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Improved

Risk Analysis for Large Projects: Bayesian Networks Approach

by

Milijana Fineman

Submitted for the degree of Doctor of Philosophy Queen Mary, University of London 2010 I certify that this thesis, and the research to which it refers, are the product of my own work, and that any ideas or quotations from the work of other people, published or otherwise, are fully acknowledged in accordance with the standard referencing practices of the discipline. I acknowledge the helpful guidance and support of my supervisor Professor Norman Fenton.

Milijana Fineman

Date

Abstract

Generally risk is seen as an abstract concept which is difficult to measure. In this thesis, we consider quantification in the broader sense by measuring risk in the context of large projects. By improved risk measurement, it may be possible to identify and control risks in such a way that the project is completed successfully in spite of the risks.

This thesis considers the trade-offs that may be made in project risk management, specifically time, cost and quality. The main objective is to provide a model which addresses the real problems and questions that project managers encounter, such as:

- If I can afford only minimal resources, how much quality is it possible to achieve?
- What resources do I need in order to achieve the highest quality possible?
- If I have limited resources and I want the highest quality, how much functionality do I need to lose?

We propose the use of a causal risk framework that is an improvement on the traditional modelling approaches, such as the risk register approach, and therefore contributes to better decision making.

The approach is based on Bayesian Networks (BNs). BNs provide a framework for causal modelling and offer a potential solution to some of the classical modelling problems. Researchers have recently attempted to build BN models that incorporate relationships between time, cost, quality, functionality and various process variables. This thesis analyses such BN models and as part of a new validation study identifies their strengths and weaknesses. BNs have shown considerable promise in addressing the aforementioned problems, but previous BN models have not directly solved the trade-off problem. Major weaknesses are that they do not allow sensible risk event measurement and they do not allow full trade-off analysis. The main hypothesis is that it is possible to build BN models that overcome these limitations without compromising their basic philosophy.

To my partner Ogo, my father Milan, my mother Bosa and my brother Bojan

Glossary

BN	Bayesian Network
CPD	Conditional Probability Distribution
СРМ	Critical Path Method
DAG	Directed Acyclic Graph
DBN	Dynamic Bayesian Network
DD	Dynamic Discretisation
KLOC	Thousand (Kilo) Lines of Code
NPT	Node Probability Table
MCS	Monte Carlo Simulation
00	Object Oriented
PERT	Program Evaluation and Review Technique
РМВоК	Project Management Body of Knowledge
PRM	Project Risk Management
VaR	Value at Risk

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1. Introduction

Many large-scale projects are unsuccessful due to insufficient analysis of the risks involved which usually results in escalating costs, delay and poor delivery. In particular the perception of major project failures is heightened due to the well publicised failures of large construction projects such as airports, bridges or public buildings. Information about the overrunning of public projects appears in the media more often, but large overruns also exist in private industry. The 2008 Heathrow Terminal 5 fiasco is a classic example of perceived project failure. Despite the enormous attention project risk management has received since the 1990s, the track record of projects is fundamentally poor, particularly for large projects.

Project risk management consists of identifying, monitoring, controlling and measuring risk. This project focuses on one especially important component of risk management - namely the quantitative aspect. Quantification has always been a key component of risk management, but until very recently the quantitative aspects focused entirely on insurance type risk. In this thesis, we consider quantification in the broader sense of measuring risk in the context of large projects. By improved risk measurement it may be possible to identify and control risks in such a way that the project is completed successfully in spite of the risks.

The criteria against which a project's success or failure can be measured are cost, time and quality, often referred to as The Iron Triangle, see Figure 1.1. Ideally, every project manager would like their projects to satisfy all three of the above criteria. However, the reality is that due to project constraints, trade-offs need to be made which usually result in only two of the three criteria being met, as implied by the Iron Triangle. Many factors need to be considered when deciding whether to compromise on time, cost and/or quality. The problem is that it is not always possible to amend one of these factors without having an impact on one or more of the other factors. For example, reducing the time could have a serious impact on cost and/or quality. The key point is that it is possible to trade-off quality for lesser time spent, but also less cost.

Currently project management literature only covers the theory behind the classic 'tradeoff' problem between cost, time and quality but it does not provide a decision-support system for trade-off analysis, in such a way that project managers can monitor and see which projects are on target in different phases of a project. This thesis is interested in providing a decision-support system motivated by the real problems and questions that face real project managers:

- If I can afford only minimal resources, how much quality is it possible to achieve?
- What resources do I need in order to achieve the highest quality possible?
- If I have limited resources and I want the highest quality, how much functionality do I need to lose?



Figure 1.1 The Iron Triangle

What is needed is a new approach to quantitative risk assessment that satisfies the following requirements:

- 1. Able to model and measure trade-offs between time, cost and quality; in such a way as to be able to answer questions such as those mentioned previously.
- 2. Able to produce an overall risk score for the project which: a) takes into account the overall success criteria and b) is available at any stage of the project life cycle and not just at the end of the project.
- 3. Is dynamic, i.e. able to take into account new information in order to revise its predictions and assessments for the overall risk score.
- 4. Is able to capture notions of cause and effect such as the possibility of avoiding risks by using controls and mitigants. Ideally also be able to capture opportunities as well as risks since these will have an impact on the overall success of the project.
- 5. Able to quantify unavoidable uncertainty in all of this.
- 6. The approach can be used by practitioners who have no mathematical/statistical background.

The research hypothesis is: We can provide an approach and template model which satisfies all of the above requirements and can be used by decision makers (working on large projects). The

approach is based on Bayesian Networks (BNs). BNs will be used because they provide effective decision-support for problems involving uncertainty and probabilistic reasoning, since they are able to combine diverse data.

In addition to satisfying the above requirements the proposed approach has the following benefits inherited from the BNs methodology:

- a. Handle and make predictions with incomplete data sets
- b. Combine diverse types of data sets including both subjective beliefs and objective data
- c. Overturn previous beliefs in light of new evidence
- d. Learn and explicitly model causal factors and their relationships
- e. Reason from effect to cause and vice versa
- f. Arrive at decision based on visible auditable reasoning and improve decision making for managers

The thesis is organised into eight chapters as follows.

Chapter 2 discusses the background and overview of project risk management. Project risk management is introduced together with project risk management standards. This is followed by a comprehensive list of risk factors for large projects with a discussion of the reasons for project failure and project success. The chapter finishes with a comprehensive review of state-of-the-art project risk management tools.

Chapter 3 provides the necessary background on BNs including their theoretical and technical framework. This provides sufficient information to discuss the advantages of BNs when applied to project risk management modelling.

Chapter 4 gives a detailed description of existing BN project risk models and their limitations. Models that include trade-off analysis as well as models that cover other aspects of project risk management are examined.

Chapter 5 is one of the main new contributions of this thesis and it argues that standard project risk quantification framework is inadequate. Overview of the risk definitions and how they have evolved to include opportunities are included. We present a new causal risk framework and models created to demonstrate it.

This is the original work and an earlier version of this work has been published: *Fineman, M. and Fenton N. E., Quantifying Risks Using Bayesian Networks, IASTED Int. Conf. Advances* *in Management Science and Risk Assessment (MSI 2009), Beijing, China, 2009, IASTED 662-219* [65]. I discussed the fundamental problems with a classical risk register and proposed a solution based on Bayesian Networks that incorporates opportunities into modelling.

Chapter 6 is one of the main contributions to this thesis and it describes a Causal Risk Register Model that implements risk taxonomy presented in chapter 5. The model is validated internally and externally. The model addresses key limitations of classical risk register approach.

Chapter 7 is one of the main contributions to this thesis and it describes Generic Trade-off Model that provides trade-offs between time, cost and quality. It includes requirements for the new template model and covers structure of this model. The model is an improvement on models discussed in chapter 4. The model is validated internally and externally.

This is the original work and an earlier version of this work has been published: *Fineman M., Radlinski L. and Fenton N. E., Modelling Project Trade-off Using Bayesian Networks, IEEE Int. Conf. Computational Intelligence and Software Engineering. Wuhan, China, 2009, IEEE Computer Society* **[64].** I developed a generic BN model for analysis of trade-offs between time, cost and quality in large projects. I also proposed a set of assumed rules that the model had to satisfy and demonstrated how the model can be used to support decision making by the managers in some typical scenarios. The new research content of the paper is almost entirely my own work, with contributions from the co-authors on presentation and accuracy.

Chapter 8 summarises the main points of the research undertaken for the thesis drawing conclusions.

Appendix A, Risk Factors for Large Projects

Appendix B, Risk Factors for Large Projects as Attributes

2. Overview of Project Risk Management

To understand the requirements and research hypothesis it is crucial to review and provide the background information on project risk management. In this chapter we discuss project risk management standards, since we believe risk definitions from various standards could be improved. We discuss the project risk management process and general risk issues for large projects. Numerous works have been conducted on how project success can be measured. Project success is usually defined as meeting time, cost and quality objectives. Key project factors identified will be used in the quantitative models developed and described in the subsequent chapters.

In the second part of this chapter we examine current state-of-the-art models. These vary in focus from the ones that concentrate on planning and scheduling to risk register through to alternative approaches. We first cover the planning and scheduling group of models including critical path method, PERT and Monte Carlo simulation techniques. We then cover classical risk register, followed by alternative techniques including fault trees, cognitive mapping methods and decision trees.

The new contribution of this chapter is the analysis of risk factors and improvement on how they can be phrased as attributes (Appendix B) and the analysis of the suitability of various modelling approaches to risk analysis for large projects.

2.1 Background of Project Risk Management

The first formalized project risk management approach started in the 1950s. An important milestone for indicating the beginning of quantitative project risk management was the development of scheduling techniques such as the Critical Path Method (CPM) [96] and the Program Evaluation and Review Technique (PERT) [119] which deal with risks implicitly. The main focus of those approaches was project scheduling This is a reasonably well researched area and it is not a major focus of this thesis, except if scheduling is in the context of quantifying risk assessment (tools such as the CPM and PERT, along with other project risk management tools are discussed in section 2.7).

The first article on project risk management was published by the Harvard Business Review [68]. In the beginning, the main focus was on planning, procurement and administrative functions. By the 1980's, project risk management had already become a well-recognized area in project management literature consisting of: risk identification, estimation, risk response

development and risk control. Its applications in industries were mainly time and cost risk analysis [78].

During the 1990's the focus of project risk management has changed and it began to turn from developing the quantitative side into developing and understanding the risk management process. New project risk management focus areas were cooperation and networking approaches, and managing business processes as projects. The rapid development of technology has enabled the application of project risk management in a geographically distributed business environment. Furthermore, an increasing number of risk management studies were carried out in the 1990's which report on project failures. Hence, practitioners are paying attention on learning from experience and introducing experience-based solutions of how risks could be avoided.

Companies are developing knowledge bases associated with project risk management [123]. The knowledge bases contain the descriptions of risks, but can also offer other valuable data such as suggestions for how to respond to risk. These risk knowledge bases can thus be used as organizational memory banks where experience about risks and potential risk responses are continuously recorded during project execution. It seems likely that changes and developments, such as these, in project risk management will continue.

2.2 Project Risk Management Standards

The first risk related standard ever published was Norsk Standard NS5814:1991: Krav til risikoanalyser in 1991 [143]. This standard only addressed risk analysis and it did not cover the other parts of risk assessment.

The first project risk management standard was BS 6079-3:2000: Project Management – Part 3: Guide to the Management of Business – related Project Risk by British Standards Institution in 2000 [24]. The International Electrotechnical Commission in Switzerland launched CEI/IEC 62198:2001: International Standard, Project Risk Management: Application Guidelines in 2001 [86]. In its scope section is stated that: "This International Standard is applicable to any project with technological content. It may also apply to other projects." In general it is easy to classify the standards according to their scope. The exception to this is the IEEE Standard 1540-2001: Standard for Software Life Cycle Processes – Risk Management by Institute of Electrical and Electronic Engineers in USA in 2001 [84], which states in its introduction that: "The risk management process defined in this standard can be adapted for use at an organisation level or project level."

The Risk Management Guide for DoD Acquisition by the US Department of Defence published in 2002 [182] has a limited scope of application to US defence acquisition projects.

Two project risk management standards appeared in quick succession in 2004. The Association for Project Management in the UK launched the Project Risk Analysis and Management Guide [7]; and the Project Management Institute in USA introduced the Guide to the Project Management Body of Knowledge (PMBoK): Chapter 11, Project Risk Management [151].

The focus on various standards was to create process consistency. All standards identified describe the following process steps: planning, identification, analysis, treatment and control. Terminology differs between the standards, but the process structure is similar in all of them. In the analysis step, there seems to be a dominant distinction between the two following main activities:

- 1. Risk estimation, which refers to an assessment of the likelihood of occurrence and possible consequences of the risks identified in the previous step.
- 2. Risk assessment, which refers to an evaluation of the assessed risk by comparison with the criteria and thresholds of the decision makers in order to determine the priority for treatment.

The above six standards limit their scope of application, as indicated by their title, to project risk management. However, it may be worth looking at other standards, defined in general terms since there are no significant differences in terms of the structure of the processes and the contents of the various stages. Thus it seems reasonable to also consult the following general scope standards, i.e. organisational standards:

- CAN/CSA-Q850-97: Risk Management: Guideline for Decision-Makers launched by Canadian Standards Association in 1997 [27].
- JIS Q2001: 2001(E): Guidelines for Development and Implementation of Risk Management System launched by Japanese Standards Association in 2001 [88].
- Risk Management Standard published by Institute of Risk Management/National Forum for Risk Management in the Public Sector/Association of Insurance and Risk Mangers in UK in 2002 [85].
- AS/NZS 4360:2004: Risk Management published by Standards Australia/Standards New Zealand in 2004 [9].

