.e. the maturity levels of PQM practices) was assumed in this analysis, a T-norm (AND) operation, the PROD operation, was used to aggregate the effect of all the PQM practices associated with each intermediate variable (i.e., the number of a given nonconformity). The PROD operation was applied in order to imply the interaction assumed to exist among the input factors. Likewise, the independency among the sub-output factors (i.e. the nonconforming events affecting the quality level of the construction resources) was assumed; however, no interaction among them was implied in this case. Therefore, the MIN operator was used to aggregate the effect of the number of the corresponding nonconformities affecting the quality level of each of the construction resources (i.e. the output variables) involved in the analysis. On the other hand, the MAX operator was applied for the aggregation of the results for both the intermediate variables and the output variables. However, a sensitivity analysis was conducted in order to verify the stability of the FES under different model parameters. This analysis would support the selection of the appropriate model parameters under which the FES is behaving reasonably. Alternative input aggregation and output aggregation methods were tested in the computing of both the intermediate variables and the output variables, including the following:

a) Min/Max
b) Min/Bsum
c) Prod/Bsum
d) Max/Max
e) Max/Bsum
f) Gamma/Max
g) Gamma/Bsum
h) Avg/Max
i) Avg/Bsum

The scenarios described in Table 6.12 were used to conduct this stability analysis. This analysis demonstrated that only the MIN and PROD input aggregation methods were able to capture the input variations formulated in the different scenarios. On the other hand, the same outputs were obtained with either the MAX or the BSUM output aggregation methods. In fact, the outputs obtained with the initial assumptions were the same as those obtained with alternatives a, b, and c. Therefore, the model parameters initially assumed were kept.

Once the FES was integrated, it was used to conduct the analysis of the effects of PQM practices involved in the case study model. According to the proposed framework, the maturity levels of the PQM practices must be determined either in linguistic (fuzzy) terms or in crisp values, (i.e. expressed as PQIs obtained with the self-assessment procedure explained in Section 3.3), in order to start the evaluation of such PQM practices. This information is then inputted to the FES in order to obtain the quality levels of the construction resources involved in the case study. For example, Table 6.2 contains the PQIs obtained with the self-assessment of the PQM practices as implemented in the organization used as case study in this research. Moreover, Table 6.2 also shows that the outputs obtained for this sample case are *average* for the Material/ Equipment Supply, *very good* for the Design Information, and *very good* for the Work Conditions. In order to verify the reliability of these results, they were contrasted against the real state of the quality issues experienced in the projects undertaken by the case study organization. Regarding this, Figures E.1, E.2, and E.3 in Appendix E show that the nonconformities related to the supply of material and equipment have been a recurrent issue that affects the performance parameters of the construction projects. Therefore, it can be said that the *average* quality level of the Material/Equipment Supply in contrast to the *very good* quality level of the Design Information and the Work Conditions makes sense.

Table 6.2: Inputs and outputs in the sample case used to demonstrate the application of the modelling approach

Inputs		**Outputs**	
PQM practices	**PQI**	**Construction Resources**	**Quality Level (Fuzzy Value)**
Expediting	78%		
Supplier Qualification	50%	Material/Equipment Supply	Average
Internal and External Examinations	55%		
Change & Communication Management	75%		
Operability & Value Review	59%	Design Information	Very Good
Constructability Review	69%		
Personnel Qualification and Training	81%		
Risk Management	68%	Work Conditions	Very Good
Safety Management	84%		

On the other hand, notice that when the maturity level of the *Internal and External Examinations* practice is upgraded from 55% to 76% in Table 6.2, while the other two practices affecting the *material supplying* (i.e. the *Expediting* and *Supplier Qualification*) keep the same maturity level, the corresponding quality level of the *material supplying* is still *average*. This means that this action may not have a significant effect on the performance improvement of the construction operation. However, when the maturity level of the *Supplier Qualification* practice is upgraded to 70% (i.e., instead of the original 50% of the example in Table 6.2) then the resulting quality level of material supplying would correspond to *very good* instead of the *average* quality level obtained with the original PQIs shown in Table 6.2. This suggests that the *Supplier Qualification* practice has a more significant effect on the quality level of the *material supplying* than the *Internal and External Examinations* practice. Therefore, it is necessary to identify what PQM practices have the most significant effect on the performance of the construction resources in order to make the improvement process more efficient. The following section is dedicated to analyzing the sensitivity of the effect of each of the PQM practices on the quality of the resources involved in the case study project.

6.2.1.1 Sensitivity analysis of the effect of PQM practices on the construction resources

The significance of the specific effect of each of the PQM practices on the performance of the construction resources was analyzed separately for every one of the resources. This analysis would allow the identification of the improvement actions on the PQM system that should be prioritized in order to efficiently increase the quality performance of the construction resources. In this case, the specific PQM practices affecting the performance of the *material/equipment supplying*, the *design information*, and the *work conditions* were analyzed. Table 6.3 shows the main PQM practices that affect each of such construction resources.

Table 6.3: Results of the first treatment in the sensitivity analysis

Construction Resources	Inputs		Outputs
	PQM practices	PQIs	(Quality Level of Resources)
Material/ Equipment Supplying	Expediting	0% while others at 100%	Good
	Supplier Qualification	0% while others at 100%	Poor
	Internal and External Examinations	0% while others at 100%	Good
Design Information	Change & Communication Mngmnt	0% while others at 100%	Very Good
	Constructability Review	0% while others at 100%	Good
	Internal and External Examinations	0% while others at 100%	Very Good
	Expediting	0% while others at 100%	Very Good
	Operability & Value Review	0% while others at 100%	Good
	Personnel Qualification and Training	0% while others at 100%	Average
Work Conditions	Constructability Review	0% while others at 100%	Very Good
	Internal and External Examinations	0% while others at 100%	Very Good
	Personnel Qualification and Training	0% while others at 100%	Average
	Risk Management	0% while others at 100%	Very Good
	Safety Management	0% while others at 100%	Poor

The first treatment included in this analysis, involved setting the PQI of only one of the PQM practices affecting a given construction resource at 0%, while the other practices were set at 100%. For this treatment, it was assumed that the lower the resulting quality level the more significant the effect of the PQM practice that was set at 0%. By observing the effect of such settings on the quality level of the resource, it was possible to discriminate the PQM practices that have the most significant effect on the resource. For example, as seen in Table 6.4, when *Expediting* was set at 0% along with *Supplier Qualification* and *Internal and External Examinations* at 100%, the quality level of the *Material/Equipment Supplying* resource resulted to be *Good*. Instead, when *Supplier*

Qualification was set at 0% with *Expediting and Internal* and *External Examinations* at 100%, the quality level of such resource resulted to be *Average*. By observing the quality levels obtained with this treatment, it was possible to conclude that the *Suppler Qualification* practice has the most significant impact on the performance of the *Material/Equipment Supplying* resource. Likewise, from the results included in Table 6.3 it can be assumed that the *Personnel Qualification and Training*, *Constructability Review*, and *Operability and Value Review* are the practices with a significant effect on the performance of the *Design Information* resource. However, the *Personnel Qualification and Training* practice is the only one with the most significant effect on the quality of *Design Information.* While, on the other hand, the *Change & Communication Management*, *Internal & External Examinations*, and *Expediting* practices have no apparent effect on such resource as any variation was perceived on the resulting quality level when the PQI of any of these practices was eventually set at 0%. Moreover, *Safety Management* and *Personnel Qualification and Training* are the only practices with a significant effect on the quality of the *Work Conditions* resource, though the former one seems to have the most significant effect on that resource.

A second treatment was conducted in order to reinforce the conclusions obtained with the first one. This time, one of the PQM practices affecting a specific construction resource was set at 100%, while the other practices were set at 0%. Therefore, this treatment also clarified what PQM practices would have the most significant contribution towards the performance improvement of each of the construction resources. Moreover, note that in this treatment the higher the resulting quality level of the construction resource the more significant the effect of the PQM practice set at 100%. For example, as seen in Table 6.4, when *Expediting* was set at 100% along with the *Supplier Qualification* and *Internal & External Examinations* practices set at 0%, the quality level of the *Material/ Equipment Supplying* resource resulted in *Very Poor*, which means that the *Expediting* practice may not be a significant contributor to the improvement of such resource. Instead, the *Supplier Qualification* and the *Internal & External Examinations* practices do have a significant contribution to the improvement of the *Material/Equipment Supplying*. However, as the highest quality level (i.e. *Average*) resulted when *Supplier Qualification* was set at 100%, this practice can be deemed the most significant driver to the performance improvement of the *Material/Equipment Supplying*.

Table 6.4: Results of the second treatment in the sensitivity analysis

Construction Resources	Inputs		Outputs
	PQM practices	PQIs	(Quality Level of Resources)
Material/ Equipment Supplying	Expediting	100% while others at 0%	Very Poor
	Supplier Qualification	100% while others at 0%	Average
	Internal and External Examinations	100% while others at 0%	Very Poor
Design Information	Change & Communication Mngmnt	100% while others at 0%	Very Poor
	Constructability Review	100% while others at 0%	Very Poor
	Internal and External Examinations	100% while others at 0%	Very Poor
	Expediting	100% while others at 0%	Very Poor
	Operability & Value Review	100% while others at 0%	Very Poor
	Personnel Qualification and Training	100% while others at 0%	Poor
Work Conditions	Constructability Review	100% while others at 0%	Very Poor
	Internal and External Examinations	100% while others at 0%	Very Poor
	Personnel Qualification and Training	100% while others at 0%	Very Poor
	Risk Management	100% while others at 0%	Very Poor
	Safety Management	100% while others at 0%	Very Poor

In addition, as also seen in Table 6.4, *Personnel Qualification and Training* appears as the only practice with a significant contribution to the improvement of the *Design Information* resource. On the other hand, the analysis of the PQM practices affecting the *Work Conditions* resource turned out to be an interesting case as any of the practices was identified as significant contributors to the improvement of this resource (i.e. no increase was observed on the quality level of the resource). However, based on the results of the first treatment the PQIs of the two PQM practices having a significant effect on the quality of the *Work Conditions* were set at 100% at the same time, while the others remained at 0%. This is shown in Table 6.5. When the *Safety Management* and *Personnel Qualification and Training* practices were simultaneously set at 100% an increase on the quality level of the resource was achieved, i.e. this resulted in a *Average* quality level. It was afterwards realized that in order to achieve a significant improvement on the quality of the *Work Conditions*, it would be necessary to enhance the maturity level of both PQM practices.

Table 6.5: Results for the special case in the second treatment

Construction Resource	Inputs PQM practices	PQI	Outputs (Quality Level of the Resources)
Work Conditions	Constructability Review	0%	Average
	Internal and External Examinations	0%	
	Personnel Qualification and Training	100%	
	Risk Management	0%	
	Safety Management	100%	

Based on the findings obtained with the two previous treatments, the significance of the effect of the PQM practices on the quality of the construction resources was graded into three different levels: *low*, *medium*, and *high*. Table 6.6 points out the level of significance of the effect of the PQM practices on the quality performance of each of the construction resources.

Table 6.6: Grading of the significance of the effect of PQM practices on the construction resources

Construction Resources	PQM practices	Significance of the Effect on the resource
Material/ Equipment Supplying	Expediting	Medium
	Supplier Qualification	High
	Internal and External Examinations	Medium
Design Information	Change & Communication Management	Low
	Constructability Review	Medium
	Internal and External Examinations	Low
	Expediting	Low
	Operability & Value Review	Medium
	Personnel Qualification and Training	High
Work Conditions	Constructability Review	Low
	Internal and External Examinations	Low
	Personnel Qualification and Training	High
	Risk Management	Low
	Safety Management	High

Finally, a third treatment was implemented as part of this analysis. This time the PQIs of the PQM practices whose effect on the quality of the resources was *high* were set at 100%, while the PQIs of those practices whose effect was *medium* were set at a value that seeks to match the quality level of the corresponding construction resource at *Good*. As seen in Table 6.7, for the *Material/Equipment Supplying* resource PQIs of just 23% were necessary in the *Expediting* and *Internal & External Examinations* practices to achieve this. This means that the quality level of the *Material/Equipment Supplying* resource is mostly explained by the performance of the *Suppler Qualification* practice. On the other hand, as also seen in Table 6.7, for the *Design Information* resource PQIs of only 51% in the *Constructability Review* and 50% in the *Operability & Value Review* practices were necessary in order to match a quality level at *Good*, even when the PQIs of the practices with a *low* effect on the resource were set at 0%. Moreover, when the *Constructability Review*, *Operability & Value Review*, and *Personnel Qualification and Training* practices were simultaneously set at 100%, the quality level of the *Design Information* resulted in *Good.* This means that in order to achieve the *Very Good* quality level the support of the practices with *low* effect on the *Design Information* may be required anyway. Finally, the support of the practices with *Low* effect on the *Work Conditions* resource was necessary to achieve a quality level corresponding to *Good*, as seen in Table 6.7. However, PQIs of just 23% in those practices were necessary to achieve this.

With this third treatment, it was demonstrated that in order to make efficient the improvement process in the PQM system those practices or processes with a *high* effect on the construction resources should primarily be identified and developed. However, the support of the practices with *medium* and *low* effect on the construction resources is still required to achieve the highest quality performance level in the resources.

In addition, the impact that improvements to the PQM systems may have on the construction operation being analyzed can be estimated with the application of the other computer-based applications included in the proposed modelling approach and which are detailed throughout the following sections.

Table 6.7: Results of the third treatment in the sensitivity analysis

Construction Resources	PQM practices	Significance of the Effect	PQIs	Quality Level of Resources
Material/ Equipment Supplying	Expediting	Medium	23%	Good
	Supplier Qualification	High	100%	
	Internal and External Examinations	Medium	23%	
Design Information	Change & Communication Mngmnt	Low	0%	Good
	Constructability Review	Medium	51%	
	Internal and External Examinations	Low	0%	
	Expediting	Low	0%	
	Operability & Value Review	Medium	50%	
	Personnel Qualification and Training	High	100%	
Work Conditions	Constructability Review	Low	23%	Good
	Internal and External Examinations	Low	23%	
	Personnel Qualification and Training	High	100%	
	Risk Management	Low	23%	
	Safety Management	High	100%	

6.2.1.2 Defuzzification of the linguistic terms in the input interfaces

A subsequent analysis, (described in Section 6.3), conducted to evaluate the effect of the PQM practices on the performance of the construction operations requires single crisp values that respectively represent each of the linguistic terms established to assess the maturity level of the PQM practices. This is especially necessary when linguistic (fuzzy) terms are used as inputs to the corresponding FES. For example, when the decision-maker assumes the *maturity level* of a given PQM practice as *Stable formal system* (see

Figure 6.3), it should be noted that the corresponding MF has PQI values with nonzero membership values in common with nonzero membership values of the *No formal approach* MF in the range of 30 to 40%; the *Reactive approach* MF in the range of 30 to 70%; the *Continual improvement approach* MF in the range of 60 to 90%; and the *Best-in-class performance* MF in the range of 70 to 90%. Therefore, by asserting that the maturity level is *Stable formal system*, the user is also implicitly asserting that it is *No formal approach*, *Reactive approach*, *Continual improvement approach*, and *Best-in-class performance*, but not with a degree of membership of 1.0. Accordingly, all these implicit MFs must be taken into account to calculate a crisp value that represents the assertion that the maturity level is *Stable formal system*. An approach is proposed in order obtain a single defuzzified value (i.e., a PQI value in this case) from the MFs developed to represent these linguistic terms (see Figure 6.3). The defuzzification of the MFs is attained with the following procedure:

a. Identify the values a corresponding to the intersection points of the MF being assessed, (e.g. *Stable formal system*), with the other MFs within the domain of the variable. For example, the *Stable formal system* MF intersects the *No formal approach* MF at point $a = 35\%$ in Figure 6.3.

b. Determine the respective degrees of membership (μ) of such intersection points. For example, μ is approximately 0.17 for $a = 35\%$ in Figure 6.3.

c. Determine the distance d between the intersection points and their respective closest x value belonging with a $\mu = 1$ to the MF being assessed. For example, as seen in Figure 6.3, the x value belonging to the *Stable formal system* MF with a $\mu =$

1.0 and which is the closest to a, is b = 60%. Therefore, in this case the required distance $d = 60 - 35 = 25$.

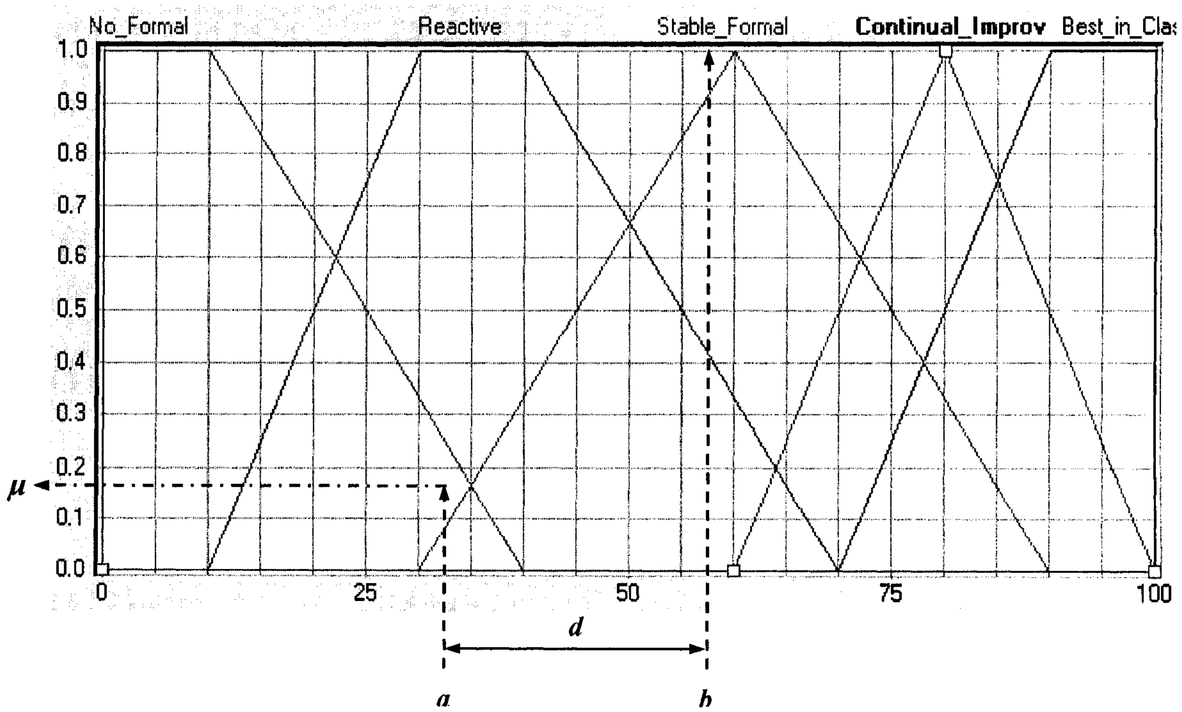


Figure 6.3: Sample of the defuzzification of the MFs for evaluating the maturity level of the PQM practices

d. Calculate the products of the degrees of membership of the intersection points and the corresponding distances d determined before. For example, for a = 35%, μ = 0.17 and d = 25. Therefore, the required product is 25×0.17 = 4.25.

e. Sum the obtained products corresponding to all the intersection points. In this sample case, the *Stable formal system* MF intersects four MFs (i.e., the *No formal approach*, *Reactive approach*, *Continual improvement approach*, and *Best-in-class performance* MFs), thus four products were obtained.

f. Add the sum product previously obtained to the x value corresponding to the lowest value a among the intersection points in the MF being analyzed. The obtained value is the defuzzified value that will represent the linguistic term being assessed. For example, the lowest intersection point among the four corresponding to the abovementioned example, is $a = 35\%$. In this case, the sought value is then $x = 35\% + 25.35 = 60.35\% \approx 60\%$.

Table 6.8 shows the calculation of the defuzzified values for the five linguistic terms used to evaluate the maturity level of the PQI practices. The suitability of the values obtained in Table 6.8 was confirmed by verifying that the same outputs were obtained with the fuzzy terms and their corresponding defuzzified values as inputs to the FES. These defuzzified values were further applied in Section 6.3.

Table 6.8: Calculation of the defuzzified values representing the maturity levels of the PQM practices

Linguistic (Fuzzy) Terms	No Formal Approach			Reactive Approach			Stable Formal System			Continual Improvement			Best-in-Class Performance			Defuzzified Value (PQI)
	a	μ	d	a	μ	d	a	μ	d	a	μ	d	a	μ	d	
No Formal Approach				22%	0.60	12	35%	0.17	25							21.45 ≈ 21%
Reactive Approach	22%	0.60	8				50%	0.67	10	64%	0.20	24				38.30 ≈ 38%
Stable Formal Syst	35%	0.17	25	50%	0.67	10				72%	0.60	12	78%	0.40	18	60.35 ≈ 60%
Continual Improvement				64%	0.20	16	72%	0.60	8				85%	0.75	5	75.75 ≈ 76%
Best-in-Class Performance							78%	0.40	12	85%	0.75	5				86.55 ≈ 87%

6.2.2 Implementation of the fuzzy logic-based procedure to estimate the statistical parameters of the nonconforming indicators

Based on the procedure detailed in Section 3.2.2, a MATLAB program was formulated to facilitate the estimating of the statistical parameters of the number of nonconformities in each of the construction activities being analyzed and the duration of delays due to the occurrence of such nonconformities. This fuzzy logic analysis system requires as inputs the membership functions and fuzzy inference rules developed within the SOKE module, which was detailed in Sections 5.3. Moreover, the estimates computed with this component of the ICBS are based on the construction resources' quality performance levels obtained with the FES implementation that was previously described. Therefore, by entering all this information into the MATLAB program code, which has been included in Appendix I, the statistical parameters of the nonconformance indicator being analyzed can be obtained. For example, based on the fuzzy outputs of the sample case included in Table 6.2 the corresponding fuzzy rules, which are shown in Table 6.9, were applied in order to estimate the mean and the standard deviation of the number of nonconformances in each of the open-cut construction activities being analyzed in this case (i.e. excavation, pipe installation, bedding, and backfilling). The complete list of fuzzy rules that eventually could be applied with this fuzzy logic analysis are shown in Tables H.4(a, b, c, d) in Appendix H. Likewise, the mean and the standard deviation of the duration of delays due to the nonconformances occurred in each of such construction activities were estimated. The estimates of the statistical parameters for this sample case project are shown in Table 6.10. Notice that since the membership functions of duration of delays were built and entered in the MATLAB program in terms of hours, it was necessary to convert the outputs to minutes in order to be used in the simulation model.

Table 6.9: Fuzzy inference rules that apply to the case study project

Activity	Construction Resource	Quality Level (Q)	Frequency of Occurrence (F)	Adverse Consequences (C)	Number of Nonconformances (N)	Duration of Delays (D)
Excavation	Work Conditions	Good	Often	Medium	Medium	Small
	Design Information	Good	Often	Mild	Small	Small
	Material Supplying	Average	Usual	Medium	Medium	Medium
Bedding	Work Conditions	Good	Often	Mild	Small	Small
	Design Information	Good	Often	Mild	Small	Small
	Material Supplying	Average	Usual	Medium	Medium	Large
Pipe Installation	Work Conditions	Good	Often	Mild	Small	Small
	Design Information	Good	Often	Mild	Small	Small
	Material Supplying	Average	Usual	Medium	Medium	Medium
Backfilling	Work Conditions	Good	Often	Mild	Small	Small
	Design Information	Good	Often	Mild	Small	Small
	Material Supplying	Average	Usual	Medium	Medium	Medium

Table 6.10: Statistical parameters estimated for the NIs

Inputs		Outputs			
Construction Resource	Quality Level	Nonconformance Indicator		Mean	Standard Deviation
Material/Equipment Supplying	Average	Number of Nonconformities	Excavation	2.41	1.12
			Bedding	2.22	1.11
			Pipe Installation	2.72	1.35
Design Information	Very Good		Backfilling	2.22	1.11
		Duration of Delays (minutes)	Excavation	165.07	86.40
Work Conditions	Very Good		Bedding	255.33	143.31
			Pipe Installation	164.90	85.95
			Backfilling	164.90	85.95

As established in the ICBS, the statistical parameters obtained with this fuzzy logic analysis system are fed to the corresponding simulation project model in order to estimate the completion time and productivity of the operation being analyzed, i.e. the open-cut construction operation in this case. This is detailed throughout the following section.

6.2.3 Implementation of the simulation project model to estimate the effect of the PQM system on the performance of operations

A discrete-event simulation model of a typical open-cut construction process was developed to estimate the effect of the performance maturity level of PQM practices on the operation's completion time and productivity. The Common template, a general purpose oriented simulation tool embedded in the Simphony.NET simulation platform that was developed by the NSERC/Alberta Construction Industry Research Chair at the University of Alberta, was used to simulate the effect of different combinations of maturity levels of the PQM practices under analysis. The Common template enables the user to graphically model a system by using pre-defined modelling elements or creating new ones that represent network activities involved in the construction operation under study. However, only the pre-defined modelling elements of the Common template were used for building the simulation model of the case study project. The pre-defined modelling elements include elements for handling hierarchical modelling, entity creation and routing, resources, statistics, activities, and tracing. The description of the function of each element in the Common template is available in the General Purpose Simulation Template User's Guide for Simphony [NSERC/Alberta Construction Industry Research Chair 2000].

The information described in Section 6.1 was used to model the open-cut case study project. However, in order to facilitate the simulation process the case study sewer project was adjusted to a length of 400 meters. Moreover, it is necessary to highlight that the simulated process is a simplification of the actual construction process and was intended only for the purposes of this research work. As well, for the purposes of this simulation project model, one linear meter of installed sewer pipe was assumed as each of the entities that would go throughout the simulation model.

The activities in Table 6.1 were included in the simulation project model, which is shown in Figure 6.4 as built with Simphony.NET. One cycle of the modeled open-cut construction process starts with the *excavation* activity, which is followed by the *detailing excavation* activity. However, observing the established distance buffer between the activities the detailing of the excavation will not start before at least 20 meters of excavation are done. It is worth mentioning that the distance buffers have been modeled with the Consolidate modelling elements. When 40 meters of excavation are already detailed the process continues with the *bedding* activity, which requires the same six laborers used in the detailing of the excavation. Likewise, the *pipe installation* activity will be able to start once at least 20 meters of the bed that will receive the sections of sewer pipe are finished. In addition, the *pipe installation* activity will require the loader that is also employed in the *bedding* activity. When at least 20 linear meters of pipe are installed, the finishing of the section of bedding supporting the already installed pipe can be started. Finally, the backfilling activity will be able to start when a section of 40 meters of the bedding is totally finished. It is important to point out that the activities will start every time the amount of their respective antecedent activities, required by the distance buffers, is completed and the resources to perform them are available.

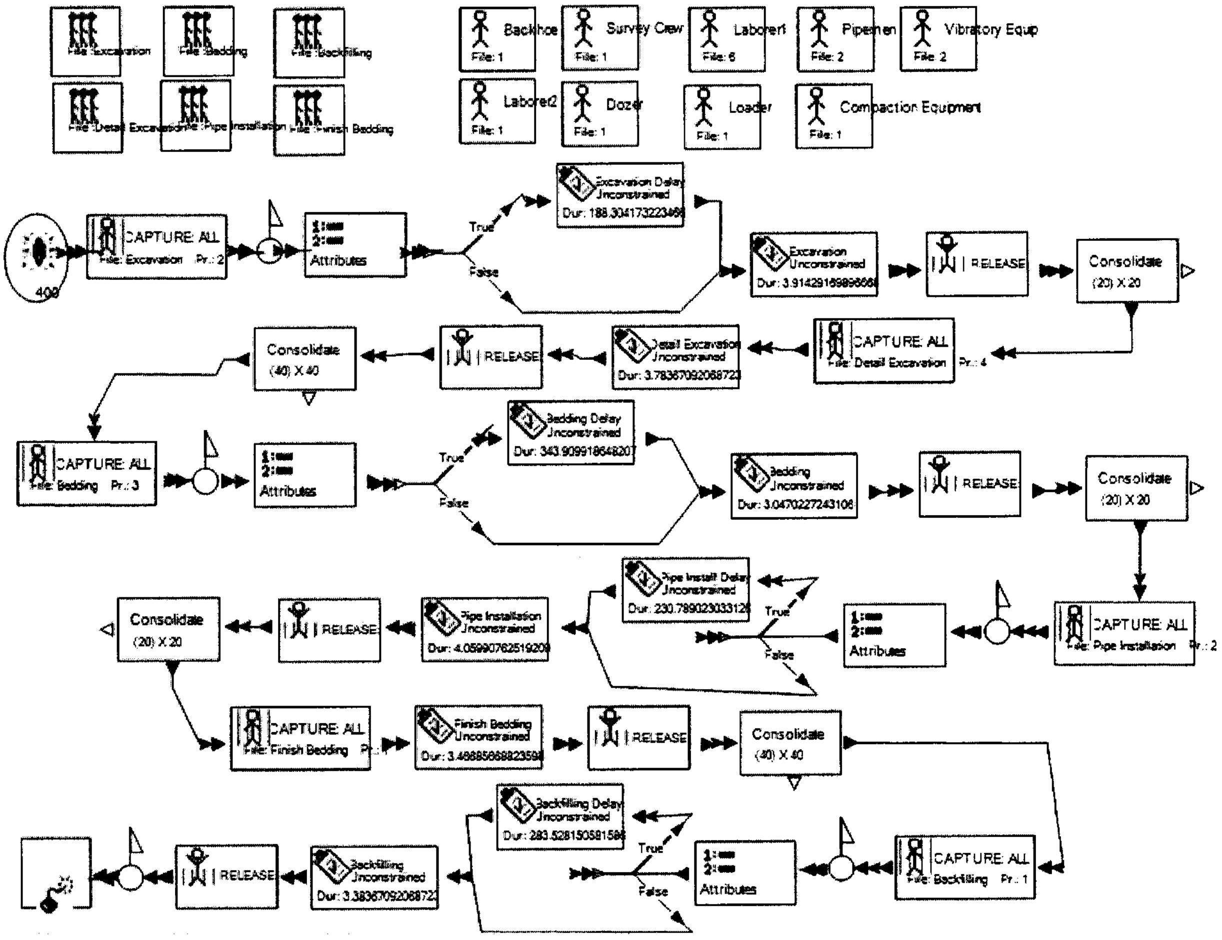
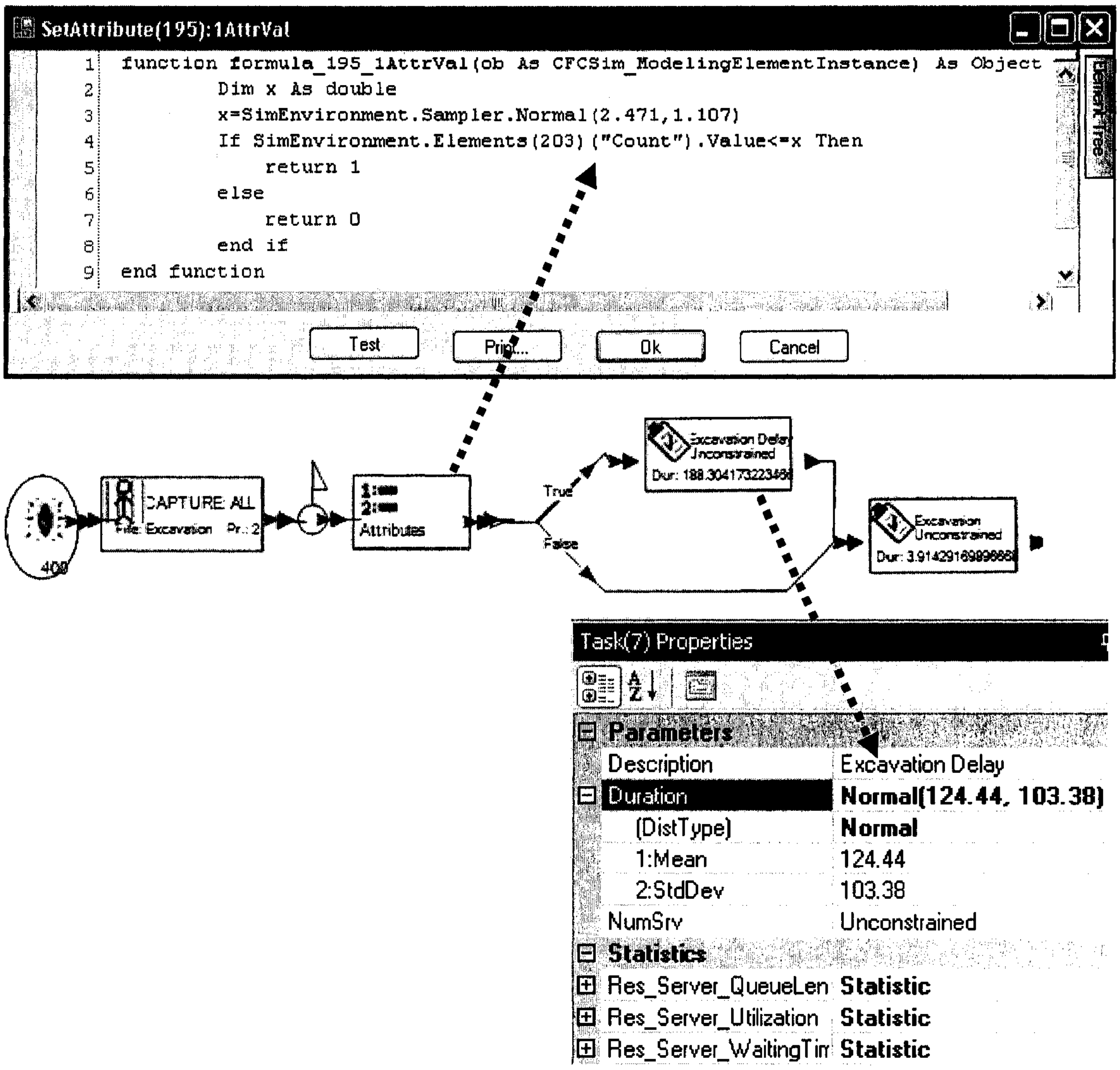


Figure 6.4: Case Study simulation model implemented in Simphony.NET

As seen in Figure 6.4, the appropriate modelling elements of the Common template were used to simulate the aforementioned process. In addition, modelling elements were adapted to input the statistical parameters that represent the effect of the nonconforming indicators (NIs). Figure 6.5 shows that the statistical parameters of the *number of nonconformances* should be entered in the Attribute elements of the simulation model while the statistical parameters of the *duration of delays* should be entered in the Task elements, which were used to model the delays in each of the activities. This way, for every simulation run, a random number of nonconforming events will be simulated for each of the activities according to their respective statistical parameters. Moreover, for every simulated nonconforming event, a random number representing its corresponding delay duration will be generated. As a result, the effect of the occurrence of nonconforming events will be reflected on the operation's completion time estimate.