In subsequent discussions about risk definition and processes the following standards have been used: Risk Management Standard published by Institute of Risk Management/National Forum for Risk Management in the Public Sector/Association of Insurance and Risk Mangers in UK in 2002, AS/NZS 4360:2004: Risk Management published by Standards Australia/Standards New Zealand in 2004, the Project Management Institute in USA introduced Guide to the Project Management Body of Knowledge (PMBoK): Chapter 11, Project Risk Management.

2.3 Project Risk Management Process

In advocating the use of project risk management, Wideman [189] observed that:

"Experience on many projects reveals poor performance in terms of reaching scope, quality, time and cost objectives. Many of these shortcomings are attributed either to unforeseen events which might or might not have been anticipated by more experienced project management, or to foreseen events for which the risks were not fully accommodated."

Wideman's observation manages to encapsulate three central ideas in project risk management practice:

- 1. Identifying events with negative consequences
- 2. Estimating their probability and impact
- 3. Responding appropriately

Wideman's process requires that we first identify 'risk events'. We then estimate the probability that each risk will occur, and the impact on the project if it does occur. Thirdly we determine an appropriate response to the risk.

Research of failed software projects showed that "their problems could have been avoided or strongly reduced if there had been an explicit early concern with identifying and resolving their high-risk elements" (Boehm [19]). Hence, Boehm [19] suggested a process consisting of two main phases:

- 1. Risk assessment, which includes identification, analysis and prioritization.
- 2. Risk control, which includes risk management planning, risk resolution and risk monitoring planning, tracking and corrective action.

Fairley [53] proposes about seven steps:

- 1. Identify the risk factors
- 2. Assess risk probabilities and effects
- 3. Develop strategies to mitigate the identified risks
- 4. Monitor the risk factors
- 5. Invoke a contingency plan
- 6. Manage the crisis
- 7. Recover from the crisis

The Software Engineering Institute [168], a leading source of methodologies for managing software development projects, looks at project risk management as consisting of five distinct phases: identification, analysis, response planning, tracking and control. In its Guide to the Project Management Body of Knowledge, the Project Management Institute [151] gives a good overview of typical PRM processes consisting of four phases: identification, quantification, response development and control.

Kliem and Ludin [103] present a four phases process: identification, analysis, control and reporting. Chapman and Ward [32] outline a generic PRM process consisting of nine phases: define the key aspects of the project, focus on a strategic approach to risk management, identify where the risks might arise, structure the information about the risk assumptions and relationships, assign ownership of the risks and responses, estimate the extent of the uncertainty, evaluate the relative magnitude of the various risks, plan the responses and manage by monitoring and controlling the execution. From this brief review it is noticeable that there is general agreement regarding what is included in the process, with the differences depending on variations in the level of detail and on the assignment of activities to steps and phases.

It is in response to the risk stage that project risk management lays a claim to rationality. The expected value of the risk can be calculated as first described by Bernoulli in 1738 [16]:

"If the utility of each possible profit expectation is multiplied by the number of ways in which can it occur, and we then divide the sum of these products by the total number of possible cases, a mean utility will be obtained, and the profit which corresponds to this utility will equal the value of risk in question."

This concept of expected value allows us to evaluate risk responses. Let net response gain for a given risk response be defined as the gain in expected value less the cost of applying the risk response. The rational risk treatment is then the response among all possible alternatives that has the greatest net response gain.

The risk response planning process prescribed in the PMBOK offers a number of categories of risk treatments. If the expected value of the untreated risk is sufficiently high, one might decide to accept the risk (pg. 263). Otherwise, one might treat the risk by transferring it, for example, by insuring against it. Alternatively, one could avoid the risk by adopting a new course of action through which the risk cannot occur, or one could mitigate the risk by taking action to reduce its probability or impact (pg. 261-2). Techniques based on the traditional expected utility theory do not accurately describe human decision making and techniques based on expected monetary value raise even more concerns [101]. Review of multiple criteria decision analysis (MCDA) indicates popularity of multiattribute utility theory [50].

2.4 General Risk Issues for Major Large Scale Projects

Risks differ according to the type of project. For example, oil platforms are technically difficult, but they typically face few institutional risks since they are socially desired because of the high revenues they bring to communities and countries [94, 174]. Nuclear-power projects also pose high technical risks, however, they have higher social and institutional risks.

It is often said that the real risks in any project are the ones that you fail to recognise. This would imply that when identifying potential sources of risk, a broad scope should be adopted, thereby reducing the chances of overlooking important areas of risk. The emphasis should therefore be on generating a comprehensive list of risks rather than prematurely identifying a limited set of key risks. During the identification of risks there is a natural tendency to simply omit recording some risks because their impacts are immediately considered to be of a minor nature. This has obvious dangers in that omitting seemingly minor problems can mean that the combined effect of large numbers of apparently minor risks may be underestimated. In addition, there is also a tendency to omit recording risks where an effective response cannot be attributed to it, and this too has an obvious danger since potentially some risks are overlooked.

First it is important to be able to identify:

- new risks
- risks of which the scale may have changed, for instance, because of a context that has developed
- long known risks that have not been studied in depth
- risks of which social awareness has grown, for example, it may be that a risk that has been dominant in the past has been eliminated or reduced which creates new priorities.

2.5 What is a successful project?

Project success is a core concept of project management. Therefore, it is important that success objectives are defined and specified [87, 105, 112, 196, 159]. Oisen [144] in the 1970s suggested cost, time and quality as the success criteria for project management and the success of projects. Since then these criteria are usually included in the description of project management. Many other writers Turner [181], Morris and Hough [130], Wateridge [185, 186], deWitt [41, 42], McCoy [129], Pinto and Slevin [150], Babu and Suresh [9], Saarinen [167], Khang et al. [99], Ballantine et al. [12] and Kerzner [97, 98] all agree cost, time and quality should be used as success criteria. Some authors suggest that other criteria in addition to cost, time and quality could be used to assess projects [169, 175].

In the early 1980s more comprehensive definitions were developed. Baker et al. defined project success as follows: "If the project meets the technical performance specifications and/or mission to be performed and if there is a high level of satisfaction concerning the project outcome among: key people in the parent organisation, key people in the client organisation, key people in the project team and key users or clientele of the project effort, the project is considered an overall success." [11]

Freeman and Beale [67] concluded that success means different things to each professional. An architect may consider success in terms of aesthetic appearance, an engineer in terms of technical competence, an accountant in terms of pounds spent under budget, a human resource manager in terms of employee satisfaction, etc. The importance of the concept of project success was reflected by the Project Management Institute devoting its 1986 Annual Seminar and Symposium to this topic.

It is important to understand the concept of project success in order to explore it further. Time, cost and quality are the basic criteria to project success and they are identified and discussed in almost every article on project success [8]. Atkinson [8] called these three criteria the "Iron Triangle". He further suggested that while other definitions on project management success have developed, the iron triangle is always included in the alternative definitions.

The study performed by Crawford et al. [36] during the period of 1994–2003 confirms the fact that project management places great emphasis on ensuring conformance to time, budget and quality constraints. All projects are, to a certain degree, unique complex undertakings. However, there are significant similarities - most projects have restrictions in time and costs as well as certain demands for quality. As a result the project manager may find it extremely difficult to stay within the Iron Triangle. Kohrs and Welngarten [105] reported trade-offs that project manager must make: "Good! Fast! Cheap! Pick any two." The Iron Triangle is the 'magic combination' that is continuously pursued by the project manager throughout the life cycle of the project [25, 78, 92, 72, 113, 130, 155, 165].

If the project were to flow smoothly, according to plan, there might not be a need for trade-off analysis. Unfortunately, most projects eventually get into crises such that it is no longer possible to maintain the delicate balance necessary to attain the desired performance within time and cost [101]. The deviations are normally overruns, in the case of time and cost, whereas the quality deviation is usually a shortfall. No two projects are ever exactly alike, and trade-off analysis would be an ongoing effort throughout the life of the project, continuously influenced by both the internal and external environment. Experienced project managers may have planned

trade-offs in reserve in the event that anticipated crises arise hence recognising that trade-offs are essential in effective project risk management.

For example, if we can achieve high quality this may compensate for cost and time. Or if there is timely delivery which enables a 'first-to-market' advantage (Microsoft products for example), then we may be willing to compromise with a low quality end-product. In the case of software projects we include functionality as part of quality and by doing this we can compare success. For example, how many function points [157] you deliver with how many defects at what cost and time. This means we can measure functionality objectively.

There are many reports on project overruns and it would be a conservative estimate to state that approximately 50% of construction projects overrun [130] and approximately 63% of all information systems projects encounter substantial budget overrun [130], with overrun values "typically between 40 and 200 percent" [130]. Project sponsors claim that although, "most projects are eventually completed more or less to specification", they are "seldom on time and within budget" [196]. It has even been suggested that a "good rule of thumb is to add a minimum of 50% to every time estimate, and 50% to the first estimate of the budget" [196].

At first glance, a project that does not meet the three success factors of time, cost and quality would appear to be a failure, but this is not necessarily so. It is 'perceived' success or failure that is important and provided a project achieves a satisfactory level of technical performance, in retrospect it may be considered a success by the parties involved, despite exceeding its cost and time targets. This of course depends on whether cost and time targets were fixed or not. In addition, although the project cost more and took longer than the client originally perceived, the client may accept that this was unavoidable, was for good reason, that it received value for money, and the project was still a commercial success. The criterion of success or failure is whether the project sponsor, owner, client and other parties concerned, including the project manager's parent company, are satisfied with the final outcome of the project.

2.6 Factors affecting success or failure of projects

The identification of project success factors can be used to analyse the reasons for project success and failure. Since the 1960s, many theoretical and empirical studies have been completed on success factors of a project.

The success and failure factors were first introduced by Rubin and Seeling [164]. They investigated the impact of a project manager's experience on the project's success and failure. They concluded that the number of projects previously managed by a project manager has

minimal impact on the project's performance, whereas the size of the previously managed projects does affect the project's performance.

Pinto and Selvin [150] reported that the critical success of a project depends on ten factors. These are: project mission, top management support, project schedules, client consultation, personnel recruitment, technical tasks, client acceptance, monitoring and feedback, communication and trouble-shooting. Anton listed six factors to enhance project success. These factors are: planning effort in design and implementation, project manager goal commitment, project team motivation, project manager technical capabilities, scope and work definition and control system.

Belassi and Tukel [14] categorised these factors into four main groups. These are factors relating to: the project managers, the project, the organisation and the external environment.

UK experience

In the UK, two studies identified the factors leading to the failure of projects. Duffy and Thomas [49] identified the following reasons for the failure of projects:

- Project management in the client, consultant, contractor and supplier organisations is an important factor in poor project performance.
- Inappropriate project organisation is usually the key to an unsuccessful project. Here the roles and responsibilities in the project parties have not been clearly defined.
- Lack of direction and control in the project team often results in low productivity and a failure to meet delivery dates.
- On many projects consideration of an appropriate contract strategy is left until late in the project, when the full range of options available to the client cannot be considered.
- Often the scope of work is not defined adequately to those participating in the project.
- Frequently the level of planning is inappropriate to the scope of the project. Project stages are not clearly identified with agreed deliverables.

US experience

The major research work on the subject was carried out in the USA by Baker, Murphy and Fisher [11], who studied 650 projects. They identified a large number of factors which affected the

success of projects, the failure of projects and those which affected both success and failure, as shown in Table 2.1. They also consolidated their findings and identified the following:

- The prime factors leading to project failure:
 - Poor coordination
 - Human relations
- The prime factors leading to project success:
 - Adequate and appropriate organisational structures
 - o Adequate and appropriate planning and control mechanisms

We will incorporate their research findings in later chapters of this thesis when we build a quantitative model for project risk analysis.

Factors affecting both success and failure				
Goal commitment of project team				
Accurate initial cost estimates				
Adequate project team capability				
Adequate funding to completion				
Adequate planning and control techniques				
Minimal start-up difficulties				
Task (versus social) orientation				
Absence or bureaucracy				
On-site project manager				
Clearly established success criteria				
Factors affecting				
Failure	Success			
Inadequate project manager:	Project manager commitment to:			
Human skills	• Established schedules			
Technical skills	• Established budgets			
• Influence	Technical performance goals			
Authority				
Insufficient use of status and progress reports	Frequent feedback from the parent organisation			
Use of superficial status/progress reports	Frequent feedback from the client			
Insufficient client influence	Client commitment to:			

Poor coordination with the client	Established schedules							
	• Established budgets							
Lack of rapport with the client	Technical performance goals							
Client disinterest in budget criteria								
Lack of project team participation in decision- making	Project team participation in determining schedules and budgets							
Lack of project team participation in problem- solving								
Excessive structuring within project team								
Job insecurity within project team								
Lack of team spirit and sense of mission within project team								
Parent organisation stable, non-dynamic,	Parent commitment to:							
lacking strategic change	Established schedules							
	• Established budgets							
Poor coordination with parent organisation	Technical performance goals							
Lack of rapport with parent organisation	Parent enthusiasm							
Poor relations with parent organisation	Parent desire to build up internal capabilities							
Project more complex than the parent has completed before	Adequate control procedures, especially for dealing with changes							
Inability to freeze design early								
Inability to close out the effort	Judicious use of networking techniques							
Inadequate change procedures	Minimal number of public/government							
Unrealistic project schedules	agencies involved							
Initial under-funding	Lack of excessive government red tape							
New 'type' of project	Enthusiastic public support							
Poor relations with public officials	Lack of legal encumbrances							
Unfavourable public opinion								

Table 2.1 Factors affecting the success or failure of projects [11]

Very often a project team might use a table (such as the one in Table 2.2) to prompt their thinking about risks for their project. The team can decide which factors are relevant at what rating, and then proceed to state the specific risks they suspect could affect their project. By doing this they would develop a risk register.

When the project completes, the team should review its performance against the risk management documentation to see if there are factors to add to this table or if there are cues that should be changed to help future projects in the organization better identify their risks.

					Rating (check one)						
Factor ID	Risk Factors	Low Risk Cues	Medium Risk Cues	High Risk Cues	L	М	H	NA	NI	TBD	Notes
Mission	and Goals										
1	Project Fit to Customer Organization	directly supports customer organization mission and/or goals	indirectly impacts one or more goals of customer	does not support or relate to customer organization mission or goals							
2	Project Fit to Provider Organization	directly supports provider organization mission and/or goals	indirectly impacts one or more goals of provider	does not support or relate to provider organization mission or goals							
3	Customer Perception	customer expects this organization to provide this product	organization is working on project in area not expected by customer	project is mismatch with prior products or services of this organization							
4	Work Flow	little or no change to work flow	will change some aspect or have small affect on work flow	significantly changes the work flow or method of organization							

 Table 2.2 Sample risk factors for large projects [45]

For the complete table, please refer to Appendix A. It consists of 14 categories with a total of 77 risk factors listed.

As Table 2.1 and 2.2 confirm, major studies carried out do identify separate factors affecting large projects i.e. factors affecting project success and factors affecting project failure. In fact many researchers do not realise that these factors are symmetrical. To prove this, we have created our table covering key project factors based on the studies we have mentioned above. In our table, factors are in fact attributes that can be either good or bad, Table 2.3.

Adequacy of PM	Good	Bad					
Mission and Goals							
Project Fit to Customer	directly supports customer	does not support or relate to					
Organization	organization mission and/or	customer organization mission					
	goals	or goals					
Project Fit to Provider	directly supports provider	does not support or relate to					
Organization	organization mission and/or	provider organization mission					
	goals	or goals					
Customer Perception	customer expects this	project is mismatch with prior					
	organization to provide this	products or services of this					
	product	organization					
Work Flow	little or no change to work	significantly changes the work					
	flow	flow or method of					
		organization					
Goal commitment of project	High goal commitment of	Low goal commitment of					
team	project team	project team					

Table 2.3 Key Project Factors

For the complete table, please refer to Appendix B.

2.7 State-of-The-Art on Modelling Project Risk

2.7.1 Planning and scheduling tools

Critical Path Method

The Critical Path Method (CPM) is one of the most frequently used project scheduling tools. A schedule "network" represents the project strategy [82]. "Network" analysis procedures originated from the traditional Gantt chart. When the results of a CPM analysis are fitted to a calendar time, the project plan becomes a schedule. The CPM is overwhelmingly the standard approach for considering the effects of delays on a project [190].

The CPM identifies the longest path in the network called the critical path by calculating activities time parameters. Any delay in an activity on the critical path will delay the entire

project. The paths that are not critical can be delayed, if they have scheduling flexibility, without necessarily delaying the project.

The CPM models the activities and their dependency. Hence, it is not possible to start some activities until others are finished. These activities need to be completed in a sequence, with each stage being completed before the next stage can begin. Since real projects do not work this way, the CPM is just the beginning of project schedule management. Some key reservations about the standard CPM:

- It is based on single-point estimates and therefore gives a false notion that the future can be predicted precisely. One common misconception is that since estimates are based on most likely estimates, things will even out by the law of averages [90]. In almost all cases, the CPM completion date is not the most likely. [82]
- The activities on the critical path may not be the most likely to delay the project. Tasks not on the critical path can, due to deviations from the plan, end up on the critical path. The use of the CPM can therefore direct management's attention to activities not likely to delay the project. The duration of each task is an estimate subject to uncertainty [90]. The critical path may vary and single tasks may or may not be on the critical path when randomness is accounted for.
- Project duration is probabilistic and therefore predictions of completion dates should be accompanied by probabilities. The duration calculated by the CPM is simply an addition of the most likely estimates, which is only accurate if everything goes according to plan.
 [82] The CPM date is rarely a good approximation of the most likely date. Even with a single path project, the CPM date is almost always far too optimistic [71].
- The CPM does not account for path convergence and therefore tends to underestimate the duration of the project. For example, if three parallel activities all have an estimated duration of 10 days, the CPM calculated duration will be 10 days. However, if any one of the activities is delayed, this estimation will not hold. The likelihood of meeting the predicted merge date is the product of the probabilities of each of the joining paths [71].
- The project duration calculated by the CPM is accurate only if everything goes according to plan. This is rare in real projects.
- In many cases the completion dates the CPM produces are unrealistically optimistic and highly likely to be overrun, even if the schedule logic and duration estimates are accurately implemented.

- The CPM completion date is not even the most likely project completion date, in almost all cases.
- The path identified as the "critical path" using traditional CPM techniques may not be the one that will be most likely to delay the project and which may need management attention.

PERT

The PERT (Program Evaluation and Review Technique) is a variation on Critical Path Analysis developed in the 1950's. It was able to incorporate uncertainty in activity duration by making it possible to schedule a project while not knowing precisely the details and durations of all the activities [40, 119, 130, 132]. For each activity PERT gives three estimations: optimistic, most likely and pessimistic times. Also, it identifies the minimum time needed to complete the total project.

In the 1960s PERT was a great success. However, in the 1970s doubts were raised about the theoretical assumptions of PERT and its practicality. The assumption of independence between activities and also assumption that all estimates have a Beta distribution are not practical. More importantly the PERT assumes that the probability distribution of the project completion time is the same as that of the critical path. The possibility that the critical path identified may not end up being the critical path is ignored. Hence, the PERT consistently underestimates the expected project completion time and produces overly optimistic estimates for the project duration.

Monte Carlo Simulation Tools

Monte Carlo simulation (MCS) can be used to overcome some challenges associated with CPM and PERT. It was first proposed for project scheduling in the early 1960s. The technique became dominant only in 1980s when sufficient computer power became available. Each simulation is generated by randomly pulling a sample value for each input variable. These input sample values are then used to calculate the results, i.e. total project duration, total project cost, project finish time. The duration of each activity is estimated by shortest, most likely and longest duration and also the shape of the distribution (Normal, Beta etc.). Then critical path calculation is repeated several times. A sufficient number of runs provide a probability distribution for the possible results (i.e. time, cost) [91].

The following project risk management tools apply Monte Carlo analysis:

- Pertmaster Project Risk [149]
- @Risk [1]
- Deltek Risk+ [43]
- Risk+ from S/C Solutions Inc. [161]
- Crystall Ball [38]
- Risky Project Professional 2.1[162]
- PROAct [152]
- Project Risk Analysis [154]

Each MCS tool has its own specific functionalities. The following features are common to all of them:

- Assign different statistical distributions including custom distributions to project inputs (task duration, cost, etc.)
- Output results in different formats.

MCS can also provide a sensitivity analysis by measuring the correlation between the project inputs (task duration, finish time etc.) and the project outputs (project duration, cost etc.). This gives an indication of how much the duration of each task affects completion of other tasks and also the tasks that are most likely to cause delay on the project.

The classic Monte Carlo simulation method has a number of limitations. The serious flaw in traditional MCS is the assumption of statistical independence for individual activities which share risk factors in common with other activities [183]. MCS tools assume that the marginal distribution of uncertainty for individual activities in the project completely define the multivariate distribution for project schedule. Van Dorp and Duffey [183] demonstrated that failure to model such dependence during MCS can result in the underestimation of total uncertainty in project schedule. Statistical distributions of project inputs such as task durations should be obtained based on reliable historical data. In most large, novel projects this information is not available and using the MCS may not improve estimations [183].

2.7.2 Risk Register Approach

The standard tool for project risk management is the so-called *risk register* [33, 184, 29, 37, 191, 193]. Many organisations store their risks in undisclosed forms of registers [146, 34]. A risk register is a list of the typical risk factors of project failure compiled based on the experiences

from past projects. A risk register usually takes the form of a questionnaire or a risk list. The questionnaire consists of a set of questions that ask about the current state of the project. The questions directly indicate the existing risk factors and also guide towards some potential risk factors. The risk factors are identified usually by negative answers. Research conducted by the Design Information Group at Bristol University found that 67% of questionnaire respondents documented their risks on either paper or a computer based risk register [37].

There are various statements in the literature describing the role of a risk register. Williams [193] states that a risk register has two main roles:

- 1. To serve as a repository of knowledge
- 2. To begin analysis and plans that flow from it.

As such, the risk register should be used to keep log of the risks to a project. Chapman and Ward state that, to enable the documentation of the sources of the risk and their responses, as well as their classification, "the risk register identify phase involves compiling a list, a log or register" [33]. Within this, they identify that the documentation produced through the utilisation of project risk management can be regarded as a "by-product...rather than a central concern" [33]. Furthermore Ward states that "the purpose of the summary risk register is to help the project team review project risks on a regular basis throughout the project" [184]. The risk register is used as a formal method of identifying, quantifying and categorising the risks, as well as providing the means of developing a cost-effective method of controlling them [71].

The risk register consists of three entities. A register of the risks itself as suggested by the title, which is the main focus of the system, and two supporting documents, to include information on the risk owner and risk reduction and mitigation plans. Once the risks have been identified, assessed and possibly analysed, they are placed into the risk register. Additional information about the risks to the project can be held within the risk owner and risk reduction and mitigation plans entities.

Williams [193], Carter et al. [29] and Ward [184] all give examples of the type of information or items which can be stored in the risk register. Their general consensus is that the risk register should contain a description of the risk, its impact and probability. Hence, risk is decomposed into two components:

- Probability of the risk
- Impact the risk can cause.

Risk is then quantified as the measure:

risk = *probability x impact*

Many additional items that could potentially be included within the risk register.

A risk register involves a considerable dose of subjectivity especially where the project state is being assessed. A common technique to reduce the subjectivity in a risk register is to gather the answers from different sources.

The publicly available risk identification risk registers are particularly useful in practice because of their accessibility and comprehensiveness. Some public risk registers currently available are:

- Taxonomy-Based Questionnaire [28] not very detailed, but wide-ranging questionnaire proposed by SEI in 1993. It consists of 194 mostly yes-no questions (some with sub-questions) arranged in 3 risk taxonomy classes (product engineering, development environment and program constraints) divided further into 3 to 5 elements each with 3 to 8 attributes.
- Risk Assessment Checklist [179] general questionnaire proposed by Rob Thomsett in 1992 to assess risk in the very early stages of a project. It consists of 64 test questions in 3 risk areas (user environment, team environment, system complexity). Coverage of the user environment is quite unique to this risk register. The questionnaire is supplemented with a method to assess the overall level of project risk, which evaluates each answer with a given number of points. The total number of points is then compared against a predefined scale, which assigns a risk level (high, medium or low) to a given range of points.
- Software Development Checklist [127] very detailed technically oriented questionnaire proposed by Steve McConnell in 1993. It consists of 511 yes-no questions in 5 major areas (requirements, design, construction, quality assurance, outsourcing). This checklist is exceptionally detailed and comprehensive with regard to the implementation practices (371 questions).
- Complete List of Schedule Risks [128] comprehensive list of risk factors for the exceeded schedule risk compiled by Steve McConnell in 1996. It consists of 109 risk factors in 12 areas (e.g. requirements, design, customer, end-user, personnel,

management). This risk list is also published on the Internet. It is quite well known and used in the industry.

Capers Jones' 60 Risk Factors [90] – list of 60 common risk factors for the general risk of
project failure compiled by Capers Jones in 1994. Each risk factor is extensively
described in a 20-point text structure including severity and frequency, root causes,
methods of prevention and control, as well as effectiveness and cost of known therapies.
Information on known remedies, support, and references for each risk factor makes this
risk list especially useful.

2.7.3 Alternative general graphical tools

This thesis proposes the use of graphical methods [113], namely Bayesian Networks (BNs), for project risk management. However, there are alternative graphical tools and that is what we will review next.

Fault trees

Fault tree analysis was developed by Bell Telephone Laboratories in 1962 for the US Air Force for use with the Minuteman system. It was later adopted and extensively applied by the Boeing Company [72, 160]. This is a graphical technique that provides a systematic description of the combinations of possible occurrences in a system, which can result in a system failure [14]. Fault tree analysis is a top-down method of analysing an undesirable event to determine all the ways that the event can happen, based on the behaviour of the components, lower-level assemblies, and interfaces.

The most serious outcome is selected as the Top Event. A fault tree is then constructed by relating the sequences of events with AND and OR logical gates, which individually or in combination, could lead to the Top Event. Probabilities are assigned to each event and at an OR gate the probabilities must be added to give the probability of the next event, whereas at an AND gate, the probabilities are multiplied. Therefore it is possible to identify the failures that have the greatest influence on the End Event.