In order to appreciate the quantitative variation in the productivity of the operation resulting from the effect of the occurrence of nonconforming events, the simulation project model was first run excluding such effects. This means that the statistical parameters of the *number of nonconformances* in all the activities were set to zero. The outputs obtained with ten simulation runs of this first scenario are included in Table 6.11. After that, the simulation model was run again introducing the effect of the occurrence of nonconforming events. This means that the statistical parameters of the *number of nonconformances* and the *duration of delays due to nonconformances*, included in Table 6.10, were inputted into the simulation process of each corresponding activity. It is important to highlight that both the *number of nonconformances* and the duration *of delays* were assumed normally distributed as the statistical parameters obtained from fuzzy logic analysis include the mean and standard deviation of such analyzed NIs. Table 6.11 contains the outputs obtained with the effect of the occurrence of nonconforming events during the simulation process.



```
function formula_195_1AttrVal(ob As CFCSim_ModelingElementInstance) As Object
        Dim x As double
        x=SimEnvironment.Sampler.Normal(2.471,1.107)
        If SimEnvironment.Elements(203)("Count").Value<=x Then
            return 1
        else
            return 0
        end if
end function
```

Parameters	
Description	Excavation Delay
Duration	**Normal(124.44, 103.38)**
(DistType)	**Normal**
1:Mean	124.44
2:StdDev	103.38
NumSrv	Unconstrained
Statistics	
Res_Server_QueueLen	**Statistic**
Res_Server_Utilization	**Statistic**
Res_Server_WaitingTir	**Statistic**

Figure 6.5: Input of the statistical parameters of nonconforming indicators in the simulation project model

As seen in Table 6.11, the effect of the NIs on the output of the simulated operation can be deemed significant. Comparing the mean completion time obtained in Scenario 1 to the one obtained in Scenario 2, an increase of around 63% due to the effect of the nonconforming events was found. The obtained performance outputs could facilitate the decision to improve the PQM system. However, in order to evaluate the effect of the PQM practices on the performance outputs of the open-cut construction operation, it is necessary to simulate several different scenarios. The following section is dedicated to this analysis.

Table 6.11: Simulation outputs with and without the effect of the NIs

Scenario	Mean Completion Time (Hours)	Productivity (Meter/Hour)			Sample Number of Simulated Nonconformances	
		Min	Mean	Max		
Scenario 1: Excluding the effect of nonconforming indicators	94.56	0.16	4.23	4.92	Excavation	0
					Bedding	0
					Pipe Install	0
					Backfilling	0
Scenario 2: Including the effect of nonconforming indicators	153.94	0.02	2.60	4.25	Excavation	3
					Bedding	1
					Pipe Install	4
					Backfilling	2

6.3 Sensitivity analysis of the effect of PQM practices on the performance of the construction operations

This analysis involves the alternating of the performance maturity levels of the PQM practices being analyzed in the case study project. The different computer-based applications, whose implementation was detailed throughout Section 6.2, were used to conduct experiment with alternative inputs assumed for different scenarios. This means that every scenario was defined by a particular set of maturity levels of the PQM practices, which were alternately inputted to the simulation model in order to estimate the respective performance outputs of the operation (i.e. the completion time and the productivity). Based on the percentage of improvement on the productivity of the operation, the impact that the different scenarios would have on the performance of the operations can be evaluated. Moreover, the framework proposed in this research work assumes that such evaluation could facilitate the decision-making about the strategies that should be implemented in order to improve the PQM system being analyzed.

Nine different scenarios were formulated with a sequential and continual increase in the performance maturity level of the PQM system. This means that the maturity level of some of the PQM practices involved in the system was increased for the scenario next to a previous one. The assumed scenarios were formulated in linguistic (fuzzy) terms, as this is simpler than using crisp values (i.e. PQI values) while appropriate for the purposes of this sample application. Moreover, the formulation of the scenarios was based on the findings of the sensitivity analysis that determined the effect of PQM practices on the construction resources (see Section 6.2.1.1). For example, the upgrading of the maturity levels of the PQM practices from one scenario to the next one was determined under the premise that the PQM practices with a low, medium, and high impact were known (see Table 6.8). Table 6.12 shows primarily the input settings (i.e. the maturity levels of the PQM practices) that were assumed for each of the nine scenarios. This table also shows the statistical parameters of the NIs (i.e. the mean and standard deviation of the number of nonconformances and the duration of delays) obtained with these input settings for each of the construction activities involved in the sample systems being analyzed.

Fifty simulation runs were completed for each of the scenarios included in this analysis. Table 6.13 contains the outputs corresponding to each of the scenarios, including the estimates of the completion time and the productivity of the operation, (i.e. the open cut construction process in this case). In fact, Table 6.13 includes the mean completion time and the mean productivity that were respectively obtained after running the simulation model with the inputs assumed for each scenario. In addition, this table also includes the percentage of *productivity increase* from a given scenario to the following one. For example, the productivity increase from Scenario 1 to Scenario 2 is 10.67% because of the relation between the mean productivity in Scenario 2 and Scenario 1, i.e. 1.66 and 1.50 meter/hour respectively. Another parameter included in Table 6.13 is the *total increase of the maturity level* of the PQM practices, which results of totaling the differences between the maturity levels of the PQM practices in a given scenario and the subsequent one. As this is expressed in quantitative terms, the equivalent PQI (defuzzified) values, which correspond to each of the linguistic (fuzzy) terms evaluating these maturity levels (refer to Section 6.2.1.2), were applied in the computation. The fuzzy and crisp values representing the performance maturity level of the PQM practices assumed in the scenarios for simulation, are shown in Table 6.12. Moreover, Table 6.14 includes an example of the calculation of the total increase of maturity level for Scenario 1, based on the PQIs in Scenario 2. The purpose of getting the total increase of maturity level is to make possible the computation of a *Relative Productivity Improvement Index* (see Table 6.13) that depicts a relation between the productivity increase and the corresponding total maturity level increase. This parameter is required to make a fair evaluation of the improvement actions implemented in the different scenarios and, at that time, determine the most efficient strategies for improving the system under analysis.

Table 6.12: Settings in different scenarios formulated for the sensibility analysis

		Scenarios →	1	2	3	4	5
Performance Maturity Level of PQM Practices	Expediting	Fuzzy	No Formal	No Formal	Reactive	Reactive	Reactive
		Crisp	21%	21%	38%	38%	38%
	Supplier Qualification	Fuzzy	No Formal	No Formal	Reactive	Stable	Continual
		Crisp	21%	21%	38%	60%	76%
	Internal / External Examinations	Fuzzy	No Formal	No Formal	Reactive	Reactive	Reactive
		Crisp	21%	21%	38%	38%	38%
	Change & Communication	Fuzzy	No Formal	No Formal	No Formal	No Formal	Reactive
		Crisp	21%	21%	21%	21%	38%
	Operability & Value Review	Fuzzy	No Formal	Reactive	Reactive	Reactive	Reactive
		Crisp	21%	38%	38%	38%	38%
	Constructability Review	Fuzzy	No Formal	Reactive	Reactive	Reactive	Reactive
		Crisp	21%	38%	38%	38%	38%
	Personnel Qualification & T.	Fuzzy	No Formal	Stable	Stable	Stable	Continual
		Crisp	21%	60%	60%	60%	76%
	Risk Management	Fuzzy	No Formal	No Formal	No Formal	No Formal	Reactive
		Crisp	21%	21%	21%	21%	38%
	Safety Management	Fuzzy	No Formal	No Formal	Reactive	Stable	Continual
		Crisp	21%	21%	38%	60%	76%
Quality Level of Construction Resources	Material Supplying		Very Poor	Very Poor	Poor	Average	Good
	Design Information		Very Poor	Poor	Average	Average	Average
	Work Conditions		Very Poor	Very Poor	Very Poor	Good	Good
Statistical Parameters of the Number of Nonconformances	Excavation	Mean	3.98	3.20	3.00	2.47	2.29
		SD	0.82	1.26	1.34	1.11	1.09
	Bedding	Mean	4.00	3.09	2.79	2.22	2.00
		SD	0.79	1.30	1.30	1.11	1.06
	Pipe Installation	Mean	5.51	5.11	4.36	2.72	2.45
		SD	1.10	1.05	1.32	1.35	1.26
	Backfilling	Mean	3.83	3.75	3.28	2.22	2.00
		SD	1.13	1.11	1.37	1.11	1.06
Statistical Parameters of the Duration of Delays (minutes)	Excavation	Mean	354.23	291.55	301.82	168.84	101.51
		SD	156.07	126.76	117.50	85.58	101.69
	Bedding	Mean	354.23	326.63	258.21	251.19	185.01
		SD	156.07	147.06	115.56	114.00	82.47
	Pipe Installation	Mean	344.75	362.80	374.24	164.90	143.90
		SD	159.70	155.62	149.18	85.95	83.97
	Backfilling	Mean	344.75	361.81	301.06	164.90	143.90
		SD	159.70	154.36	119.87	85.95	83.97

Continuation of Table 6.12

		Scenarios →	6	7	8	9
Performance Maturity Level of PQM Practices	Expediting	Fuzzy	Reactive	Reactive	Stable	Continual
		Crisp	38%	38%	60%	76%
	Supplier Qualification	Fuzzy	Continual	Continual	Continual	Best-in-Class
		Crisp	76%	76%	76%	87%
	Internal / External Examinations	Fuzzy	Reactive	Reactive	Stable	Continual
		Crisp	38%	38%	60%	76%
	Change & Communication	Fuzzy	Reactive	Reactive	Stable	Stable
		Crisp	38%	38%	60%	60%
	Operability & Value Review	Fuzzy	Reactive	Reactive	Stable	Continual
		Crisp	38%	38%	60%	76%
	Constructability Review	Fuzzy	Reactive	Stable	Stable	Continual
		Crisp	38%	60%	60%	76%
	Personnel Qualification & T.	Fuzzy	Best-in-Class	Best-in-Class	Best-in-Class	Best-in-Class
		Crisp	87%	87%	87%	87%
	Risk Management	Fuzzy	Reactive	Stable	Stable	Stable
		Crisp	38%	60%	60%	60%
	Safety Management	Fuzzy	Continual	Continual	Continual	Best-in-Class
		Crisp	76%	76%	76%	87%
Quality Level of Resources	Material Supplying	Crisp Fuzzy	Good	Good	Good	Very Good
	Design Information	Crisp Fuzzy	Good	Good	Very Good	Very Good
	Work Conditions	Crisp Fuzzy	Good	Very Good	Very Good	Very Good
Statistical Parameters of the Number of Nonconformances	Excavation	Mean	2.26	1.93	1.42	1.34
		SD	1.07	0.81	1.07	1.09
	Bedding	Mean	1.48	1.45	0.95	0.91
		SD	0.50	0.50	0.78	0.81
	Pipe Installation	Mean	1.97	1.94	1.44	1.44
		SD	0.81	0.80	1.06	1.06
	Backfilling	Mean	1.48	1.46	0.94	0.89
		SD	0.50	0.50	0.78	0.85
Statistical Parameters of the Duration of Delays (minutes)	Excavation	Mean	49.55	45.57	21.43	23.11
		SD	46.80	46.00	28.75	29.20
	Bedding	Mean	185.01	176.10	161.68	83.11
		SD	82.47	84.99	87.56	29.20
	Pipe Installation	Mean	88.76	51.89	41.63	42.18
		SD	29.97	48.65	47.27	46.66
	Backfilling	Mean	88.76	87.69	56.64	53.74
		SD	29.97	29.91	46.97	51.11

Table 6.13: Analysis of simulation outputs obtained in the different scenarios

Scenarios →	1	2	3	4	5	6	7	8	9
Mean Completion Time (hours)	266.67	240.96	217.39	150.94	136.52	118.69	115.27	108.11	102.30
Mean Productivity (meter/hour)	1.50	1.66	1.84	2.65	2.93	3.37	3.47	3.70	3.91
Productivity Increase	NA	10.67%	10.84%	44.02%	10.57%	15.02%	2.06%	6.63%	5.68%
Total Increase of Maturity Level	NA	73%	68%	44%	82%	11%	44%	44%	92%
Relative Productivity Improvement	NA	0.15	0.16	1.00	0.13	1.37	0.05	0.15	0.06

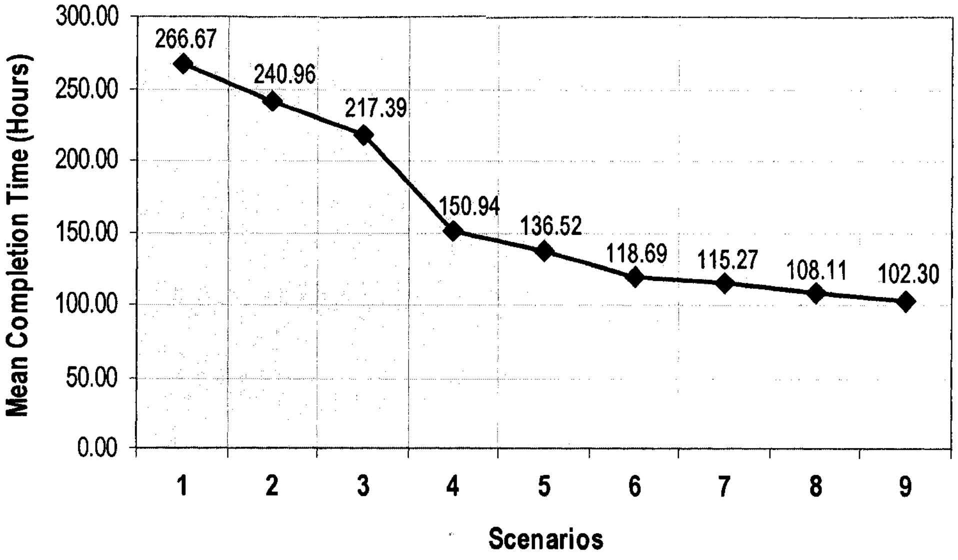


Figure 6.6: Effect of the maturity level of PQM practices on the completion time of the case study operation

Table 6.14: Example of the calculation of the total increase of maturity level

Scenarios ➔		2	3	Difference of PQIs
Expediting	Fuzzy	No Formal	Reactive	17%
	Crisp	21%	38%	
Supplier Qualification	Fuzzy	No Formal	Reactive	17%
	Crisp	21%	38%	
Internal / External Examinations	Fuzzy	No Formal	Reactive	17%
	Crisp	21%	38%	
Change & Communication	Fuzzy	No Formal	No Formal	0%
	Crisp	21%	21%	
Operability & Value Review	Fuzzy	Reactive	Reactive	0%
	Crisp	38%	38%	
Constructability Review	Fuzzy	Reactive	Reactive	0%
	Crisp	38%	38%	
Personnel Management	Fuzzy	Stable	Stable	0%
	Crisp	60%	60%	
Risk Management	Fuzzy	No Formal	No Formal	0%
	Crisp	21%	21%	
Safety Management	Fuzzy	No Formal	Reactive	17%
	Crisp	21%	38%	
Total Increase of Maturity Level ➔				**68%**

In addition, Table 6.15 includes a description of each of the scenarios assumed for this analysis, as well as comments on the outputs obtained with them. The outputs of the analysis exposed the effect that the performance maturity of the PQM system has on the performance of the construction operation. Figure 6.6 shows the variation of the completion time throughout the different simulated scenarios. In this case, this variation revealed a steady increase of the operation's performance explained by the continuous improvement actions assumed with the different scenarios. In general, this confirmed that the higher the performance maturity of the PQM system, the better the performance of the construction operations. Therefore, this also verified the consistency of the membership functions and inference rules involved in the system analyzed in this case study. However, because of the lack of actual data regarding the measuring of the effect of PQM practices on the performance of construction operations, the validation of the outputs was reduced to the scrutiny of the managers involved in this case study. In this case, the quality manager in the study organization agreed with the variation observed in the completion time of the construction operation, (see Figure 6.6), due to the effect of the maturity level of the PQM practices. According to him, the difference between the performance improvement rate observed from the *No Formal* to the *Formal Stable* maturity levels, (see scenarios 1 to 4 in Figure 6.6), and from the *Formal Stable* to the *Best-in-class* maturity levels, (see scenarios 4 to 9 in Figure 6.6), confirmed the sense of the outputs obtained with this analysis. This is related to the consideration of the managers in the study organization that the highest performance improvements are achieved during the early stages of the performance improvement process.

It is important to highlight that although the analysis of these scenarios was intended for verifying the sensitivity of construction performance operations to the effect of the maturity level of the PQM practices, the proposed modelling approach is intended to make possible the experimentation of different strategies for supporting the decision-making regarding the implementation of PQM practices. For example, based on the analysis of the scenarios in Figure 6.13, the decision makers would be able to recognize that the implementation of Scenario 7 (see Table 6.13) is worthless, as the relative productivity improvement index is small, and, then, other alternatives should be evaluated. Therefore, this sensitivity analysis demonstrated that the proposed modelling approach could actually facilitate the evaluation of the effect of a PQM system on the performance of a construction operation and the determination of the most appropriate improvement actions on the PQM processes to increase the quality performance of projects.

Table 6.15: Description of the scenarios assumed for the analysis

Scenario	Description (refer to Tables 6.12 and 6.13)
1	The first scenario was intended to be the one with the lowest quality performance and, with this aim, the maturity levels of the PQM practices were all set as *No Formal Approach.* A mean completion time of 266.67 hours and a mean productivity of 1.50 meters/hour were achieved under the conditions formulated for this scenario. These initial estimates provided a reference to evaluate the outputs of the subsequent scenarios.
2	The improvement of the Design Information was pursued with the upgrading of the practices specifically affecting this resource. The practices with a medium impact on Design were upgraded to *Reactive Approach* and the one with a high impact (i.e. the Personnel Qualification and Training) to *Stable Formal System.* Note that with this action the quality of Design Information barely reached the *poor* state, which resulted in a productivity increase of 10.67% with regard to Scenario 1.
3	The Scenario 2 was upgraded by increasing to *Reactive Approach* the maturity level of the practices with a medium and high impact on the resources. Note that these upgrades were still not enough to move the Work Conditions resource from the *very poor* state. This resulted in a productivity increase of 10.67%, which can be deemed an average achievement.
4	The three PQM practices with a high impact on the resources were set to *Stable Formal System,* while the maturity levels of the others practices remained unchanged with regard to Scenario 3. This simple upgrade had a significant positive effect on the productivity of the operation as an increase of 44% with regard to the one obtained in Scenario 3 was achieved.
5	Taking into account the positive effects of the upgrade assumed in Scenario 4, the same three practices with a high impact on the resources were set wit a *Continual Improvement Emphasized Approach*, while all the other practices were maintained with a *Reactive Approach* maturity level. However, the effect on the performance of the operation was not quite significant this time: a regular productivity increase of 10.57% was obtained now. This is explained by the fact that only the improvement of the quality level of the Material Supplying resource was attained with this upgrade. This may also mean that in this case the experts, involved in the development of this analysis system, considered that the most significant effects on the performance of the operation should be observed during the early stages of the improvement process.
6	Only the Personnel Qualification & Training practice, which was identified as a key practice within the PQM system, was upgraded to *Best-in-class Performance*, while the others were maintained the maturity levels assumed in Scenario 5. This simple action had a relatively significant effect on the productivity of the operation as an increase of 15.02% was achieved with only 11% of total maturity level increase. In fact, note that the relative productivity improvement index is the highest among all the scenarios simulated in this analysis.

Continuation of Table 6.15.

Scenario	Description (refer to Tables 6.12 and 6.13)
7	The improvement of the quality level of the Work Conditions resource was pursued in this scenario. In order to achieve this, the maturity level of the Constructability Review and the Risk Management practices were upgraded to *Stable Formal System*. Although the Work Conditions reached the *very good* quality level, only a meager productivity improvement (2.06% with respect to Scenario 6) was achieved. Moreover, note that the relative productivity improvement index estimated in this scenario is the lowest among all the scenarios simulated in this analysis.
8	The practices with a low and medium impact on the resources were set as *Stable Formal System*, while the practices with a high impact were maintained with the same maturity levels assumed in Scenario 7. Although this resulted in a mediocre productivity increase, it should be noted that the relative productivity improvement index is not as low as in Scenario 7. This could be an indication of the worthiness of implementing this scenario, due to its efficiency for improving the productivity.
9	The practices with a low impact on the resources remained with their *Stable Formal System* maturity level; the practices with a medium impact were all set at the *Continual Improvement Emphasized Approach* level; and the practices with a high impact were set at the *Best-in-class Performance* level. This allowed all the construction resources to attain the *very good* quality level, which resulted in a mediocre productivity improvement (5.68%) despite the fact that the effort to increase the maturity level was the highest (92%) among all the scenarios evaluated in this analysis. This can be recognized with the low relative productivity improvement index (0.06) resulting from this relation. Therefore, this fact may suggest that at some point within the improvement process of the PQM system, a maturity level will be reached in which limited improvement of the productivity would be achieved. This simulation-aided approach would facilitate the identification of such point within the quality improvement process. As no more improvements of the quality level of resources would be achieved with further upgrades to the maturity level of the PQM practices, this was the last scenario evaluated in this analysis.

6.4 Summary and conclusions

This chapter verified the applicability of the proposed modelling approach of evaluating the effect of a PQM system on the performance of construction operations. With that purpose, the application of the computer-based modelling techniques, whose use was projected as part of the modelling approach, was illustrated through their implementation in the analysis of a case study operation. These computer-based applications included:

1. A fuzzy expert system that inferred, based on the PQIs of the PQM practices involved in the system being evaluated, the quality level of the construction resources involved in the open-cut construction operation being analyzed.
2. A fuzzy logic-based procedure to estimate, based on the quality level of the resources involved in the undertaking of the open-cut construction operation, the statistical parameters of the NIs, i.e. the number of nonconformities and the duration of delays due to the occurrence of nonconformity events. These parameters were estimated for each of the activities included in the operation.
3. A discrete-event simulation project model that estimated the effect of alternative performance maturity levels of the PQM system on the completion time and the productivity of the case study operation. Such effects were modelled with the statistical parameters of the NIs as inputs to the simulation project model.

Although it was not within the scope of this research work, it should be admitted that the integration of these computer-based applications into a computer system with a user-friendly interface would have further facilitated the implementation of the evaluation framework. Future work should consider the integration of the components included in this simulation modelling approach. However, the interaction of the aforementioned computer-based applications permitted the accomplishment of two sensitivity analyses that would be required to evaluate the effect of a PQM system on the performance of construction operations, including:

1. A sensitivity analysis of the effect of the performance maturity level of PQM practices on the performance quality level of construction resources. This analysis identified the significance of the effect of each specific PQM practice on the quality of construction

resources, as low, medium, or high. This determined what improvement actions on the PQM system should be prioritized in order to make efficient the quality performance increase of the resources.

2. A sensitivity analysis of the effect of the performance maturity level of PQM practices on the performance outcomes of the construction operations. This analysis determined the most appropriate improvement strategies that would produce a significant increase of the performance outcomes of construction operations.

In addition, the application of the modelling approach in this chapter demonstrated its applicability in evaluating the effect of a PQM system on the performance of construction operations. However, it should also be acknowledged that the application of this modelling approach is limited to the evaluation of the effect of the management initiatives on the performance of construction operations, while the inclusion of other factors affecting the performance was not within the scope of this research work. Therefore, the estimates obtained through its application are not intended for estimating purposes but for supporting decision-making concerning the performance improvement process in project organizations. Nevertheless, further research work could incorporate this approach in simulation models integrating the effect of diverse factors on the performance of construction operations, for estimating purposes.

CHAPTER 7
SUMMARY AND CONCLUSIONS

7.1 Summary of research results

This report has presented the development of a Project Quality Management Assessment Framework (PQMAF) for the evaluation of the effect of project quality management (PQM) on the performance of construction operations. For the development of the framework it was assumed that the performance maturity of PQM practices affects the quality performance of the construction resources, which eventually may cause nonconforming events that will affect the performance of construction operations. This framework includes a modelling approach that integrates tacit and explicit knowledge and experience that construction organizations have, along with existing analysis modelling techniques, such as fuzzy logic and discrete-event simulation. The intention of the proposed framework is to support managers on the assessment of project uncertainties and interactions involved in the quality management systems (QMS) implemented in construction organizations to deal with the quality performance of projects. Specifically, the modelling approach proposed within the PQMAF pursues the generation of simulation models that are capable of estimating the effect of PQM practices on the performance of construction operations. The performance parameters that this modelling approach suggests for the evaluation of such effects are the completion time and the productivity of the operations being analyzed. The estimates obtained through this simulation modelling approach are intended to support decision-making concerning the improvements that the PQM system requires in order to increase the performance of projects. Elements of the methodology developed in this research work are summarized as follows:

Successes and limitations in prior quality performance modelling efforts, described in Chapter 2, inspired some of the concepts incorporated into the proposed modelling approach. The modelling of quality and performance management systems in construction organizations, the identification of factors involved in such systems, the interactions among them, and their measurement were some of these concepts. Chapter 3 described how existing modelling techniques could be integrated into a simulation modelling approach to estimate the effect of the performance of PQM factors on the performance of specific construction operations. Moreover, Chapter 4 clarifies how simulation models of that kind can be developed and applied within the PQMAF in order to make decisions concerning the improvement actions that should be implemented in the PQM system in order to increase the performance of construction operations. This involved a process that was integrated as two main components of the PQMAF:

1. The Project Nonconformance Assessment Approach (PNAA), which provides the information and knowledge that is needed for developing the membership functions and inference rules of the fuzzy logic-based analysis models comprised within the proposed modelling approach. Intended for such a purpose, the PNAA takes advantage of the nonconformance records that ISO 9001 certified organizations are required to document, along with a disaggregated approach to elicit the required knowledge through two independent modules:

   i) The specific-PQM-system knowledge elicitation module (SPQMSKE), which should provide the knowledge-based assessments required to develop a fuzzy expert system intended for inferring the quality level of the main construction resources involved in the operation under analysis.

ii) The specific-operation knowledge elicitation module (SOKE), which should provide the knowledge-based assessments required to develop the fuzzy logic-based analysis systems that estimate, based on the quality level of the construction resources, the statistical parameters of two nonconforming indicators: (a) the number of nonconformities and (b) the duration of delays, for each of the construction activities under analysis.

The implementation of the PNAA was detailed in Chapter 5.

2. The Interactive-Computer-based System (ICBS), which focuses on the development and implementation of the computer-based applications that will interactively compute the performance outcomes (i.e. the completion time and productivity) of the construction operations that are affected by the performance of the PQM practices implemented for dealing with the quality of projects. These computer-based applications included:

i) A fuzzy expert system (FES) to infer, based on the maturity level of each of the PQM practices involved in the system being evaluated, the quality level of the construction resources involved in the construction operation being analyzed. The Process Quality Indexes (PQIs) are meant to represent objectively the performance maturity level of the PQM practices and are the crisp inputs that are required to perform the aforementioned inference with the FES.

ii) A fuzzy logic-based procedure to estimate, based on the quality level of the resources involved in the undertaking of the operation being analyzed, the statistical parameters of the nonconforming indicators, i.e. the number of nonconformities and the duration of delays due to the occurrence of nonconformity events. These indicators represent the consequences of the performance level of PQM practices on the performance outcomes of a construction activity and, therefore, their statistical parameters should be estimated for each of the activities included in the operation.

iii) A discrete-event simulation project model to estimate the effect of alternative performance maturity levels of PQM practices on the performance parameters of the operation being analyzed. Such an effect is modelled with the aforementioned statistical parameters as the inputs to the simulation project model. On the other hand, the completion time and the productivity are suggested as appropriate performance parameters to evaluate this effect.

The implementation of the ICBS was illustrated in Chapter 6 using an open-cut construction project as sample case. In addition, the interaction of the aforementioned computer-based applications permitted the accomplishment of two sensitivity analyses that would accomplish the evaluation of the effect of a PQM system on the performance of construction operations, including:

1. A sensitivity analysis of the effect of the performance maturity level of PQM practices on the performance quality level of construction resources. This analysis identified the significance of the effect of each specific PQM practice on the quality of construction resources, as low, medium, or high. This determined what improvement actions on the PQM system should be prioritized in order to make efficient the quality performance increase of the construction resources.

2. A sensitivity analysis of the effect of performance maturity level of PQM practices on the performance outcomes of the construction operations. This analysis determined the most appropriate improvement strategies that would produce a significant increase of the performance outcomes of construction operations.

These sensitivity analyses demonstrated the applicability of the modelling approach proposed in this research work for evaluating the effect of a PQM system on the performance of a construction operation and determining the most appropriate improvement actions on the PQM processes to increase the quality performance of projects.

7.2 Research contributions

The outcome of this research project provides contributions in several areas. At a global level, this research work has developed a unique methodology for modelling project quality performance integrating construction knowledge and experience along with existing simulation modelling techniques, and a powerful analysis structure. The following are significant aspects of the contributions:

1. A methodology to evaluate the effect of project quality management on the performance of construction operations in order to support decision-making concerning the improvements that PQM systems required for increasing the performance of projects. It combines basic quality performance-related records with knowledge-based assessments elicited from the project team. The knowledge-based assessments are organized in a causal model structure for analyzing construction operation

performance, where the identification of the factors included in the PQM system to be evaluated is based on nonconformance records. Some of the features as quality performance evaluation methodology include the following:

- It has predictive capabilities to help in establishing performance improvement targets.
- It incorporates risks and uncertainties, which are involved in the factors affecting the quality performance of construction projects, in the analysis.
- It allows a more comprehensive quality performance evaluation than the currently available methods, which are usually limited to the analysis of rework.
- It allows the relative comparison of the effects of alternative management actions on the performance of the project operations.
- It allows the evaluation of the effects on project operation performance of two or more quality management initiatives interacting simultaneously.
- It provides sensitivity capabilities to identify the most significant quality drivers (i.e. project management processes and operation resources) for operation performance.
- It provides productivity outputs as well as explanatory capabilities through the model causal structure. This can help managers to obtain a better understanding of quality-related factors that affect project performance, to identify opportunities for improvement, and take effective actions.

In addition, this research also confirmed the cognitive value of the methodology as a problem solving process. The proposed modelling framework provides a systematic and structured process for a project team discussion on relevant quality-related planning issues in a project. The methodology would encourage project team planning, goal setting, and commitment to project goals.

2. Extensions to simulation modeling: The approach to simulation modelling proposed in this research is characterized by an innovative use and integration of existing modelling techniques. A number of adaptations and extensions to previous analysis models were carried out, including the following:

   - Development of a procedure to generate fuzzy expert systems based on empirical information contained in basic quality-related records that ISO 9001 certified organizations are required to document.
   - Application of the fuzzy logic-based assessment method developed by Ayyub and Eldukair [1989] to estimate the effect of factors associated with random, human-based, or system uncertainty on the performance of construction operations. In this case, the method was adapted to estimate the effects of the quality level of construction resources on quality performance of construction activities.
   - Adaptation of an algorithm to perform probabilistic inference that integrates probabilistic information obtained from the fuzzy logic-based models. The proposed algorithm provides performance estimates that allow the evaluation of the simultaneous effect of multiple PQM factors on the performance of construction operations.
   - Adaptation of knowledge elicitation tools to facilitate the assessment of variables representing the performance and effect of PQM factors.

3. The planned computer implementation of this methodology can have substantial benefits. The prototype version developed for this report has allowed the testing of the algorithms and has demonstrated the capabilities of the modelling approach for the evaluation of quality management systems in projects. Some benefits expected from its implementation are:
   - Formalization and facilitation of the analysis effort concerning the improvement of quality performance in projects: The analysis capabilities will be comparable with a costly and lengthy decision analysis, but at a fraction of the effort and cost.
   - Project-based organizations should find this methodology interesting for the inexpensive exploration of project management strategies. Many decisions not worthy of more systematic analysis may be better evaluated and understood, improving the effectiveness of management decisions.
   - It may open doors to innovation by providing a tool to systematically evaluate new and untried project management strategies.
4. The proposed framework provides a modelling approach for capturing and formalizing construction experts' knowledge and integrating empirical information taken from basic nonconformance reports. A systematic methodology for knowledge acquisition in the modelling process supports one of the major difficulties found in practice for the development of this type of model. The knowledge is stored in modules that are self-contained and independent. Some of the features resulting from the above system are:
   - It facilitates isolation and captures expertise. Each expert can contribute with his/her own expertise in a specific area.

- It automatically introduces causal relationships that describe the interactions among project quality management variables.
- It can be easily updated without altering the model structure.

5. As a research tool, this methodology is an attempt to rigorously analyze the basis of project quality performance in such a way that that prediction and causal analysis can be assessed in the same structure. The exploration of project quality management strategies can provide information on the mechanisms, interactions, and the most effective ways of achieving improved performance. The availability of this methodology offers new approaches to the study of quality failures, supports the exploration of fundamental questions in construction project performance, and facilitates the detection of new research areas. The following are some of the model features as a research tool:

- The model can use subjective and historical information.
- The representation scheme provides an important aid for the identification of the factors involved in a decision, facilitating communication and discussion with industrial experts.
- It does not assume that either the model itself or the parameters are constant. The flexibility of the modelling approach provides mechanisms for incorporating feedback in a way that supports continuous improvement in the quality of both the data and model structure.
- New factors can be easily incorporated into the model structure.

Furthermore, the concepts applied can be extended beyond the specific problem addressed in this research work.

7.3 Research extension and testing of the PQMAF

Additional research and testing of the modelling approach could lead to the improvement of the proposed assessment framework. Ideally, construction organizations could adopt this model, so that the model data structure becomes a standard for information gathering. Several benefits could be obtained from using the model as part of a monitoring and feedback process. Some examples are discussed in the following paragraphs.

Feedback obtained on modifications to the *Specific Project Quality Management Knowledge* could lead to the design of specialized knowledge bases categorized by project type, project size, construction method, industries, companies, or other parameters that may reflect differences in the system to be analyzed and/or the experts' assessments. On the other hand, improvements to the *Specific Operation Knowledge* should focus on the reduction of bias in the assessment process and on the capture of true expertise in each specific area. The knowledge base included in this report represents the experience of members of the organization that served as case study for the purposes of this research and may need to be reviewed in particular cases.

Further research on issues concerning the development of the fuzzy logic models, such as the generation of membership functions and inference rules could be valuable extensions. For instance, the generation of membership functions and inference rules based on the expertise of several other organizations would permit obtaining more unbiased assessments that would help to improve the accuracy in the predictions, without adding complexity to the model information requirements.

The estimates obtained with the proposed modelling approach are intended to be used only for supporting decision making concerning quality performance improvement. However, this modelling approach could be integrated within other models dealing with the estimation of the effect of further different factors, such as weather conditions. This would permit the obtaining of more accurate estimates that could be used for project programming purposes.

Furthermore, cost-benefit analyses of the implementation of project management initiatives could be carried out if the modelling approach is formulated for evaluating the effect of such initiatives on the cost of the operation being analyzed. The quality of the contractors' management can be evaluated with this modelling approach for benchmarking and selection purposes. In addition, although the model presented in this research is especially designed to evaluate project quality performance, several management decision areas could directly use the model structure. In general, systems that share the same structure of drivers are good candidates for being analyzed with this model. If an equivalent conceptual model structure, consisting of management processes, operational resources, and operation performance outcomes, accommodates well the problem under study, it is possible to use the methodology without major modifications.