Advantages of fault tree analysis are:

- Provides insight into the system behaviour
- A graphic aid for management
- Identifies failures deductively
- Handles complex systems more easily
- Provides options for management and others to perform either qualitative or quantitative reliability analysis
- Allows concentration on one particular failure at a time

In contrast, some of the disadvantages are as follows:

- Independence assumption between the causes
- A time consuming approach
- A costly method
- It considers components in either a working or failed state. More specifically, the components partial failure states are difficult to handle
- Difficult to use for large projects
- The end results are difficult to check.

Cognitive Mapping Methodologies

Cognitive mapping methods have been applied in research in a project context by Eden et al. [50] to study disruption and delays in projects; Williams [194] proposes using causal mapping and system dynamics to model complex projects; Williams et al. [194] used causal mapping to explore risks in projects; Maytorena et al. [124] employed causal mapping to explore the process of risk identification in projects and Klein proposed cognitive mapping to model project trade-offs [101], to name a few. In a broader management science context cognitive mapping methods could be combined with other methodologies such as MCDM [16].

The cognitive mapping methodology is built on the premise that all individuals gain an understanding of the world they inhabit through developing a set of beliefs, assumptions, and a knowledge base that is used to make sense of the world around them. The decision makers use "personal models" when making decisions and it is through the dissection of their explanations using cognitive mapping techniques that researchers are able to gain greater insight into the perceived complexities of the issues.

Cognitive mapping techniques are used to identify an individual's beliefs about a particular domain and to depict these diagrammatically. Swan [175] in her review of cognitive mapping as a management research tool highlights that the product of these mapping techniques, although typically referred to as cognitive maps, are not cognitive maps in the "psychological sense". It is not "an internal mental representation" but a visual representation of an individual's subjective data which helps in the understanding and analysis of specific elements of an individual's thoughts rather than thinking [175].

The maps are a network of nodes and arrows as links where the direction of the arrow implies believed causality. Hence, when constructed by group cognitive maps are known as 'cause maps'. Cognitive maps are usually derived through interviews and they are intended to represent the subjective world of the interviewee. Cognitive mapping is a formal modelling technique with rules for its development. Cognitive maps are characterised by an hierarchical structure which is most often in the form of a means/ends graph with goal type statements at the top of the hierarchy.

Eden's causal mapping is an interactive decision-support tool used to capture and analyse complex problems and decision making [52]. Eden's mapping approach is based on Kelly's Personal Construct Theory [95], which provides a sound basis for understanding how individuals make sense of their experiences. This focus on problem solving and action makes it appropriate for 'problem structuring' and uncovering solution options. Kelly's theory provides the rules for mapping.

For representational purposes a cognitive map is drawn as short pieces of text linked with arrows. Generally a statement at the tail of an arrow is taken to cause, or influence, the statement at the arrowhead. An important aspect of Kelly's theory argues that we make sense of situations through similarities and differences. Hence, we seek to identify each statement as having two contrasting poles. For cognitive maps the causality relates the first phrase of the bi-polar statement to the first phrase of the second statement. When an arrow head is shown with a negative sign attached then the first pole of the tail statement implies the second pole of the head statement. Typically a concept which has no implication is referred as a 'head' and a node which has no in-arrows is referred to as a 'tail'.

It is a well-founded methodology with a limited number of usable analysis software packages that allow for a detailed analysis of individual maps. One of the most advanced software packages is Decision ExplorerTM [13]. In practice, the maps are built out of concepts linked to each other by arrows in a hierarchical form that indicate the nature of the linkage. From this the structure of the map has the potential of being analysed in a number of ways. Its disadvantage is that it does not allow for content analysis to be carried out easily. However, it can be used in combination with other specialist software packages for this purpose.

This technique provides clear procedures for collecting data, and it allows for a systematic analysis of that data and is supported by a software package, which increases the reliability of the analysis. However, it does not provide the full use of causal modelling i.e. building quantitative models. We will provide this with using Bayesian Networks.

Decision Tree

A decision tree is a graphical diagram consisting of nodes and branches used to model and evaluate a decision process which consists of an alternating sequence of actions and uncertainty consequences [30, 80]. There are two node types:

- Rectangle represents the decision to be made. The branches from decision nodes are the alternative choices. The manager can implement only one alternative.
- Circle represents chance node. The branches from chance nodes have some element of uncertainty as to whether or not they will occur.

The core of the decision tree is aggregating the payoff values and their associated probabilities into a single quantity that can be compared with each other. The aggregation procedure is repeated until the decision maker can identify the action to be chosen at the initial node and the subsequent decision nodes. The most commonly used method for the decision tree is the expected monetary value (EMV), which maximises the expected payoff as the evaluation criteria. If the monetary value is replaced with utility, which measures the decision maker's preference in an interval scale, the EMV decision rule would become the maximising expected utility (EU). The utility analysis is a powerful framework for decisions involving risk, but it has some limitations. As discussed in [20], it cannot include the portfolio effect of the decision maker's attitude, as the decision maker's attitude changes dynamically. Another limitation is the famous Allais paradox [101], where people sometimes violate the basic assumptions on which the utility approach is based. So in most cases it is usual to use only the EMV rule. However, this might not produce the best result since the EMV rule does not consider the decision maker's attitude. Yager pointed out the shortcomings of the EMV rule [199, 201, 200] such as the use of the expected values that associate a neutral attitude to the decision maker.

For the solutions of constructing decision functions which allow for the inclusion of decision attitude and probabilistic information in uncertainty, Yager comprehensively investigated this problem in various conditions, and proposed a mechanism for combining probabilistic information about the state of nature with information about the decision maker's attitude.

2.8 Discussion

Every project involves some degree of risk, but that risk can be controlled with careful analysis. One of the key responsibilities of a project manager is to anticipate project risks, and then to devise the means for controlling those risks before they can get out of hand. This is where the risk management process comes in. Risk is a complex notion and it is very difficult to capture all major aspects of project risk. The fast changing environment and the complexity of projects has increased risk exposure.

Project risk management operates in a complex and dynamic environment that is constantly confronted with various risks. It is therefore imperative that project managers should consider all possible risk factors affecting a given project. Furthermore, they should take corrective actions to control and manage the identified risks. An effective risk management approach can provide a framework for project mangers which enables them to identify and assess potential risk factors and to then take the necessary actions in order to achieve the desired objectives of a given project.

Risk management can be a challenging process because it requires anticipating future events. However, instead of only trying to look into the future, we can manage risk by looking at the past. By examining prior project experiences, you can get a better insight into risk probabilities and if you can anticipate an event, you should be able to weigh up the consequences, and control the outcome.

All novel projects are risky and once a project has started even experienced project managers can make ineffective choices. Hence, we need project risk analysis and project risk management tools in order to help us with decision making.

We have reviewed the techniques currently in use within the area of project risk management. Furthermore, we have established the requirements which must be satisfied and, as we can see in Table 2.4, there is no current state-of-the-art tool which satisfies all the requirements. Even what is considered as standard to project risk management (the risk register) does not satisfy two of the criteria. We believe it is possible to develop a tool which satisfies all the requirements using BNs. In the next chapter we introduce the BN technique.

Expectations for	Expectations met by:								
project risk analysis tool	СРМ	PERT	Pert Master	@Risk	Risk Register	Fault Trees	Cognitive Mapping Methodologies	Decision Tree	
1) Model trade- offs between time, cost and quality	No	No	No	No	No	No	No	No	
2) Produce overall risk score	No	No	Yes	Yes	Yes	No	No	No	
3) Dynamic model	No	No	Yes	Yes	Yes	No	No	No	
4) Problem structuring and qualitative analysis	No	No	No	No	Yes	Yes	Yes	Yes	
5) Model key notions of causal effect	No	No	No	No	No	No	Yes	No	
6) Quantify uncertainty	No	Yes	Yes	Yes	Yes	Yes	No	Yes	

Table 2.4 Expectations for project risk analysis tool

3. Bayesian Networks

This chapter introduces the formal technique for quantitative risk assessment called Bayesian networks (BNs). The current state of the art of this subject is laid-out in detail. Bayes theorem and its uses are described. Recent developments in the area, such as ranked nodes and dynamic discretisation, are also covered in detail.

This chapter also offers basic BNs background knowledge which lays the foundation to be able to understand the models reviewed in chapter 4 and the models developed and described in chapter 6 and 7. The new contribution of this chapter is a compact introduction to the BNs and a detailed review of recent developments used to build BNs.

3.1 Background

Bayesian networks (BNs) have been established as practical representations of knowledge for reasoning under uncertainty. They are based on modelling ideas that have been around for some time. The representation was first introduced in 1921 by the statistician Wright [197] for the analysis of crop failure. It was reinvented by many forms of research [54, 89, 122, 137, 135, 172, 147, 74, 92, 118, 204, 138, 155, 177, 195] under various names, such as causal networks, causal probabilistic networks, graphical probability networks, belief networks, and influence diagrams. Bayesian networks, are also called, generative models, probabilistic cause-effect models and causal models.

All inference in BNs is performed using Bayes Theorem. Bayes Theorem is all about how to revise our beliefs in the light of new evidence. To illustrate Bayes Theorem, we start with a simple two node BN in Figure 3.1.



Figure 3.1 BN of 'Project Late' risk

In this example we assume for simplicity that both nodes have just two states (true and false). The arc from 'Poor Project Management' to 'Project Late' simply indicates that the former influences the latter. To compute Bayes we need the prior probabilities given in Table 3.2.

Н	P(H)	Н	False	True	
False	0.1	Ε	P(E H)		
True	0.9	False	0.9	0.3	
		True	0.1	0.7	

Table 3.1 Probabilities for H and E

Suppose that H represents the statement 'Poor Project Management' and E represents 'Project Late'. The probability for H is P(H). Since this node does not have parent nodes the NPT (Node Probability Table) for this node is very simple. We only have to assign a probability to each of the two possible values 'True' and 'False'. NPT in Table 3.1 tells us that the probability of H being 'False' is 0.1 and the probability of H being 'True' is 0.9. We are interested in knowing what the probability is for H given the evidence E. We write this as P (H| E). The inference in the model is performed based on Bayes Theorem. Mathematically Bayes theorem is expressed as:

$$P(H|E) = \frac{P(H) P(E|H)}{P(E)}$$
(2-1)

Where it is possible to update our belief in hypothesis *H* given *E*. The left-hand term, P(H|E) is known as the posterior probability, or the probability of *H* after considering *E*. The term P(H) is the prior probability of *H*. The term P(E|H) is the conditional probability of E given H. Finally, the last term P(E) is the prior probability of E.

We know from the NPTs that P(H) = 0.1 and P(E|H) = 0.7. The NPTs do not provide the denominator value directly, but they do provide it indirectly and we can calculate it using the following equation:

$$P(E) = P(E|H)P(H) + P(E|not H)P(not H)$$

$$= 0.7(0.1) + 0.1(0.9)$$

$$= 0.153$$
(2-2)

Therefore, substituting these values in Bayes' Theorem we get

$$P(H|E) = 0.7 * 0.1 / 0.153 = 0.457.$$
(2-3)

Thus, the observation that there are profits in the company increases the probability that there is follow on work with this client up to 0.457.

While we can perform the necessary probabilistic reasoning manually when there are just two variables, things are more complex as we introduce additional variables and dependencies. This is why we need the mechanism and algorithms of BNs.

3.2 Bayesian Network Definition



In Figure 3.2 we apply this definition to a BN example model.

Figure 3.2 'Project overspend' risk – BN theory applied

Each node in a BN model has a specific type. Common types are:

- Discrete where the states are point real numbers e.g. '-2', '0', '1.5', '33.4' etc.
- Continuous where the states are intervals between real numbers e.g. '-20 -10',

(-10 - 0)', (0 - 10)', (10 - 15)' etc. Or point real numbers.

- Labelled where the states are expressed as words which cannot be transformed into a numerical scale e.g. 'red', 'green', 'blue', 'yellow'.
- Boolean where there are two states 'True' and 'False'.

The conditional probability can be defined in two ways:

- Conditional probability distributions (CPD) used for continuous variables.
- Node probability tables (NPT) used for discrete and labelled variables.

A BN model that contains both discrete and continuous variables is called a hybrid Bayesian Network [121, 140].

Let us now enter observations into the model. We can assume that the project has 'Unfavourable exchange rate' and 'Poor project management'. In a scenario like this, the probability of 'Project overspend' increases to 80% (Figure 3.3 d). As expected this is a higher probability than the initial one, since we are now sure that there is 'Unfavourable exchange rate' and 'Poor project management'.

If we assume that there is favourable exchange rate, but 'Poor project management' the model predicts that the likelihood of 'Project overspend' is actually 60% which is still higher than initially assumed (Figure 3.3 c). Finally if we assume there is favourable exchange rate and project management is not poor the model predicts that the likelihood of 'Project overspend' drops down to 20% (Figure 3.3 b).



Figure 3.3 'Project overspend' - different scenarios

In complex real-life BN models that we use, the Bayesian inference calculations are performed using various efficient algorithms implemented in BN toolkits. They can be either:

- Exact e.g. variable elimination, clique tree propagation, recursive conditioning, enumeration etc.
- Approximate e.g. direct sampling, Markov chain sampling, variational methods, loopy propagation.

More theoretical aspects of BNs can be found in [135, 89, 147].