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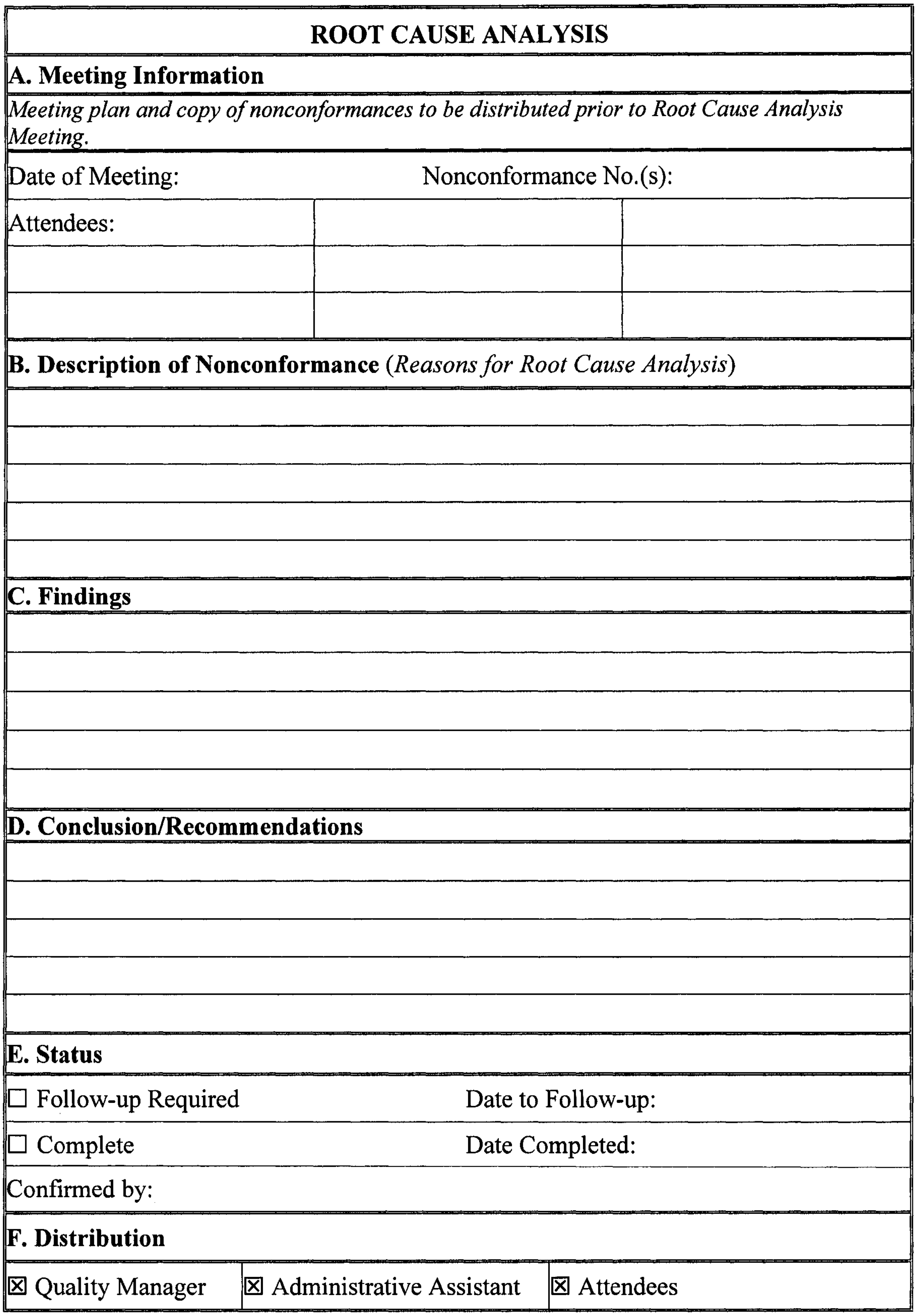
APPENDIX A

REPORT FORMS FOR TRACKING NONCONFORMITIES IN D&C ORGANIZATION

NONCONFORMANCE REPORT	
A. Description	Nonconformance No.:
Project No.:	Location No.:
Address:	Originator:
Customer:	Phone No.:
Nonconformance Description: (*use back space if necessary*)	
Completed by:	Date:
B. Disposition	
☐ Remedial processing to correct prior to delivery ☐ Use as with agreement from the customer ☐ Rework to meet specified requirements	☐ Rework to meet modified requirements ☐ Return for credit or replacement ☐ Reject
Comments: (*use back space if necessary*)	
☐ Perform Root Cause Analysis	
Immediate Supervisor:	Date:
C. Disposition Completed	
Immediate Supervisor:	Date:
Confirmed by General Supervisor:	Date:
D. Distribution	

☒ Originator	☒ Quality Manager	☒ Area Nonconformance File	
☐ Customer	☐ Warehouse Administrator	☐ Vendor	Other:

Figure A.1: Nonconformance Report form originally used by case study organization



ROOT CAUSE ANALYSIS

A. Meeting Information

Meeting plan and copy of nonconformances to be distributed prior to Root Cause Analysis Meeting.

Date of Meeting: Nonconformance No.(s):

Attendees:		

B. Description of Nonconformance (*Reasons for Root Cause Analysis*)

C. Findings

D. Conclusion/Recommendations

E. Status

☐ Follow-up Required Date to Follow-up:

☐ Complete Date Completed:

Confirmed by:

F. Distribution

☒ Quality Manager ☒ Administrative Assistant ☒ Attendees

Figure A.2: Root Cause Analysis form originally used by case study organization

NONCONFORMANCE REPORT

A. Description	Nonconformance No.:
Project No.:	Location No.:
Address:	Originator:
Customer:	Phone No.:

Nonconformance Description: (*use back space if necessary*)

Construction Activity affected by Nonconformance:

B. Estimate of the Effects of Nonconformance

Duration of Disruptions		
Interruptions	Low Productivity Periods	Reworks
Hours/Days	Hours/Days	Hours/Days
Hours/Days	Hours/Days	Hours/Days

Cost of Wasted Resources (Material, Labor, Equipment, and Overhead)

Description of Wasted Resource	Quantity	Unit	$/Unit	Subtotal
			Total Cost:	

Completed by:	Date:

C. Disposition

☐ Remedial processing to correct prior to delivery	☐ Rework to meet modified requirements
☐ Use as with agreement from the customer	☐ Return for credit or replacement
☐ Rework to meet specified requirements	☐ Reject

Comments: (*use back space if necessary*)

☐ Perform Root Cause Analysis

Immediate Supervisor:	Date:

D. Disposition Completed

Immediate Supervisor:	Date:
Confirmed by General Supervisor:	Date:

E. Distribution

☒ Originator	☒ Quality Manager	☒ Area Nonconformance File	
☐ Customer	☐ Warehouse Administrator	☐ Vendor	Other:

Figure A.3: Improved Nonconformance Report

ROOT CAUSE ANALYSIS

A. Meeting Information

Meeting plan and copy of nonconformances to be distributed prior to Root Cause Analysis Meeting.

Date of Meeting: Nonconformance No.(s):

Attendees:		

B. Description of Nonconformance (*Use back space if necessary*)

Construction Activity affected by Nonconformance:

C. Findings

D. Conclusion/Recommendations

E. Status

☐ Follow-up Required Date to Follow-up:

☐ Complete Date Completed:

Confirmed by:

F. Identification of Causes of Nonconformities

Construction Resources

Cause 1	Cause 2	Cause 3 (Root Cause)

Project Management Processes/Practices Affecting the Performance of Resources

1st	PQI:	1st	PQI:	1st	PQI:
2nd	PQI:	2nd	PQI:	2nd	PQI:

Completed by: Date:

E. Distribution

☒ Quality Manager ☒ Administrative Assistant ☒ Attendees

Figure A.4: Improved Root Cause Analysis

Table A.1: Approaches to report consequence indicators of nonconformances

Indicator	Identification on work site	Reporting approach
Disruptions (Delays)	• Interruptions	Number of work hours, days, or weeks a given activity was temporarily discontinued
	• Low Productivity Periods	– Number of work hours, days, or weeks during which a given activity was observed to progress at a slower pace than in the average workdays – Estimate of the productivity rates that prevailed during such low productivity periods in order to work out the total delay time of the activity
	• Reworks	Number of work hours, days, or weeks that were dedicated to the rework
Over Costs	• Material Waste	Quantity (e.g. pieces, volume, weight) of each type of material that have been detected as wasted due to a nonconforming event, so that it is possible to calculate the following for each type of material: *Material over cost* = Quantity of material wasted × Unit price of material
	• Labor Waste	Number of extra man-hours of each job position needed to compensate for the work time misplaced in the nonconformance, so that it is possible to calculate the following for each type of job position: *Labor over cost* = Total number of extra man-hours × $/man-hour
	• Equipment Waste	Number of extra hours that each equipment was required in the performance of the activity, due to delays caused by the occurrence of nonconformances. Thus, for each equipment it is possible to calculate: *Equipment over cost* = Total number of extra hours × $/hour
	• Overhead Waste	Number of work hours the activity was delayed due to the occurrence of a nonconforming event; thus it is possible to calculate: *Overhead over cost* = Total delay hours × $/hour

APPENDIX B

DEFINITIONS OF THE CONSTRUCTION RESOURCES AND PROJECT QUALITY PRACTICES EMPLOYED IN CONSTRUCTION OPERATIONS CARRIED OUT BY THE D&C ORGANIZATION

Table B.1: Definitions of construction resources and cause analysis guides

1 Information	Refers to all procedures, plans, drawings, specifications, standards, reports, and any other document relevant to the project and its respective activities. In order to assure the activities and operations are developed as planed and as required by the project specifications, information should be available and delivered to the all personnel at different levels in the organization taking part in the development of the project. **Cause Analysis**: Information is delivered through different organizational levels by several sources taking part in the project organization such as the scheduling staff, estimating staff, drafting staff, external and internal suppliers, survey staff, different levels of supervision and others entities taking part in the project organization. Thus, information should be considered as a second or third level driver, which means that the information source should be identified as the root driver causing information issues. However, Information could be considered as a first level driver when the information source is not well identified or irrelevant to the project organization. **Quality of Information** is defined by its availability, accuracy, completeness, appropriateness, on-time delivery, and any other characteristic that assess the usefulness of the information delivered to the person that requires it to perform the assigned job. Quality of information may affect the performance goals at the operation level.
2 Design/ Drafting	Design and drafting refers to the activities that are undertaken by project managers and drafting staff to issue the plans, specifications, drawings, and other construction documents that define the scope of the work to be performed during the construction phase of the project. A project design team is responsible for executing the design phase from initial development to completion of the design. These staff's responsibilities are significant within the performance of work, as they are suppliers of information needed for the development of projects. **Cause Analysis**: Design or drafting activities should be considered as first level drivers when any action from drafting staff originates a nonconformance or deviation in the achievement of performance goals at the operation level. Design/Drafting can also be classified as a second or third level driver when another known driver makes the design/drafting staff generate the nonconformance (e.g. the information provided by the customer to develop the design). **Quality of Design**: The constructability of the engineering design defines, primarily, the quality of project design. Constructability of a project refers not only to the adequacy of information on plans and in specifications to construct the project, but also to other aspects that can affect the job, such as site restrictions, economics of the proposed construction, availability of materials, construction equipment requirements, local work force availability, and environmental considerations. Thus, the accuracy, appropriateness, and on-time delivery of information contained in the respective drawings are important factors to consider in the assessment of the quality of project design and drafting. It is important to notice that serviceability is not considered, for the purpose of this study, a characteristic of the quality of design, as only those factors affecting the performance of the work are intended to be assessed. The following activities listed here may determine the quality of design: • Design requirement verification • Design validation • Constructability review • Design checks • Specification review • Design review: Bases and assumptions / Calculations • Drafting control: Review / Release • Change control: Design / Specifications / Drawings • Documentation control: Drawings / Engineering records / Job history • Standard documentation preparation: Design methods / Specifications Two types of design deviations should be avoided: design errors are the result of mistakes or errors made in the project design; design omissions result when a necessary item or component is omitted from the design. The quality of design and drafting may affect the performance goals at the operation level.

3	Construction/ Equipment Workmanship (Labor Crew)	Workmanship refers to the supplying and performance of two different groups of personnel: (1) workers assigned to construction operations of projects and (2) workers to operating the equipment or performing at the shops (i.e. mechanical, electrical, and fabrication shops). In this case, it is important to identify the driver as Construction Workmanship or as Equipment Workmanship for root cause analysis purposes. Construction workmanship includes pipemen, open-cut laborers, tunnel laborers, carpenters, welders, asphalt/concrete cutters, pressure testers, hoist operators, and mole operators. Equipment Workmanship includes electricians, welders, mechanics, yard laborers, yard equipment operators, repairmen, carpenters, equipment operators, yard equipment operators, truck drivers, yardmen, and yard truck drivers. Work performed by workmanship depends on instructions usually provided by foremen, senior foremen, and general supervisors. **Cause Analysis**: as personnel at the lower levels in the project organization receiving work instructions from and being supervised by supervision staff, it can be expected workmanship is usually classified as a second, third, or even lower level driver. However, the nonconformance should be carefully evaluated to determine that actually the workmanship is not the originator of any performance deviation. For example, not following work instructions given by the supervisor, absenteeism, late arrivals, strikes, and other eventualities, are some of the cases when workers should be considered as originators of nonconformances. **Quality of Workmanship** is primarily defined by the skill and training level, motivation level, team-work potential, as well as any other dimension that determine the performance and behavior of the crew members. These dimensions may determine a list of aptitudes and attitudes of workers that *may affect the expected quality and productivity of the operations, such as:* Productivity Educational Achievement Safety Reliability Initial Skills Honesty Work Ethic Trainability Attendance Friendly Possess Company Spirit Cooperative Enthusiastic Product Quality (Source: Quality of Labor Survey, July 1997 by Southeastern Illinois Regional Planning & Development Commission in cooperation with Central Illinois Public Service Company)
4	Material & Equipment Supplying from Vendors	Refers to the provision, by vendors and manufacturers, of material and equipment required to perform *construction and other field operations (e.g. operations for open-cut and tunnel* construction), or supportive work required for such operations (e.g. fabrication, electrical and mechanical work, equipment maintenance). Materials fabricated for a special design coming from an external supplier should be considered as well. However, supplying of material for technical and administrative work should not be included within this driver category, neither the supplying of construction, technical, or consultancy services as these are considered as contractor deliveries. **Cause Analysis**: Vendor organizations usually generate nonconformances as first level drivers due to a variety of causes such as the supply of poor quality or out of specification products, delivery of wrong orders, missing or wrong information, and the delay of product delivery, among others. Vendors should also be considered as first level drivers when they intermediate the supply of products between the manufacturer and the D&C organization. However, external suppliers should be considered as second or third level drivers if they were prompted to be part of a nonconformance by other drivers such as receiving a wrong requisition from any D&C purchaser (e.g. estimating staff, stores staff, and others). **Quality of Supplying** is defined as the capability of vendors to supply material and equipment on the time, in the accurate amount, and with the specified quality and characteristics established in the purchase order. In this case, it is assumed the purchase order conformances to the time, amount, and quality of material or equipment required for the appropriate performance of the work.

5 In-House Supplying & Logistic	Refers to the supplying of material and equipment from any warehouse administered by the D&C organization to any construction site or shop where work is to be performed. Such provision, carried out by the stores staff and the dispatch staff, includes the purchasing, handling, storage, inspection, and issue of material. Though, the Central Store into the scope of the D&C organization, the supplying and any other supportive work from them should be considered within this driver category. However, the supplying of material for technical and administrative work from these stores should not be included. **Cause Analysis**: In one hand, internal stores could be the origin of nonconformances (first level driver) due to a variety of causes such as not following inspection procedures, issue of wrong purchase orders, issue of wrong or missing information, and the delay of material delivery, among others. And in the other hand, they should be considered as second or third level drivers if they were prompted to be part of a nonconformance due to other drivers such as vendors, estimating and scheduling staff, supervisors, and others. **Quality of Internal Supplying** is defined as the capability of internal stores to supply material and equipment on the time, in the accurate amount, and with the specified quality and characteristics required for the appropriate performance of the work.
6 Subcontractor Services	Refers to the provision of technical, operational, and managerial services required for the development of a project. Any individual or organization, external to the D&C organization, who furnishes services in accordance with a procurement document, is in this study termed as a contractor and may include any of the following: subcontractors, fabricators, consultants and their sub-tier levels. Contracted services may include the full or partial provision of construction works, fabrication, external consultancies, utility supplying, surveying and stacking, and others relevant services for the development of the project. However, it is important to notice the supplying of material and equipment are not considered within this driver category as they should be classified as external or internal supplying. **Cause Analysis**: external contractors are usually generate nonconformances as first level drivers due to a variety of causes such as the supply of poor quality or out of specification services, delivery of wrong information, delays on service delivery, failing to complete the work contracted, not fulfilling safety and environmental requirements, and any other condition adverse to the conformance of requirements established in the contract. Contractors should also be considered as first level drivers when they intermediate the supply of services between other sub-contractors and the D&C organization. However, they should be considered as second or third level drivers if they were prompted to be part of a nonconformance by other drivers such as receiving wrong instructions or information from any D&C manager, technician, or supervisor (e.g. project managers, engineers, inspectors, foremen, and others). **Quality of Contractor Servicing** is defined as the fulfillment of requirements regarding the quality, time, cost, safety, environmental conditions, and other performance goals established for the service in the contract or agreement held with the D&C organization.

7 Construction/ Equipment Supervision	Supervision refers to the job performed by construction and equipment supervisors who are responsible for continuous supervision, coordination, and completion of the planned activities or operations performed at the construction site or at the shops (i.e. mechanical, electrical, and fabrication shops). Construction Supervision is executed at different levels in the organization and includes the following staff: general supervisors, senior foremen and foremen for open-cut and tunnel construction; meanwhile the Equipment Supervision includes the equipment general supervisor, equipment foreman, shop foreman, electrical foreman, equipment support foreman, yard foremen, and the heavy equipment foreman. In this case, it is important to identify the driver as Construction Supervision or as Equipment Supervision for root cause analysis purposes. It is important to highlight only supervision directly committed to the undertaking of operational activities should be categorized in this driver, which means administrative and technical supervisors should not as they are considered part of other technical and administrative drivers (e.g. design, estimating, etc) **Cause Analysis**: Several faults may apply to consider supervision as first level drivers, specially when: (1) failing to supply appropriate work instructions to personnel at lower levels or information to lower or higher levels, (2) issuing wrong requisitions or purchase orders for materials or equipment to be supplied, (3) failing to perform appropriate inspection of work, (4) not following the procedures under its responsibility, and any other action generating a nonconformance or performance affection to the work being performed. Nevertheless, if the supervision receives wrong instructions or information they may cause the nonconformance as a second or third level driver. **Quality of Supervision** is defined based on the accuracy, appropriateness, and opportunity of the instructions and information supplied to lower and higher levels in the project organization.
8 Estimating / Scheduling	This driver refers to the performance of all tasks under the responsibility of the estimating staff and/or the scheduler, which primarily includes preparing the project estimates and preparing and maintaining the project schedules respectively. These staff's responsibilities are significant within the performance of work, as they are suppliers of information needed for the development of projects. It should be specially noticed that as the estimating staff is authorized to submit purchasing orders, could be a potential generator of nonconformances regarding the supplying of materials, equipment, or services. **Cause Analysis**: Estimating and/or scheduling, as suppliers of important information for the appropriate performance of the project activities, could be first level drivers of non-conformances if missing or wrong information or instructions lay on the performance of any estimating or scheduling staff, or if any procedure under such staff responsibility are not followed appropriately. This includes the administration of purchasing documents. In the cases they receive wrong information or miss any information from other drivers (e.g. from the customer organization, design/drafting section, project management), they may cause the nonconformance as a second or higher level driver. **Quality of Estimating/Scheduling** is defined based on the accuracy, appropriateness, and opportunity of the cost/time-related information supplied to lower and higher levels in the project organization.
9 Equipment	Refers to the provision and performance of the equipment necessary for the development of construction and yard operations. This driver includes any nonconformance originated from equipment issues except those which origin is known to be related to the performance of equipment supervision or equipment workmanship. Break downs, failures, low productivity, and delays on the supplying of equipment are examples of this type of non-conformance. **Cause Analysis**: Equipment, as a resource administrated and operated by other drivers, fails because of the performance of such other drivers. As this is the case, Equipment is usually categorized as a second or higher driver and, when possible, first level drivers affecting equipment should be identified and reported (e.g. wrong information from scheduling could be the cause of delay on the equipment delivery to the work site). Only when the root cause affecting equipment is not well identified, equipment should be classified as a first level driver (e.g. low productivity of equipment could be related to poor maintenance, manufacture defects, poor skills of operator, suitability to perform the job, or several other factors). **Quality of Equipment** is defined as the adequate and on-time delivery, with the optimal operating conditions, of the equipment as to perform the job with the quality, safety, time, and cost expected or established in the project plan.

10 Shop Services	Refers to the provision and performance of the mechanical, electrical, fabrication and welding work required for both the undertaking of on-site operations of specific projects and the maintenance of the equipment. This driver includes any nonconformance originated from the work delivered from the shops, except those which origin is known to be related to the performance of shop supervision or shop workmanship. Defective or delayed works delivered from the shops, and which in turn affect the performance goals of construction operations, are examples of this type of nonconformance. **Cause Analysis**: Shop services are usually identified as a second or higher driver as most of the times a nonconformance related to the shops lays on issues originated by other drivers such as wrong information, poor supervision or inspection, mistakes on drawings, and others. Therefore, first level drivers affecting shop work should be identified when possible (e.g. wrong information from drawings could be the cause of rework and delays on the performing of work at the shops). Only when the root cause affecting shop work is not well identified, shop services should be classified as a first level driver. **Quality of Shop Services** is defined as the fulfillment of requirements established in the project plans regarding the quality, time, cost, safety, environmental conditions, and other performance goals established for work to be carried out in the shops.
11 Surveying	Refers to the supplying and performance of survey activities required for the appropriate development of construction operations. Primary survey tasks include the measuring of elevations and alignments of graded systems, locating of major points for a project along a centerline or offset, verifying construction activities meet all applicable safety regulations, notifying and reporting survey findings and results to the interested parties, as well as testing and maintaining equipment for surveying. Surveying is required for different construction operations involved in a project, which include: • Open-cut surveying • Water renewal surveying • Preliminary survey for tunnels • Survey of the working shaft • Survey of the undercut • Survey of the tunnel The personnel undertaking survey activities required for a specific project includes the survey supervisor, survey staff, tunnel foreman, open-cut senior foreman, as well as the open-cut foreman. However, surveying can be subcontracted to an external organization which in such case the driver should be identified as *Contractor Servicing*. **Cause Analysis**: Surveying activities may be the root cause (first level drivers) of nonconformances when staff makes mistakes during the performance of survey activities in such a way that survey outcomes do not conform to the specifications of the project plan, or wrong information is supplied to other entities within the organization. Especially, survey poor performance usually generates reworks and delays in construction operations; though safety issues could be also generated. Of course, cost overruns are expected at the end as well. Surveying could be a second level driver or higher, when wrong information or instructions are provided to staff performing survey activities for a project (e.g. project drawings including mistakes may affect the work performed by survey staff). **Quality of Surveying** can be defined by the accuracy and opportunity on the performance of survey activities described before, in such a way that construction operations can be carried out according to specifications and plans established for the project.
12 Inspection/ Testing	Refers to the measuring, examining, testing, and/or gagging of one or more characteristics of a material or service, with the purpose of comparing the results with specified requirements to determine conformity. Inspectors are responsible for verifying conformance to specific requirements in different processes requiring inspection and testing, such as: • Stores inspections • Equipment repair inspections • On-site inspection and testing • Contract inspection and testing • Pressure, exfiltration, and infiltration testing • Preventive maintenance inspection • Fabrication inspection and testing These inspection and testing procedures are executed by different positions within the organization, including: the stores staff, the equipment general supervisor, the senior foreman and the foremen, the garage foreman, the senior electrician, the equipment maintenance employees, the on-site construction inspectors, the pressure testers, and any other employee or laborer delegated to perform inspection and testing tasks. For the purposes of nonconformance reporting, personnel performing inspection or testing activities should be considered as inspectors (i.e. identify cause of

	nonconformance as *Inspection/Testing*). When an external firm is contracted to provide inspection or testing services then the driver should be identified as *Contractor Services*. **Cause Analysis**: defective inspection is usually the origin of further nonconformances such as delayed detection of defective material or work, which may result in waste, rework, delays, and cost overruns in the performance of operations; in such case, inspection should be considered as the root or first level driver. Only in the cases when inspectors receive wrong information from other drivers or resources, inspection should be considered as a second or higher level driver. **Quality of Inspection** is defined as the accurate and opportune fulfillment of procedures established to execute the inspection of specific processes. Inspection procedures refer, primarily, to the testing of materials, services, and construction outcomes, as well as to the reporting of inspection results to interested stakeholders within the project organization.
13 Security	Refers to the appropriate provision of security, including control and protection, for the D&C's yards and facilities, as well as of the properties owned by D&C and the owner which are located on construction sites where projects are being carried out. Provision of information on security matters is also considered one important task for security. Responsibility for security is deployed on personnel positioned at different levels within the D&C organization which include the equipment general supervisor, technical assistant, yard foreman, warehouse administrator, corporate security staff, and, in some degree, on all employees of D&C. For the purposes of nonconformance reporting, if a security nonconformance is originated by any of these personnel the driver should still be identified as *Security*. On the other hand, it is important to notices that in the case security firms and janitorial firms take part on the provision of security services the driver causing the nonconformance should be identified as *Contractor Servicing*. **Cause Analysis**: When any of the parties responsible for security fails to appropriately apply security procedures or to provide accurate and opportune information on security matters, losses, damages, and other eventualities may occur on the properties under control; in such case, Security should be identified as the root cause (first level driver) of the nonconformance. As security responsibility is usually deployed to all the organization in order to cover all the security aspects, very few cases would make this driver a second, or higher, level driver; for example, one case could be the delay on the supply of information to control the facilities if such delay is not caused by any of the personnel responsible for security listed before. **Quality of Security** can be defined as the appropriate and opportune fulfillment of procedures established for security purposes, in such a way that any loss, damage, or any other eventualities are avoided in the organization's facilities and construction sites.
14 Customer Inputs	Refers to the performance of the person or organization that owns and/or initiates the construction project and who is responsible for the full or partial financing of the project. Two categories of customer ownership can be identified: (1) private and (2) public, each one having a different role and, therefore, a different influence on the development of the project. Nevertheless, the customer's organization is, in general, responsible for establishing the project requirements and for communicating them to other project team members. Thus, the supply of information is a major responsibility of the customer that, depending on its accuracy and opportunity, may have a positive or negative impact on construction operations. For example, the opportune and accurate information of change orders initiated by the owner has been reported as a major factor contributing to quality deviations. **Cause Analysis**: as a supplier of information, the customer's organization happens to be the root cause (first level driver) of the problem when it is involved in a nonconformance. However, on some occasions the customer's organization could be a second or higher level driver if any other team member provides wrong information that would make it generate a nonconformance. **Quality of Customer** can be defined as the accurate and opportune supply of information and/or feedback required to develop different stages or phases of the project, namely conceptualization, design, construction, operation, maintenance, and final disposition.

15 Procedures	For the purpose of this study, procedure is defined as the description or documentation of the specific steps, tasks, resources, and organizational authorities and responsibilities which are necessary to standardize the performing of a managerial, technical, or operational activity or process in the corporate and the project organizations. Standard procedures are expected to facilitate the achievement of the objectives established for the activity/process as they make more controllable the way work is performed. Procedures are usually documented in the manual of procedures, quality policy manual, project management plan, project quality plan, and the manual of work instructions. This includes the establishment of organizational structures for the corporate and project organizations, as well as the deployment of authority and responsibility in such organizations. **Cause Analysis**: There are two different approaches to the analysis of procedures. One is regarding the quality or appropriateness of the procedure itself, which depends on whether the procedure describes the appropriate and clear way to achieve the objective planned for the activity/process or it needs some adjustment given the evidence it is not appropriately supporting the achievement of such objective. In this case, a procedure could be the root cause (first level driver) in a nonconformance report. The second approach is regarding the appropriateness on the execution or accomplishment of the steps, tasks, or indications the procedure establishes. This depends on whether the personnel involved in the execution of the procedure appropriately perform the established steps, tasks or indications or not. In this second case, a procedure should be a lower level driver as some other driver (personnel) should be responsible for not following appropriately the way established in the procedure to achieve the objective of the process; therefore, procedures should be classified as second or third level drivers and linked to the higher level drivers that made them cause a nonconformance. **Quality of Procedures**: As well as in the cause analysis, there are two approaches to the definition of quality of procedures. One is the appropriateness of the way established in the procedure to accomplish the objective of the process, and the other is the appropriateness and opportunity of the execution or accomplishment of the procedure. Procedures should be improved when it is detected they are not working well as to accomplish the objectives of the process for which the procedure has been established; but, meanwhile, they are assumed to indicate the "right way" to perform the process.
16 Work Conditions	Two different approaches to the assessment of work conditions should be considered. One refers to the physical environment of the site where the job/project is being performed. This first approach includes work conditions due to: • Utilities or facilities constructed in the past being maintained, repaired, or extended; • Environmental factors such as the soil, air, and water around the job site, as well as the weather conditions; • Space available to perform the job and to transit on the site; • All, in general, the physical elements common to the site that may affect the performance of the resources involved in the job/project. The other approach refers to the moral environment created into the organization. This environment is due to the promotion of motivation, satisfaction, development and performance of people in the organization. **Cause Analysis**: Physical environment can be the root cause of nonconformance reports in case they regard to the weather and other environmental factors, or to conditions generated by higher level drivers difficult to identify; for example, it is difficult or useless to identify the drivers that have generated the poor conditions of utilities to be maintained or replaced which may be affecting the performance of labor. Nevertheless, in other cases it is possible to identify drivers causing a poor physical environment; for example, the supplying of materials could be identified as the factor causing congestions on site. Moral environment is, in general, affected by higher level drivers from the corporate and/or project organization. Drivers affecting moral environment are difficult to identify as some part of the organization or the whole organization could be involved in the affectation, or even the own morale of each worker. **Quality of Work Conditions** can be defined as the appropriateness of the physical and moral environment in the job site as to perform the job as planned. This means to complete the project/job on the time, budget, quality, and safety expected for the project/job. Furthermore, good quality of work conditions is opposite to work environments favoring interruptions, disruptions, reworks, accidents, or any other nonconformance during the performance of the job.

Table B.2: Description of project quality management practices and project management processes

Based on the Quality Performance Management System proposed by the Construction Industry Institute (Ledbetter, 1994)			
Practices	**Description**	**Examples of Activities** (Neese and Ledbetter, 1991)	
1a. Project Quality System Management	The activities of managing and performing the quality management system in the project. This includes: • Developing quality improvement programs, standards and goals. • Indoctrination and training. • Data collection, analysis, and reporting.	• Quality System/Program development • Quality orientation activities • Quality team activities • Continuous performance improvement training • Project quality planning meetings • Client quality planning meetings • Drafting a Quality Plan/Quality Policy • Quality committee meetings	• Quality Management/Administration Quality performance reporting • Quality performance interpretation/auditing • Client quality perception surveys/clinics • Design quality progress review • Drafting a Quality Project Philosophy • Malcomb Baldridge Award requirement planning
2a. Supplier Qualification	Activities to investigate and evaluate the capabilities and qualifications of contractors, subcontractors, and suppliers to assure that they will be able to deliver products or services that will meet all requirements. • Evaluating the ability of suppliers, vendors, contractors and subcontractors to perform capability. • Developing a certification system and compiling rating scores to measure supplier performance.	• Contracting strategy planning • Contractor/vendor prequalification • Supplier quality planning • Supplier reviews/ratings • Contract/PO technical review • Contractor/PO commercial review • Qualification of supplier's product	• Product or service quality audits • Warranty review/planning • "Preferred Vendor" qualification • Pre-Award vendor shop inspection
3a. Expediting	Activities with suppliers prior to their delivery of product or service (all purchased materials, equipment, services, and third-party engineering information) to assure that they will deliver on schedule. Principally, this includes procurement and contracts expediting.	• Contract control • Long lead equipment planning • Expediting/Traffic planning • Traffic routing studies • Routing expediting	• Expediting third party engineering information • Expediting client purchased Material/Equipment/Services
4a. Constructability Review	Activities to ascertain whether the design enables the most efficient construction to be used and whether the planned construction methods are the most efficient. Engineering and construction perform constructability review early in design. Construction, with engineering support, performs constructability reviews early in construction. • Activities to ensure that the most efficient design and planned construction methods are used to maximize the chance of constructing perfect utilities. • Construction site layout studies, dewatering studies, prefabrication studies, etc.	• Dewatering studies • Prefabrication/preassembly studies • Foundation system studies • Rigging studies • Specification reviews • Standardization Planning/Review of design • Startup sequencing	• Maintenance/Operating Accessibility reviews • Welding procedure reviews • Construction equipment usage planning • Construction warehousing review/planning • Site mobilization planning

5a. Operability and Value Review	Activities of appraising/reviewing designs to find and eliminate over-design and over-specification. This would be an independent review for such items as oversize structural members, oversize equipment and/or over-specified materials. This includes determining if the design is in compliance with client, industry and government requirements in terms of operability, process hazards and operability reviews, value engineering studies, etc.	• Design feasibility studies • Construction feasibility studies • Hazard/Operability Studies/Design review • Discounted rate of return analysis • Materials of construction studies • Major technological advantages • Process simulation studies
6a. Internal Examinations	Activities of inspecting, testing, and checking of the products/services already produced internally within the organization to determine if they meet requirements. • Reviewing, checking, inspecting, testing and observing services/products produced internally in the organization. • Reviewing designs, drafting and documentation. • Soil testing, concrete testing, hydro-testing piping, etc.	• Interdisciplinary drawing checking/review • Interdisciplinary procurement document checking/review • Field Quality Auditing/Sampling • Quality control techniques, monitoring, measuring and defect elimination • Quality Assurance Activities/Practices • Internal Quality Inspections • Statistical Quality Control Activities • Concrete Slump Testing • Soil Compaction Testing • Product Design Qualification Testing • Review of Test/Inspection Data • Trouble Shooting/Failure Analysis
7a. External Examinations	Activities of inspecting, checking, and testing of the products/services produced externally to the organization to determine if they meet requirements. • Reviewing, checking, inspecting, testing and observing services/products produced externally by others. • Inspection of material/equipment received, vendor document reviews, etc.	• Third Party Review of Design • Third Party Review of Construction • Checking of Vendor Prints • Shop Inspections, Vendor Equipment, Material Fabrication • Offsite Field/Shop Trials • Laboratory Testing • Outside Endorsements/ Certifications • Receiving Inspection of Vendor Supplied Material/Equipment

Based on the Project Management Processes proposed by ISO 10006:2003 (Guidelines for Quality Management in Projects) and the Project Management Institute (PMBOK Guide – 2000 Edition)

Processes	**Description**	**Examples of Activities** (ISO 10006:2003)
1b. Integration Management	Project Integration Management includes the processes required to ensure that the various elements of the project are properly coordinated. It involves making tradeoffs among competing objectives and alternatives to meet or exceed stakeholder needs and expectations. Major processes included in this initiative are: • Project Management Plan Development: Activities to integrate and coordinate all project plans to create a consistent, coherent document. • Interaction Management: Activities to	• *Project Management Plan Development* includes – Identifying details of relevant past projects in order to make use of the experience gained from them. – When the purpose of the project is fulfilling requirements of a contract, performing contract reviews to ensure that contract requirements can be met – When the project is not the result of a contract, performing an initial review to establish the requirements, and confirm they are appropriate and achievable. – Documenting the customer's and other interested parties' requirements, the input source of such requirements to allow traceability, as well as the project objectives. – Identifying and documenting the project processes and their purposes. – Defining the Work Breakdown Structure for the project.

	manage the interactions (which are not planned) in the project in order to facilitate the interdependencies (which are planned) between processes. • Process and Project Closure: Activities to ensure the processes and project are properly completed.	– Integrating plans resulting from the planning of PM processes such as the quality plan, work breakdown structure, project schedule, project budget, risk management plan, communication plan, and purchasing plan. – Reviewing all plans included in the PM plan to ensure consistency and to resolve any discrepancy. – Identifying or referencing the product characteristics and how they should be measured. – Providing a baseline for progress measurement control (e.g. preparing and scheduling plans for reviews and progress evaluations). – Defining performance indicators and how to measure them. – Planning for regular assessments to monitor progress that facilitate the undertaking of preventive and corrective actions and the verification of project objectives validity in a changing project environment. – Verifying the project's quality plan is compatible with the corporate quality management system. • *Interaction Management* includes – Identifying organizational interfaces, such as the - project organization's connection and reporting lines with the various functions of the corporate organization, - interfaces between functions within the project organization. – Establishing procedures for interface management – Planning for project inter-functional meetings – Resolving issues such as conflicting responsibilities or changes to risk exposure • *Process and Project Closure* includes – Defining the closure of processes and the project during the initiation stage and taking into account experience gained from previous projects. – Ensuring all records are compiled, distributed within the project and to the corporate organization. – Undertaking a complete review of project performance, whatever the reason for project closure and taking into account all relevant records. – Preparing appropriate reports, based on this review, highlighting experience that can be used by other projects and for Continual Improve. – Ensuring the customer has formally accepted the project product to consider the project completed. – Communicating the closure of the project to other interested parties.
2b. Scope Management	Scope-related processes define the project's product, its characteristics and how such characteristics are to be measured or assessed. Scope-related processes aim to • translate the customers' and other related parties' needs and expectations into activities required to achieve the project's objectives, and to organize these activities' • ensure the personnel work within the scope during the realization of these activities, • ensure activities carried out in the project meet the requirements described in the scope.	The scope-related processes are: • *Concept Development* activities include the – Translation customer needs and expectations for product and processes into documented requirements, including statutory and regulatory aspects. – Identification of interested parties and translation of their needs into documented requirements which, when relevant, the customer should agree. • *Scope Development* activities include the – Identification of the characteristics of the project's and the documentation of them in measurable terms as completely as possible. – Specification of how the characteristics will be measured and how their conformity to the requirements will be assessed. • *Definition of Activities* include the

		– Systematic organization of the project into manageable activities to meet customer requirements for product and processes. – Definition of each activity in such a way that its results are measurable. – Definition of activities related to the quality management practices, progress evaluations, and to the preparation and maintenance of a PM plan. – Identification and documentation of the interactions between activities that could potentially cause problems between the project organization and the interested parties.
3b. Change Management	Activities of identification, evaluation, authorization, documentation, implementation, and control of changes to the scope, project objectives, and to the project management plan. This includes the: • Analysis of the intent, extent and impact of the change before it is authorized. • Agreement with customer and other relevant interested parties on the implementation of changes that affect the project objectives.	• Identification of negative and positive impacts of changes • Root cause analysis of negative impacts to implement preventive actions and improvements in the project process. • Establishment of procedures to – document changes, – coordinate changes across inter-linked project processes, – resolve conflicts generated by changes, • Identification of aspects of change affecting personnel
4b. Time Management	Time-related processes aim to determine dependencies and duration of activities and to ensure timely completion of the project. The time-related processes are: • Activity Definition: Identifying the specific schedule activities that need to be performed to produce the various project deliverables. • Planning of activity dependencies: Identify inter-relationships and the logical interactions and dependencies among project activities. • Estimation of resources: Estimating the type and quantities of resources required to perform each schedule activity. • Estimation of duration: Estimate the duration of each activity in connection with the specific conditions and the resources required. • Schedule development: Inter-relate the project time objectives, activity dependencies and their durations as the framework for developing general and detailed schedules. • Schedule control: Control the realization of the project activities, for confirming the proposed schedule or for taking adequate actions for recovering from delays.	• *Planning of Activity Dependencies* includes activities to: – Identify the interdependencies among project activities and to review them for consistency. – Justify and document any need for change to data from activity identification – Verify standard or past experience project network diagrams for appropriateness of use in present project. • *Estimation of Duration* includes activities to: – Establish duration estimates of activities by personnel with responsibility for those activities. – Verify duration estimates from past experience for accuracy and applicability to present project conditions. – Document inputs to the estimation process and make them traceable to their origins. – Evaluate, document and mitigate risks associated to the uncertainty in duration estimation. – Involve the customer and other interested parties in duration estimation, when required or appropriate. • *Schedule Development* includes activities to: – Identify input data for schedule development and check it for conformity to specific project conditions. – Implement standardized schedule formats, suitable for different user needs. – Check the relationships of duration estimates to activity dependencies for consistency. – Resolve inconsistencies before schedules are finalized and issued. – Inform the customer and other interested parties during schedule development and involve them in the development when required. – Analyze and take into account external inputs in the schedule. • *Schedule Control* includes activities to: – Establish the timing of schedule reviews and frequency of data collection, to ensure adequate control cover project activities. – Analyze project progress to identify trends and possible

		uncertainties in the work remaining in the project. – Identify and analyze deviations from the schedule and act upon if significant. – Identify root causes for variances from schedule, both favorable and unfavorable. – Take actions to ensure unfavorable variances do not affect project objective. – Agree with customer and interested parties on changes that affect the project objectives before implementation. – Coordinate revisions of the schedule with other project processes when developing the plan for remaining work. – Monitor external inputs (e.g. customer-dependant inputs expected in project) – Inform customer and interested parties of any proposed changes to the schedule and involve them in making decisions that affect them.
5b. Cost Management	Cost-related processes aim to forecast and manage the project costs in order to ensure the project is completed within budget constrains, and that cost information can be provided to the corporate organization. The cost-related processes are: • Cost Estimation: Developing cost estimates for the project. • Budgeting: Using results from cost estimation to produce the project budget. • Cost Control: Controlling costs and deviations from the project budget.	• *Cost Estimation* include activities to: – Ensure cost estimation considers relevant sources of information. – Verify cost estimates from past experience for accuracy and applicability to present project conditions. – Document costs and make them traceable to their origins. – Budget sufficient funds for the establishment, implementation and maintenance of the project quality management system. – Take into account present and forecast trends in the economic environment. – Identify, evaluate, document, and act upon significant uncertainties. – Enable the establishment of budgets using the cost estimates. • *Budgeting* include activities to: – Ensure the budget is consistent with the project objectives. – Identify and document any assumptions, uncertainties, and contingencies. – Ensure the budget includes all authorized costs and its form is suitable for project cost control. • *Cost Control* include activities to: – Establish and document a cost control system and associated procedures, prior to any expenditure. The system should be communicated to those responsible for authorizing work or expenditure. – Establish timing of reviews and frequency of data collection and forecasts, in order to ensure adequate control over activities and related information. – Verify the remaining work can be completed within the remaining budget. – Identify deviations from the budgets and analyze and act upon if significant. – Analyze project cost trends using techniques such as earned value analysis. – Review the plan for the remaining work to identify uncertainties. – Identify root causes for favorable and unfavorable variances to budget. – Take actions to ensure unfavorable variances do not affect project objective – Provide data for Continual Improve obtained from the evaluation of favorable and favorable variances. – Ensure decisions on corrective actions are based on facts (i.e.

		considering the implications for other project processes and objectives). – Ensure changes in the project cost are appropriately approved and authorized prior to expenditure. – Ensure information needed for the timely release of funds is available and provided as input to the resource control process. – Review the project costs as defined in the PM plan.
6b. Material Resources Management	Resource Management includes the processes to ensure that the various resources involved in the execution of the project are properly coordinated. Examples of resources include equipment, facilities, finance, materials, information computer software, space, personnel, and services. Processes included are: • Resource Planning: identifying, estimating, scheduling and allocating all relevant resources. • Resource Control: comparing actual usage against resource plans and taking action if needed.	• *Resource Planning* includes – Identifying what resources will be needed for the project and when will be required according to the project schedule. – Determining how, and from where, resources will be obtained and allocated. – Verifying plans are suitable for resource control. – Evaluating the stability, capability, and performance of organizations supplying resources. – Identifying constrains on resources such as availability, safety, cultural considerations, international agreements, labor agreements, governmental regulations, funding, and the impact of the project on the environment. – Documenting resource plans, including estimates, allocation, and constrains, together with assumptions made. Include this in the PM plan. • *Resource Control* includes – Performing reviews to ensure that sufficient resources are available to meet the project objectives. – Documenting, in the PM plan, the timing of reviews and the frequency of associated data collection and forecasts of resource requirements. – Defining procedures to ensure decisions on actions to be taken consider the implications for other project processes and objectives. – Verifying changes in resource plans affecting the project objectives are agreed with customers and other interested parties before implementation. – Verifying revisions of forecasts of resource requirements are coordinated with other project processes when developing the plan for remaining work. – Identifying and recording root causes for shortages or excesses to use data as input for Continual Improve.
3a. Personnel Management	Personnel-related processes aim to create an environment in which personnel can contribute effectively and efficiently to the project. Special attention should be given to activities in personnel management as the quality and success of a project will depend on the participating personnel. • Establishment of Project Organizational Structure (POS): defining an organization tailored to suit the needs of the project, roles in the project, and authorities and responsibilities. • Qualification and Allocation of Personnel: selecting and assigning sufficient personnel with appropriate competence to suit the project needs. Includes testing the people's ability to perform work to specified quality	• *Establishment of the Project Organizational Structure* includes: – Reviewing and considering previous project experience for the selection of the most appropriate organizational structure. – Verifying the POS is established in accordance with the requirements and policies of the corporate organization and conditions particular to the project – Verifying the POS is appropriate to the project scope, the size of the project team, local conditions and the processes employed. – Verifying the POS is designed to encourage effective and efficient communication and cooperation between all participants. – Verifying division of authority and responsibility within project organization is compatible with that in the corporate organizational structure. – Identifying and establishing relationships of the project organization to the - customer and other interested parties

	standards. • Training and Team Development: training of personnel to perform quality activities and to develop individual and team skills and ability to enhance project performance.	- functions of the corporate organization supporting the project (particularly those in charge of monitoring schedules, quality, and costs) - other relevant projects in the same corporate organization. – Preparing and documenting job role descriptions, including assignments of responsibility and authority. – Planning and carrying out reviews of the POS to determine whether it continues to be suitable and adequate. • *Qualification and Allocation of Personnel* includes – Defining the necessary competence in terms of education, training, skills and experience for personnel working on the project – Developing selection criteria to be applied at all levels of personnel being considered for the project. – Planning and performing craft certification/testing, drug/substance abuse testing/ administration, annual employee performance reviews. – Verifying selection of personnel is based on the job or role descriptions. – Verifying, when assigning members to project teams, that personal interests, personal relationships, strengths and weaknesses are considered. – Confirming and communicating to all concerned the assignment of personnel to specific jobs or roles. – Monitoring the overall performance, including the effectiveness and efficiency of personnel in their job assignments, to verify the assignments are appropriate. – Ensuring a management representative is appointed with responsibility for establishing, implementing, and maintaining the project's QMS. – Communicating changes of personnel in the project organization to the customer and relevant interested parties if the change affects them. • *Training and Team Development* includes – Preparing a personnel training plan – Providing training and quality education seminars – Training personnel for quality assurance/control activities and for making them aware of the relevance of their project activities in the achievement of the project objectives. – Retraining or recognizing achievement based on results. – Establishing a work environment that encourages excellence, effective working relationships, trust and respect within the team and the project. – Encouraging the participation of personnel in team development activities to improve team performance – Encouraging and developing consensus-based decision making, structured conflict resolution, clear, open and effective communication and mutual commitment to customer satisfaction. – Involving personnel affected by changes in the project, in the planning and implementation of the change.
7b. Risk Management	Risk-related processes aim to minimize the impact of potential negative events and to take full advantage of opportunities for improvement. The risk-related processes are: • Risk identification: Determining risks in the project. • Risk assessment: Evaluating the	• *Risk Identification* should consider risks in: – Cost, time, and quality, as well as in security, dependability, professional liability, information technology, safety, health and environment. – Any applicable current and anticipated statutory or regulatory requirements. – Interactions between different risks.

	probability of occurrence of risk events on the project. • Risk treatment: Developing plans for responding to risks. • Risk control: Implementing and updating the risk plans.	– Implementing new technologies and developments. • *Risk Assessment* should take into account: – Analysis and evaluation of identified risks to the project processes and to the project's product. – Experience and historical data from previous projects. – Qualitative and quantitative methods for risk analysis. – Identification of levels of risk acceptable and exceeded for the project. – Communication of risk analysis results to relevant personnel. • *Risk Treatment* should include: – Solutions to eliminate, mitigate, transfer, share or accept risks. – Plans to take advantage of opportunities. – Developing solutions for potential risks arising from activity-, process- and product-related interactions between the project, the originating, and the interested parties' organizations. – Verification of the addressing of undesirable effects, new risks or residual risks resulting from the implementation of solutions. – Contingencies to manage risks made in the time schedule or in the budget. • *Risk Control* should include: – Iterative process of risk identification, risk assessment, and risk treatment throughout the project. – Encouragement to personnel to anticipate and identify risks and report them to the project organization. – Maintaining risk management plans ready for use. – Reports on project risk monitoring as part of progress evaluations.
8b. Safety Management	Includes the processes required to assure that the construction project is executed with appropriate care to prevent accidents that cause personal injury or property damage. The Safety Management processes are: • Safety planning • Safety plan execution • Safety administration and reporting Safety Management is a subset of Risk Management but because it is functionally so specialized and important on every construction project it deserves separate consideration. Good safety practice on a construction project can reduce or eliminate accidents and injury to personnel, improve effectiveness of performance and reduce total project cost.	• *Safety Planning* should include: – Undertaking a job site analysis, this includes a survey of the geographical and physical hazards of the site. –Identifying, based on the hazard analysis, the many hazards to personnel involved in the construction, as well as the general public or suppliers who may only have a fleeting presence on site. –Reviewing the normal hazards involved in the type of construction anticipated. –Considering government laws and regulations, contract, and owner requirements in developing the project safety plan. –Making decisions as to the measures to be taken to deal effectively with such hazards and safety requirements of stakeholders. –Selecting subcontractors based on their safety programs and choosing those who have a good record of safety performance. –Offering incentives in order to encourage the work force to observe safe work practices. –Developing a project safety plan, this is the guiding document for a safe project and is based on the aforementioned inputs. –Granting authority to an experienced individual to act as the project Safety Officer. –Including the estimated cost of the safety plan in the formation of the budget for construction of the project. • *Safety Plan Execution* should include: Applying and implementing the safe construction practices on-site in accordance with the requirements of the plan. This includes: -Providing personnel protective equipment, e.g. harnesses, respirators, head and foot gear, and protective clothing.

		- Providing safety equipment to perform the construction tasks, e.g. trench wall bracing, safety nets, warning devices, and similar equipment. - Performing periodic checks of equipment such as cranes and lifting devices for fitness, and verifying that site vehicles are fitted with back-up alarms. - Providing safety communication such as barriers and signs, bulletin boards, initial safety indoctrination meetings, toolbox meetings, etc. - Training and educating all personnel on safety issues for regular and special construction activities. - Carrying out daily inspections and safety audits to the project, by the Safety Officer and other authorized stakeholders, for its compliance with the safety plan. - Investigating each accident, as to cause, and a complete report made of what happened and why, often with pictures. - Establishing and stocking a first aid station on-site. - Arranging with a near hospital and/or providing a doctor's office for medical assistance in the even of an accident on-site, beyond the care of the on-site first aid station. - Implementing drug-testing programs as a safety requirement. • *Safety Administration and Records* should include: – Keeping records and reporting general health data of employees, drug testing results, and other specialized data that may be related to environmental hazards. – Issuing inspection logs and reports of safety inspections by the project safety officer and his/her staff, containing comments on the activity observed and any correction made. – Maintaining records of training given and to whom, meetings held on the subject of safety, who attended and the date of instruction. – Maintaining records of all injuries requiring treatment, even if minor, and employee illness resulting in absence from work. – Documenting completely all investigations as to cause and result, damage to property and equipment and injuries. – Including photographs and video records as part of the documentation of accident and safety infraction reporting.
9b. Communication Management	Communication-related processes aim to facilitate the exchange of information necessary for the project, and include the following: • Communication planning • Information management • Communication control Such processes include activities to ensure timely and appropriate generation, collection, dissemination, storage and ultimate disposition of project information, as well as the establishment of appropriate communication processes for the project and the implementation of a communication system.	• *Communication Planning* includes the: – Planning of the communication system considering the needs of the corporate organization, project organization, customers and other interested parties. – Documentation of the communication plan, which should include the: - identification of who will send and receive information; - reference of relevant document control, record control and security procedures. - definition of the information that will be formally communicated, the media used to transmit it and the frequency of communication; - the requirements for the purpose, frequency, timing and records of meetings, - the format language and structure of project documents and records to ensure compatibility; - the format for progress evaluation reports designed to highlight deviations from the project management plan. • *Information Management* performed by the project organization includes the: – Definition and documentation of the information management

		system, which should involve internal and external sources of information. – Establishment of procedures defining the controls for information preparation, collection, identification, classification, updating, distribution, filing, storage, protection, retrieval, retention time and disposition of project's information. Design control should be emphasized in this process. – Recording of conditions prevailing at the time the information was recorded. – Ensuring of security of information (confidentially, availability and integrity) – Presentation and distribution of information with relevance to the needs of recipients and with strict adherence to time schedules. – Documentation of all agreements affecting project performance, including informal ones. – Establishment of appropriate rules and guidelines for different types of meetings. – Distribution of meeting agenda to personnel whose attendance is required. – Documentation of minutes of meetings and distribution to relevant interested parties. – Use of data, information, and knowledge to set and meet the project organization's objectives. –Evaluation and improvement of the management of information. • *Communication Control* includes: – Ensuring the communication system continues meeting the project's needs, by controlling, monitoring and reviewing it.
10b. Improvement Management	Improvement-related processes aim to enable Continual Improve in both current and future projects by using the results of measurement and of analysis from project processes to take decisions on corrective and preventive actions. Such processes include the: • Measurement and analysis of performance • Implementation of corrective and preventive actions.	• *Measurement of Performance* may include the: – Evaluation of individual activities and processes – Auditing – Evaluation of actual resources used, along with cost and time, compared to the original estimates – Evaluation of supplier performance – Achievement of project objectives – Satisfaction of customers and other interested parties. – Recording of nonconformities. • *Analysis of Performance* includes to: – Analyze the records of nonconformities in the project's product and processes in order to assist learning and provide data for improvement. • *Implementation of Improvements* includes to: – Use information relevant to the project and derived from the information management system to support decision making on preventive and corrective actions.

APPENDIX C

SELF-ASSESSMENT OF PQM PRACTICES – SAMPLE OF AN EVALUATION QUESTIONNAIRE AND CALCULATION OF PROCESS QUALITY INDEXES

SAFETY MANAGEMENT EVALUATION[*]

In order to gain insight into the comprehensiveness of your company's SAFETY MANAGEMENT program, please rate each question by checking the box designating one of the five possible rankings.

Health and Safety Program Management

1. A safety plan is prepared and authorized for the undertaking of every project.

Not at all	Inadequate	Adequate	Good	Superior	Score
		✓			2

2. Someone is assigned responsibility for health and safety in every project.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

3. There is a health and safety manual or handbook available to all personnel.

Not at all	Inadequate	Adequate	Good	Superior	Score
		✓			2

4. A set time is devoted to health and safety issues during management meetings.

Not at all	Inadequate	Adequate	Good	Superior	Score
	✓				1

5. Health and safety rules and regulations are established for all employees and/or specific jobs.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

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[*] Based on the Safety and Health Program Evaluation included in Reese, C.D. and Eidson, J.V. [2006], *Handbook of OSHA Construction Safety and Health*, 2nd edition, Taylor & Francis: Boca Raton, FL, pages 87-90.

6. Supervisors are held accountable for health and safety during merit pay evaluations.

Not at all	Inadequate	Adequate	Good	Superior	Score
	✓				1

7. A set of specific goals for safety and health are established and revised yearly.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

Inspections/Audits

8. Safety and health inspections are regularly conducted (usually on a weekly basis for medium or large projects, or when conditions change, or when a new process or procedure is implemented) during the construction of projects.

Not at all	Inadequate	Adequate	Good	Superior	Score
		✓			2

9. Unsafe conditions or hazards are found and corrected immediately.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

10. A preventive equipment maintenance program is in place.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

11. Operators of equipment perform daily inspections.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

12. Good housekeeping is prevalent on all jobsites.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

13. A procedure for the monitoring of health hazards is appropriately followed.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

14. Written inspection reports are completed.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

15. Inspection reports are disseminated and open to everyone.

Not at all	Inadequate	Adequate	Good	Superior	Score
		✓			2

16. Job observations are done in adequate periods to improve work practices.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

17. Job observations result in new practices, workplace design, training, retraining, or task analysis.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

Illness and Injury Investigations

18. All incidents involving injury or illness are investigated.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

19. All incidents of equipment damage are investigated.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

20. Written reports are generated for all incidents.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

21. Preventive recommendations are made based on illness and injury investigations.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

22. Preventive recommendations are actually implemented.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

23. Employees review incident reports.

Not at all	Inadequate	Adequate	Good	Superior	Score
		✓			2

24. Incident data is analyzed to determine illness and injury trends.

Not at all	Inadequate	Adequate	Good	Superior	Score
	✓				1

Task Analysis

25. Inspections, job observations, and incident investigations result in a task analysis.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

26. Task analyses result in changes in work practices or workplace design.

Not at all	Inadequate	Adequate	Good	Superior	Score
		✓			2

27. Task analyses are used to facilitate the development of safety programs.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

28. Task analyses result in new training or retraining.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

Safety Training

29. All employees receive health and safety training.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

30. Employees receive site-specific training.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

31. Employees are given job-specific or task-specific training.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

32. Management and supervisors receive health and safety training.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

33. Training records are maintained.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

Personal Protective Equipment (PPE)

34. Proper PPE is always available when required.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

35. Employees have been trained in the use of PPE.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

36. A respirator program (29CFR 1910.134) is established, if needed.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

37. Rules and use of PPE are enforced.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

Communication and Promotion of Health and Safety

38. Health and safety measures are visible.

Not at all	Inadequate	Adequate	Good	Superior	Score
		✓			2

39. The company/contractor health and safety goals are communicated to all interested parties.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

40. Health and safety meetings are held.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

41. Health and safety talks convey relevant information.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

42. Personal health and safety contacts are made.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

43. Bulletin boards are used to communicate health and safety issues.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

44. Those responsible for health and safety request feedback.

Not at all	Inadequate	Adequate	Good	Superior	Score
		✓			2

45. Health and safety suggestions are given consideration and/or used.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

46. Supervisors are interested in health and safety.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

47. An award/incentive program tied to safety and health is implemented.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

48. Health and safety exhibits or posters are used.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

49. Paycheck stuffers on safety and health are used.

Not at all	Inadequate	Adequate	Good	Superior	Score
		✓			2

50. Safety and health handouts have been used.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

51. Employees are recognized for contributions toward the health and safety program.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

52. Top management extend considerable effort to assure an effective health and safety program.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

53. Supervisors support and enforce all aspects of the health and safety program.

Not at all	Inadequate	Adequate	Good	Superior	Score
				✓	4

54. Employees insist on doing all tasks in a safe and healthy manner.

Not at all	Inadequate	Adequate	Good	Superior	Score
			✓		3

55. Off-the-job health and safety is promoted as part of the total health and safety program.

Not at all	Inadequate	Adequate	Good	Superior	Score
		✓			2

Example of the calculation of the PQI of Safety Management

In order to quantify the extent to which the safety management program is integrated to the project management system, the following score is used and recorded in the score box provided for each question:

Not at all	0
Inadequate	1
Adequate	2
Good	3
Superior	4

Then, the rating scores of all of the questions should be totaled up. Notice that this can be done for each of the categories in which the evaluation is subdivided. For instance, Table C.1 shows a score sheet with the sum of rating scores for each category.

Table C.1: Example of PQI calculation

Category	Total Rating Score	Maximum Score	PQI
Health and Safety Program Management	15	28	53.6
Inspections/Audits	32	40	80.0
Illness and Injury Investigations	21	28	75.0
Task Analysis	11	16	68.8
Safety Training	20	20	100.0
Personal Protective Equipment	15	16	93.8
Communication and Promotion of Health and Safety	55	72	76.4
Total	**169**	**220**	**76.8**

Using the sum of the rating scores, the PQI is calculated. This is done by dividing the sum of the rating scores of each category by the maximum possible score for the category, a multiplying by 100. This should also be done for obtaining the total PQI of the process under evaluation, as shown in the following example:

$$\text{Process Quality Index} = \frac{\text{Total Rating Score}}{\text{Maximum Score}} \times 100 = \frac{169}{220} \times 100 = 76.8\%$$

Table C.1 also shows the PQI for each of the categories and for the whole process.

APPENDIX D

FORMS FOR SURVEYING THE PQM SYSTEM IN THE CASE STUDY ORGANIZATION AND ELICITING KNOWLEDGE-BASED ASSESSMENTS

Form D.1

Preliminary study of quality systems implemented in construction organizations

This survey is being conducted by the Construction Engineering and Management Graduate Program at the University of Alberta. All information provided will be strictly confidential. If you have any questions regarding this survey instrument, please contact graduate student Gilberto Corona at 780•492•3496 or gilberto@ualberta.ca. Thank you in advance for your contribution to this study.

Survey Objectives:

- Learn about the organization of the firm and its approach to the performance of construction projects.
- Get a better understanding on the quality system implemented in the organization and the processes under ISO 9001:2000 certification.
- Learn about the management information system implemented in the organization as part of the quality assurance system.
- Identify potential factors that could be measured and used in the modeling of quality management processes for performance assessment purposes (e.g. failure rates, quality costs, etc.).

Organization: ______________________ **Date:** __________

Respondent's Name: ______________________ **Position:** __________

Years of experience in this organization: __________ **Total years of experience:** __________

Documents provided: ☐ Quality Assurance Manual ☐ Manual of procedures
☐ Quality reports ☐ Quality data forms ☐ Others:

Please, respond to the following questions based on your experience in this organization

a) The Organization

1. What is the kind of projects undertaken by this organization?

2. What organizational structure is used to manage the projects carried out by this organization? (Levels of organization, kind of organizational structure: by function, by kind of work, etc)

3. What stages of the project are carried out by this organization? (definition, planning, design, construction, operation)

4.Who are customers of this organization? Could you prioritize them?

b) The Quality System

5.What quality documents and/or systems are issued to assure the adequate development of every project? (Project management plan, quality plan, project management information system, etc.?

6.What management processes involved in the originating organization are ISO 9001:2000 certified? How long these processes have been certified?

7.What management processes carried out by the project organization are ISO 9001:2000 certified? How long these processes have been certified?

8.What design processes carried out by the project organization are ISO 9001:2000 certified? How long these processes have been certified?

9.What construction processes carried out by the project organization are ISO 9001:2000 certified? How long these processes have been certified?

10. What operation processes carried out by the project organization are ISO 9001:2000 certified? How long these processes have been certified?

11. What would you say it is the performance maturity level of the quality assurance system implemented in those processes? (Maturity level to deal with quality problems according to the following table)

Maturity level	Performance level	Guidance
1	No formal approach	No systematic approach evident, no results, poor results or unpredictable results.
2	Reactive approach	Problem- or corrective-based systematic approach; minimum data or improvement results.
3	Stable Formal approach	Systematic process-based approach, early stage of systematic improvements; data available on conformance to objectives and existence of improvement trends.
4	Continual Improve	Improvement process in use; good results and sustained improvement trends.
5	Best-in-Class	Strongly integrated improvement process; best-in-class benchmarked results demonstrated.

12. How often is the quality assurance system reviewed and improved?

13. What process or activity within the design/production/operation system would you say has the highest failure rate?

14. What do you think is the best action implemented within project development to assure the quality of the processes?

c) The Management Information System

15. Could you briefly explain how the MIS works within the quality system?

16. What quality parameters are measured for the measurement of performance? (Quality costs, failure rates, etc.) How quality data is collected from projects?

17. How are performance records used to support the assessment and improvement of the project operations?

18. What specific data analyses are carried out to assess its performance and identify areas for improvement?

19. How does management use corrective action for evaluating and eliminating recorded problems affecting project performance?

20. What specific actions have been taken for performance improvement on project development? (Give some examples please)

Form D.2
Knowledge elicitation for the development of membership functions of PQM variables

This study is part of an ongoing research project within the Construction Engineering and Management Graduate Program at the University of Alberta. All information provided will be strictly confidential. If you have any questions regarding this study instrument, please contact graduate student Gilberto Corona at 780•492•3496 or gilberto@ualberta.ca. Thank you in advance for your participation and contribution.

Study Objectives

- Elicit knowledge-based assessments of factors involved in the Project Quality Management (PQM) system established in this organization to manage the quality of construction operations, in order to develop an expert system that permits the analysis of such factors.

Interviewee Information

Organization: ______________________________ Date: __________

Respondent's Name: ____________________ Position: ______________

Years of experience in this organization: __________ Total years of experience: ________

Years of experience in project management: ________

Questions for grading the magnitude of linguistic terms used to evaluate the performance of PQM factors involved in open-cut construction projects

This study focuses on the assessment of factors affecting the quality of open-cut construction operations. A previous analysis of the Quality Management Information System evidenced that the most important factors are those included in Figure 1 annexed to this questionnaire.

I. Evaluating the performance maturity level of the PQM practices

Based on your expertise, please assign an appropriate numerical value or range of values for each of the linguistic terms established to evaluate the performance maturity level, in terms of Process Quality Index (PQI) values, of the PQM practices previously discussed.

In trying to establish a general numerical guideline for the assessment of the maturity levels, consider the lowest value of *No Formal Approach* as zero and the highest value of *Best-in-Class* as 100. You can make your assessments by overrunning the bounds between one level and the next one if you are uncertain on what term a given value should belong to (for example, *No Formal Approach* is between 0 and 40, Reactive Approach is between 20 and 50, Stable –

Formal System is between 40 and 70, etc.). You can also propose a different or additional performance maturity level in the space provided.

Please, refer to Table 1 for consulting the characteristics of each of the proposed maturity levels of PQM practices and to Table 2 annexed to this questionnaire in case you need to consult the description of any of these practices/processes.

Questions	Answers
1. For the performance maturity level of the **Supplier Qualification** practice	
a. From zero to what value would you consider as ***No Formal Approach***?	From *Zero* To
b. What range of values as ***Reactive Approach***?	From To
c. What range of values as ***Stable Formal***?	From To
d. What range of values as ***Continual Improve***?	From To
e. From what value to 100 as ***Best-in-Class***?	From To *100%*
f. Other level (specify please):	From To
2. For the performance maturity level of the **Expediting** practice	
a. From zero to what value would you consider as ***No Formal Approach***?	From *Zero* To
b. What range of values as ***Reactive Approach***?	From To
c. What range of values as ***Stable Formal***?	From To
d. What range of values as ***Continual Improve***?	From To
e. From what value to 100 as ***Best-in-Class***?	From To *100%*
f. Other level (specify please):	From To
3. For the performance maturity level of the **Internal and External Examination** practice	
a. From zero to what value would you consider as ***No Formal Approach***?	From *Zero* To
b. What range of values as ***Reactive Approach***?	From To
c. What range of values as ***Stable Formal***?	From To
d. What range of values as ***Continual Improve***?	From To
e. From what value to 100 as ***Best-in-Class***?	From To *100%*
f. Other level (specify please):	From To

4. For the performance maturity level of the **Risk Management** practice

a. From zero to what value would you consider as ***No Formal Approach***?	From *Zero*	To
b. What range of values as ***Reactive Approach***?	From	To
c. What range of values as ***Stable Formal***?	From	To
d. What range of values as ***Continual Improve***?	From	To
e. From what value to 100 as ***Best-in-Class***?	From	To *100%*
f. Other level (specify please):	From	To

5. For the performance maturity level of the **Constructability Review** practice

a. From zero to what value would you consider as ***No Formal Approach***?	From *Zero*	To
b. What range of values as ***Reactive Approach***?	From	To
c. What range of values as ***Stable Formal***?	From	To
d. What range of values as ***Continual Improve***?	From	To
e. From what value to 100 as ***Best-in-Class***?	From	To *100%*
f. Other level (specify please):	From	To

6. For the performance maturity level of the **Safety Management** practice

a. From zero to what value would you consider as ***No Formal Approach***?	From *Zero*	To
b. What range of values as ***Reactive Approach***?	From	To
c. What range of values as ***Stable Formal***?	From	To
d. What range of values as ***Continual Improve***?	From	To
e. From what value to 100 as ***Best-in-Class***?	From	To *100%*
f. Other level (specify please):	From	To

7. For the performance maturity level of the **Change and Communication Management** practice

a. From zero to what value would you consider as ***No Formal Approach***?	From *Zero*	To
b. What range of values as ***Reactive Approach***?	From	To
c. What range of values as ***Stable Formal***?	From	To
d. What range of values as ***Continual Improve***?	From	To
e. From what value to 100 as ***Best-in-Class***?	From	To *100%*
f. Other level (specify please):	From	To

8. For the performance maturity level of the **Operability and Value Review** practice				
a. From zero to what value would you consider as ***No Formal Approach***?	From	*Zero*	To	
b. What range of values as ***Reactive Approach***?	From		To	
c. What range of values as ***Stable Formal***?	From		To	
d. What range of values as ***Continual Improve***?	From		To	
e. From what value to 100 as ***Best-in-Class***?	From		To	*100%*
f. Other level (specify please):	From		To	

9. For the performance maturity level of the **Personnel Qualification and Training** practice				
a. From zero to what value would you consider as ***No Formal Approach***?	From	*Zero*	To	
b. What range of values as ***Reactive Approach***?	From		To	
c. What range of values as ***Stable Formal***?	From		To	
d. What range of values as ***Continual Improve***?	From		To	
e. From what value to 100 as ***Best-in-Class***?	From		To	*100%*
f. Other level (specify please):	From		To	

II. Evaluating the quality performance of construction resources in open-cut construction

Based on your judgment, please assign an appropriate numerical value or range of values for each of the linguistic terms established to evaluate the quality performance of the construction resources involved in open-cut projects.

As a numerical guideline for your assessments, consider the lowest value of *Very Poor* as zero and the highest value of *Very Good* as 10. You can overrun the bounds between one level and the next one for making your assessments if you are uncertain on what term a given value should belong to (for example, *Very Poor* is between 0 and 3 and *Poor* is between 2 and 4).

Please, refer to Table 3 annexed to this questionnaire in case you need to consult the description of any of the following construction resources.