3.3 Node Independence Assumptions

The nodes or variables in BNs are usually of three types:

- 1. Hypothesis variables variables of interest.
- 2. Information variables variables whose state can be observed.
- 3. Mediating variables variables introduced for a special purpose, for example, to reflect the independence properties in the domain.

The definition of BNs and the chain rule require that the independence assumptions are respected. Two events are independent if the occurrence of one event makes it neither more nor less probable that the other event occurs. In probability theory two events A and B are independent if $P(A\cap B)=P(A)P(B)$. In other words, the probability that both events will occur is equal to the product of their separate probabilities. Therefore, independence is equivalent to saying that observing B does not have any effect on the probability of A. In graph theory the word independent usually means pairwise disjoint or mutually nonadjacent. In this context, independence is a form of immediate nonadjacency. An independent set or coclique is a set of vertices of which no pair is adjacent. Two sets A and B are independent if their intersection $A \cap B = \emptyset$, where \emptyset is the empty set. One of the methods of checking that these assumptions hold is known as d-separation [148].

The rules of d-separation are based on the three fundamental connections in Bayesian networks Figure 3.4:

Serial Connection X->Y->Z: Information may be transmitted through the connection unless the state of Y is known. Example: If we observe the 'Subcontractor fails to deliver key component' (Y), any knowledge that there is a 'Project dependence on subcontractor'(X) is irrelevant to any hypothesis (or belief) that the 'Project late' (Z). On the other hand, if we do not know whether 'Subcontractor fails to deliver key component' or not, observing a 'Project dependence on subcontractor' will increase our belief about

'Subcontractor fails to deliver key component', which in turn will increase our belief about 'Project late'.

- 2. Diverging Connection X<-Y->Z: Information may be transmitted through the connection unless the state of Y is known. Example: If we observe the 'Project dependence on subcontractor' (Y) and then that the 'Subcontractor fails to deliver key component' (X), the added knowledge that the 'Subcontractor fails to deliver key component' (X) will tell us nothing more about the 'Internal staff misunderstand true requirements' (Z) than the information gained from observing the 'Project dependence on subcontractor' alone. On the other hand, if we do not know whether a project is dependent on subcontractor or not, an internal staff misunderstand true requirements report will increase our belief in 'Project dependence on subcontractor', which in turn will increase our belief about the 'Subcontractor fails to deliver key component'.
- 3. Converging Connection X->Y<-Z: Information may be transmitted through the connection only if information about the state of Y or one of its descendants is available. For example, if we know that the 'Project late' (Y) and that the 'Subcontractor fails to deliver key component' (X), then this will affect our belief about whether 'Internal staff misunderstand true requirements' or not (Z), as the 'Project late' leads us to believe that this was caused by 'Subcontractor fails to deliver key component', rather than the 'Internal staff misunderstand true requirements'. On the other hand, if we have no knowledge about the state of the 'Project late', then observing that 'Internal staff misunderstand true requirements' will not affect our belief about whether the 'Subcontractor fails to deliver key component' about whether the 'Subcontractor fails to deliver key component' or not.</p>



Figure 3.4 'Project late' BN

Two variables X and Z are d-separated if for all paths between X and Z there is an intermediate variable such as Y that either

- The connection is serial or diverging and Y is instantiated (i.e. its value is known), or
- The connection is converging and neither Y nor any of its descendants have received evidence.

In the example of Figure 3.4, the set of nodes {Subcontractor fails to deliver key component, Internal staff misunderstand true requirements} d-separates {Project dependence on subcontractor} and {Project late}, because 'Subcontractor fails to deliver key component' blocks the path (Project dependence on subcontractor, Subcontractor fails to deliver key component, Project late) and 'Internal staff misunderstand true requirements' blocks the path (Project dependence on subcontractor, Internal staff misunderstand true requirements, Project late). In both cases, the blocking node is linear on the path. Furthermore, {Project dependence on subcontractor} d-separates {Subcontractor fails to deliver key component} and {Internal staff misunderstand true requirements} and {Internal staff misunderstand true requirements} and {Internal staff misunderstand true requirement} and {Internal staff misunderstand true requirements} and {Internal staff misunderstand true requirement} and {Internal staff misunderstand true requirements}, where 'Project dependence on subcontractor' is diverging on the only path between them, (Subcontractor fails to deliver key component, Project dependence on subcontractor, Internal staff misunderstand true requirements).

If X and Z are not d-separated, they are d-connected. Dependence and independence relies on what you know (and do not know). In other words, the available evidence plays a significant role when determining the dependence and independence relations.

We can distinguish various patterns of plausible common sense reasoning that are supported by BNs. These patterns can be explained using the example network in Figure 3.5; to ensure that the example is as simple as possible we assume that all nodes are discrete, having the two possible states 'true' and 'false':

- Predictive: If we believe that 'Unfavourable exchange rate', then it becomes more plausible for us that the 'Project overspend'. If we find out that 'Unfavourable exchange rate' is true, the 'Project overspend' has become more plausible for us. We can also observe predictive pattern in the example in Figure 3.4.
- Diagnostic: Suppose we observe that 'Project overspend' is true then both 'Unfavourable exchange rate' and 'Poor project management' become more likely as shown in Figure 3.6.
- Explaining away:



Figure 3.6 'Project overspend' is 'true'

If we observe 'Project overspend' is true (Figure 3.6) then the most likely explanation is 'Unfavourable exchange rate' while revised probability for 'Poor project management' is still low. However, if we observe that the 'Project late' is also true (Figure 3.7) then we see that 'Project overspend' is most likely caused by 'Poor project management' and not 'Unfavourable exchange rate'. Hence, the 'Project overspend' is *explained away* by the observation that the project is late.



Figure 3.7 'Project overspend' is 'true' and 'Project late' is 'false'

3.4 Bayesian Network Modelling Techniques

Usually domain experts can determine the important variables which need to be included in the model and the links between them. Specifying unconditional and conditional probabilities for each node is not an easy task. In models where there are many states per variable and nodes with many parents it is a very complex task to elicit consistent NPTs or CPDs manually. In this study we used a BN tool called AgenaRisk which supports defining NPTs and CPDs using expressions which often simplify the task of model preparation and reduce the time needed to build a model.

One of the biggest challenges in BNs is completing NPTs [48]. For example, if a node with 5 states has two parents each with 5 states then the child node NPT has 125 cells to complete. This section introduces different ways of making that task easier. Another challenge is continuous nodes. In section 3.5.3 we discuss how to handle continuous nodes.

3.4.1 Noisy OR

For Boolean Nodes with multiple parents, noisyOR allows us to quickly model a range of complex situations that would be far too difficult to do by manually completing an NPT [44, 173, 203]. Therefore, the NoisyOR operator is one of the most powerful operators. Let us observe an example where we are trying to predict whether a project is going to run over schedule. Assume the node F is the node 'Schedule overrun'. Suppose we decide that we identify five factors that can influence F, namely:

- Poor management (A)
- Requirements creep (B)
- Process inefficiencies (C)
- Inadequate business environment (D)
- Lack of project commitment (E)

The structure of such a model is shown in Figure 3.8. For simplicity, in this example, let us assume that the nodes A to E are independent and they all influence the node F. In this case we cannot use a Boolean expression, because there will always be uncertainty about F. For example, even if all the parents are 'True' we cannot say with certainty that F will be 'True'. On the other hand, if we try to complete the NPT for node F manually we have 64 entries to complete which would be extremely tedious and prone to error. Moreover, imagine trying to complete any such

entry; for example, the entry for F being 'True' when A is 'True', B is 'False', C is 'False', D is 'True', E is 'False'. This seems unnecessary because the effects of the parent nodes on F are essentially independent. We want to somehow quantify the impact of A on F independently of considering all of the combinations of states of the other parents. The NoisyOR operator is exactly what we need in this case.

For a node with n parents the noisyOR operator has n+1 parameters. So in our example with 5 parents there are 6 parameters that we have to specify. For each parent we specify a parameter that is a value between 0 to 1 that captures the probability that F will be 'True' if this parent is 'True'.

If we believe there is a 0.4 probability that poor management will cause a schedule overrun then the parameter for the node A will be 0.4. Similarly, if we believe there is a 0.2 probability that requirements creep will cause a schedule overrun then the noisy-or parameter for the node B will be 0.2, etc. That gives us 5 parameters in this case. The final parameter, called the leak value, is also a value between 0 and 1, which captures the amount of 'noise' in the model.

The leak parameter can be regarded as the extent to which there are missing factors from the model that can contribute to F being 'True'. If we set node A to be 'True' and all other factors to be 'False' (Figure 3.8) then the probability of a node F is 0.19, which is higher than the value 0.1 associated with the node A. This is because the leak parameter is above 0. If the leak parameter is set to 0 than the probability of a node F would be equal to 0.1.



Figure 3.8 Node A 'True' and other factors are 'Flase'

Suppose we are confident that the five factors here are the only ones that impact on F. Then we would set the leak parameter to be 0. In this case, if all of the parents are 'False' then F will be 'False' with 100% probability. For example, if the leak parameter is set to 0.1 (as opposed to 0) we are saying that there is 10% chance due to other factors missing from the model which can cause F to be 'True' (Figure 3.9).



Figure 3.9 Leak value set to 0.1

At the other extreme if the leak value is set to 1 then no matter what the values are for any of the parent nodes the node F will always be 'True'. Hence, when the leak value is 1 there is 'maximum' noise and the model tells us nothing at all.

3.4.2 Ranked Nodes

Many of the BN models, including the ones reviewed in chapter 4 and new ones created and discussed in chapter 6 and 7, use ranked nodes. Ranked nodes are used to model real-world variables typically measured on a discrete subjective scale. Typically we use either 3, 5 or 7 point scales:

- 3-point from 'low to high'
- 5-point from 'very low' to 'very high'
- 7-point from 'lowest' to 'highest'.

If we consider the simple BN model example in Figure 3.9 where all variables are ranked nodes measured on a 5-point scale, we would have to define 125 probability values in the NPT for 'Actual staff quality'. It would be possible to elicit this number from experts for a 5-point and a 3-

point scale, but inconsistencies would arise (for example assigning dissimilar probabilities to similar states). For a 7-point scale exhaustive elicitation would become infeasible. In real-world models, when the statistical data available is limited, an exhaustive elicitation is not possible [48, 187].

Ranked nodes simplify this problem [56], since in a ranked node the whole range of possible values is internally defined as the interval [0, 1]. This range is divided into an appropriate number of intervals. Each interval is associated with one label e.g. low, medium, high. In our example considering ranked node contains five states from 'very low' to 'very high', the intervals automatically created for each label are:

- 'very low' [0-0.2]
- 'low' [0.2-0.4]
- 'medium' [0.4-0.6]
- 'high' [0.6-0.8]
- 'very high' [0.8-1]

This underlying numerical scale, invisible to the user, simplifies the task of generating the NPTs, because we can use a simple numerical function to generate a good approximate NPT. These kind of ranked nodes are widely used and accepted [56]. In addition company studied in chapter 6 used these type of ranked nodes.



Figure 3.10 Qualitative example using ranked nodes

For example, in the BN of Figure 3.10, experts agree with the following:

- When 'Quality of staff' and 'Quality of staff training' are both very high the distribution of 'Actual staff quality' is heavily skewed toward very high.
- When 'Quality of staff' is very high and 'Quality of staff training' is low 'Actual staff quality' is still high.

- When 'Quality of staff' is low and 'Quality of staff training' is high 'Actual staff quality' is skewed toward low.
- When 'Quality of staff' and 'Quality of staff training' are both very low the distribution of 'Actual staff quality' is heavily skewed toward very low.

Such relations suggest 'Actual staff quality' is a distribution whose mean is a weighted sum of the parents. Hence, various weighted expressions significantly simplify the process of defining NPTs. In equation (2-4) we have used a weighted expression to define the NPT for 'Actual staff quality' from Figure 3.12:

$$AS = wmean (2, SQ, 1, ST)$$

(2-4)

This expression tells us that 'Actual staff quality' is a weighted mean of 'Staff quality' and 'Staff training quality', with the former having twice the impact than the latter.

Ranked nodes very often use Truncated Normal (TNormal) distribution [56]. This is a Gaussian distribution that has been truncated at both ends. Considering it is a Gaussian distribution, it has to specify the mean (μ) and the standard deviation (σ). The difference between Normal and TNormal is that TNormal has finite end points, hence the range (a and b) of the distribution must also be specified. This range is always [0, 1] in ranked nodes.

To demonstrate this we would have to add a variance (σ^2) of 0.001 to our earlier example:

AS = TNormal (wmean(2, SQ, 1, ST), 0.001, 0, 1) (2-5) When we run this model for the following two scenarios the result achieved is presented in Figure 3.11 :

- Scenario 1: 'Quality of staff' = 'very high' and 'Quality of staff training' = 'very low'
- Scenario 2: 'Quality of staff' = 'very low' and 'Quality of staff training' = 'very high'.



Figure 3.11 Predicted 'Actual staff quality'

Figure 3.12 shows the result of defining different variance in a ranked node.





To use these expressions it is sufficient to provide the weights w(i) for each parent variable X(i) without the need to manually analyse all combinations of states of the parent variables. The following types of weighted expressions can be used in AgenaRisk:

- Weighted mean function (wmean) calculates an arithmetic average of a set of variables adjusted by the weights reflecting the importance of each variable used in the expression.
- Weighted min function (wmin) assumes that when the values of the variables are different, the aggregated value of them is lower than their average. For example, to have quality staff it is necessary not just to have good people, but also to provide them with good training. If either the people or the training is insufficient then the result will be poor. However, really good people can compensate to a small extent for lack of training. Therefore, the necessary function for staff quality is wmin with small weighting in favour of good people. The variation from the average depends on the weights assigned. When all weights are large this function produces a result close to normal MIN function selecting the lowest value from the set provided. When all weights are '1' then the weighted min is a simple average.
- Weighted max function (wmax) works in a similar way as weighted min function, except that the higher, not lower, value is selected from the set provided.
- Min-max mixture function is a weighted mixture of min and max functions where weights are not assigned to individual variables, but to the whole min and max functions.

3.4.3 Continuous Nodes

In many models we are required to model variables which are continuous for example, actual length of project delay or percentage overspend etc. Until recently most BN algorithms assumed all variables are discrete. Therefore the associated BN algorithms are tailored to handle discrete variables and it is not possible to directly model continuous nodes. The properties of BNs make it attractive to look for possibilities of including continuous nodes in the general

formulation and analysis. Hence, many BN tools adopt various forms of numerical approximation for quantifying continuous nodes.

In *static discretisation* it is necessary to predefine intervals and the range of the continuous distribution is split into a finite set which does not change regardless of evidence entered into the model. Therefore it is necessary to guess the state ranges before running the calculation and consequently make assumption that it is possible to know the resulting probability distribution of the results beforehand. For example, if we have a model to predict the profit we will have at the end of the year and we enter the following observation into a node 'Profit measured in pounds' = 100. Because we are using static discretisation, the discretisation for 'Profit measured in pounds' is such that an observation of 100 cannot be distinguished from an observation of 1000 since both values fall in the interval 100-1000. Hence, although 'Profit measured in pounds' was entered as point value, in the model it is still treated as rather wide interval. Number of previously build BN models that we will discuss in more detail in chapter 4 use static discretisation.

Undesirable effects that can follow from a static discretisation are:

- The shape of the distribution can be entirely misleading.
- Summary statistics such as mean, median and variance become inaccurate.
- Evidence entered into a poor discretisation becomes less precise.
- Extra care is required when arithmetic functions are involved between variables.

Pearl [148] was one of the first researchers to devise algorithms for the inclusion of continuous variables in a network topology. He suggested an inference scheme in which the leaf nodes represented independent Gaussian distributions. The network topology was restricted to singly connected graphs (only one directed path between any two nodes) and the child nodes were deterministic, linear functions of their parents. When using Gaussian distribution specific assumptions had to be made and that was the only time it was possible to get analytical solution. Therefore this approach is unrealistic. Hence, the most viable solution is to apply various forms of discretisation to approximate continuous nodes by a BN model.

Discretisation is traditionally known as a subdivision of a continuous range into a set of subranges or intervals [107]. Discretisation may also be understood as a categorisation or classification of a given dataset. If the variables of the domain are discretised one by one, a discretisation is univariate. A discretisation divides the state space into subspace, or hyperintervals, with the same dimensionality as the original state space.

The problem facing modellers is that it is not always clear in advance where the main body of the probability mass will reside. This can be particularly problematic for dynamic BNs. In this case, the probability mass will often move across timeslices, so that a discretisation which is appropriate for one timeslice turns out to be inappropriate for another.

A solution, involving dynamic discretisation, has been proposed by Neil, Tailor and Marquez [141]. The dynamic discretisation algorithm outline is as follows:

- 1. Calculate the current marginal probability distribution for a node given its current discretisation.
- 2. Split the discrete state with the highest entropy error into two equally sized states.
- 3. Repeat steps 1 and 2 until converged to an acceptable level of accuracy.
- 4. Repeat steps 1, 2 and 3 for all nodes in the BN.

This algorithm has been implemented into the AgenaRisk toolset. Hence, we can simply set a numeric node as a simulation node without having to worry about pre-defined intervals. It is sufficient to define a single interval [x, y] for any variable that is bounded below by x and above by y, while for infinite bounds we only need introduce one extra interval. This is the approach that has been adopted in the subsequent models.

3.4.4 Object Oriented Bayesian Networks

Object Oriented Bayesian Networks (OOBN) were introduced to help model large and complex systems [106]. The idea of OOBNs was based on the object-oriented programming languages and they provide a robust, flexible and efficient framework. It is possible to build complex models by using OOBNs. With objects we can modularise the model into chunks representing logical groupings of risks or time dependencies between objects. In an OOBN we are essentially modelling sequential time series processes where each 'time-slice' in the time series is modelled as BN. OOBNs are used in some example models discussed in the next chapter as well as the model developed in this thesis.

The basic element in an OOBN is an object. For multiple objects we can define *classes*. Classes of objects provide the ability to describe a general and reusable network that can be used in many different contexts. Figure 3.13 shows a model composed of two risk objects. Each object is linked to the network with *reference link* that connects an output node in one object to an input node in other object (dashed link in Figure 3.13).



Figure 3.13 OOBN – structural representation

Figure 3.14 shows how objects are linked in AgenaRisk to build a large BN.



Figure 3.14 OOBN in AgenaRisk

Important advantages of OOBN are [106]:

- Natural representation of objects that are composed of lower level objects.
- Classes of objects explicitly represented which allows the incorporation of inheritance.
- Natural model fragment reuse.
- Ability to speed up the inference process by encapsulation of objects within other objects and the code reuse.
- Ability to support a natural framework for abstraction and refinement.

3.5 Strengths and Limitations of Bayesian Networks

The strengths of BNs over alternative techniques are:

- Explicit incorporation of uncertainty
- BNs, in contrast to classical statistics, can model causal factors explicitly. This makes them an ideal tool for predicting the future.
- The graphical nature of a BN makes it a powerful communication tool. Causal relationships among the variables or nodes can be seen easily without the need to compute probabilities.

- BNs are intuitive, conceptual and easily understandable. This helps at the development stage when the model is being discussed between the project manager and the various parties.
- Ability to combine subjective data (expert knowledge) and objective data. This is a great advantage especially when objective data is scarce or when there is the need to incorporate expert opinion in the model.
- A BN will update the probability distribution for every unknown variable whenever an observation is entered into any node i.e. reason from effect to cause and vice versa.
- The model can be easily updated or previous beliefs modified in light of new evidence, for example the notion of explaining away evidence.
- BNs can be used to perform sensitivity or "what-if" analyses to examine the sensitivity of predictions, or conclusions against initial assumptions.
- BNs can make predictions with incomplete data. If no observation is entered then the model assumes prior distribution.
- BNs are capable of modelling highly complex systems. The areas of application mentioned earlier demonstrate this.

Bayesian networks do have some limitations. Originally BNs were constructed based on human heuristics and thus have been subject to human biases. The fact is that a BN model is only as good as the modeller and experts who produced it, since it is a representation of the modeller and the experts' perceptions of reality. Therefore best fit is chosen given the modeller and experts.

Another limitation centres on the extent of the quality of the prior beliefs used in Bayesian inference processing. The usefulness of a BN is based on the reliability of its prior knowledge. An excessively optimistic or pessimistic expectation of the quality of these prior beliefs will either distort the entire network or invalidate the results. Hence, it is difficult to empirically validate model estimates in models built only on expert knowledge.

3.6 Application of Bayesian Networks

Bayesian networks have had considerable applications in many fields both in academia and industry. Hundreds of publications have described BNs application in various fields [61]. In the academic field, Nikovski [142] applied BNs to problems in medical diagnosis, Hansson and Mayer [77], Ames et al. [5] in heuristic search, Marcot et al. [120] in ecology, Heckermann [75] in data mining and Breese and Heckerman [22] in intelligent trouble shooting systems, Xenos [197] to predict and assess students' behavior, Rodin *et al.* [163] in biology, Andradottir [6] in simulation.

The industrial application of Bayesian technology spans several fields: Fenton *et al.* [61, 57, 55, 58] applied BNs to software quality measurement, Neil *et al.* [136, 137] in financial operational risk scenarios, Langseth and Lindqvist [110] in software maintenance modeling, Bobbio et al. [18]; Langseth [111]; Ingleby and West [83] in general software reliability modeling, Lucas *et al.* [116] in biomedicine and health-care, Hackerman et al. [76] in medical diagnosis, Borsuk et al. [21] in environmental science.

3.7 Summary

In this chapter we have reviewed Bayes Theorem and how it is used when building BNs. Also we have looked at the advantages and the disadvantages of BNs. This chapter has provided an introduction to BNs and the different types of BN structure in order to enable the reader to understand the models developed later in the thesis.

In the next chapter, we will look at BN models which address project trade-off analysis; as well as BN models that address and support different features of project risk management (SIMP, MODIST and Productivity model). Later in the chapter, we will look at construction projects BNs, Khodakarami's model and operational risk models.

4. Existing BN Project Risk Management Models

This chapter focuses on the review of existing BN models. The models to which the author had access have been extensively tested. BN models that address trade-offs are reviewed as well as a group of other BN models related to project risk management and relevant to this thesis. It is demonstrated how such models can be used to provide useful information for decision makers, and the advantages and disadvantages of these models are discussed. The new contribution of this chapter is a thorough analysis, some of it (SIMP model) which was not displayed before in public domain, of selected existing BN models for project risk management.

4.1 Introduction to Bayesian Net Modelling

We will specifically look at BN models which address project trade-off analysis. These models are: SIMP [3], MODIST [4, 63] and Productivity model [157]. SIMP and MODIST attempted for the first time ever to look at project risk management trade-off issues, and are of particular interest in this thesis, since the author has drawn motivation for analysing trade-offs from these models. In the second part of this chapter, we will look at construction projects BNs, Khodakarami's model and operational risk models. These models address and support different features of project risk management. All of the models were used to provide improved methods of risk analysis and assessment for project managers in different areas and are discussed in more detail in the sections that follow.

4.2 BN models addressing trade-off analysis

4.2.1 SIMP - Major Projects BN

Model background

The SIMP project was based on the practices of a major international defence company for risk and risk criteria. SIMP project objective was to determine whether BNs can model defence system engineering processes and derive predictions about risk and uncertainty for decision support. The project aimed to develop methods and tools for quantitative risk assessment and requirements analysis in complex systems engineering domains. The motivation for this research lay in systems cost over-runs, delayed delivery and inadequate performance of complex systems in the military and civil sectors. Trade-offs addressed between these variables served as inspiration for the author's focus on modelling trade-offs in large projects. These problems were caused by poor organisation of the systems engineering process, weak risk assessment, inability to manage risk and poor requirements analysis. Since this is a commercial model it provides the basis for commercial application of trade-off analysis and models that implement it. The SIMP project focused on improving the systems engineering process and the quality of the system's products, in particular to enhance the requirements capture to make systems fit for purpose.

Model structure

The aim of the SIMP model was to predict and assess overall risk status of large and complex systems engineering projects. The SIMP model is aimed at project managers. There are six sub-nets in the model:

- Resource performance variables capturing the quality of the contribution that the resources make to the project (*e.g. subcontract management, procurement, information, planning, organisation effectiveness, motivation, staff, facilities*)
- Technical quality variables capturing the quality of the contribution that the technical parts make to the project (*e.g. interfacing, design solution, key subsystems, obsolescence, technical facilities*)
- Schedule variables capturing the 'real' schedule that is suggested by the project risk attributes (*e.g. budget constraints, process efficiency, requirements, business environment*) and variables capturing current schedule of the project (*e.g. actual schedule differential above agreed*) The schedule is expressed as the deviation from that of the nominal project.
- Cost variables capturing the 'real' cost that is suggested by the project risk attributes (*e.g. process efficiency, requirements, business environment*) and variables capturing the current cost of the project (*e.g. actual cost differential above agreed*). The cost is expressed as the deviation from that of the nominal project.
- Performance represents the overall performance of the system being built. It is directly influenced by two variables: *actual schedule differential* and *actual cost differential*.
- Reputation variables capture the reputation in the commercial environment (*e.g. actual schedule differential above agreed, actual cost differential above agreed*)

Figure 4.1 shows the key part of the model that enables managers to perform trade-off analysis between:

• Time – represented by *schedule differential implied by project attributes* and *actual schedule differential*

- Cost represented by *cost differential implied by project attributes* and *actual cost differential*
- Performance represented by *actual schedule differential* and *actual cost differential*

All the nodes in the model are labelled nodes and their NPTs are defined manually.



Figure 4.1 SIMP model – trade-off part [3]

Prediction and trade-off analysis using SIMP model

The relationship between the nodes described in the previous section is fairly complex. In order to clarify this relationship we will consider what kind of cost, schedule and performance trade-off reasoning the model supports.

Suppose we know something went wrong and all nodes affecting three indicators (resources, management and technical quality) are 'very low'. In addition suppose that the 'Actual cost above agreed cost' should be as 'expected' meaning effectively that this is a fixed price contract and it is not allowed to go over budget. The first simple use of the model is as a scorecard type assessment by observing how the model evaluates the overall technical quality and performance quality (Figure 4.2).



Figure 4.2 SIMP model – predicted distributions for 'Technical Quality' and 'Resource Performance'

The distributions are centred around 'low' for 'Technical Quality' and 'very low' for 'Resource Performance' (although there is still small probability that it could be higher for 'Technical Quality'). However, much more interesting than these predictions are predictions for the output nodes. For example, we can observe 'Cost Diff Implied by Proj Qualities' and 'Performance' (Figure 4.3).