Questions	**Answers**			
1. For the quality performance level of the **Material/Equipment Supplying**				
a. From zero to what value would you consider it as ***Very Poor***?	From	*Zero*	To	
b. For ***Poor***?	From		To	
c. For ***Average***?	From		To	
d. For ***Good***?	From		To	
e. From what value to 10 for ***Very Good***?	From		To	*Ten*

2. For the quality performance level of the **Stacking**

a. From zero to what value would you consider it as ***Very Poor***?	From	*Zero*	To	
b. For ***Poor***?	From		To	
c. For ***Average***?	From		To	
d. For ***Good***?	From		To	
e. From what value to 10 for ***Very Good***?	From		To	*Ten*

3. For the quality performance level of the **Equipment**

a. From zero to what value would you consider it as ***Very Poor***?	From	*Zero*	To	
b. For ***Poor***?	From		To	
c. For ***Average***?	From		To	
d. For ***Good***?	From		To	
e. From what value to 10 for ***Very Good***?	From		To	*Ten*

4. For the quality performance level of the **Work Conditions**

a. From zero to what value would you consider it as ***Very Poor***?	From	*Zero*	To	
b. For ***Poor***?	From		To	
c. For ***Average***?	From		To	
d. For ***Good***?	From		To	
e. From what value to 10 for ***Very Good***?	From		To	*Ten*

5. For the quality performance level of the **Design/Drafting Information**

a. From zero to what value would you consider it as ***Very Poor***?	From	*Zero*	To	
b. For ***Poor***?	From		To	
c. For ***Average***?	From		To	
d. For ***Good***?	From		To	
e. From what value to 10 for ***Very Good***?	From		To	*Ten*

6. For the quality performance level of the **Labor Crew**

a. From zero to what value would you consider it as ***Very Poor***?	From	*Zero*	To	
b. For ***Poor***?	From		To	
c. For ***Average***?	From		To	
d. For ***Good***?	From		To	
e. From what value to 10 for ***Very Good***?	From		To	*Ten*

7. For the quality performance level of the **Supervision**

a. From zero to what value would you consider it as ***Very Poor***? From *Zero* To

b. For ***Poor***? From To

c. For ***Average***? From To

d. For ***Good***? From To

e. From what value to 10 for ***Very Good***? From To *Ten*

III. Questions for grading the magnitude of linguistic terms used to evaluate the effect of the quality performance level of resources upon the performance of open-cut construction activities

The variables representing the effect of the quality performance level of resources involved on the performance of open-cut construction activities include the (i) **frequency of occurrence** of the quality performance levels of the resources and (ii) the **adverse consequences** of such quality performance levels upon the performance of construction activities.

1. Based on your judgment, please assign a number or range of times in every 10 that appropriately represent each of the linguistic terms established to assess the **frequency of occurrence** of the quality performance levels of the construction resources involved in any open-cut construction project. For example, *very unusual* frequency of occurrence would be 0 to 1 times in every 10 while *very usual* would be 9 to 10 times in every 10.

   As a numerical guideline for the assessment of the **frequency of occurrence**, consider the lowest value of the *Very Unusual* term as 0/10 and the highest value of the *Very Usual* term as 10/10. You can overrun the bounds between one term and the next one for making your assessments if you are uncertain on what term a given value should belong to (for example, *Very Unusual* is between 0 and 2/10 and *Unusual* is between 2 and 4/10). You can also skip the assessment of any of the extreme linguistic terms established (i.e. *Very Unusual* or *Very Usual*) if you consider they are unsuitable for the assessment of the frequency of occurrence.

What value or range of values would you consider as											
a. ***Very Unusual***?	[✓ 0/10]	1/10	2/10	3/10	4/10	5/10	6/10	7/10	8/10	9/10	10/10
b. ***Usual***?	0/10	1/10	2/10	3/10	4/10	5/10	6/10	7/10	8/10	9/10	10/10
c. ***Often***?	0/10	1/10	2/10	3/10	4/10	5/10	6/10	7/10	8/10	9/10	10/10
d. ***Usual***?	0/10	1/10	2/10	3/10	4/10	5/10	6/10	7/10	8/10	9/10	10/10
e. ***Very Unusual***?	0/10	1/10	2/10	3/10	4/10	5/10	6/10	7/10	8/10	9/10	[✓ 10/10]

2. Based on your judgment, please assign a value or range of values that appropriately represent each of the linguistic terms established to assess the **adverse consequence**.

   As a numerical guideline for the assessment of the **adverse consequence**, consider the lowest value of the *Very Mild* term as zero and the highest value of the *Very Severe* term as 10. You can overrun the bounds between one term and the next one for making your assessments if you are uncertain on what term a given value should belong to (for example, *Very Mild* is between 0 and 2 and *Mild* is between 2 and 4). You can also skip the assessment of any of the extreme linguistic terms established (i.e. *Very Mild* or *Very Severe*) if you consider they are unsuitable for the assessment of the adverse consequence.

What value or range of values would you consider as											
a. ***Very Mild***?	[✓ 0.0]	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
b. ***Mild***?	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
c. ***Medium***?	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
d. ***Severe***?	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
e. ***Very Severe***?	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	[✓ 10.0]

Final comments you want to add:

THANKS FOR YOUR CONTRIBUTION!

Form D.3

Knowledge elicitation for the development of membership functions and inference rules of variables defining the effect upon the performance of the open-cut construction activities

This study is part of an ongoing research project within the Construction Engineering and Management Graduate Program at the University of Alberta. All information provided will be strictly confidential. If you have any questions regarding this study instrument, please contact graduate student Gilberto Corona at 780•492•3496 or gilberto@ualberta.ca. Thank you in advance for your participation and contribution.

Study Objectives

- Elicit knowledge-based assessments of effects of factors involved in the Project Quality Management (PQM) system established in this organization, upon the quality performance of open-cut construction activities.

Interviewee Information

Organization: ______________________________ Date: __________

Respondent's Name: ____________________ Position: __________

Years of experience in this organization: __________ Total years of experience: __________

Years of experience in open-cut construction: __________

I. Questions for grading the scale of linguistic terms used to evaluate the consequence indicators of nonconformances in open-cut construction activities

This section focuses on the assessment of variables representing the consequences of nonconformances occurred during the undertaking of **open-cut construction** activities, which eventually will affect the schedule of the project. These variables include (i) the **Number of Nonconformances** and (ii) the **Duration of Delays due to Nonconformances**. Please, note that in this case a nonconformance refer to the following disruptions:

- **Interruptions**, when an activity is temporarily discontinued due to nonconformances related to the delays on the supplying of resources (labor, material, equipment, information, instructions, etc.), unforeseen work conditions, and accidents.
- **Low productivity periods**, when work is observed progressing at a slower pace than in normal or average workdays. This could be caused by nonconformities concerning delays on the supplying of resources, unforeseen work conditions, and/or poor performance of labor or equipment, etc.
- **Reworks**, when a part or the entire work already executed in a given activity needs to be redone due to not succeeding on meeting the specifications or requirements.

Also consider that adverse **weather conditions are not deemed causes of nonconformances** in this case.

1. Based on your expertise, assign an appropriate numerical value or range of values for each of the linguistic terms established to evaluate the **Number of Nonconformances** that may occur during the undertaking of an open-cut construction project that is similar to the one you are currently appointed to, in terms of type (i.e. sanitary sewer) and size (i.e. between 700 and 1000 ft). Please, consider the planned duration of each of the required activities (i.e. excavation, pipe installation, and bedding) to make your assessments.

You can overrun the bounds between one level and the next one for making your assessments if you are uncertain on what term a given value should belong to (for example, the *Very Small* is between 0 and 2 and *Small* is between 1 and 3). You can also skip the assessment of any of the linguistic terms; please, leave the space in blank and mark the box to point out that you consider the term is unsuitable for the assessment of the number of nonconformances in open-cut construction activities. You should then assume that the lowest value is zero for the first term you consider as the initial one for assessing the number of nonconformances.

1. In the **Excavation**, what **number of nonconformances** would you consider as													**Skip?**
a. ***Very Small?***	0	1	2	3	4	5	6	7	8	9	10	> 10	
b. ***Small?***	0	1	2	3	4	5	6	7	8	9	10	> 10	
c. ***Medium?***	0	1	2	3	4	5	6	7	8	9	10	> 10	
d. ***Large?***	0	1	2	3	4	5	6	7	8	9	10	> 10	
e. ***Very Large?***	0	1	2	3	4	5	6	7	8	9	10	> 10	

2. In the **Pipe Installation**, what **number of nonconformances** would you consider as													**Skip?**
a. ***Very Small?***	0	1	2	3	4	5	6	7	8	9	10	> 10	
b. ***Small?***	0	1	2	3	4	5	6	7	8	9	10	> 10	
c. ***Medium?***	0	1	2	3	4	5	6	7	8	9	10	> 10	
d. ***Large?***	0	1	2	3	4	5	6	7	8	9	10	> 10	
e. ***Very Large?***	0	1	2	3	4	5	6	7	8	9	10	> 10	

3. In the **Bedding**, what **number of nonconformances** would you consider as													**Skip?**
a. ***Very Small?***	0	1	2	3	4	5	6	7	8	9	10	> 10	
b. ***Small?***	0	1	2	3	4	5	6	7	8	9	10	> 10	
c. ***Medium?***	0	1	2	3	4	5	6	7	8	9	10	> 10	
d. ***Large?***	0	1	2	3	4	5	6	7	8	9	10	> 10	
e. ***Very Large?***	0	1	2	3	4	5	6	7	8	9	10	> 10	

2. Based on your judgment, please circle a value or range of values that according to your experience would appropriately represent each of the linguistic terms established for the **Duration of a Delay** event (in hours) due to the occurrence of a nonconformance during the undertaking of the open-cut construction activities.

You can overrun the bounds between one level and the next one for making your assessments if you are uncertain on what term a given value should belong to (for example, the *Very Small* is between 0 and 2.0 hours and *Small* is between 1.0 and 3.0 hours). You can also skip the assessment of any of the linguistic terms; please, leave the space in blank and mark the box to point out that you consider the term is unsuitable for the assessment of the duration of delays due to nonconformances in open-cut construction activities. You should then assume that the lowest value is zero for the first term you consider as the initial one for assessing the duration of delays.

For the **duration of a delay event due to a nonconformance**, what number of **hours** would you consider as													**Skip?**
a. ***Very Small***?	< 1.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	> 10.0	
b. ***Small***?	< 1.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	> 10.0	
c. ***Medium***?	< 1.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	> 10.0	
d. ***Large***?	< 1.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	> 10.0	
e. ***Very Large***?	< 1.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	> 10.0	

II. Questions for eliciting the inference rules of the effect of the performance of construction resources upon open-cut activities

This section focuses on the assessment of variables related to the effect of the performance of the construction resources involved in the undertaking of **open-cut construction** activities. In this case, *the performance of resources refers to the capability of the resources to accomplish their corresponding task within the operation without being the direct cause of nonconformances.* Moreover, the requirements for quality performance for each of the construction resources to be evaluated are briefly described in Table 1 annexed to this survey.

The variables you will be required to evaluate include:

- The frequency of occurrence of the performance levels of the construction resources in a given activity,
- The combined effect of the performance levels of construction resources and the frequency of occurrence of such performance levels upon the level of adverse consequences on the activity under analysis,
- The effect of the level of adverse consequences upon the number of nonconformities and the duration of delays in the activity under analysis.

Based on your experience, please link the given linguistic terms that better describe the effect of each of the performance levels of the construction resources upon the aforementioned variables in an open-cut construction project that is similar to the one you are currently appointed to, in terms of type (i.e. sanitary sewer) and size (i.e. between 700 and 1000 ft). For example, assuming the performance level of **Material Supplying** (from Vendors) during the excavation of trench activity is **Poor**,

1. What is the Frequency of the Occurrence of the **Poor** performance of material supplying in excavation?
   Answer 1: **Often**
2. Then, what is the Adverse Consequence of the **Poor** performance of material supplying to the completion time of the excavation activity?
   Answer 2: **Severe**
3. Then, what is the expected Number of Nonconformances to occur during the excavation activity given the level of adverse consequences?
   Answer 3: **Large**
4. And, what is the expected Duration of a single Delay due to the occurrence of a nonconformance during the excavation activity, given the level of adverse consequences?
   Answer 4: **Medium**

The answers provided above for the effect of **Poor** performance of material supplying on the excavation activity are depicted in the following table.

Performance Level of Material Supplying	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
Poor	Very Unusual	Very Mild	Very Small	Very Small
	Unusual	Mild	Small	Small
	[✓ **Often**]	Medium	Medium	[✓ **Medium**]
	Usual	[✓ **Severe**]	[✓ **Large**]	Large
	Very Usual	Very Severe	Very Large	Very Large

1. Evaluation of the effect of the performance of construction resources on EXCAVATION

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
a.Evaluate the effect of the performance of the **Material/ Equipment Supplying (from Vendors) on Excavation**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
b.Evaluate the effect of the performance of the **Stacking Subcontracted Service on Excavation**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
c. Evaluate the effect of the performance of the **Equipment on Excavation**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
d. Evaluate the effect of the performance of the **Work Conditions on Excavation**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
e. Evaluate the effect of the performance of the **Design/ Drafting Information on Excavation**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

2. Evaluation of the effect of the quality of construction resources on PIPE INSTALLATION

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
a. Evaluate the effect of the performance of the **Material/ Equipment Supplying from Vendors on Pipe Installation**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

	Performance Level	Frequency of Occurrence of the Performance Level	Adverse Consequence	Number of Nonconformances	Duration of Delays due to Nonconformances
b. Evaluate the effect of the performance of the **Stacking Subcontracted Service on Pipe Installation**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

	Performance Level	Frequency of Occurrence of the Performance Level	Adverse Consequence	Number of Nonconformances	Duration of Delays due to Nonconformances
c. Evaluate the effect of the performance of the **Equipment on Pipe Installation**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
d.Evaluate the effect of the performance of the **Work Conditions on Pipe Installation**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
e.Evaluate the effect of the performance of the **Design/ Drafting Information on Pipe Installation**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

3. Evaluation of the effect of the quality of construction resources on BEDDING

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
a. Evaluate the effect of the performance of the **Material/ Equipment Supplying from Vendors on Bedding**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
b. Evaluate the effect of the performance of the **Stacking Subcontracted Service on Bedding**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
c. Evaluate the effect of the performance of the **Equipment on Bedding**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
d. Evaluate the effect of the performance of the **Work Conditions on Bedding**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

	Performance Level	*Frequency of Occurrence of the Performance Level*	*Adverse Consequence*	*Number of Nonconformances*	*Duration of Delays due to Nonconformances*
e.Evaluate the effect of the performance of the **Design/ Drafting Information on Bedding**	Very Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Poor	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Average	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large
	Very Good	Very Unusual	Very Mild	Very Small	Very Small
		Unusual	Mild	Small	Small
		Often	Medium	Medium	Medium
		Usual	Severe	Large	Large
		Very Usual	Very Severe	Very Large	Very Large

Final comments you want to add:

THANKS FOR YOUR CONTRIBUTION!

APPENDIX E

ANALYSIS OF NONCONFORMANCE RECORDS CONTAINED IN THE D&C's QIMS

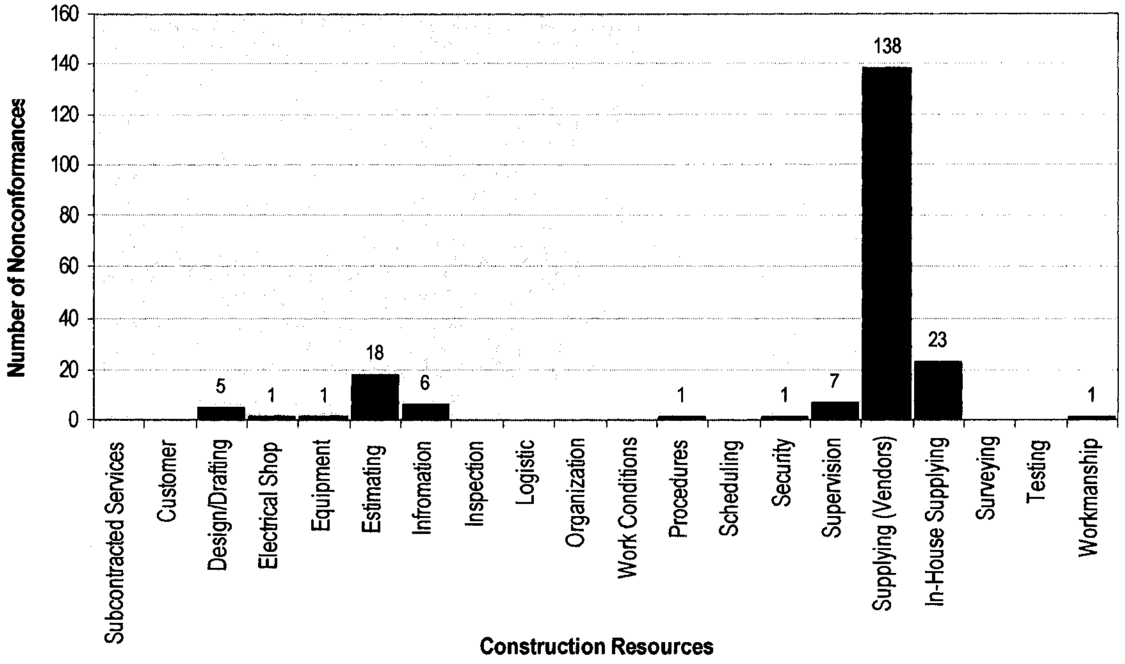

Figure E.1: Frequency of nonconformances that affected the cost of construction projects

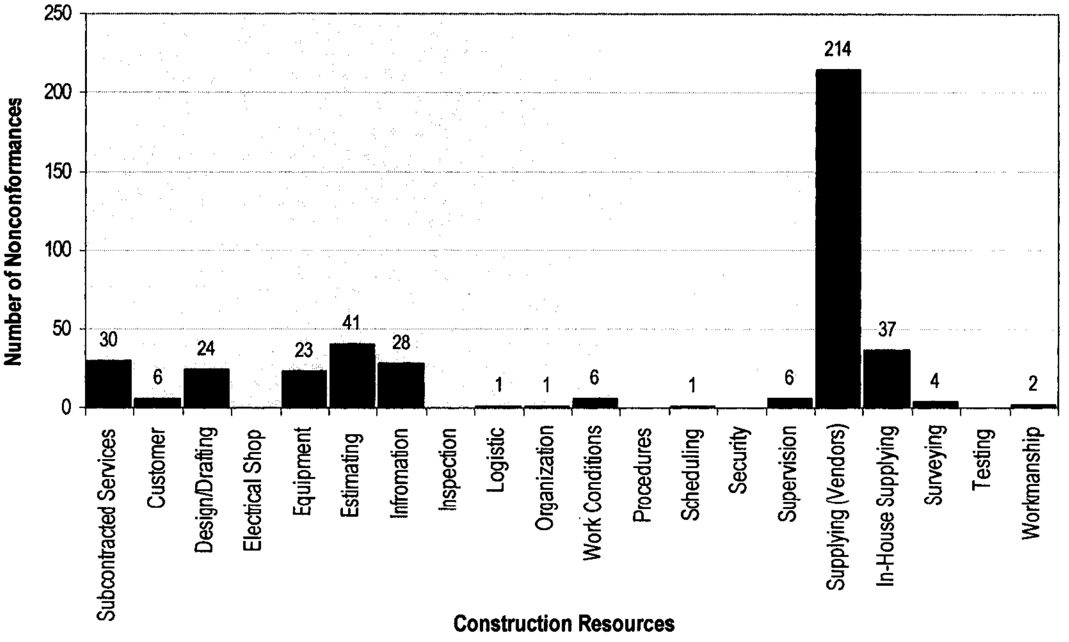

Figure E.2: Frequency of nonconformances that affected the schedule of construction projects

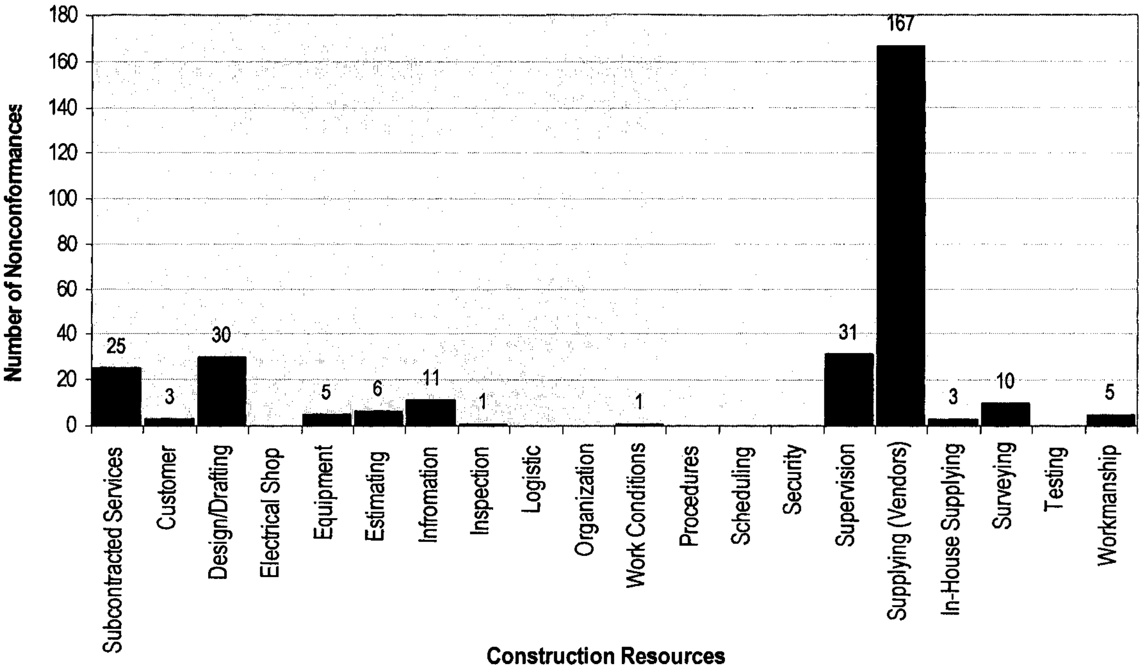

Figure E.3: Frequency of nonconformances that affected the quality* of construction projects

*Nonconformances affecting quality refer to out of specification works that required rework to comply with specifications.

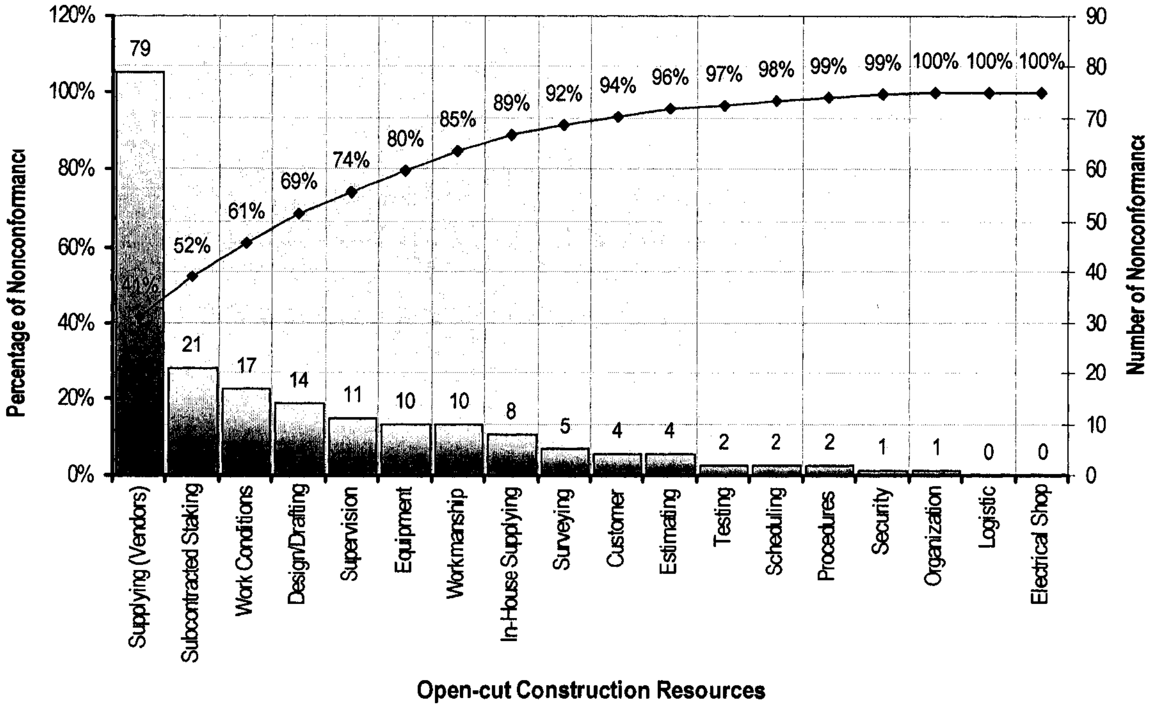

Figure E.4: Pareto analysis of nonconformances affecting quality in open-cut construction projects

APPENDIX F

PROCEDURES FOR OPEN-CUT CONSTRUCTION PROJECTS IN D&C

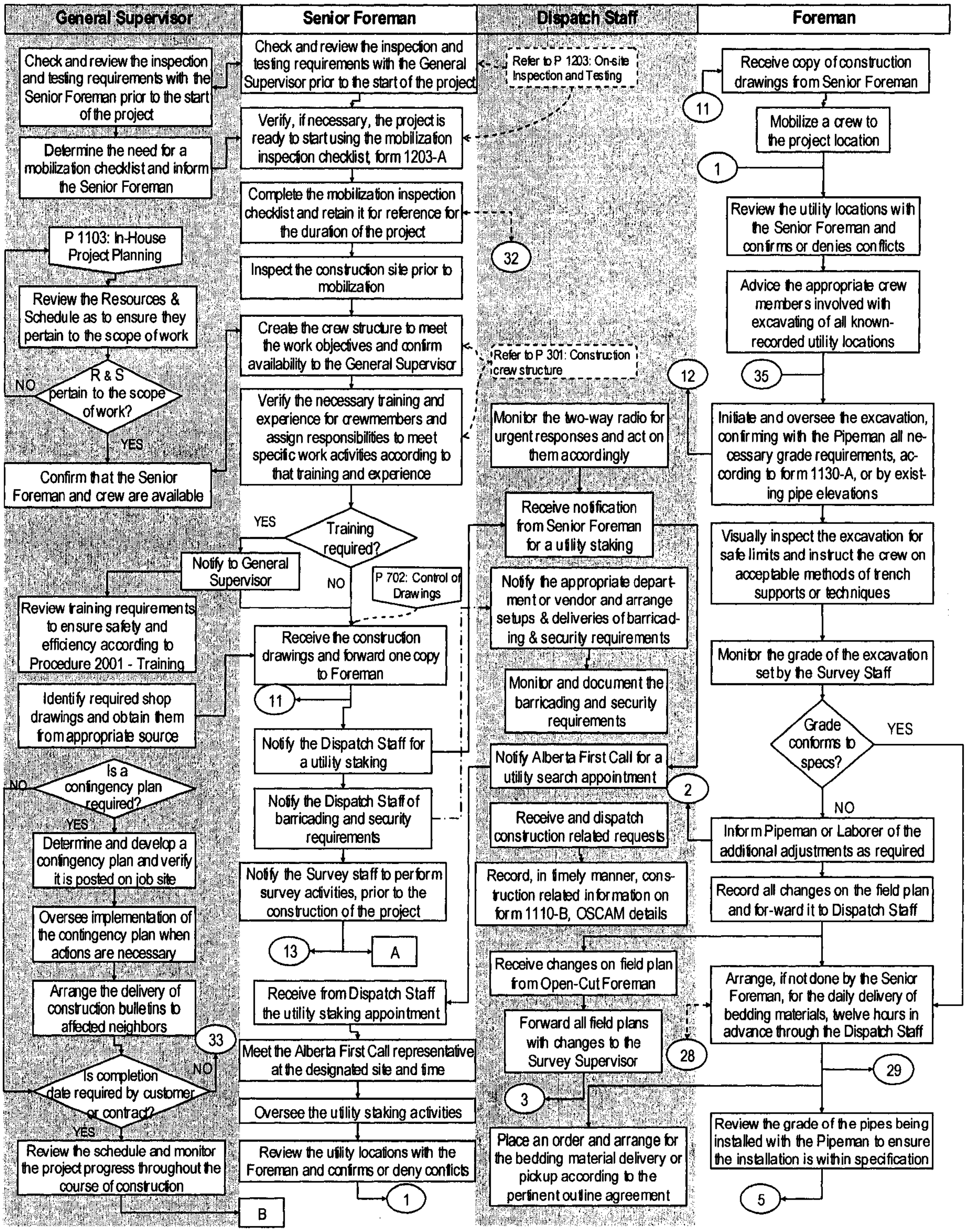

Figure F.1: Open-cut construction procedures in D&C

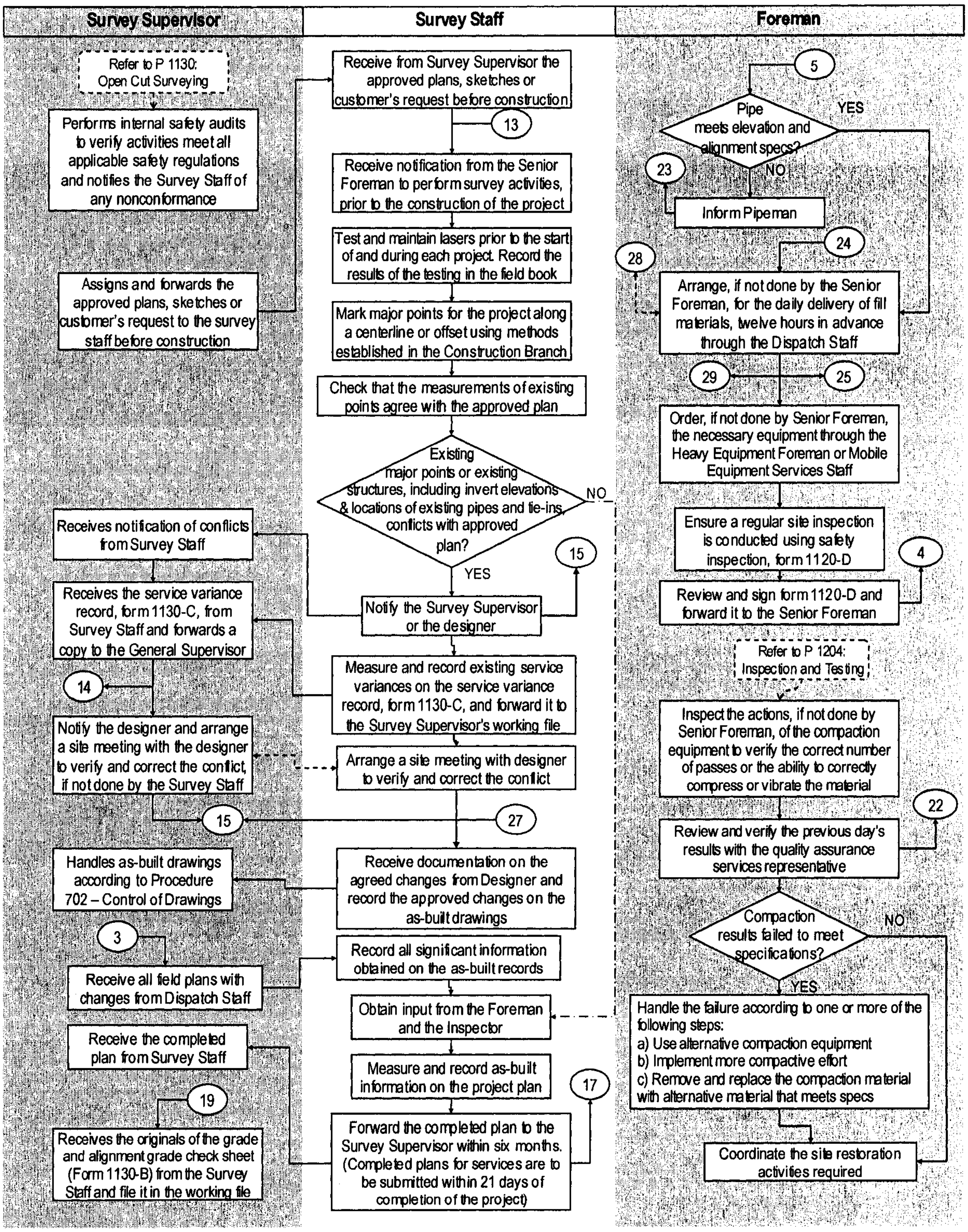

Figure F.1: Open-cut construction procedures in D&C (continuation)

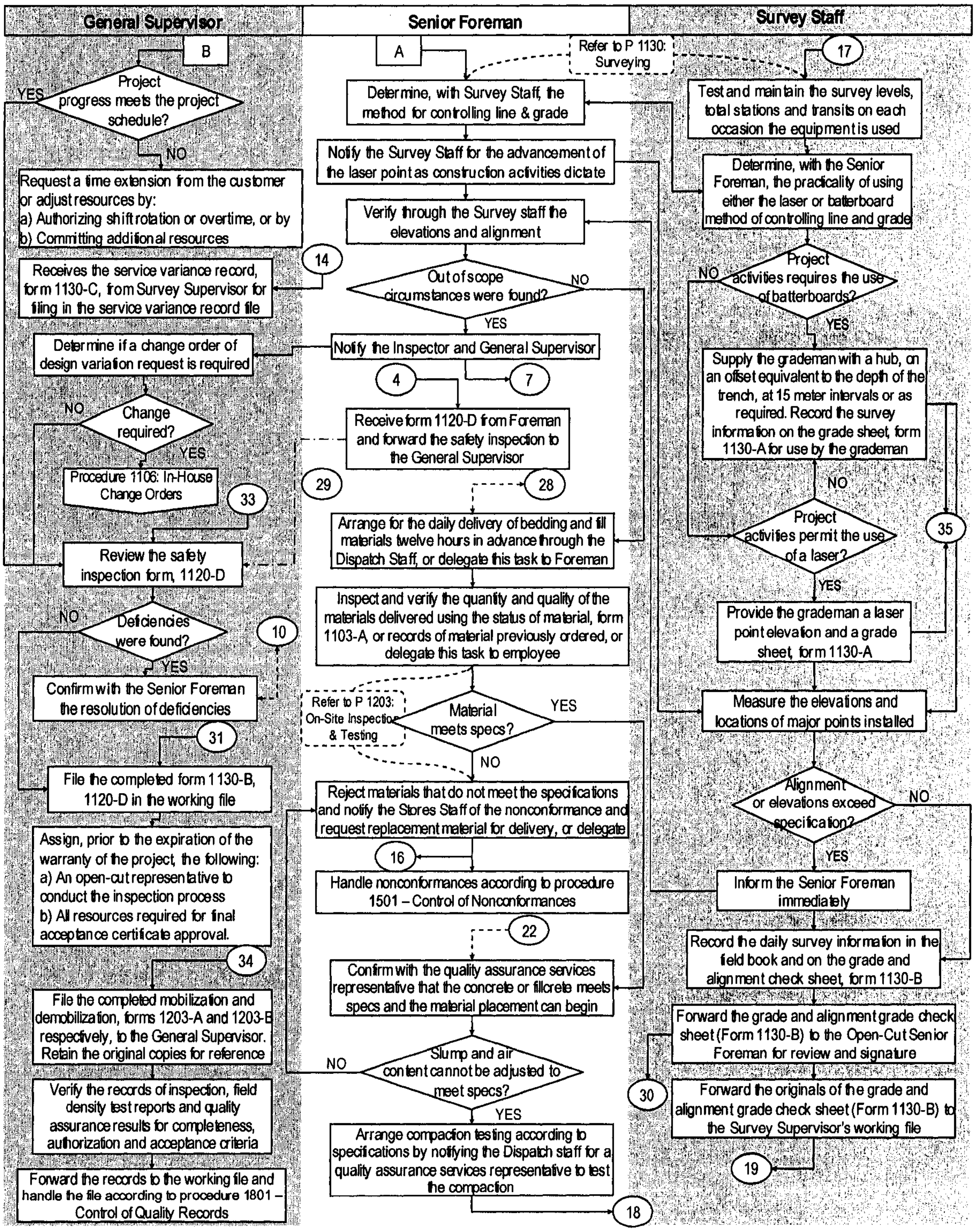

Figure F.1: Open-cut construction procedures in D&C (continuation)

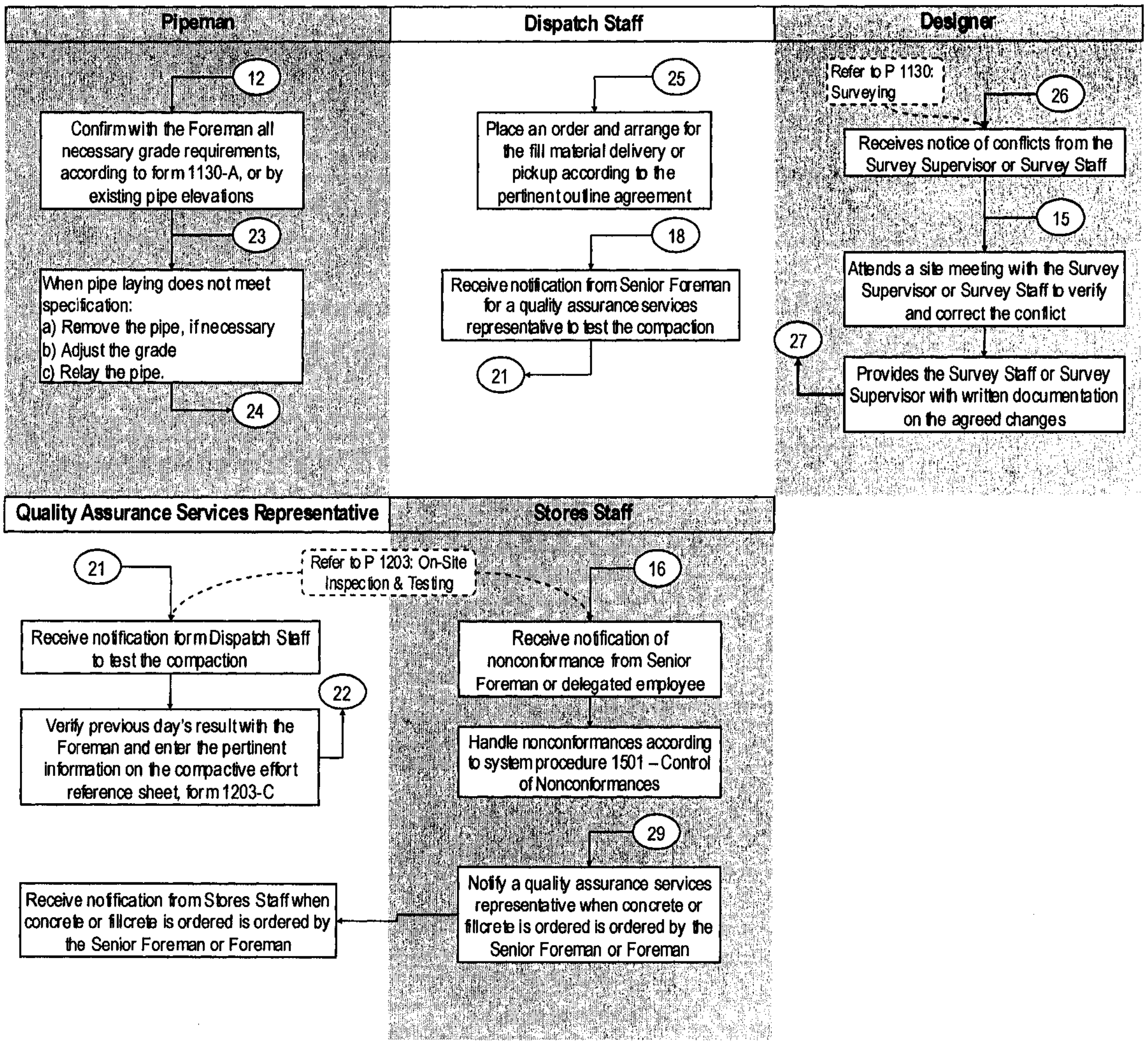

Figure F.1: Open-cut construction procedures in D&C (continuation)

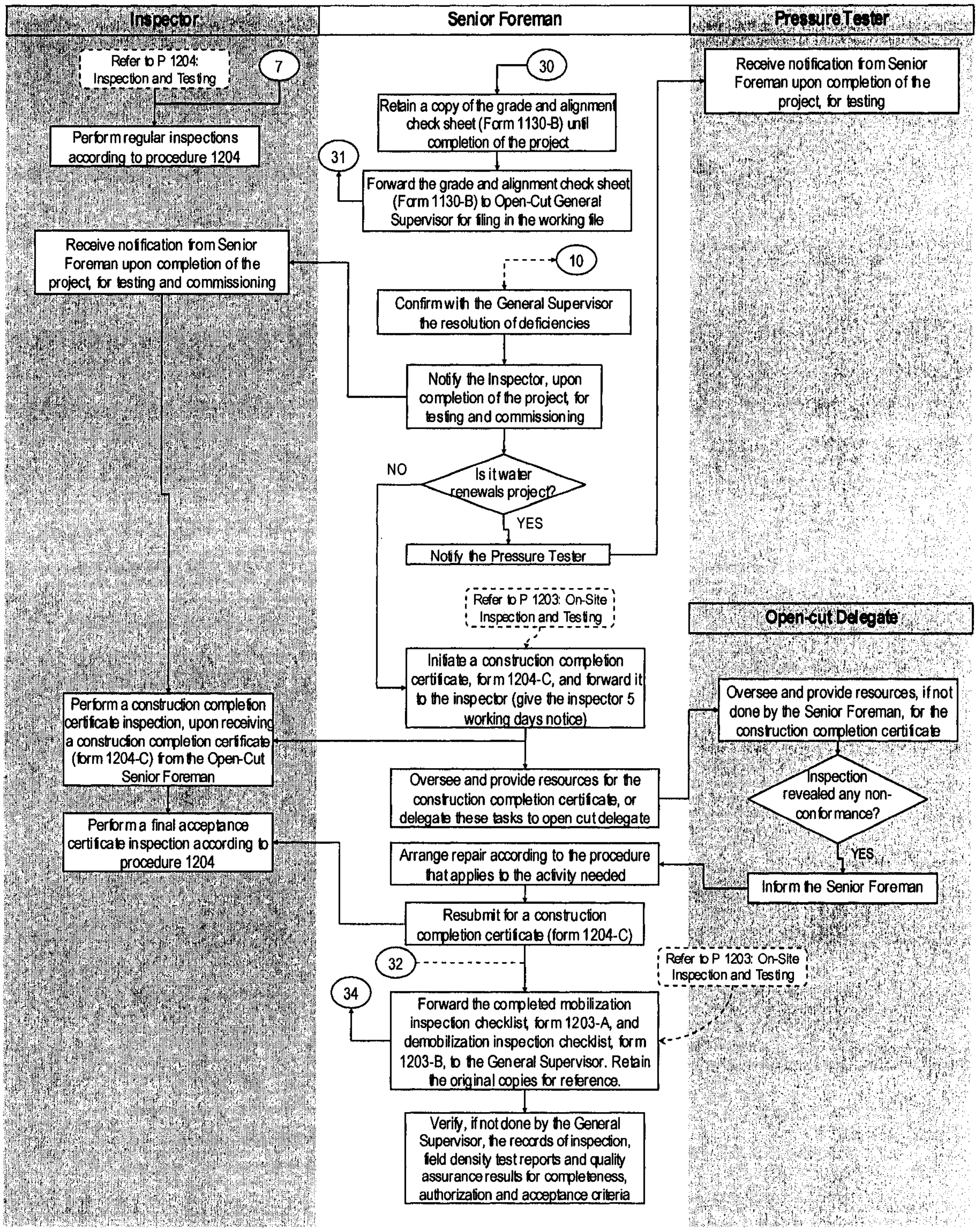

Figure F.1: Open-cut construction procedures in D&C (continuation)

APPENDIX G

FUZZY MEMBERSHIP FUNCTIONS GENERATED FOR THE CASE STUDY

Table G.1 (a): Fuzzy membership functions for the performance maturity level of PQM practices

Linguistic Terms	Fuzzy Membership Functions											
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	Shape
No Formal Approach =	1.00	1.00	0.67	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Trap
Reactive Approach =	0.00	0.00	0.50	1.00	1.00	0.67	0.33	0.00	0.00	0.00	0.00	Trap
Stable Formal =	0.00	0.00	0.00	0.00	0.33	0.67	1.00	0.67	0.33	0.00	0.00	Triang
Continual Improve =	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00	0.50	0.00	Triang
Best-in-Class =	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00	1.00	Trap

Table G.1 (b): Fuzzy membership functions for the quality performance level of construction resources (Q)

Linguistic Terms	Fuzzy Membership Functions											
	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	Shape
Very Poor =	1.00	1.00	0.67	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Trap
Poor =	0.00	0.33	0.67	1.00	1.00	0.50	0.00	0.00	0.00	0.00	0.00	Trap
Average =	0.00	0.00	0.00	0.00	0.33	0.67	1.00	0.50	0.00	0.00	0.00	Triang
Good =	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00	1.00	0.50	0.00	Trap
Very Good =	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.67	1.00	Triang

Table G.1 (c): Fuzzy membership functions for the frequency level of occurrence of the quality levels (F)

Linguistic Terms	Fuzzy Membership Functions											
	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	Shape
Very Unusual =	1.00	1.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Trap
Unusual =	0.00	0.50	1.00	1.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	Trap
Often =	0.00	0.00	0.00	0.00	0.50	1.00	1.00	0.50	0.00	0.00	0.00	Trap
Usual =	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00	1.00	0.50	0.00	Trap
Very Usual =	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00	1.00	Trap

Table G.1 (d): Fuzzy membership functions for the adverse consequences (C)

Linguistic Terms	Fuzzy Membership Functions											
	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	Shape
Very Mild =	1.00	1.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Trap
Mild =	0.00	0.50	1.00	1.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	Trap
Medium =	0.00	0.00	0.00	0.00	0.50	1.00	1.00	0.50	0.00	0.00	0.00	Trap
Severe =	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00	1.00	0.50	0.00	Trap
Very Severe =	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00	1.00	Trap

Table G.2 (a): Fuzzy membership functions representing the Number of Nonconformances in open-cut construction activities

Open-cut Construction Activity	Linguistic Terms	Fuzzy Membership Functions											
		0.0	1.0	2.0	3.0	4.0	5.0						Shape
EXCAVATION	Very Small =	1.0	0.67	0.33	0.00	0.00	0.00						Triang
	Small =	0.00	1.00	0.67	0.33	0.00	0.00						Triang
	Medium =	0.00	0.50	1.00	0.67	0.33	0.00						Triang
	Large =	0.00	0.00	0.00	0.50	1.00	0.00						Triang
	Very Large =	0.00	0.00	0.00	0.33	0.67	1.00						Triang

		0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0				
PIPE INSTALLATION	Very Small =	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0				Triang
	Small =	0.00	1.00	1.00	0.50	0.00	0.00	0.00	0.00				Trap
	Medium =	0.00	0.00	0.33	0.67	1.00	0.50	0.00	0.00				Triang
	Large =	0.00	0.00	0.00	0.00	0.50	1.00	0.50	0.00				Triang
	Very Large =	0.00	0.00	0.00	0.00	0.25	0.50	0.75	1.00				Triang

		0.0	1.0	2.0	3.0	4.0	5.0						
BEDDING	Very Small =	1.0	0.5	0.0	0.0	0.0	0.0						Triang
	Small =	0.00	1.00	0.50	0.00	0.00	0.00						Triang
	Medium =	0.00	0.50	1.00	0.67	0.33	0.00						Triang
	Large =	0.00	0.00	0.00	1.00	0.50	0.00						Triang
	Very Large =	0.00	0.00	0.00	0.33	0.67	1.00						Triang

		0.0	1.0	2.0	3.0	4.0	5.0						
BACKFILLING	Very Small =	1.0	0.5	0.0	0.0	0.0	0.0						Triang
	Small =	0.00	1.00	0.50	0.00	0.00	0.00						Triang
	Medium =	0.00	0.50	1.00	0.67	0.33	0.00						Triang
	Large =	0.00	0.00	0.50	1.00	0.50	0.00						Triang
	Very Large =	0.00	0.00	0.00	0.00	0.50	1.00						Triang

Table G.2 (b): Fuzzy membership functions for the Duration of Delays due to Nonconformances in open-cut construction activities

Linguistic Terms	Fuzzy Membership Functions											
	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	Shape
Very Small =	1.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Triang
Small =	0.00	1.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Triang
Medium =	0.00	0.00	1.00	1.00	0.67	0.33	0.00	0.00	0.00	0.00	0.00	Trap
Large =	0.00	0.00	0.33	0.67	1.00	1.00	0.75	0.50	0.25	0.00	0.00	Trap
Very Large =	0.00	0.00	0.00	0.00	0.33	0.67	1.00	1.00	1.00	1.00	1.00	Trap

APPENDIX H

FUZZY INFERENCE RULES GENERATED FOR THE CASE STUDY

Table H.1(a): Calculations for determining the rule consequents of the Nonconformity Level of Nonconformances effecting the Design/Drafting

Rule consequents of the *Number of Late Deliveries of Design Information*

	Change & Communication Mananagement	R.I.	I.O	CE	Expediting	R.I.	I.O	CE	Total CE	Normal CE	Consequent
R1	No Formal Approach	0.50	-4	-2	No Formal Approach	0.50	-4	-2	-4	0.00	Very High
R2	No Formal Approach	0.50	-4	-2	Reactive Approach	0.50	0	0	-2	0.25	High
R3	No Formal Approach	0.50	-4	-2	Stable Formal	0.50	2	1	-1	0.38	High
R4	No Formal Approach	0.50	-4	-2	Continual Improve	0.50	3	1.5	-0.5	0.44	Average
R5	No Formal Approach	0.50	-4	-2	Best-in-Class	0.50	4	2	0	0.50	Average
R6	Reactive Approach	0.50	0	0	No Formal Approach	0.50	-4	-2	-2	0.25	High
R7	Reactive Approach	0.50	0	0	Reactive Approach	0.50	0	0	0	0.50	Average
R8	Reactive Approach	0.50	0	0	Stable Formal	0.50	2	1	1	0.63	Low
R9	Reactive Approach	0.50	0	0	Continual Improve	0.50	3	1.5	1.5	0.69	Low
R10	Reactive Approach	0.50	0	0	Best-in-Class	0.50	4	2	2	0.75	Low
R11	Stable Formal	0.50	2	1	No Formal Approach	0.50	-4	-2	-1	0.38	High
R12	Stable Formal	0.50	2	1	Reactive Approach	0.50	0	0	1	0.63	Low
R13	Stable Formal	0.50	2	1	Stable Formal	0.50	2	1	2	0.75	Low
R14	Stable Formal	0.50	2	1	Continual Improve	0.50	3	1.5	2.5	0.81	Very Low
R15	Stable Formal	0.50	2	1	Best-in-Class	0.50	4	2	3	0.88	Very Low
R16	Continual Improve	0.50	3	1.5	No Formal Approach	0.50	-4	-2	-0.5	0.44	Average
R17	Continual Improve	0.50	3	1.5	Reactive Approach	0.50	0	0	1.5	0.69	Low
R18	Continual Improve	0.50	3	1.5	Stable Formal	0.50	2	1	2.5	0.81	Very Low
R19	Continual Improve	0.50	3	1.5	Continual Improve	0.50	3	1.5	3	0.88	Very Low
R20	Continual Improve	0.50	3	1.5	Best-in-Class	0.50	4	2	3.5	0.94	Very Low
R21	Best-in-Class	0.50	4	2	No Formal Approach	0.50	-4	-2	0	0.50	Average
R22	Best-in-Class	0.50	4	2	Reactive Approach	0.50	0	0	2	0.75	Low
R23	Best-in-Class	0.50	4	2	Stable Formal	0.50	2	1	3	0.88	Very Low
R24	Best-in-Class	0.50	4	2	Continual Improve	0.50	3	1.5	3.5	0.94	Very Low
R25	Best-in-Class	0.50	4	2	Best-in-Class	0.50	4	2	4	1.00	Very Low

Rule consequents of the *Number of Errors in Drawings & Specifications*

	Internal and external examinations	R.I.	I.O	CE	Personnel Qualification & Training	R.I.	I.O	CE	Total CE	Normal CE	Consequent
R1	No Formal Approach	0.33	-4	-1.32	No Formal Approach	0.67	-4	-2.68	-4	0.00	Very High
R2	No Formal Approach	0.33	-4	-1.32	Reactive Approach	0.67	0	0	-1.32	0.34	High
R3	No Formal Approach	0.33	-4	-1.32	Stable Formal	0.67	2	1.34	0.02	0.50	Average
R4	No Formal Approach	0.33	-4	-1.32	Continual Improve	0.67	3	2.01	0.69	0.59	Average
R5	No Formal Approach	0.33	-4	-1.32	Best-in-Class	0.67	4	2.68	1.36	0.67	Low
R6	Reactive Approach	0.33	0	0	No Formal Approach	0.67	-4	-2.68	-2.68	0.17	Very High
R7	Reactive Approach	0.33	0	0	Reactive Approach	0.67	0	0	0	0.50	Average
R8	Reactive Approach	0.33	0	0	Stable Formal	0.67	2	1.34	1.34	0.67	Low
R9	Reactive Approach	0.33	0	0	Continual Improve	0.67	3	2.01	2.01	0.75	Low
R10	Reactive Approach	0.33	0	0	Best-in-Class	0.67	4	2.68	2.68	0.84	Very Low
R11	Stable Formal	0.33	2	0.66	No Formal Approach	0.67	-4	-2.68	-2.02	0.25	High
R12	Stable Formal	0.33	2	0.66	Reactive Approach	0.67	0	0	0.66	0.58	Average
R13	Stable Formal	0.33	2	0.66	Stable Formal	0.67	2	1.34	2	0.75	Low
R14	Stable Formal	0.33	2	0.66	Continual Improve	0.67	3	2.01	2.67	0.83	Very Low
R15	Stable Formal	0.33	2	0.66	Best-in-Class	0.67	4	2.68	3.34	0.92	Very Low
R16	Continual Improve	0.33	3	0.99	No Formal Approach	0.67	-4	-2.68	-1.69	0.29	High
R17	Continual Improve	0.33	3	0.99	Reactive Approach	0.67	0	0	0.99	0.62	Low
R18	Continual Improve	0.33	3	0.99	Stable Formal	0.67	2	1.34	2.33	0.79	Low
R19	Continual Improve	0.33	3	0.99	Continual Improve	0.67	3	2.01	3	0.88	Very Low
R20	Continual Improve	0.33	3	0.99	Best-in-Class	0.67	4	2.68	3.67	0.96	Very Low
R21	Best-in-Class	0.33	4	1.32	No Formal Approach	0.67	-4	-2.68	-1.36	0.33	High
R22	Best-in-Class	0.33	4	1.32	Reactive Approach	0.67	0	0	1.32	0.67	Low
R23	Best-in-Class	0.33	4	1.32	Stable Formal	0.67	2	1.34	2.66	0.83	Very Low
R24	Best-in-Class	0.33	4	1.32	Continual Improve	0.67	3	2.01	3.33	0.92	Very Low
R25	Best-in-Class	0.33	4	1.32	Best-in-Class	0.67	4	2.68	4	1.00	Very Low

Note: R.I.= Relative Importance, I.O. = Impact on the Output, CE = Combined Effect, R1, R2,...= Number of the Rule

Continuation Table H.1(a)

Rule consequents of the *Number of Changes on Design*

	Constructability review	R.I.	I.O	CE	Operability & Value Review	R.I.	I.O	CE	Total CE	Normal CE	Consequent
R1	No Formal Approach	0.50	-4	-2	No Formal Approach	0.50	-4	-2	-4	0.00	Very High
R2	No Formal Approach	0.50	-4	-2	Reactive Approach	0.50	0	0	-2	0.25	High
R3	No Formal Approach	0.50	-4	-2	Stable Formal	0.50	2	1	-1	0.38	High
R4	No Formal Approach	0.50	-4	-2	Continual Improve	0.50	3	1.5	-0.5	0.44	Average
R5	No Formal Approach	0.50	-4	-2	Best-in-Class	0.50	4	2	0	0.50	Average
R6	Reactive Approach	0.50	0	0	No Formal Approach	0.50	-4	-2	-2	0.25	High
R7	Reactive Approach	0.50	0	0	Reactive Approach	0.50	0	0	0	0.50	Average
R8	Reactive Approach	0.50	0	0	Stable Formal	0.50	2	1	1	0.63	Low
R9	Reactive Approach	0.50	0	0	Continual Improve	0.50	3	1.5	1.5	0.69	Low
R10	Reactive Approach	0.50	0	0	Best-in-Class	0.50	4	2	2	0.75	Low
R11	Stable Formal	0.50	2	1	No Formal Approach	0.50	-4	-2	-1	0.38	High
R12	Stable Formal	0.50	2	1	Reactive Approach	0.50	0	0	1	0.63	Low
R13	Stable Formal	0.50	2	1	Stable Formal	0.50	2	1	2	0.75	Low
R14	Stable Formal	0.50	2	1	Continual Improve	0.50	3	1.5	2.5	0.81	Very Low
R15	Stable Formal	0.50	2	1	Best-in-Class	0.50	4	2	3	0.88	Very Low
R16	Continual Improve	0.50	3	1.5	No Formal Approach	0.50	-4	-2	-0.5	0.44	Average
R17	Continual Improve	0.50	3	1.5	Reactive Approach	0.50	0	0	1.5	0.69	Low
R18	Continual Improve	0.50	3	1.5	Stable Formal	0.50	2	1	2.5	0.81	Very Low
R19	Continual Improve	0.50	3	1.5	Continual Improve	0.50	3	1.5	3	0.88	Very Low
R20	Continual Improve	0.50	3	1.5	Best-in-Class	0.50	4	2	3.5	0.94	Very Low
R21	Best-in-Class	0.50	4	2	No Formal Approach	0.50	-4	-2	0	0.50	Average
R22	Best-in-Class	0.50	4	2	Reactive Approach	0.50	0	0	2	0.75	Low
R23	Best-in-Class	0.50	4	2	Stable Formal	0.50	2	1	3	0.88	Very Low
R24	Best-in-Class	0.50	4	2	Continual Improve	0.50	3	1.5	3.5	0.94	Very Low
R25	Best-in-Class	0.50	4	2	Best-in-Class	0.50	4	2	4	1.00	Very Low

Table H.1(b): Calculations for determining the rule consequents of the Quality Level of the Design/Drafting Information

	Number of changes on design	R.I.	I.O	CE	Number of errors in drawings & specifications	R.I.	I.O	CE	Number of late deliveries of information	R.I.	I.O	CE	Total CE	Normal CE	Consequent
R1	Very Low	0.40	3	1.2	Very Low	0.40	4	1.6	Very Low	0.20	4	0.8	3.6	1.00	Very Good
R2	Very Low	0.40	3	1.2	Very Low	0.40	4	1.6	Low	0.20	2	0.4	3.2	0.95	Very Good
R3	Very Low	0.40	3	1.2	Very Low	0.40	4	1.6	Average	0.20	-1	-0.2	2.6	0.87	Very Good
R4	Very Low	0.40	3	1.2	Very Low	0.40	4	1.6	High	0.20	-3	-0.6	2.2	0.82	Good
R5	Very Low	0.40	3	1.2	Very Low	0.40	4	1.6	Very High	0.20	-4	-0.8	2	0.79	Good
R6	Very Low	0.40	3	1.2	Low	0.40	3	1.2	Very Low	0.20	4	0.8	3.2	0.95	Very Good
R7	Very Low	0.40	3	1.2	Low	0.40	3	1.2	Low	0.20	2	0.4	2.8	0.89	Very Good
R8	Very Low	0.40	3	1.2	Low	0.40	3	1.2	Average	0.20	-1	-0.2	2.2	0.82	Good
R9	Very Low	0.40	3	1.2	Low	0.40	3	1.2	High	0.20	-3	-0.6	1.8	0.76	Good
R10	Very Low	0.40	3	1.2	Low	0.40	3	1.2	Very High	0.20	-4	-0.8	1.6	0.74	Good
R11	Very Low	0.40	3	1.2	Average	0.40	-1	-0.4	Very Low	0.20	4	0.8	1.6	0.74	Good
R12	Very Low	0.40	3	1.2	Average	0.40	-1	-0.4	Low	0.20	2	0.4	1.2	0.68	Good
R13	Very Low	0.40	3	1.2	Average	0.40	-1	-0.4	Average	0.20	-1	-0.2	0.6	0.61	Average
R14	Very Low	0.40	3	1.2	Average	0.40	-1	-0.4	High	0.20	-3	-0.6	0.2	0.55	Average
R15	Very Low	0.40	3	1.2	Average	0.40	-1	-0.4	Very High	0.20	-4	-0.8	0	0.53	Average
R16	Very Low	0.40	3	1.2	High	0.40	-3	-1.2	Very Low	0.20	4	0.8	0.8	0.63	Average
R17	Very Low	0.40	3	1.2	High	0.40	-3	-1.2	Low	0.20	2	0.4	0.4	0.58	Average
R18	Very Low	0.40	3	1.2	High	0.40	-3	-1.2	Average	0.20	-1	-0.2	-0.2	0.50	Average
R19	Very Low	0.40	3	1.2	High	0.40	-3	-1.2	High	0.20	-3	-0.6	-0.6	0.45	Poor
R20	Very Low	0.40	3	1.2	High	0.40	-3	-1.2	Very High	0.20	-4	-0.8	-0.8	0.42	Poor
R21	Very Low	0.40	3	1.2	Very High	0.40	-4	-1.6	Very Low	0.20	4	0.8	0.4	0.58	Average
R22	Very Low	0.40	3	1.2	Very High	0.40	-4	-1.6	Low	0.20	2	0.4	0	0.53	Average
R23	Very Low	0.40	3	1.2	Very High	0.40	-4	-1.6	Average	0.20	-1	-0.2	-0.6	0.45	Poor
R24	Very Low	0.40	3	1.2	Very High	0.40	-4	-1.6	High	0.20	-3	-0.6	-1	0.39	Poor
R25	Very Low	0.40	3	1.2	Very High	0.40	-4	-1.6	Very High	0.20	-4	-0.8	-1.2	0.37	Poor
R26	Low	0.40	2	0.8	Very Low	0.40	4	1.6	Very Low	0.20	4	0.8	3.2	0.95	Very Good
R27	Low	0.40	2	0.8	Very Low	0.40	4	1.6	Low	0.20	2	0.4	2.8	0.89	Very Good
R28	Low	0.40	2	0.8	Very Low	0.40	4	1.6	Average	0.20	-1	-0.2	2.2	0.82	Good
R29	Low	0.40	2	0.8	Very Low	0.40	4	1.6	High	0.20	-3	-0.6	1.8	0.76	Good
R30	Low	0.40	2	0.8	Very Low	0.40	4	1.6	Very High	0.20	-4	-0.8	1.6	0.74	Good

Note: R.I.= Relative Importance, I.O. = Impact on the Output, CE = Combined Effect, R1, R2,...= Number of the Rule

Continuation Table H.1(b)

R31	Low	0.40	2	0.8	Low	0.40	3	1.2	Very Low	0.20	4	0.8	2.8	0.89	Very Good
R32	Low	0.40	2	0.8	Low	0.40	3	1.2	Low	0.20	2	0.4	2.4	0.84	Good
R33	Low	0.40	2	0.8	Low	0.40	3	1.2	Average	0.20	-1	-0.2	1.8	0.76	Good
R34	Low	0.40	2	0.8	Low	0.40	3	1.2	High	0.20	-3	-0.6	1.4	0.71	Good
R35	Low	0.40	2	0.8	Low	0.40	3	1.2	Very High	0.20	-4	-0.8	1.2	0.68	Good
R36	Low	0.40	2	0.8	Average	0.40	-1	-0.4	Very Low	0.20	4	0.8	1.2	0.68	Good
R37	Low	0.40	2	0.8	Average	0.40	-1	-0.4	Low	0.20	2	0.4	0.8	0.63	Average
R38	Low	0.40	2	0.8	Average	0.40	-1	-0.4	Average	0.20	-1	-0.2	0.2	0.55	Average
R39	Low	0.40	2	0.8	Average	0.40	-1	-0.4	High	0.20	-3	-0.6	-0.2	0.50	Average
R40	Low	0.40	2	0.8	Average	0.40	-1	-0.4	Very High	0.20	-4	-0.8	-0.4	0.47	Average
R41	Low	0.40	2	0.8	High	0.40	-3	-1.2	Very Low	0.20	4	0.8	0.4	0.58	Average
R42	Low	0.40	2	0.8	High	0.40	-3	-1.2	Low	0.20	2	0.4	0	0.53	Average
R43	Low	0.40	2	0.8	High	0.40	-3	-1.2	Average	0.20	-1	-0.2	-0.6	0.45	Poor
R44	Low	0.40	2	0.8	High	0.40	-3	-1.2	High	0.20	-3	-0.6	-1	0.39	Poor
R45	Low	0.40	2	0.8	High	0.40	-3	-1.2	Very High	0.20	-4	-0.8	-1.2	0.37	Poor
R46	Low	0.40	2	0.8	Very High	0.40	-4	-1.6	Very Low	0.20	4	0.8	0	0.53	Average
R47	Low	0.40	2	0.8	Very High	0.40	-4	-1.6	Low	0.20	2	0.4	-0.4	0.47	Average
R48	Low	0.40	2	0.8	Very High	0.40	-4	-1.6	Average	0.20	-1	-0.2	-1	0.39	Poor
R49	Low	0.40	2	0.8	Very High	0.40	-4	-1.6	High	0.20	-3	-0.6	-1.4	0.34	Poor
R50	Low	0.40	2	0.8	Very High	0.40	-4	-1.6	Very High	0.20	-4	-0.8	-1.6	0.32	Poor
R51	Average	0.40	-1	-0.4	Very Low	0.40	4	1.6	Very Low	0.20	4	0.8	2	0.79	Good
R52	Average	0.40	-1	-0.4	Very Low	0.40	4	1.6	Low	0.20	2	0.4	1.6	0.74	Good
R53	Average	0.40	-1	-0.4	Very Low	0.40	4	1.6	Average	0.20	-1	-0.2	1	0.66	Good
R54	Average	0.40	-1	-0.4	Very Low	0.40	4	1.6	High	0.20	-3	-0.6	0.6	0.61	Average
R55	Average	0.40	-1	-0.4	Very Low	0.40	4	1.6	Very High	0.20	-4	-0.8	0.4	0.58	Average
R56	Average	0.40	-1	-0.4	Low	0.40	3	1.2	Very Low	0.20	4	0.8	1.6	0.74	Good
R57	Average	0.40	-1	-0.4	Low	0.40	3	1.2	Low	0.20	2	0.4	1.2	0.68	Good
R58	Average	0.40	-1	-0.4	Low	0.40	3	1.2	Average	0.20	-1	-0.2	0.6	0.61	Average
R59	Average	0.40	-1	-0.4	Low	0.40	3	1.2	High	0.20	-3	-0.6	0.2	0.55	Average
R60	Average	0.40	-1	-0.4	Low	0.40	3	1.2	Very High	0.20	-4	-0.8	0	0.53	Average
R61	Average	0.40	-1	-0.4	Average	0.40	-1	-0.4	Very Low	0.20	4	0.8	0	0.53	Average
R62	Average	0.40	-1	-0.4	Average	0.40	-1	-0.4	Low	0.20	2	0.4	-0.4	0.47	Average
R63	Average	0.40	-1	-0.4	Average	0.40	-1	-0.4	Average	0.20	-1	-0.2	-1	0.39	Poor

Continuation Table H.1(b)

R64	Average	0.40	-1	-0.4	Average	0.40	-1	-0.4	High	0.20	-3	-0.6	-1.4	0.34	Poor
R65	Average	0.40	-1	-0.4	Average	0.40	-1	-0.4	Very High	0.20	-4	-0.8	-1.6	0.32	Poor
R66	Average	0.40	-1	-0.4	High	0.40	-3	-1.2	Very Low	0.20	4	0.8	-0.8	0.42	Poor
R67	Average	0.40	-1	-0.4	High	0.40	-3	-1.2	Low	0.20	2	0.4	-1.2	0.37	Poor
R68	Average	0.40	-1	-0.4	High	0.40	-3	-1.2	Average	0.20	-1	-0.2	-1.8	0.29	Poor
R69	Average	0.40	-1	-0.4	High	0.40	-3	-1.2	High	0.20	-3	-0.6	-2.2	0.24	Very Poor
R70	Average	0.40	-1	-0.4	High	0.40	-3	-1.2	Very High	0.20	-4	-0.8	-2.4	0.21	Very Poor
R71	Average	0.40	-1	-0.4	Very High	0.40	-4	-1.6	Very Low	0.20	4	0.8	-1.2	0.37	Poor
R72	Average	0.40	-1	-0.4	Very High	0.40	-4	-1.6	Low	0.20	2	0.4	-1.6	0.32	Poor
R73	Average	0.40	-1	-0.4	Very High	0.40	-4	-1.6	Average	0.20	-1	-0.2	-2.2	0.24	Very Poor
R74	Average	0.40	-1	-0.4	Very High	0.40	-4	-1.6	High	0.20	-3	-0.6	-2.6	0.18	Very Poor
R75	Average	0.40	-1	-0.4	Very High	0.40	-4	-1.6	Very High	0.20	-4	-0.8	-2.8	0.16	Very Poor
R76	High	0.40	-3	-1.2	Very Low	0.40	4	1.6	Very Low	0.20	4	0.8	1.2	0.68	Good
R77	High	0.40	-3	-1.2	Very Low	0.40	4	1.6	Low	0.20	2	0.4	0.8	0.63	Average
R78	High	0.40	-3	-1.2	Very Low	0.40	4	1.6	Average	0.20	-1	-0.2	0.2	0.55	Average
R79	High	0.40	-3	-1.2	Very Low	0.40	4	1.6	High	0.20	-3	-0.6	-0.2	0.50	Average
R80	High	0.40	-3	-1.2	Very Low	0.40	4	1.6	Very High	0.20	-4	-0.8	-0.4	0.47	Average
R81	High	0.40	-3	-1.2	Low	0.40	3	1.2	Very Low	0.20	4	0.8	0.8	0.63	Average
R82	High	0.40	-3	-1.2	Low	0.40	3	1.2	Low	0.20	2	0.4	0.4	0.58	Average
R83	High	0.40	-3	-1.2	Low	0.40	3	1.2	Average	0.20	-1	-0.2	-0.2	0.50	Average
R84	High	0.40	-3	-1.2	Low	0.40	3	1.2	High	0.20	-3	-0.6	-0.6	0.45	Poor
R85	High	0.40	-3	-1.2	Low	0.40	3	1.2	Very High	0.20	-4	-0.8	-0.8	0.42	Poor
R86	High	0.40	-3	-1.2	Average	0.40	-1	-0.4	Very Low	0.20	4	0.8	-0.8	0.42	Poor
R87	High	0.40	-3	-1.2	Average	0.40	-1	-0.4	Low	0.20	2	0.4	-1.2	0.37	Poor
R88	High	0.40	-3	-1.2	Average	0.40	-1	-0.4	Average	0.20	-1	-0.2	-1.8	0.29	Poor
R89	High	0.40	-3	-1.2	Average	0.40	-1	-0.4	High	0.20	-3	-0.6	-2.2	0.24	Very Poor
R90	High	0.40	-3	-1.2	Average	0.40	-1	-0.4	Very High	0.20	-4	-0.8	-2.4	0.21	Very Poor
R91	High	0.40	-3	-1.2	High	0.40	-3	-1.2	Very Low	0.20	4	0.8	-1.6	0.32	Poor
R92	High	0.40	-3	-1.2	High	0.40	-3	-1.2	Low	0.20	2	0.4	-2	0.26	Poor
R93	High	0.40	-3	-1.2	High	0.40	-3	-1.2	Average	0.20	-1	-0.2	-2.6	0.18	Very Poor
R94	High	0.40	-3	-1.2	High	0.40	-3	-1.2	High	0.20	-3	-0.6	-3	0.13	Very Poor
R95	High	0.40	-3	-1.2	High	0.40	-3	-1.2	Very High	0.20	-4	-0.8	-3.2	0.11	Very Poor