Figure 4.3 SIMP model – predicted distributions for 'Cost Diff Implied by Proj Qualities' and 'Performance'

So the model predicts rather bad consequences. The cost differential says that, based on the project properties the cost overrun is likely to be 'worse than terrible'. However, we know the actual cost is fixed. Hence, the performance prediction is likely to be disastrous. If we change actual cost constraint for 'Actual cost diff above agreed cost' to 'worse than terrible' (in other words we increase budget over the original agreed budget) the performance prediction improves (Figure 4.4).



Figure 4.4 SIMP model – predicted distribution for 'Performance' when budget has been increased

However, it is still significantly below average. There are two reasons for this, both of which model shows clearly:

- 1. We still have poor technical quality and resource performance and these are not fully compensated by the increase in the budget.
- 2. If we check the prediction for 'Schedule Diff implied by Project Attributes' we find that the schedule differential is predicted to be 'worse than terrible', meaning that we really need to increase the schedule time.

Therefore if 'Actual schedule diff above agreed schedule' is increased to 'worse than terrible' the prediction for performance improves significantly and it now looks good (Figure 4.5). Hence, given the poor quality attributes we can still deliver a good system, but only by significant cost and schedule overruns.



Figure 4.5 SIMP model – predicted distribution for 'Performance' when budget and schedule has been increased

Suppose now we replace values entered for 'Actual schedule diff above agreed schedule' and 'Actual cost diff above agreed cost' with 'expected'. In other words the project cannot go over budget or schedule. In addition suppose that we have a requirement for the performance to be sensational. What happens now is that both overall resource performance and technical quality increase significantly despite the evidence that these are poor (Figure 4.6).



Figure 4.6 SIMP model – predicted distributions for 'Technical Quality' and 'Resource Performance' when budget and schedule are fixed and performance sensational

4.2.2 MODIST project risk– Software projects BN

Model structure

The aim of MODIST project risk was to predict and assess the overall risk and quality status of large software projects. The model is aimed at project managers. Figure 4.7 illustrates the schematic view of the model.

The six subnets in the model are:

- Distributed communication and management variables capturing the nature and scale of the distributed aspects of the project management and the extent to which these are well managed (e.g. *communications management adequacy, subcontract management adequacy, interaction management adequacy, overall management quality*). This is shown in Figure 4.8.
- Requirements and specification variables relating to the extent to which the project is likely to produce accurate and clear requirements and specifications (e.g. requirements difficulty, requirements stability, specification accuracy)



Figure 4.7 MODIST – Schematic view [4]

- Process quality variables relating to the quality of the development processes used in the project (e.g. *specification process quality, specification clarity, development and testing quality, overall process quality*)
- People quality variables relating to the quality of people working on the project (e.g. *staff motivation, staff turnover, general level of staff experience, overall staff quality, overall people quality*)
- Functionality delivered variables relating to the amount of the new functionality delivered on the project, including the resources assigned to the project (e.g. *total number of inputs and outputs, KLOC (thousands of lines of code) delivered, language, new functionality delivered*)
- Quality delivered variables relating to both the final quality of the system delivered and the extent to which it provides user satisfaction (e.g. *level of problem reports, quality delivered, user satisfaction*)

The key part of the model enables managers to perform trade-off analysis between:

- Quality represented by both user satisfaction and quality delivered
- Effort represented by the *average number of people full time* working on the project

- Time represented by the *project duration*
- Functionality meaning *functionality delivered*

One of the main limitations of MODIST trade-off analysis is the fact that it applies only to software engineering projects. Functionality in the MODIST model is based on function points which are a well known measure of software output. This is built into NPTs for functionality and therefore it is specific to software engineering projects and not easily extendable.

Management and Communication Subnet

We will show this subnet (Figure 4.8) in more detail in order to examine some of the techniques used. This subnet models the size of a project team, its geographical diversity, the amount of work that has been subcontracted and the quality of the subcontracted work.

Ranked nodes discussed in section 3.4.2 are used extensively in this subnet and throughout the entire model. In Figure 4.7 nodes with \mathbb{R} symbol are ranked nodes and 10 out of 12 nodes in this subnet are ranked nodes. The dominance of the ranked nodes indicates the scale of expert judgement required in this subnet and indeed the model. This model focuses on quantifying aspects of software projects which are often omitted due to the lack of data.

This subnet also makes extensive use of the TNormal expression discussed in section 3.5.2. All the nodes in Figure 4.8 with symbol have their NPTs defined using TNormal expression. For example, NPT for *Communications management adequacy* node is: Communications management adequacy = TNormal (wmax(2.0, sdc, 5.0, cmq), 0.005, 0.0, 1.0) i.e. it is a TNormal whose mean is a weighted maximum of its two parent nodes and whose

variance is 0.005.



Figure 4.8 Management and communication subnet [3]

Prediction and trade-off analysis using MODIST model

Suppose our project requirement is to deliver the system assessed as being of size 5000 function points. Hence, the only observation we enter is the one for *New functionality delivered*. The model will give predicted distributions for the effort and time necessary to develop the system (Figure 4.9 a) and b) – 'nominal' scenario). The distributions have relatively high variances due to the minimal data entered. Model predicts, based on the median values, that we will need an average of 31 people full time for 35 months to deliver a system with required functionality *delivered;* then we can observe that we will need more people full time to deliver a system (Figure 4.9 a) and b) – 'fixed time' scenario). Model predicts that we will need an average of 35 people full time for 39 months to deliver a system with required functionality. The model also predicts that we can probably only achieve the target if we have high *process and people quality* (Figure 4.9 c)). The distribution for this node before and after entering the quality requirements is quite different.



c) Process and people quality

Very Low Low

Figure 4.9 MODIST model – predicted distributions for fixed quality

0.4 0.32 0.24 0.16 0.08 0.0

Suppose now that we do not have the amount of time for system development that the model predicts since we have a fixed price contract and we can afford just 15 full-time people for 18 months. Still assuming that we must deliver 5000 function points and perfect quality then the model predicts the distribution for *process and people quality* as shown in Figure 4.10. It is clear that *process and people quality* almost certainly has to be 'very high'.

Medium

High

Very High



Figure 4.10 MODIST model - prediction distribution for fixed quality, schedule and effort

If for example, we know that *process and people quality* is only average then we can look at possible trade-offs between functionality and quality. If we still insist on 5000 function points and remove the quality requirement the model predicts the quality very likely to be abysmal. If we keep the perfect quality requirement, but remove the functionality delivered requirement, the model predicts a vastly reduced number of function points with the median of 566 compared to the original 5000.

4.2.3 Radlinski's "Productivity" Model

The MODIST project risk model discussed in the previous section is one part of the MODIST toolset. Another part is the MODIST phase model. The Phase Model enables detailed defect prediction to be performed at a lower level i.e. not for the whole project but for individual teams. A single-phase model enables predictions for a single software development phase. It is possible to join together copies of the phase-based model to form complex multi-phase models that reflect any particular lifecycle used. Radlinski's model is an extension to the MODIST phase model and an attempt to have a unified model. A high level overview of Radlinski's Productivity Model [157] is shown in Figure 4.11. Its aim is to model software risk assessment at the project level. The model is too large to be considered all at once. Therefore it is natural to breakdown the model into smaller subnets.



Figure 4.11 Main subnets of Productivity model [157]

The key part of the model is the trade-off part which is influenced by:

- uncontrollable project factors
- process and people quality
- effort allocation
- development activities (specification, coding and testing).

The structure of the Productivity Model (Figure 4.11) consists of subnets for:

1. Prior defect and productivity rates and prior effort

These are the values, taken from a typical past project, for the prior defect rate, the prior productivity rate, and the prior effort. It is possible for users' to provide them as observations from the past project database.

2. Uncontrollable project factors

These are the external factors which are not under control of the software development company. In this model they include: project complexity, project novelty, project scale, quality of input documentation, positive customer involvement, negative customer involvement, and deadline pressure.
- 3. Development activities:
 - a. Specification and documentation

This subnet contains variables related to requirements quality, specification process and people quality and change of effort on specification which altogether influence the specification and documentation process effectiveness.

b. Coding

This subnet contains variables related to coding process and people quality, change of effort on coding and the influence on coding effectiveness caused by the documentation quality.

c. Testing

This subnet contains variables related to testing process and people quality, change of effort on testing and the influence on testing effectiveness caused by the documentation quality and coding effectiveness.

4. Revised defect and productivity rates

These are the rates adjusted by: uncontrollable project factors, documentation quality, coding effectiveness and testing effectiveness. The adjusted rates influence the relationships between variables in the trade-off component.

5. Trade-off component

Software functionality is calculated as the product of revised effort and revised productivity rate. Similarly, the number of defects is calculated as the product of delivered number of units and revised defect rate.

The Productivity Model provides the following distinctive features which were not available in previous models:

1. Allows the user to enter custom prior productivity rate and prior defect rate.

Companies normally keep records and analyse data from their past projects. Productivity and defect rates are among the easiest to be extracted from such databases. Even if a company does not collect effort data [158], they are often easy to estimate post hoc.

2. Enables the user to perform trade-off analysis with variables expressed on a numeric scale.

- 3. Enables the user to apply different units of measurement up to the extent where the users perform the analysis using their custom units.
- 4. The impact of qualitative factors can be easily changed by changing the weights in the node expressions. A questionnaire is provided which can help determine users' opinions on the relationships between various model variables.
- 5. Allows target values for numeric variables to be defined as intervals, not just as point values. For example, this model can answer questions such as: how can we achieve a defect rate between 0.04 and 0.07 defects/function points for a project of a specific size with other possible constraints.

Other features of the Productivity Model, which were partially available in the past models, include:

- 1. The model can be easily extended by adding other qualitative factors.
- 2. Numeric variables in this model are dynamically discretised.

However, there are also several places where enhancements could be made for Productivity Model:

1. Causal framework for risk compatibility

The structure of the Productivity Model can be improved. The model should be compatible with the causal framework for risk. Uncontrollable project factors directly influence revised productivity and defect rates; and not any of the development activities. Hence, the Productivity Model is not causal model.

2. Incorporating code reuse

The Productivity Model assumes that there is no code reused from past projects. To make the model more realistic, code reuse may be incorporated into the model. To model this properly more details are required about the reused code; for example whether the reused code is a complete module or rather smaller pieces of code from various modules, how good was the development process when the reused code was originally written and tested and what is the typical proportion of reused code out of the total code delivered.

3. Integrating detailed defect prediction with trade-off analysis

The Productivity Model is an integrated model in the sense that it can predict both effort and quality (revised defect rate, number of defects). However, the prediction for the number of defects is less detailed i.e. detailed data on the potential number of defects depending on project size, potential number of defects adjusted by specification and documentation adequacy, number of defects inserted as a result of imperfect coding process, number of defects found, number of defects fixed, number of defects in the reused code (Revised Defect Prediction Model only).

4. User satisfaction

The Productivity Model captures software quality as the number of defects, which can be objectively counted by testers or managers. It does not refer in any way to how future users will perceive software quality. User satisfaction could for example capture adequacy of the software to meet user needs, appearance of the interface, software performance and level of training and quality of documentation.

4.3 Other BN PRM models

4.3.1 BN models in construction projects

One of the early efforts of applying BNs to project performance were carried out by McCabe et al. in 1998 [126, 125]. They developed a BN to improve an approach for modelling of construction performance (Figure 4.12). The BN is used to evaluate the performance at each resource interaction/queuing location based on performance indices. Five performance indices have been developed: queue length index, queue wait time index, customer delay index, server utilisation index and server quantity index. The indices are effect variables in the BN model and they are evaluated at each queuing location. If the value of any of the performance indices does not fall between the lower and upper bounds for that index then a remedial action needs to be performed. The cost and duration nodes were added to allow the improvement process to take different approaches to diagnosing the performance. For example, if performance indices provide evidence that the queue wait time is too long; depending on where the focus has been placed there can be two outcomes:

- If the focus is placed on a shortened duration, then the action would be to increase the number of servers.
- If cost is the major factor, then action would be to reduce the number of customers.



Figure 4.12 Conditional Relationships BN model [125]

Resource variables are causal nodes that represent changes to the construction project that are within the control of the project manager. The causal variables in their model are the following Boolean nodes: too many servers, too few servers, too many customers, too few customers, server too big, server too small, customer too big and customer too small. If conflicting causes for poor performance are suggested, the evaluation will be considered inconclusive and neither cause will be forwarded to the final evaluation.

Nasir et al. in 2003 [134] applied BNs for the first time in construction project's scheduling. Their model provides suggestions for the upper and lower activity duration limits based on the project's characteristics. Based on literature and expert opinion they identified 10 specific categories for building construction schedules. The categories are as follows: environment, geotechnical, labour, owner, design, area conditions, political, contractor, contractor nonlabour resources and material. Within each category they identified detailed risk variables (in total 69 risks). All the risk variables are divided into two types:

- The schedule risk variables
- The activity variables.

The first type of variables are input nodes where the evidence may describe the project condition. The second type of variables are output nodes.

Activity variables were divided into 8 groups that represent all the types of activities in a construction schedule. The groups were as follows: mobilization/demobilization, foundation/piling, labour intensive, equipment intensive, mechanical/electrical, roof/external, demolition and commissioning. Each group was modelled with two nodes where one node represented the pessimistic value and the other node represented the optimistic value.