Continuation Table H.1(b)

R96	High	0.40	-3	-1.2	Very High	0.40	-4	-1.6	Very Low	0.20	4	0.8	-2	0.26	Poor
R97	High	0.40	-3	-1.2	Very High	0.40	-4	-1.6	Low	0.20	2	0.4	-2.4	0.21	Very Poor
R98	High	0.40	-3	-1.2	Very High	0.40	-4	-1.6	Average	0.20	-1	-0.2	-3	0.13	Very Poor
R99	High	0.40	-3	-1.2	Very High	0.40	-4	-1.6	High	0.20	-3	-0.6	-3.4	0.08	Very Poor
R100	High	0.40	-3	-1.2	Very High	0.40	-4	-1.6	Very High	0.20	-4	-0.8	-3.6	0.05	Very Poor
R101	Very High	0.40	-4	-1.6	Very Low	0.40	4	1.6	Very Low	0.20	4	0.8	0.8	0.63	Average
R102	Very High	0.40	-4	-1.6	Very Low	0.40	4	1.6	Low	0.20	2	0.4	0.4	0.58	Average
R103	Very High	0.40	-4	-1.6	Very Low	0.40	4	1.6	Average	0.20	-1	-0.2	-0.2	0.50	Average
R104	Very High	0.40	-4	-1.6	Very Low	0.40	4	1.6	High	0.20	-3	-0.6	-0.6	0.45	Poor
R105	Very High	0.40	-4	-1.6	Very Low	0.40	4	1.6	Very High	0.20	-4	-0.8	-0.8	0.42	Poor
R106	Very High	0.40	-4	-1.6	Low	0.40	3	1.2	Very Low	0.20	4	0.8	0.4	0.58	Average
R107	Very High	0.40	-4	-1.6	Low	0.40	3	1.2	Low	0.20	2	0.4	0	0.53	Average
R108	Very High	0.40	-4	-1.6	Low	0.40	3	1.2	Average	0.20	-1	-0.2	-0.6	0.45	Poor
R109	Very High	0.40	-4	-1.6	Low	0.40	3	1.2	High	0.20	-3	-0.6	-1	0.39	Poor
R110	Very High	0.40	-4	-1.6	Low	0.40	3	1.2	Very High	0.20	-4	-0.8	-1.2	0.37	Poor
R111	Very High	0.40	-4	-1.6	Average	0.40	-1	-0.4	Very Low	0.20	4	0.8	-1.2	0.37	Poor
R112	Very High	0.40	-4	-1.6	Average	0.40	-1	-0.4	Low	0.20	2	0.4	-1.6	0.32	Poor
R113	Very High	0.40	-4	-1.6	Average	0.40	-1	-0.4	Average	0.20	-1	-0.2	-2.2	0.24	Very Poor
R114	Very High	0.40	-4	-1.6	Average	0.40	-1	-0.4	High	0.20	-3	-0.6	-2.6	0.18	Very Poor
R115	Very High	0.40	-4	-1.6	Average	0.40	-1	-0.4	Very High	0.20	-4	-0.8	-2.8	0.16	Very Poor
R116	Very High	0.40	-4	-1.6	High	0.40	-3	-1.2	Very Low	0.20	4	0.8	-2	0.26	Poor
R117	Very High	0.40	-4	-1.6	High	0.40	-3	-1.2	Low	0.20	2	0.4	-2.4	0.21	Very Poor
R118	Very High	0.40	-4	-1.6	High	0.40	-3	-1.2	Average	0.20	-1	-0.2	-3	0.13	Very Poor
R119	Very High	0.40	-4	-1.6	High	0.40	-3	-1.2	High	0.20	-3	-0.6	-3.4	0.08	Very Poor
R120	Very High	0.40	-4	-1.6	High	0.40	-3	-1.2	Very High	0.20	-4	-0.8	-3.6	0.05	Very Poor
R121	Very High	0.40	-4	-1.6	Very High	0.40	-4	-1.6	Very Low	0.20	4	0.8	-2.4	0.21	Very Poor
R122	Very High	0.40	-4	-1.6	Very High	0.40	-4	-1.6	Low	0.20	2	0.4	-2.8	0.16	Very Poor
R123	Very High	0.40	-4	-1.6	Very High	0.40	-4	-1.6	Average	0.20	-1	-0.2	-3.4	0.08	Very Poor
R124	Very High	0.40	-4	-1.6	Very High	0.40	-4	-1.6	High	0.20	-3	-0.6	-3.8	0.03	Very Poor
R125	Very High	0.40	-4	-1.6	Very High	0.40	-4	-1.6	Very High	0.20	-4	-0.8	-4	0.00	Very Poor

Table H.2(a): Calculations for determining the rule consequents of the Nonconformity Level of Nonconformances effecting the Work Conditions

Rule consequents of the *Number of Unexpected Work Conditions*

Constructability review		R.I.	I.O	CE	Internal and external examination	R.I.	I.O	CE	Risk management	R.I.	I.O.	CE	Total CE	Normal CE	Consequent
R1	No Formal Approach	0.33	-4	-1.32	No Formal Approach	0.33	-3	-0.99	No Formal Approach	0.33	-3	-0.99	-3.3	0.00	Very High
R2	No Formal Approach	0.33	-4	-1.32	No Formal Approach	0.33	-3	-0.99	Reactive Approach	0.33	0	0	-2.31	0.14	Very High
R3	No Formal Approach	0.33	-4	-1.32	No Formal Approach	0.33	-3	-0.99	Stable Formal	0.33	2	0.66	-1.65	0.23	High
R4	No Formal Approach	0.33	-4	-1.32	No Formal Approach	0.33	-3	-0.99	Continual Improve	0.33	3	0.99	-1.32	0.27	High
R5	No Formal Approach	0.33	-4	-1.32	No Formal Approach	0.33	-3	-0.99	Best-in-Class	0.33	4	1.32	-0.99	0.32	High
R6	No Formal Approach	0.33	-4	-1.32	Reactive Approach	0.33	0	0	No Formal Approach	0.33	-3	-0.99	-2.31	0.14	Very High
R7	No Formal Approach	0.33	-4	-1.32	Reactive Approach	0.33	0	0	Reactive Approach	0.33	0	0	-1.32	0.27	High
R8	No Formal Approach	0.33	-4	-1.32	Reactive Approach	0.33	0	0	Stable Formal	0.33	2	0.66	-0.66	0.36	High
R9	No Formal Approach	0.33	-4	-1.32	Reactive Approach	0.33	0	0	Continual Improve	0.33	3	0.99	-0.33	0.41	Average
R10	No Formal Approach	0.33	-4	-1.32	Reactive Approach	0.33	0	0	Best-in-Class	0.33	4	1.32	0	0.45	Average
R11	No Formal Approach	0.33	-4	-1.32	Stable Formal	0.33	2	0.66	No Formal Approach	0.33	-3	-0.99	-1.65	0.23	High
R12	No Formal Approach	0.33	-4	-1.32	Stable Formal	0.33	2	0.66	Reactive Approach	0.33	0	0	-0.66	0.36	High
R13	No Formal Approach	0.33	-4	-1.32	Stable Formal	0.33	2	0.66	Stable Formal	0.33	2	0.66	0	0.45	Average
R14	No Formal Approach	0.33	-4	-1.32	Stable Formal	0.33	2	0.66	Continual Improve	0.33	3	0.99	0.33	0.50	Average
R15	No Formal Approach	0.33	-4	-1.32	Stable Formal	0.33	2	0.66	Best-in-Class	0.33	4	1.32	0.66	0.55	Average
R16	No Formal Approach	0.33	-4	-1.32	Continual Improve	0.33	3	0.99	No Formal Approach	0.33	-3	-0.99	-1.32	0.27	High
R17	No Formal Approach	0.33	-4	-1.32	Continual Improve	0.33	3	0.99	Reactive Approach	0.33	0	0	-0.33	0.41	Average
R18	No Formal Approach	0.33	-4	-1.32	Continual Improve	0.33	3	0.99	Stable Formal	0.33	2	0.66	0.33	0.50	Average
R19	No Formal Approach	0.33	-4	-1.32	Continual Improve	0.33	3	0.99	Continual Improve	0.33	3	0.99	0.66	0.55	Average
R20	No Formal Approach	0.33	-4	-1.32	Continual Improve	0.33	3	0.99	Best-in-Class	0.33	4	1.32	0.99	0.59	Average
R21	No Formal Approach	0.33	-4	-1.32	Best-in-Class	0.33	4	1.32	No Formal Approach	0.33	-3	-0.99	-0.99	0.32	High
R22	No Formal Approach	0.33	-4	-1.32	Best-in-Class	0.33	4	1.32	Reactive Approach	0.33	0	0	0	0.45	Average
R23	No Formal Approach	0.33	-4	-1.32	Best-in-Class	0.33	4	1.32	Stable Formal	0.33	2	0.66	0.66	0.55	Average
R24	No Formal Approach	0.33	-4	-1.32	Best-in-Class	0.33	4	1.32	Continual Improve	0.33	3	0.99	0.99	0.59	Average
R25	No Formal Approach	0.33	-4	-1.32	Best-in-Class	0.33	4	1.32	Best-in-Class	0.33	4	1.32	1.32	0.64	Low
R26	Reactive Approach	0.33	0	0	No Formal Approach	0.33	-3	-0.99	No Formal Approach	0.33	-3	-0.99	-1.98	0.18	Very High

Note: R.I.= Relative Importance, I.O. = Impact on the Output, CE = Combined Effect, R1, R2,...= Number of the Rule

Continuation Table H.2(a)

R27	Reactive Approach	0.33	0	0	No Formal Approach	0.33	-3	-0.99	Reactive Approach	0.33	0	0	-0.99	0.32	High
R28	Reactive Approach	0.33	0	0	No Formal Approach	0.33	-3	-0.99	Stable Formal	0.33	2	0.66	-0.33	0.41	Average
R29	Reactive Approach	0.33	0	0	No Formal Approach	0.33	-3	-0.99	Continual Improve	0.33	3	0.99	0	0.45	Average
R30	Reactive Approach	0.33	0	0	No Formal Approach	0.33	-3	-0.99	Best-in-Class	0.33	4	1.32	0.33	0.50	Average
R31	Reactive Approach	0.33	0	0	Reactive Approach	0.33	0	0	No Formal Approach	0.33	-3	-0.99	-0.99	0.32	High
R32	Reactive Approach	0.33	0	0	Reactive Approach	0.33	0	0	Reactive Approach	0.33	0	0	0	0.45	Average
R33	Reactive Approach	0.33	0	0	Reactive Approach	0.33	0	0	Stable Formal	0.33	2	0.66	0.66	0.55	Average
R34	Reactive Approach	0.33	0	0	Reactive Approach	0.33	0	0	Continual Improve	0.33	3	0.99	0.99	0.59	Average
R35	Reactive Approach	0.33	0	0	Reactive Approach	0.33	0	0	Best-in-Class	0.33	4	1.32	1.32	0.64	Low
R36	Reactive Approach	0.33	0	0	Stable Formal	0.33	2	0.66	No Formal Approach	0.33	-3	-0.99	-0.33	0.41	Average
R37	Reactive Approach	0.33	0	0	Stable Formal	0.33	2	0.66	Reactive Approach	0.33	0	0	0.66	0.55	Average
R38	Reactive Approach	0.33	0	0	Stable Formal	0.33	2	0.66	Stable Formal	0.33	2	0.66	1.32	0.64	Low
R39	Reactive Approach	0.33	0	0	Stable Formal	0.33	2	0.66	Continual Improve	0.33	3	0.99	1.65	0.68	Low
R40	Reactive Approach	0.33	0	0	Stable Formal	0.33	2	0.66	Best-in-Class	0.33	4	1.32	1.98	0.73	Low
R41	Reactive Approach	0.33	0	0	Continual Improve	0.33	3	0.99	No Formal Approach	0.33	-3	-0.99	0	0.45	Average
R42	Reactive Approach	0.33	0	0	Continual Improve	0.33	3	0.99	Reactive Approach	0.33	0	0	0.99	0.59	Average
R43	Reactive Approach	0.33	0	0	Continual Improve	0.33	3	0.99	Stable Formal	0.33	2	0.66	1.65	0.68	Low
R44	Reactive Approach	0.33	0	0	Continual Improve	0.33	3	0.99	Continual Improve	0.33	3	0.99	1.98	0.73	Low
R45	Reactive Approach	0.33	0	0	Continual Improve	0.33	3	0.99	Best-in-Class	0.33	4	1.32	2.31	0.77	Low
R46	Reactive Approach	0.33	0	0	Best-in-Class	0.33	4	1.32	No Formal Approach	0.33	-3	-0.99	0.33	0.50	Average
R47	Reactive Approach	0.33	0	0	Best-in-Class	0.33	4	1.32	Reactive Approach	0.33	0	0	1.32	0.64	Low
R48	Reactive Approach	0.33	0	0	Best-in-Class	0.33	4	1.32	Stable Formal	0.33	2	0.66	1.98	0.73	Low
R49	Reactive Approach	0.33	0	0	Best-in-Class	0.33	4	1.32	Continual Improve	0.33	3	0.99	2.31	0.77	Low
R50	Reactive Approach	0.33	0	0	Best-in-Class	0.33	4	1.32	Best-in-Class	0.33	4	1.32	2.64	0.82	Very Low
R51	Stable Formal	0.33	2	0.66	No Formal Approach	0.33	-3	-0.99	No Formal Approach	0.33	-3	-0.99	-1.32	0.27	High
R52	Stable Formal	0.33	2	0.66	No Formal Approach	0.33	-3	-0.99	Reactive Approach	0.33	0	0	-0.33	0.41	Average
R53	Stable Formal	0.33	2	0.66	No Formal Approach	0.33	-3	-0.99	Stable Formal	0.33	2	0.66	0.33	0.50	Average
R54	Stable Formal	0.33	2	0.66	No Formal Approach	0.33	-3	-0.99	Continual Improve	0.33	3	0.99	0.66	0.55	Average
R55	Stable Formal	0.33	2	0.66	No Formal Approach	0.33	-3	-0.99	Best-in-Class	0.33	4	1.32	0.99	0.59	Average
R56	Stable Formal	0.33	2	0.66	Reactive Approach	0.33	0	0	No Formal Approach	0.33	-3	-0.99	-0.33	0.41	Average

Continuation Table H.2(a)

R57	Stable Formal	0.33	2	0.66	Reactive Approach	0.33	0	0	Reactive Approach	0.33	0	0	0.66	0.55	Average
R58	Stable Formal	0.33	2	0.66	Reactive Approach	0.33	0	0	Stable Formal	0.33	2	0.66	1.32	0.64	Low
R59	Stable Formal	0.33	2	0.66	Reactive Approach	0.33	0	0	Continual Improve	0.33	3	0.99	1.65	0.68	Low
R60	Stable Formal	0.33	2	0.66	Reactive Approach	0.33	0	0	Best-in-Class	0.33	4	1.32	1.98	0.73	Low
R61	Stable Formal	0.33	2	0.66	Stable Formal	0.33	2	0.66	No Formal Approach	0.33	-3	-0.99	0.33	0.50	Average
R62	Stable Formal	0.33	2	0.66	Stable Formal	0.33	2	0.66	Reactive Approach	0.33	0	0	1.32	0.64	Low
R63	Stable Formal	0.33	2	0.66	Stable Formal	0.33	2	0.66	Stable Formal	0.33	2	0.66	1.98	0.73	Low
R64	Stable Formal	0.33	2	0.66	Stable Formal	0.33	2	0.66	Continual Improve	0.33	3	0.99	2.31	0.77	Low
R65	Stable Formal	0.33	2	0.66	Stable Formal	0.33	2	0.66	Best-in-Class	0.33	4	1.32	2.64	0.82	Very Low
R66	Stable Formal	0.33	2	0.66	Continual Improve	0.33	3	0.99	No Formal Approach	0.33	-3	-0.99	0.66	0.55	Average
R67	Stable Formal	0.33	2	0.66	Continual Improve	0.33	3	0.99	Reactive Approach	0.33	0	0	1.65	0.68	Low
R68	Stable Formal	0.33	2	0.66	Continual Improve	0.33	3	0.99	Stable Formal	0.33	2	0.66	2.31	0.77	Low
R69	Stable Formal	0.33	2	0.66	Continual Improve	0.33	3	0.99	Continual Improve	0.33	3	0.99	2.64	0.82	Very Low
R70	Stable Formal	0.33	2	0.66	Continual Improve	0.33	3	0.99	Best-in-Class	0.33	4	1.32	2.97	0.86	Very Low
R71	Stable Formal	0.33	2	0.66	Best-in-Class	0.33	4	1.32	No Formal Approach	0.33	-3	-0.99	0.99	0.59	Average
R72	Stable Formal	0.33	2	0.66	Best-in-Class	0.33	4	1.32	Reactive Approach	0.33	0	0	1.98	0.73	Low
R73	Stable Formal	0.33	2	0.66	Best-in-Class	0.33	4	1.32	Stable Formal	0.33	2	0.66	2.64	0.82	Very Low
R74	Stable Formal	0.33	2	0.66	Best-in-Class	0.33	4	1.32	Continual Improve	0.33	3	0.99	2.97	0.86	Very Low
R75	Stable Formal	0.33	2	0.66	Best-in-Class	0.33	4	1.32	Best-in-Class	0.33	4	1.32	3.3	0.91	Very Low
R76	Continual Improve	0.33	3	0.99	No Formal Approach	0.33	-3	-0.99	No Formal Approach	0.33	-3	-0.99	-0.99	0.32	High
R77	Continual Improve	0.33	3	0.99	No Formal Approach	0.33	-3	-0.99	Reactive Approach	0.33	0	0	0	0.45	Average
R78	Continual Improve	0.33	3	0.99	No Formal Approach	0.33	-3	-0.99	Stable Formal	0.33	2	0.66	0.66	0.55	Average
R79	Continual Improve	0.33	3	0.99	No Formal Approach	0.33	-3	-0.99	Continual Improve	0.33	3	0.99	0.99	0.59	Average
R80	Continual Improve	0.33	3	0.99	No Formal Approach	0.33	-3	-0.99	Best-in-Class	0.33	4	1.32	1.32	0.64	Low
R81	Continual Improve	0.33	3	0.99	Reactive Approach	0.33	0	0	No Formal Approach	0.33	-3	-0.99	0	0.45	Average
R82	Continual Improve	0.33	3	0.99	Reactive Approach	0.33	0	0	Reactive Approach	0.33	0	0	0.99	0.59	Average
R83	Continual Improve	0.33	3	0.99	Reactive Approach	0.33	0	0	Stable Formal	0.33	2	0.66	1.65	0.68	Low

Continuation Table H.2(a)

R84	Continual Improve	0.33	3	0.99	Reactive Approach	0.33	0	0	Continual Improve	0.33	3	0.99	1.98	0.73	Low
R85	Continual Improve	0.33	3	0.99	Reactive Approach	0.33	0	0	Best-in-Class	0.33	4	1.32	2.31	0.77	Low
R86	Continual Improve	0.33	3	0.99	Stable Formal	0.33	2	0.66	No Formal Approach	0.33	-3	-0.99	0.66	0.55	Average
R87	Continual Improve	0.33	3	0.99	Stable Formal	0.33	2	0.66	Reactive Approach	0.33	0	0	1.65	0.68	Low
R88	Continual Improve	0.33	3	0.99	Stable Formal	0.33	2	0.66	Stable Formal	0.33	2	0.66	2.31	0.77	Low
R89	Continual Improve	0.33	3	0.99	Stable Formal	0.33	2	0.66	Continual Improve	0.33	3	0.99	2.64	0.82	Very Low
R90	Continual Improve	0.33	3	0.99	Stable Formal	0.33	2	0.66	Best-in-Class	0.33	4	1.32	2.97	0.86	Very Low
R91	Continual Improve	0.33	3	0.99	Continual Improve	0.33	3	0.99	No Formal Approach	0.33	-3	-0.99	0.99	0.59	Average
R92	Continual Improve	0.33	3	0.99	Continual Improve	0.33	3	0.99	Reactive Approach	0.33	0	0	1.98	0.73	Low
R93	Continual Improve	0.33	3	0.99	Continual Improve	0.33	3	0.99	Stable Formal	0.33	2	0.66	2.64	0.82	Very Low
R94	Continual Improve	0.33	3	0.99	Continual Improve	0.33	3	0.99	Continual Improve	0.33	3	0.99	2.97	0.86	Very Low
R95	Continual Improve	0.33	3	0.99	Continual Improve	0.33	3	0.99	Best-in-Class	0.33	4	1.32	3.3	0.91	Very Low
R96	Continual Improve	0.33	3	0.99	Best-in-Class	0.33	4	1.32	No Formal Approach	0.33	-3	-0.99	1.32	0.64	Low
R97	Continual Improve	0.33	3	0.99	Best-in-Class	0.33	4	1.32	Reactive Approach	0.33	0	0	2.31	0.77	Low
R98	Continual Improve	0.33	3	0.99	Best-in-Class	0.33	4	1.32	Stable Formal	0.33	2	0.66	2.97	0.86	Very Low
R99	Continual Improve	0.33	3	0.99	Best-in-Class	0.33	4	1.32	Continual Improve	0.33	3	0.99	3.3	0.91	Very Low
R100	Continual Improve	0.33	3	0.99	Best-in-Class	0.33	4	1.32	Best-in-Class	0.33	4	1.32	3.63	0.95	Very Low
R101	Best-in-Class	0.33	4	1.32	No Formal Approach	0.33	-3	-0.99	No Formal Approach	0.33	-3	-0.99	-0.66	0.36	High
R102	Best-in-Class	0.33	4	1.32	No Formal Approach	0.33	-3	-0.99	Reactive Approach	0.33	0	0	0.33	0.50	Average
R103	Best-in-Class	0.33	4	1.32	No Formal Approach	0.33	-3	-0.99	Stable Formal	0.33	2	0.66	0.99	0.59	Average
R104	Best-in-Class	0.33	4	1.32	No Formal Approach	0.33	-3	-0.99	Continual Improve	0.33	3	0.99	1.32	0.64	Low
R105	Best-in-Class	0.33	4	1.32	No Formal Approach	0.33	-3	-0.99	Best-in-Class	0.33	4	1.32	1.65	0.68	Low
R106	Best-in-Class	0.33	4	1.32	Reactive Approach	0.33	0	0	No Formal Approach	0.33	-3	-0.99	0.33	0.50	Average
R107	Best-in-Class	0.33	4	1.32	Reactive Approach	0.33	0	0	Reactive Approach	0.33	0	0	1.32	0.64	Low
R108	Best-in-Class	0.33	4	1.32	Reactive Approach	0.33	0	0	Stable Formal	0.33	2	0.66	1.98	0.73	Low
R109	Best-in-Class	0.33	4	1.32	Reactive Approach	0.33	0	0	Continual Improve	0.33	3	0.99	2.31	0.77	Low
R110	Best-in-Class	0.33	4	1.32	Reactive Approach	0.33	0	0	Best-in-Class	0.33	4	1.32	2.64	0.82	Very Low
R111	Best-in-Class	0.33	4	1.32	Stable Formal	0.33	2	0.66	No Formal Approach	0.33	-3	-0.99	0.99	0.59	Average
R112	Best-in-Class	0.33	4	1.32	Stable Formal	0.33	2	0.66	Reactive Approach	0.33	0	0	1.98	0.73	Low

Continuation Table H.2(a)

R113	Best-in-Class	0.33	4	1.32	Stable Formal	0.33	2	0.66	Stable Formal	0.33	2	0.66	2.64	0.82	Very Low
R114	Best-in-Class	0.33	4	1.32	Stable Formal	0.33	2	0.66	Continual Improve	0.33	3	0.99	2.97	0.86	Very Low
R115	Best-in-Class	0.33	4	1.32	Stable Formal	0.33	2	0.66	Best-in-Class	0.33	4	1.32	3.3	0.91	Very Low
R116	Best-in-Class	0.33	4	1.32	Continual Improve	0.33	3	0.99	No Formal Approach	0.33	-3	-0.99	1.32	0.64	Low
R117	Best-in-Class	0.33	4	1.32	Continual Improve	0.33	3	0.99	Reactive Approach	0.33	0	0	2.31	0.77	Low
R118	Best-in-Class	0.33	4	1.32	Continual Improve	0.33	3	0.99	Stable Formal	0.33	2	0.66	2.97	0.86	Very Low
R119	Best-in-Class	0.33	4	1.32	Continual Improve	0.33	3	0.99	Continual Improve	0.33	3	0.99	3.3	0.91	Very Low
R120	Best-in-Class	0.33	4	1.32	Continual Improve	0.33	3	0.99	Best-in-Class	0.33	4	1.32	3.63	0.95	Very Low
R121	Best-in-Class	0.33	4	1.32	Best-in-Class	0.33	4	1.32	No Formal Approach	0.33	-3	-0.99	1.65	0.68	Low
R122	Best-in-Class	0.33	4	1.32	Best-in-Class	0.33	4	1.32	Reactive Approach	0.33	0	0	2.64	0.82	Very Low
R123	Best-in-Class	0.33	4	1.32	Best-in-Class	0.33	4	1.32	Stable Formal	0.33	2	0.66	3.3	0.91	Very Low
R124	Best-in-Class	0.33	4	1.32	Best-in-Class	0.33	4	1.32	Continual Improve	0.33	3	0.99	3.63	0.95	Very Low
R125	Best-in-Class	0.33	4	1.32	Best-in-Class	0.33	4	1.32	Best-in-Class	0.33	4	1.32	3.96	1.00	Very Low

Rule consequents of the *Number of Accidents*

	Personnel Qualification & Training	**R.I.**	**I.O**	**CE**	**Safety Management**	**R.I.**	**I.O**	**CE**	**Total CE**	**Normal CE**	**Consequent**
R1	No Formal Approach	0.33	-3	-0.99	No Formal Approach	0.67	-4	-2.68	-3.67	0.00	Very High
R2	No Formal Approach	0.33	-3	-0.99	Reactive Approach	0.67	-2	-1.34	-2.33	0.17	Very High
R3	No Formal Approach	0.33	-3	-0.99	Stable Formal	0.67	2	1.34	0.35	0.52	High
R4	No Formal Approach	0.33	-3	-0.99	Continual Improve	0.67	3	2.01	1.02	0.61	High
R5	No Formal Approach	0.33	-3	-0.99	Best-in-Class	0.67	4	2.68	1.69	0.70	High
R6	Reactive Approach	0.33	-2	-0.66	No Formal Approach	0.67	-4	-2.68	-3.34	0.04	Very High
R7	Reactive Approach	0.33	-2	-0.66	Reactive Approach	0.67	-2	-1.34	-2	0.22	Very High
R8	Reactive Approach	0.33	-2	-0.66	Stable Formal	0.67	2	1.34	0.68	0.57	High
R9	Reactive Approach	0.33	-2	-0.66	Continual Improve	0.67	3	2.01	1.35	0.65	High
R10	Reactive Approach	0.33	-2	-0.66	Best-in-Class	0.67	4	2.68	2.02	0.74	Average
R11	Stable Formal	0.33	2	0.66	No Formal Approach	0.67	-4	-2.68	-2.02	0.22	Very High
R12	Stable Formal	0.33	2	0.66	Reactive Approach	0.67	-2	-1.34	-0.68	0.39	High
R13	Stable Formal	0.33	2	0.66	Stable Formal	0.67	2	1.34	2	0.74	Average
R14	Stable Formal	0.33	2	0.66	Continual Improve	0.67	3	2.01	2.67	0.83	Average
R15	Stable Formal	0.33	2	0.66	Best-in-Class	0.67	4	2.68	3.34	0.91	Average
R16	Continual Improve	0.33	3	0.99	No Formal Approach	0.67	-4	-2.68	-1.69	0.26	Very High
R17	Continual Improve	0.33	3	0.99	Reactive Approach	0.67	-2	-1.34	-0.35	0.43	High

Continuation Table H.2(a)

R18	Continual Improve	0.33	3	0.99	Stable Formal	0.67	2	1.34	2.33	0.78	Average
R19	Continual Improve	0.33	3	0.99	Continual Improve	0.67	3	2.01	3	0.87	Average
R20	Continual Improve	0.33	3	0.99	Best-in-Class	0.67	4	2.68	3.67	0.96	Average
R21	Best-in-Class	0.33	4	1.32	No Formal Approach	0.67	-4	-2.68	-1.36	0.30	Very High
R22	Best-in-Class	0.33	4	1.32	Reactive Approach	0.67	-2	-1.34	-0.02	0.48	High
R23	Best-in-Class	0.33	4	1.32	Stable Formal	0.67	2	1.34	2.66	0.83	Average
R24	Best-in-Class	0.33	4	1.32	Continual Improve	0.67	3	2.01	3.33	0.91	Average
R25	Best-in-Class	0.33	4	1.32	Best-in-Class	0.67	4	2.68	4	1.00	Average

Table H.2(b): Calculations for determining the rule consequents of the Quality Level of the Work Conditions

	Number of Accidents	**R.I.**	**I.O**	**CE**	**Number of Unexpected Work Conditions**	**R.I.**	**I.O**	**CE**	**Total CE**	**Normal CE**	**Consequent**
R1	Average	0.67	3	2.01	Very Low	0.33	4	1.32	3.33	1.00	Very Good
R2	Average	0.67	3	2.01	Low	0.33	3	0.99	3.00	0.95	Very Good
R3	Average	0.67	3	2.01	Average	0.33	0	0	2.01	0.82	Good
R4	Average	0.67	3	2.01	High	0.33	-3	-0.99	1.02	0.68	Good
R5	Average	0.67	3	2.01	Very High	0.33	-4	-1.32	0.69	0.64	Average
R6	High	0.67	-2	-1.34	Very Low	0.33	4	1.32	-0.02	0.54	Average
R7	High	0.67	-2	-1.34	Low	0.33	2	0.66	-0.68	0.45	Poor
R8	High	0.67	-2	-1.34	Average	0.33	-1	-0.33	-1.67	0.32	Poor
R9	High	0.67	-2	-1.34	High	0.33	-3	-0.99	-2.33	0.23	Very Poor
R10	High	0.67	-2	-1.34	Very High	0.33	-4	-1.32	-2.66	0.18	Very Poor
R11	Very High	0.67	-4	-2.68	Very Low	0.33	4	1.32	-1.36	0.36	Poor
R12	Very High	0.67	-4	-2.68	Low	0.33	2	0.66	-2.02	0.27	Poor
R13	Very High	0.67	-4	-2.68	Average	0.33	-1	-0.33	-3.01	0.14	Very Poor
R14	Very High	0.67	-4	-2.68	High	0.33	-3	-0.99	-3.67	0.05	Very Poor
R15	Very High	0.67	-4	-2.68	Very High	0.33	-4	-1.32	-4.00	0.00	Very Poor

Note: R.I.= Relative Importance, I.O. = Impact on the Output, CE = Combined Effect, R1, R2,...= Number of the Rule

Table H.3(a): Calculations for determining the rule consequents of the Nonconformity Level of Nonconformances effecting the Material Supplying

Rule consequents of the *Number of Not in Time Deliveries of Material*											
	Expediting	**R.I.**	**I.O**	**CE**	**Supplier Qualification**	**R.I.**	**I.O**	**CE**	**Total CE**	**Normal CE**	**Consequent**
R1	No Formal Approach	0.50	-4	-2	No Formal Approach	0.50	-3	-1.5	-3.5	0.00	Very High
R2	No Formal Approach	0.50	-4	-2	Reactive Approach	0.50	0	0	-2	0.20	Very High
R3	No Formal Approach	0.50	-4	-2	Stable Formal	0.50	2	1	-1	0.33	High
R4	No Formal Approach	0.50	-4	-2	Continual Improve	0.50	3	1.5	-0.5	0.40	High
R5	No Formal Approach	0.50	-4	-2	Best-in-Class	0.50	4	2	0	0.47	Average
R6	Reactive Approach	0.50	0	0	No Formal Approach	0.50	-3	-1.5	-1.5	0.27	High
R7	Reactive Approach	0.50	0	0	Reactive Approach	0.50	0	0	0	0.47	Average
R8	Reactive Approach	0.50	0	0	Stable Formal	0.50	2	1	1	0.60	Average
R9	Reactive Approach	0.50	0	0	Continual Improve	0.50	3	1.5	1.5	0.67	Low
R10	Reactive Approach	0.50	0	0	Best-in-Class	0.50	4	2	2	0.73	Low
R11	Stable Formal	0.50	2	1	No Formal Approach	0.50	-3	-1.5	-0.5	0.40	High
R12	Stable Formal	0.50	2	1	Reactive Approach	0.50	0	0	1	0.60	Average
R13	Stable Formal	0.50	2	1	Stable Formal	0.50	2	1	2	0.73	Low
R14	Stable Formal	0.50	2	1	Continual Improve	0.50	3	1.5	2.5	0.80	Low
R15	Stable Formal	0.50	2	1	Best-in-Class	0.50	4	2	3	0.87	Very Low
R16	Continual Improve	0.50	3	1.5	No Formal Approach	0.50	-3	-1.5	0	0.47	Average
R17	Continual Improve	0.50	3	1.5	Reactive Approach	0.50	0	0	1.5	0.67	Low
R18	Continual Improve	0.50	3	1.5	Stable Formal	0.50	2	1	2.5	0.80	Low
R19	Continual Improve	0.50	3	1.5	Continual Improve	0.50	3	1.5	3	0.87	Very Low
R20	Continual Improve	0.50	3	1.5	Best-in-Class	0.50	4	2	3.5	0.93	Very Low
R21	Best-in-Class	0.50	4	2	No Formal Approach	0.50	-3	-1.5	0.5	0.53	Average
R22	Best-in-Class	0.50	4	2	Reactive Approach	0.50	0	0	2	0.73	Low
R23	Best-in-Class	0.50	4	2	Stable Formal	0.50	2	1	3	0.87	Very Low
R24	Best-in-Class	0.50	4	2	Continual Improve	0.50	3	1.5	3.5	0.93	Very Low
R25	Best-in-Class	0.50	4	2	Best-in-Class	0.50	4	2	4	1.00	Very Low

Continuation Table H.3(a)

Rule consequents of the *Number of Inaccurate Deliveries of Material*											
	Internal and external examinations	**R.I.**	**I.F.**	**CE**	**Supplier Qualification**	**R.I.**	**I.O**	**CE**	**Total CE**	**Normal CE**	**Consequent**
R1	No Formal Approach	0.50	-4	-2	No Formal Approach	0.50	-3	-1.5	-3.5	0.00	Very High
R2	No Formal Approach	0.50	-4	-2	Reactive Approach	0.50	0	0	-2	0.20	Very High
R3	No Formal Approach	0.50	-4	-2	Stable Formal	0.50	2	1	-1	0.33	High
R4	No Formal Approach	0.50	-4	-2	Continual Improve	0.50	3	1.5	-0.5	0.40	High
R5	No Formal Approach	0.50	-4	-2	Best-in-Class	0.50	4	2	0	0.47	Average
R6	Reactive Approach	0.50	0	0	No Formal Approach	0.50	-3	-1.5	-1.5	0.27	High
R7	Reactive Approach	0.50	0	0	Reactive Approach	0.50	0	0	0	0.47	Average
R8	Reactive Approach	0.50	0	0	Stable Formal	0.50	2	1	1	0.60	Average
R9	Reactive Approach	0.50	0	0	Continual Improve	0.50	3	1.5	1.5	0.67	Low
R10	Reactive Approach	0.50	0	0	Best-in-Class	0.50	4	2	2	0.73	Low
R11	Stable Formal	0.50	2	1	No Formal Approach	0.50	-3	-1.5	-0.5	0.40	High
R12	Stable Formal	0.50	2	1	Reactive Approach	0.50	0	0	1	0.60	Average
R13	Stable Formal	0.50	2	1	Stable Formal	0.50	2	1	2	0.73	Low
R14	Stable Formal	0.50	2	1	Continual Improve	0.50	3	1.5	2.5	0.80	Low
R15	Stable Formal	0.50	2	1	Best-in-Class	0.50	4	2	3	0.87	Very Low
R16	Continual Improve	0.50	3	1.5	No Formal Approach	0.50	-3	-1.5	0	0.47	Average
R17	Continual Improve	0.50	3	1.5	Reactive Approach	0.50	0	0	1.5	0.67	Low
R18	Continual Improve	0.50	3	1.5	Stable Formal	0.50	2	1	2.5	0.80	Low
R19	Continual Improve	0.50	3	1.5	Continual Improve	0.50	3	1.5	3	0.87	Very Low
R20	Continual Improve	0.50	3	1.5	Best-in-Class	0.50	4	2	3.5	0.93	Very Low
R21	Best-in-Class	0.50	4	2	No Formal Approach	0.50	-3	-1.5	0.5	0.53	Average
R22	Best-in-Class	0.50	4	2	Reactive Approach	0.50	0	0	2	0.73	Low
R23	Best-in-Class	0.50	4	2	Stable Formal	0.50	2	1	3	0.87	Very Low
R24	Best-in-Class	0.50	4	2	Continual Improve	0.50	3	1.5	3.5	0.93	Very Low
R25	Best-in-Class	0.50	4	2	Best-in-Class	0.50	4	2	4	1.00	Very Low

Continuation Table H.3(a)

Rule consequents of the *Number of Out of Specification Deliveries of Material*

	Internal and external examinations	R.I.	I.F.	CE	Supplier Qualification	R.I.	I.O	CE	Total CE	Normal CE	Consequent
R1	No Formal Approach	0.33	-4	-1.32	No Formal Approach	0.67	-4	-2.68	-4	0.00	Very High
R2	No Formal Approach	0.33	-4	-1.32	Reactive Approach	0.67	0	0	-1.32	0.34	High
R3	No Formal Approach	0.33	-4	-1.32	Stable Formal	0.67	2	1.34	0.02	0.50	Average
R4	No Formal Approach	0.33	-4	-1.32	Continual Improve	0.67	3	2.01	0.69	0.59	Average
R5	No Formal Approach	0.33	-4	-1.32	Best-in-Class	0.67	4	2.68	1.36	0.67	Low
R6	Reactive Approach	0.33	0	0	No Formal Approach	0.67	-4	-2.68	-2.68	0.17	Very High
R7	Reactive Approach	0.33	0	0	Reactive Approach	0.67	0	0	0	0.50	Average
R8	Reactive Approach	0.33	0	0	Stable Formal	0.67	2	1.34	1.34	0.67	Low
R9	Reactive Approach	0.33	0	0	Continual Improve	0.67	3	2.01	2.01	0.75	Low
R10	Reactive Approach	0.33	0	0	Best-in-Class	0.67	4	2.68	2.68	0.84	Very Low
R11	Stable Formal	0.33	2	0.66	No Formal Approach	0.67	-4	-2.68	-2.02	0.25	High
R12	Stable Formal	0.33	2	0.66	Reactive Approach	0.67	0	0	0.66	0.58	Average
R13	Stable Formal	0.33	2	0.66	Stable Formal	0.67	2	1.34	2	0.75	Low
R14	Stable Formal	0.33	2	0.66	Continual Improve	0.67	3	2.01	2.67	0.83	Very Low
R15	Stable Formal	0.33	2	0.66	Best-in-Class	0.67	4	2.68	3.34	0.92	Very Low
R16	Continual Improve	0.33	3	0.99	No Formal Approach	0.67	-4	-2.68	-1.69	0.29	High
R17	Continual Improve	0.33	3	0.99	Reactive Approach	0.67	0	0	0.99	0.62	Low
R18	Continual Improve	0.33	3	0.99	Stable Formal	0.67	2	1.34	2.33	0.79	Low
R19	Continual Improve	0.33	3	0.99	Continual Improve	0.67	3	2.01	3	0.88	Very Low
R20	Continual Improve	0.33	3	0.99	Best-in-Class	0.67	4	2.68	3.67	0.96	Very Low
R21	Best-in-Class	0.33	4	1.32	No Formal Approach	0.67	-4	-2.68	-1.36	0.33	High
R22	Best-in-Class	0.33	4	1.32	Reactive Approach	0.67	0	0	1.32	0.67	Low
R23	Best-in-Class	0.33	4	1.32	Stable Formal	0.67	2	1.34	2.66	0.83	Very Low
R24	Best-in-Class	0.33	4	1.32	Continual Improve	0.67	3	2.01	3.33	0.92	Very Low
R25	Best-in-Class	0.33	4	1.32	Best-in-Class	0.67	4	2.68	4	1.00	Very Low

Table H.3(b): Calculations for determining the rule consequents of the Quality Performance Level of the Material Supplying

	Number of inaccurate deliveries	R.I.	I.O	CE	Number of not in time deliveries of Material	R.I.	I.O	CE	Number of out of specs deliveries	R.I.	I.O	CE	Total CE	Norma l CE	Consequent
R1	Very Low	0.20	3	0.6	Very Low	0.40	4	1.6	Very Low	0.40	3	1.2	3.4	1.00	Very Good
R2	Very Low	0.20	3	0.6	Very Low	0.40	4	1.6	Low	0.40	2	0.8	3	0.94	Very Good
R3	Very Low	0.20	3	0.6	Very Low	0.40	4	1.6	Average	0.40	-1	-0.4	1.8	0.76	Good
R4	Very Low	0.20	3	0.6	Very Low	0.40	4	1.6	High	0.40	-2	-0.8	1.4	0.71	Good
R5	Very Low	0.20	3	0.6	Very Low	0.40	4	1.6	Very High	0.40	-3	-1.2	1	0.65	Average
R6	Very Low	0.20	3	0.6	Low	0.40	2	0.8	Very Low	0.40	3	1.2	2.6	0.88	Very Good
R7	Very Low	0.20	3	0.6	Low	0.40	2	0.8	Low	0.40	2	0.8	2.2	0.82	Good
R8	Very Low	0.20	3	0.6	Low	0.40	2	0.8	Average	0.40	-1	-0.4	1	0.65	Average
R9	Very Low	0.20	3	0.6	Low	0.40	2	0.8	High	0.40	-2	-0.8	0.6	0.59	Average
R10	Very Low	0.20	3	0.6	Low	0.40	2	0.8	Very High	0.40	-3	-1.2	0.2	0.53	Average
R11	Very Low	0.20	3	0.6	Average	0.40	-1	-0.4	Very Low	0.40	3	1.2	1.4	0.71	Good
R12	Very Low	0.20	3	0.6	Average	0.40	-1	-0.4	Low	0.40	2	0.8	1	0.65	Average
R13	Very Low	0.20	3	0.6	Average	0.40	-1	-0.4	Average	0.40	-1	-0.4	-0.2	0.47	Average
R14	Very Low	0.20	3	0.6	Average	0.40	-1	-0.4	High	0.40	-2	-0.8	-0.6	0.41	Poor
R15	Very Low	0.20	3	0.6	Average	0.40	-1	-0.4	Very High	0.40	-3	-1.2	-1	0.35	Poor
R16	Very Low	0.20	3	0.6	High	0.40	-2	-0.8	Very Low	0.40	3	1.2	1	0.65	Average
R17	Very Low	0.20	3	0.6	High	0.40	-2	-0.8	Low	0.40	2	0.8	0.6	0.59	Average
R18	Very Low	0.20	3	0.6	High	0.40	-2	-0.8	Average	0.40	-1	-0.4	-0.6	0.41	Poor
R19	Very Low	0.20	3	0.6	High	0.40	-2	-0.8	High	0.40	-2	-0.8	-1	0.35	Poor
R20	Very Low	0.20	3	0.6	High	0.40	-2	-0.8	Very High	0.40	-3	-1.2	-1.4	0.29	Poor
R21	Very Low	0.20	3	0.6	Very High	0.40	-4	-1.6	Very Low	0.40	3	1.2	0.2	0.53	Average
R22	Very Low	0.20	3	0.6	Very High	0.40	-4	-1.6	Low	0.40	2	0.8	-0.2	0.47	Average
R23	Very Low	0.20	3	0.6	Very High	0.40	-4	-1.6	Average	0.40	-1	-0.4	-1.4	0.29	Poor
R24	Very Low	0.20	3	0.6	Very High	0.40	-4	-1.6	High	0.40	-2	-0.8	-1.8	0.24	Very Poor
R25	Very Low	0.20	3	0.6	Very High	0.40	-4	-1.6	Very High	0.40	-3	-1.2	-2.2	0.18	Very Poor
R26	Low	0.20	2	0.4	Very Low	0.40	4	1.6	Very Low	0.40	3	1.2	3.2	0.97	Very Good
R27	Low	0.20	2	0.4	Very Low	0.40	4	1.6	Low	0.40	2	0.8	2.8	0.91	Very Good
R28	Low	0.20	2	0.4	Very Low	0.40	4	1.6	Average	0.40	-1	-0.4	1.6	0.74	Good
R29	Low	0.20	2	0.4	Very Low	0.40	4	1.6	High	0.40	-2	-0.8	1.2	0.68	Good
R30	Low	0.20	2	0.4	Very Low	0.40	4	1.6	Very High	0.40	-3	-1.2	0.8	0.62	Average

Note: R.I.= Relative Importance, I.O. = Impact on the Output, CE = Combined Effect, R1, R2,...= Number of the Rule

Continuation Table H.3(b)

R31	Low	0.20	2	0.4	Low	0.40	2	0.8	Very Low	0.40	3	1.2	2.4	0.85	Good
R32	Low	0.20	2	0.4	Low	0.40	2	0.8	Low	0.40	2	0.8	2	0.79	Good
R33	Low	0.20	2	0.4	Low	0.40	2	0.8	Average	0.40	-1	-0.4	0.8	0.62	Average
R34	Low	0.20	2	0.4	Low	0.40	2	0.8	High	0.40	-2	-0.8	0.4	0.56	Average
R35	Low	0.20	2	0.4	Low	0.40	2	0.8	Very High	0.40	-3	-1.2	0	0.50	Average
R36	Low	0.20	2	0.4	Average	0.40	-1	-0.4	Very Low	0.40	3	1.2	1.2	0.68	Good
R37	Low	0.20	2	0.4	Average	0.40	-1	-0.4	Low	0.40	2	0.8	0.8	0.62	Average
R38	Low	0.20	2	0.4	Average	0.40	-1	-0.4	Average	0.40	-1	-0.4	-0.4	0.44	Poor
R39	Low	0.20	2	0.4	Average	0.40	-1	-0.4	High	0.40	-2	-0.8	-0.8	0.38	Poor
R40	Low	0.20	2	0.4	Average	0.40	-1	-0.4	Very High	0.40	-3	-1.2	-1.2	0.32	Poor
R41	Low	0.20	2	0.4	High	0.40	-2	-0.8	Very Low	0.40	3	1.2	0.8	0.62	Average
R42	Low	0.20	2	0.4	High	0.40	-2	-0.8	Low	0.40	2	0.8	0.4	0.56	Average
R43	Low	0.20	2	0.4	High	0.40	-2	-0.8	Average	0.40	-1	-0.4	-0.8	0.38	Poor
R44	Low	0.20	2	0.4	High	0.40	-2	-0.8	High	0.40	-2	-0.8	-1.2	0.32	Poor
R45	Low	0.20	2	0.4	High	0.40	-2	-0.8	Very High	0.40	-3	-1.2	-1.6	0.26	Poor
R46	Low	0.20	2	0.4	Very High	0.40	-4	-1.6	Very Low	0.40	3	1.2	0	0.50	Average
R47	Low	0.20	2	0.4	Very High	0.40	-4	-1.6	Low	0.40	2	0.8	-0.4	0.44	Poor
R48	Low	0.20	2	0.4	Very High	0.40	-4	-1.6	Average	0.40	-1	-0.4	-1.6	0.26	Poor
R49	Low	0.20	2	0.4	Very High	0.40	-4	-1.6	High	0.40	-2	-0.8	-2	0.21	Very Poor
R50	Low	0.20	2	0.4	Very High	0.40	-4	-1.6	Very High	0.40	-3	-1.2	-2.4	0.15	Very Poor
R51	Average	0.20	0	0	Very Low	0.40	4	1.6	Very Low	0.40	3	1.2	2.8	0.91	Very Good
R52	Average	0.20	0	0	Very Low	0.40	4	1.6	Low	0.40	2	0.8	2.4	0.85	Good
R53	Average	0.20	0	0	Very Low	0.40	4	1.6	Average	0.40	-1	-0.4	1.2	0.68	Good
R54	Average	0.20	0	0	Very Low	0.40	4	1.6	High	0.40	-2	-0.8	0.8	0.62	Average
R55	Average	0.20	0	0	Very Low	0.40	4	1.6	Very High	0.40	-3	-1.2	0.4	0.56	Average
R56	Average	0.20	0	0	Low	0.40	2	0.8	Very Low	0.40	3	1.2	2	0.79	Good
R57	Average	0.20	0	0	Low	0.40	2	0.8	Low	0.40	2	0.8	1.6	0.74	Good
R58	Average	0.20	0	0	Low	0.40	2	0.8	Average	0.40	-1	-0.4	0.4	0.56	Average
R59	Average	0.20	0	0	Low	0.40	2	0.8	High	0.40	-2	-0.8	0	0.50	Average
R60	Average	0.20	0	0	Low	0.40	2	0.8	Very High	0.40	-3	-1.2	-0.4	0.44	Poor
R61	Average	0.20	0	0	Average	0.40	-1	-0.4	Very Low	0.40	3	1.2	0.8	0.62	Average
R62	Average	0.20	0	0	Average	0.40	-1	-0.4	Low	0.40	2	0.8	0.4	0.56	Average
R63	Average	0.20	0	0	Average	0.40	-1	-0.4	Average	0.40	-1	-0.4	-0.8	0.38	Poor

Continuation Table H.3(b)

R64	Average	0.20	0	0	Average	0.40	-1	-0.4	High	0.40	-2	-0.8	-1.2	0.32	Poor
R65	Average	0.20	0	0	Average	0.40	-1	-0.4	Very High	0.40	-3	-1.2	-1.6	0.26	Poor
R66	Average	0.20	0	0	High	0.40	-2	-0.8	Very Low	0.40	3	1.2	0.4	0.56	Average
R67	Average	0.20	0	0	High	0.40	-2	-0.8	Low	0.40	2	0.8	0	0.50	Average
R68	Average	0.20	0	0	High	0.40	-2	-0.8	Average	0.40	-1	-0.4	-1.2	0.32	Poor
R69	Average	0.20	0	0	High	0.40	-2	-0.8	High	0.40	-2	-0.8	-1.6	0.26	Poor
R70	Average	0.20	0	0	High	0.40	-2	-0.8	Very High	0.40	-3	-1.2	-2	0.21	Very Poor
R71	Average	0.20	0	0	Very High	0.40	-4	-1.6	Very Low	0.40	3	1.2	-0.4	0.44	Poor
R72	Average	0.20	0	0	Very High	0.40	-4	-1.6	Low	0.40	2	0.8	-0.8	0.38	Poor
R73	Average	0.20	0	0	Very High	0.40	-4	-1.6	Average	0.40	-1	-0.4	-2	0.21	Very Poor
R74	Average	0.20	0	0	Very High	0.40	-4	-1.6	High	0.40	-2	-0.8	-2.4	0.15	Very Poor
R75	Average	0.20	0	0	Very High	0.40	-4	-1.6	Very High	0.40	-3	-1.2	-2.8	0.09	Very Poor
R76	High	0.20	-2	-0.4	Very Low	0.40	4	1.6	Very Low	0.40	3	1.2	2.4	0.85	Good
R77	High	0.20	-2	-0.4	Very Low	0.40	4	1.6	Low	0.40	2	0.8	2	0.79	Good
R78	High	0.20	-2	-0.4	Very Low	0.40	4	1.6	Average	0.40	-1	-0.4	0.8	0.62	Average
R79	High	0.20	-2	-0.4	Very Low	0.40	4	1.6	High	0.40	-2	-0.8	0.4	0.56	Average
R80	High	0.20	-2	-0.4	Very Low	0.40	4	1.6	Very High	0.40	-3	-1.2	0	0.50	Average
R81	High	0.20	-2	-0.4	Low	0.40	2	0.8	Very Low	0.40	3	1.2	1.6	0.74	Good
R82	High	0.20	-2	-0.4	Low	0.40	2	0.8	Low	0.40	2	0.8	1.2	0.68	Good
R83	High	0.20	-2	-0.4	Low	0.40	2	0.8	Average	0.40	-1	-0.4	0	0.50	Average
R84	High	0.20	-2	-0.4	Low	0.40	2	0.8	High	0.40	-2	-0.8	-0.4	0.44	Poor
R85	High	0.20	-2	-0.4	Low	0.40	2	0.8	Very High	0.40	-3	-1.2	-0.8	0.38	Poor
R86	High	0.20	-2	-0.4	Average	0.40	-1	-0.4	Very Low	0.40	3	1.2	0.4	0.56	Average
R87	High	0.20	-2	-0.4	Average	0.40	-1	-0.4	Low	0.40	2	0.8	0	0.50	Average
R88	High	0.20	-2	-0.4	Average	0.40	-1	-0.4	Average	0.40	-1	-0.4	-1.2	0.32	Poor
R89	High	0.20	-2	-0.4	Average	0.40	-1	-0.4	High	0.40	-2	-0.8	-1.6	0.26	Poor
R90	High	0.20	-2	-0.4	Average	0.40	-1	-0.4	Very High	0.40	-3	-1.2	-2	0.21	Very Poor
R91	High	0.20	-2	-0.4	High	0.40	-2	-0.8	Very Low	0.40	3	1.2	0	0.50	Average
R92	High	0.20	-2	-0.4	High	0.40	-2	-0.8	Low	0.40	2	0.8	-0.4	0.44	Poor
R93	High	0.20	-2	-0.4	High	0.40	-2	-0.8	Average	0.40	-1	-0.4	-1.6	0.26	Poor
R94	High	0.20	-2	-0.4	High	0.40	-2	-0.8	High	0.40	-2	-0.8	-2	0.21	Very Poor
R95	High	0.20	-2	-0.4	High	0.40	-2	-0.8	Very High	0.40	-3	-1.2	-2.4	0.15	Very Poor

Continuation Table H.3(b)

R96	High	0.20	-2	-0.4	Very High	0.40	-4	-1.6	Very Low	0.40	3	1.2	-0.8	0.38	Poor
R97	High	0.20	-2	-0.4	Very High	0.40	-4	-1.6	Low	0.40	2	0.8	-1.2	0.32	Poor
R98	High	0.20	-2	-0.4	Very High	0.40	-4	-1.6	Average	0.40	-1	-0.4	-2.4	0.15	Very Poor
R99	High	0.20	-2	-0.4	Very High	0.40	-4	-1.6	High	0.40	-2	-0.8	-2.8	0.09	Very Poor
R100	High	0.20	-2	-0.4	Very High	0.40	-4	-1.6	Very High	0.40	-3	-1.2	-3.2	0.03	Very Poor
R101	Very High	0.20	-3	-0.6	Very Low	0.40	4	1.6	Very Low	0.40	3	1.2	2.2	0.82	Good
R102	Very High	0.20	-3	-0.6	Very Low	0.40	4	1.6	Low	0.40	2	0.8	1.8	0.76	Good
R103	Very High	0.20	-3	-0.6	Very Low	0.40	4	1.6	Average	0.40	-1	-0.4	0.6	0.59	Average
R104	Very High	0.20	-3	-0.6	Very Low	0.40	4	1.6	High	0.40	-2	-0.8	0.2	0.53	Average
R105	Very High	0.20	-3	-0.6	Very Low	0.40	4	1.6	Very High	0.40	-3	-1.2	-0.2	0.47	Average
R106	Very High	0.20	-3	-0.6	Low	0.40	2	0.8	Very Low	0.40	3	1.2	1.4	0.71	Good
R107	Very High	0.20	-3	-0.6	Low	0.40	2	0.8	Low	0.40	2	0.8	1	0.65	Average
R108	Very High	0.20	-3	-0.6	Low	0.40	2	0.8	Average	0.40	-1	-0.4	-0.2	0.47	Average
R109	Very High	0.20	-3	-0.6	Low	0.40	2	0.8	High	0.40	-2	-0.8	-0.6	0.41	Poor
R110	Very High	0.20	-3	-0.6	Low	0.40	2	0.8	Very High	0.40	-3	-1.2	-1	0.35	Poor
R111	Very High	0.20	-3	-0.6	Average	0.40	-1	-0.4	Very Low	0.40	3	1.2	0.2	0.53	Average
R112	Very High	0.20	-3	-0.6	Average	0.40	-1	-0.4	Low	0.40	2	0.8	-0.2	0.47	Average
R113	Very High	0.20	-3	-0.6	Average	0.40	-1	-0.4	Average	0.40	-1	-0.4	-1.4	0.29	Poor
R114	Very High	0.20	-3	-0.6	Average	0.40	-1	-0.4	High	0.40	-2	-0.8	-1.8	0.24	Very Poor
R115	Very High	0.20	-3	-0.6	Average	0.40	-1	-0.4	Very High	0.40	-3	-1.2	-2.2	0.18	Very Poor
R116	Very High	0.20	-3	-0.6	High	0.40	-2	-0.8	Very Low	0.40	3	1.2	-0.2	0.47	Average
R117	Very High	0.20	-3	-0.6	High	0.40	-2	-0.8	Low	0.40	2	0.8	-0.6	0.41	Poor
R118	Very High	0.20	-3	-0.6	High	0.40	-2	-0.8	Average	0.40	-1	-0.4	-1.8	0.24	Very Poor
R119	Very High	0.20	-3	-0.6	High	0.40	-2	-0.8	High	0.40	-2	-0.8	-2.2	0.18	Very Poor
R120	Very High	0.20	-3	-0.6	High	0.40	-2	-0.8	Very High	0.40	-3	-1.2	-2.6	0.12	Very Poor
R121	Very High	0.20	-3	-0.6	Very High	0.40	-4	-1.6	Very Low	0.40	3	1.2	-1	0.35	Poor
R122	Very High	0.20	-3	-0.6	Very High	0.40	-4	-1.6	Low	0.40	2	0.8	-1.4	0.29	Poor
R123	Very High	0.20	-3	-0.6	Very High	0.40	-4	-1.6	Average	0.40	-1	-0.4	-2.6	0.12	Very Poor
R124	Very High	0.20	-3	-0.6	Very High	0.40	-4	-1.6	High	0.40	-2	-0.8	-3	0.06	Very Poor
R125	Very High	0.20	-3	-0.6	Very High	0.40	-4	-1.6	Very High	0.40	-3	-1.2	-3.4	0.00	Very Poor

Table H.4(a): Fuzzy inference rules generated in the SOKE module for the Excavation activity

Construction Resource	Quality Level (Q)	Frequency of Occurrence (F)	Adverse Consequences (C)	Number of Nonconformances (N)	Duration of Delays (D)
Work Conditions	Very Poor	Unusual	Very Severe	Very Large	Large
	Poor	Often	Severe	Large	Large
	Average	Often	Medium	Medium	Large
	Good	Often	Medium	Medium	Small
	Very Good	Very Unusual	Mild	Small	Very Small
Design/Drafting Information	Very Poor	Unusual	Severe	Large	Very Large
	Poor	Often	Medium	Medium	Large
	Average	Usual	Medium	Medium	Medium
	Good	Often	Mild	Small	Small
	Very Good	Unusual	Very Mild	Very Small	Very Small
Material Supplying	Very Poor	Unusual	Severe	Large	Medium
	Poor	Often	Medium	Medium	Medium
	Average	Usual	Medium	Medium	Medium
	Good	Unusual	Mild	Small	Very Small
	Very Good	Very Unusual	Very Mild	Very Small	Very Small

Table H.4(b): Fuzzy inference rules generated in the SOKE module for the Bedding activity

Construction Resource	Quality Level (Q)	Frequency of Occurrence (F)	Adverse Consequences (C)	Number of Nonconformances (N)	Duration of Delays (D)
Work Conditions	Very Poor	Unusual	Very Severe	Large	Medium
	Poor	Often	Severe	Large	Medium
	Average	Often	Medium	Medium	Medium
	Good	Often	Mild	Small	Small
	Very Good	Very Unusual	Mild	Small	Small
Design/Drafting Information	Very Poor	Unusual	Severe	Large	Large
	Poor	Often	Medium	Medium	Medium
	Average	Usual	Medium	Medium	Medium
	Good	Often	Mild	Small	Small
	Very Good	Unusual	Very Mild	Very Small	Small
Material Supplying	Very Poor	Unusual	Very Severe	Very Large	Very Large
	Poor	Often	Very Severe	Very Large	Large
	Average	Usual	Medium	Medium	Large
	Good	Unusual	Mild	Small	Medium
	Very Good	Very Unusual	Very Mild	Very Small	Small

Table H.4(c): Fuzzy inference rules generated in the SOKE module for the Pipe Installation activity

Construction Resource	Quality Level (Q)	Frequency of Occurrence (F)	Adverse Consequences (C)	Number of Nonconformances (N)	Duration of Delays (D)
Work Conditions	Very Poor	Unusual	Very Severe	Large	Very Large
	Poor	Often	Severe	Large	Large
	Average	Often	Medium	Medium	Medium
	Good	Often	Mild	Small	Small
	Very Good	Very Unusual	Mild	Small	Very Small
Design/Drafting Information	Very Poor	Unusual	Very Severe	Very Large	Large
	Poor	Often	Very Severe	Very Large	Large
	Average	Usual	Medium	Medium	Medium
	Good	Often	Mild	Small	Small
	Very Good	Unusual	Very Mild	Very Small	Small
Material Supplying	Very Poor	Unusual	Severe	Large	Large
	Poor	Often	Severe	Large	Large
	Average	Usual	Medium	Medium	Medium
	Good	Unusual	Mild	Small	Small
	Very Good	Very Unusual	Very Mild	Very Small	Very Small

Table H.4(d): Fuzzy inference rules generated in the SOKE module for the Backfilling activity

Construction Resource	Quality Level (Q)	Frequency of Occurrence (F)	Adverse Consequences (C)	Number of Nonconformances (N)	Duration of Delays (D)
Work Conditions	Very Poor	Unusual	Very Severe	Very Large	Large
	Poor	Often	Severe	Large	Large
	Average	Often	Medium	Medium	Medium
	Good	Often	Mild	Small	Small
	Very Good	Very Unusual	Very Mild	Small	Small
Design/Drafting Information	Very Poor	Unusual	Severe	Large	Very Large
	Poor	Often	Severe	Large	Large
	Average	Usual	Medium	Medium	Medium
	Good	Often	Mild	Small	Small
	Very Good	Unusual	Very Mild	Very Small	Very Small
Material Supplying	Very Poor	Unusual	Very Severe	Very Large	Very Large
	Poor	Often	Severe	Large	Large
	Average	Usual	Medium	Medium	Medium
	Good	Unusual	Mild	Small	Small
	Very Good	Very Unusual	Very Mild	Very Small	Very Small

APPENDIX I

MATLAB PROGRAM CODE TO ESTIMATE THE STATISTICAL PARAMETERS OF NONCONFORMANCE INDICATORS

This Program works along with two additional modules: GetMatrix and GetComposition, which codes are included below this main code

```
% Enter the membership functions of the variables

% Quality Level of Construction Resources
VeryGood=[0;0;0;0;0;0;0;0;0.33;0.67;1];
Good=[0;0;0;0;0;0;0.5;1;1;0.5;0];
Average=[0;0;0;0;0.33;0.67;1;0.5;0;0;0];
Poor=[0;0.33;0.67;1;1;0.5;0;0;0;0;0];
VeryPoor=[1;1;0.67;0.33;0;0;0;0;0;0;0];

% Adverse consequences
VeryMild=[1;1;0.5;0;0;0;0;0;0;0;0];
Mild=[0;0.5;1;1;0.5;0;0;0;0;0;0];
Medium=[0;0;0;0;0.5;1;1;0.5;0;0;0];
Severe=[0;0;0;0;0;0;0.5;1;1;0.5;0];
VerySevere=[0;0;0;0;0;0;0;0;0.5;1;1];

% Frequency of occurrence
VeryUnusual=[1;1;0.5;0;0;0;0;0;0;0;0];
Unusual=[0;0.5;1;1;0.5;0;0;0;0;0;0];
Often=[0;0;0;0;0.5;1;1;0.5;0;0;0];
Usual=[0;0;0;0;0;0;0.5;1;1;0.5;0];
VeryUsual=[0;0;0;0;0;0;0;0;0.5;1;1];

% Number of Nonconformances in Excavation
VerySmall=[1;0.67;0.33;0;0;0;0;0;0;0;0];
Small=[0;1;0.67;0.33;0;0;0;0;0;0;0];
Med=[0;0.5;1;0.67;0.33;0;0;0;0;0;0];
Large=[0;0;0;0.5;1;0;0;0;0;0;0];
VeryLarge=[0;0;0;0.33;0.67;1;0;0;0;0;0];

% Enter the state of the variables according to the fuzzy rules
% previously established
% In this case, the effect of three construction resources is
% analyzed: Work Conditions, Design Information, and Material Supplying

QualityWork=Good;
QualityDesign=Good;
QualityMaterial=Average;
ACWork=Medium;
ACDesign=Mild;
ACMaterial=Medium;
FrequencyWork=Often;
FrequencyDesign=Usual;
FrequencyMaterial=Usual;
RiskWork=Med;
RiskDesign=Med;
RiskMaterial=Med;
```

```
% Refer to section 3.3.1.2.1 in the thesis report

% 1.Obtain the fuzzy Union T1 of Cartesian relations between the
% Quality Level of resources and corresponding Adverse Consequences

U1=GetMatrix(ACWork,QualityWork);
U2=GetMatrix(ACDesign,QualityDesign);
U3=GetMatrix(ACMaterial,QualityMaterial);
E=max(U1,U2);
T1=max(E,U3);

% 2.Obtain the fuzzy Union T2 of Cartesian relations between the
% Frequency of Quality Levels and the Number of Nonconformances

U4=GetMatrix(RiskWork,FrequencyWork);
U5=GetMatrix(RiskDesign,FrequencyDesign);
U6=GetMatrix(RiskMaterial,FrequencyMaterial);
T=max(U4,U5);
T2=max(T,U6);

% 3.Obtain the fuzzy Union R of the Cartesian relations between the
% Adverse Conditions and corresponding Number of Nonconformances
% The corresponding rules should be entered first

U7=GetMatrix(VerySmall,VeryMild);
U8=GetMatrix(Small,Mild);
U9=GetMatrix(Med,Medium);
U10=GetMatrix(Large,Severe);
U11=GetMatrix(VeryLarge,VerySevere);
TMP=max(U7,U8);
TMP1=max(TMP,U9);
TMP2=max(TMP1,U10);
R=max(TMP2,U11); %(Adverse conditions, Risk)

clear E T TMP TMP1 TMP2 U1 U2 U3 U4 U5 U6 U7 U8 U9 U10 U11

% 4.Obtain the composition relation M between fuzzy Unions T1 and R

M=GetComposition(T1,R);

% Enter the x values of the Frequency, Quality Level, and
% Number of Nonconformances

FrequencyValues    = [0;1;2;3;4;5;6;7;8;9;10];
QualityLevelValues = [0;1;2;3;4;5;6;7;8;9;10];
RiskValues         = [0;1;2;3;4;5;6;7;8;9;10];

% 5.Obtain the matrices of the fuzzy joint effect between M and T2

totsize=length(RiskValues);
RR=zeros(totsize,size(VeryGood,1),size(VeryUnusual,1));
for i=1:totsize
    tmp      = GetMatrix(M(:,i),T2(:,i));
    RR(:,:,i)= tmp;
end
```

```
% 6.Calculate the Statistical Parameters with the matrices
% obtained with previous step

QtoF = zeros(length(RiskValues),1);
for myR = 1 : length(RiskValues)
    myMatrix = squeeze(RR(:,:,myR));
    sumQ     = sum(myMatrix,1);
    sumQ     = sumQ .* RiskValues';
    sumF     = sum(myMatrix,2);
    sumF     = sumF .* FrequencyValues;
    maxQ     = max(sumQ);
    maxF     = max(sumF);
    if maxF > 0
        QtoF(myR) = maxQ./maxF;
    else
        QtoF(myR) = 0;
    end
end

if sum(QtoF) > 0
    pRisk = QtoF ./ sum(QtoF);
else
    pRisk = 0;
end

Prod_pRisk_RiskValues = pRisk .* RiskValues;
theMean = sum(Prod_pRisk_RiskValues);
theSD   = (sum((RiskValues.^2) .* pRisk)-(theMean^2))^0.5;

clear tmp myR myMatrix

% Show final results
disp(['--- The mean is:                    ' num2str(theMean)])
disp(['--- The standard deviation is:      ' num2str(theSD)])
```

GetMatrix code

```
function A= GetMatrix(a,b);

nA=length(a);% x holds the size of vector a
nB=length(b);% y holds de size of vector b
A = zeros(nA,nB);
for n=1:nA
    for m=1:nB
        A(n,m)=min(a(m),b(n));
    end
end
```

GetComposition code

```
function M = GetComposition(A1,B1);

sizey=size(B1,2);
sizex=size(A1,1);
for i=1:sizex
    for j=1:sizey
        tmp2=min( A1(i,:),B1(:,j)' );
        M(i,j)=max(tmp2);
    end
end
```