Both BN models reviewed in this section provided a flexible modelling environment. However, the models have the following limitations:

- They are specific to building construction projects. Therefore the models cannot be applied to other industries and different type of projects.
- They make an assumption about the input data i.e. the models assume that most likely duration is already known and takes it as an input to the model.
- The output of the model needs another approach to calculate results such as the expected project duration, the probability of delay/completion etc.
- Pre-defined values for the upper and lower bounds of activity duration i.e. the pessimistic side for the percent increase of activity duration is limited to 10%, 25%, 50% and 100%.
- All the risk variables were binary nodes; therefore many variables with more than two states were not modelled properly.
- Overly complex and unstructured models that are difficult to follow and understand.
- Diagnostic analysis (i.e. reasoning from effect to cause) which is a very powerful BN feature not used in the models.

Luu et al. in 2009 [117] continued Nasir et al. work of applying BNs to quantifying the schedule risk in construction projects. They adopted and adjusted McCabe et al.'s BN model to construction projects in Vietnam. The sixteen most significant causes of schedule delay in construction projects in Vietnam were identified. Following this, based on expert survey, 18 cause and effect relationships were established. The BN model developed was applied to two case studies. The model performed well in predicting the probability of the construction schedule delay in both studies.

4.3.2 Khodakarami's model

Khodakarami's model [100] is an extension to Nasir et al.'s work on applying BNs to project scheduling. He presents a general framework for applying BNs to project scheduling incorporating critical path methods (CPM) calculations as discussed in chapter 2. The following standard acronyms are used throughout his model:

- D: duration
- LS: latest start time
- LF: latest finish time
- EF: earliest finish time
- ES: earliest start time
- TF: The amount of time that a task can be delayed or extended without affecting project end date.

The schematic model of the BN fragment connected with an activity is shown in Figure 4.13. Each activity in a CPM network is mapped to a set of five nodes in the BN as follows:

- Central component is the 'Duration' node which models uncertainty associated with the activity's duration. In a simple case, NPT for this node can be any arbitrary probability distribution (e.g. Normal, Beta etc).
- The LS node models the latest time that an activity should start. Parent nodes are LF and duration. The NPT is an arithmetic expression of the parent nodes.
- The latest time that an activity should finish is modelled with the LF node. The parent of this node is LS. The NPT is an arithmetic expression based on the parent node.
- The LS node models the latest time that an activity should start. Parent nodes are LF and duration. The NPT is an arithmetic expression of the parent nodes.
- The earliest time that an activity may finish is modelled with EF node. Parents of this node are ES and 'Duration'. The NPT is an arithmetic expression of the parent nodes.
- The ES is the earliest time that all the predecessor activities are finished. Hence, the ES node is the earliest time that an activity can start. The NPT is an arithmetic expression that takes the maximum value of EF from all the immediate predecessor activities.



Figure 4.13 Schematic BN for an activity [100]

The model provides a new interpretation of activity criticality under uncertainty. Comparable to standard CPM, the criticality of an activity can be measured by its total float (i.e. the difference between the Latest Finish and the Earliest Finish). If TF is zero (or even worse, negative) the activity is critical as it must be completed (otherwise it causes delay to the project) by a date that is earlier than the current plan shows is possible (i.e. EF). In other words, the criticality of each activity can be estimated by comparing the probability distribution of the LF with the probability distribution of the EF of the activity. This is modelled by introducing the 'Criticality' node in the model for each activity. 'Criticality' is a Boolean node that is 'true' when $LF \leq EF$.

To demonstrate how different types of uncertainty can be modelled in a project Khodakarami proposed a BN model for the duration of a prototype activity. Activity duration depends directly on how much money is spent and/or what level of quality is achieved. Hence, there is a trade-off between the uncertainty associated with the duration and the uncertainty associated with the cost. For example, if asked to estimate the probability of delay in a particular activity of a project, a manager may respond by contending that such probability can be reduced to virtually zero if there is no limitation on spending money on the activity.

The limitations of the Khodakarami's model are:

- The model is far more complex than Monte Carlo based techniques.
- Efficient application of the model requires a well-established risk management process especially in identifying different sources of uncertainty and also in the data acquisition process.
- For large size BNs that contain continuous nodes exact inference is infeasible. Therefore, the model is not applicable for large-scale projects.

4.3.3 BN models in Operational Risk

Risk in large-scale projects is very similar to operational risk in finance, particularly the way the risk events are represented. In addition even some of the risk factors are same. Neil, Fenton et al. [137] have shown how Bayesian models can be used to improve operational risk modelling. These authors first explored the use of BNs to model statistical loss distributions in financial operational risk scenarios focusing on modelling 'long' tail or unexpected loss events. One of the first models they developed was risk control self assessment model. This model was able to do the following:

- Quantified and rated qualitative and quantitative risks
- Used Risk Maps to rate the risk contribution of each element in a COSO complaint risk structure (Business/ Process/ Activity/ Risk Control)
- Mixed loss distribution derived from internal and external loss databases and embeds these in a Risk Map.
- Forecasted the capital charge in a form of value at risk (VaR) or any other statistic.
- Coped with missing audit/assessment data and accommodates differences in expert opinions.

The model uses issues and action plans to predict the reliability of the controls being modelled. The reliability of these processes is then combined to predict the reliability of the overall task and ultimately the information predicts process reliability and the loss distribution [3]. We are in particular interested in the structure of this model and how risk events are represented. We will use and develop this structure further in chapter 5.



Figure 4.14 Risk Control Self Assessment Model [3]

Figure 4.14 shows risk control self assessment BN that models operational risk in banks. In September 1998, the Basel Committee on Banking Supervision, in reaction to a number of well-publicised financial disasters, initiated work related to operational risk. The operational risk is modelled in terms of a variety of loss event types. We know that loss is clearly dependent on the number of risks. Risk occurs if control fails. Control fails if control effectiveness fails. Control effectiveness fails if there are issues with control and if action plans put in place to deal with issues fail.

The nodes represent variables which may or may not be observable. Each node has a set of states (e.g. 'green (no issues)', 'amber (minor issue)' and 'red (major issue)' for 'Issues with control 1?'). For each variable with parents, the probability table has conditional probabilities for each combination of the parents states.

Prediction and analysis using Risk Control Self Assessment Model

In Figure 4.15 we can observe that the nominal probability for the 'Risk B Occurs' is 0.46. Suppose we know that the 'Control 3 Fails' has not worked. In fact it has failed and we have 'True' entered as the observation. In this scenario the probability updates to 1.



Figure 4.15 Probability of the 'Risk B Occurs' - nominal and one control fails

On the other hand, suppose that 'Control 3 Fails' has been successful. In this case our observation would be 'False'. In Figure 4.16 we can see that the probability of 'Risk B Occurs' has reduced to 0.27. This shows how having a control in place that works can significantly reduce risk. In fact we can observe that if both controls work and the observation entered for 'Control 3 Fails' and 'Control 4 Fails' is 'False', the risk will not occur i.e. probability for 'Risk B Occurs' is 0.



Figure 4.16 Probability of 'Risk B Occurs' - one control successful and both controls successful



Figure 4.17 Probability of 'Risk B Occurs' - one action plan in place and both action plans in place

Suppose we are at the stage where we do not know if the controls will work or not. However, we do know that we have an action plan in place. In Figure 4.17 we can observe that even having only one action plan in place still reduces the probability (in comparison to the nominal) of 'Risk B Occurs' to 0.28. If at this stage we know we have both action plans in place this will reduce the probability of 'Risk B Occurs' even further to 0.03.

They subsequently developed the following models:

- Predicting total losses from event frequency and severity
- Modelling dependence between event frequency and severity.

These models were simple and they were mainly used as examples of the potential of BNs in this area.

In their later work they have shown how to use BNs to model the operational risk in information technology infrastructure in financial and other institutions. The model was based on IT management processes as defined by ITIL [139]:

- IT infrastructure management
- IT architecture and design
- Business risk analysis
- Business continuity management.

The aim of the model was to unify each of these different perspectives and to be used by each of these activities to deal with risk and uncertainty. In order to achieve this, various asset classes in the IT architecture were modelled as well as business processes that rely on architecture to deliver business services. The model is organised in layers and shows clear dependencies between services, their constituent business processes and the IT applications that help support or deliver those processes. The model can be used to predict the reliability of the service from its constituent inputs and answer questions like 'if application X and application Y fails, does the service fail?' Furthermore it is possible to use the model to make decisions (based on) the basis of clear financial criteria, such as VaR.

Their latest model is a hybrid dynamic BN for operational risk faced by financial institutions in terms of economic capital [135]. The model has three layers:

- Loss event model (Figure 4.18) which models how the potential loss events, Et dynamically evolve over time being influenced by controls, Ct. Each control is modelled as a function of a set of operational failure modes, Oj. Failure modes are influenced by a set of causal factors which initiate the operational failure, Fi.
- Loss severity model (Figure 4.19) uses probabilities generated by the loss event model to predict total losses by severity class. Total losses are modelled using a conditional dependency model represented as a DBN.
- Aggregated loss model calculates the sum of total losses associated with each event in each time period.



Figure 4.18 Loss event model [135]



Figure 4.19 Loss severity model [135]

The authors have shown how their generalized HDBN approach can successfully model dependencies between events and processes in complex environments evolving over time. This has been illustrated by applying this approach to the financial trading process.

4.4 Integration of models

Table 4.1 provides a summary of the strengths and weaknesses of the BN models reviewed in this chapter.

Expectations	Expectations met by:					
for project risk analysis tool	SIMP	MODIST	Productivity Model	Construction projects	Khodakarami's model	Operational Risks
1) Model trade- offs between time, cost and quality	Yes	Yes	Yes	No	Yes (partially)	No
2) Produce overall risk score	No	No	No	No	No	Yes
3) Easy to incorporate and modify user defined risks	No	No	No	No	No	Yes
4) Dynamic model	No	No	No	No	Yes	Yes
5) Model key notions of causal effect	Yes	Yes	No	Yes (partially)	Yes	Yes
6) Quantify uncertainty	Yes	Yes	Yes	Yes	Yes	Yes
7) Include continuous nodes	No	No	Yes	No	Yes	Yes
8) Allows continuous variables arbitrary level of precision	No	No	Yes	No	Yes	Yes

Table 4.1 Expectations for project risk analysis tools met by existing BN models

For complete project management we need an integrated model. Such an integrated model would generally be based on the SIMP and MODIST model philosophy which enables various types of trade-off analysis. In addition an integrated model would incorporate risk event measurement/representation from Risk Control Self Assessment Model. The integrated model would focus on:

- Trade-off analysis between key project factors (time, cost and quality)
- Sensible risk event measurement.

Developing such an integrated model for large projects is the main challenge of this thesis. This is covered in chapter 6.

4.5 Summary

We have seen that it is possible to use BNs to build models that are proved to be successful in both research and industry. However, the existing models have some limitations discussed in this chapter. These limitations raise the number of well defined research challenges. Some of these challenges are addressed using relatively simple solutions. However, the most important challenges cannot be solved by extending existing models and they require building new models. These new BN models are discussed in the chapters that follow.

5. New structured approach for BN risk models

A major objective in the field of risk analysis is the development of a uniform definition of risk. In this chapter we briefly review and compare the most common risk definitions. Risk has different meanings to different people. Risks are not always associated with negative outcomes and they may represent opportunities as well. Taking big risks can be beneficial to a party that is able to accept them because it enables opportunity.

Generally risk is seen as an abstract concept whose measurement is very difficult. Based on current risk definitions we propose the causal risk framework for risk quantification, which we see as an improvement of the standard risk measure: $Risk = Probability \ x \ Impact$. By using the causal risk framework we improve the modelling approach in order to help develop better decision support systems. Improvement of the causal risk framework and its application are some of the main contributions of the whole thesis. **The earlier version of this work has been published [65].**

5.1 Background

It is clear that if/when risk strikes, it can have a range of effects on the achievement of project objectives, from total failure to a surprisingly good/better than expected outcome. The inability of project managers to deal with competing views can affect the quality and acceptability of their projects. The confusions and delays in developing, for example, product strategies and information systems to support projects can mean that opportunities can be lost.

Despite this, the traditional project risk management process as practised by the majority of project managers tends to concentrate almost exclusively on the potential negative effects of risks. As a result of this focus, considerable effort is spent on identifying and managing risks, while opportunities tend to be overlooked. We argue that if the synergy between risks and opportunities is recognised and properly managed, it can ensure that unwelcome negative effects are minimised while at the same time maximising the chances of exploiting unexpected positive effects.

Entrepreneurs, for example, perceive risk differently from project managers. Shane and Venkatraman [168] suggest that entrepreneurs who identify an opportunity sooner appear to accept greater amounts of risk because others lack the knowledge to properly understand (and assess) the opportunity. Therefore, asymmetry in knowledge will lead to differing perceptions of risk regarding a given decision.

5.2 Identification of Risks

There are many techniques for risk identification, such as brainstorming and workshops, questionnaires and interviews. The appropriate combination of techniques should be used, since there isn't a single best method. Each of the commonly used risk identification techniques listed could be used equally effectively to identify opportunities as well as risks. To demonstrate this we will first list illustrative examples of common risks in large projects [60]. In the next section we will use the same technique to list potential opportunities in large projects.

Typical risks

- 'Insufficient use of status and progress reports'
- 'Insufficient client influence'
- 'Poor rapport/coordination with the client'
- 'Lack of project team participation in decision-making/problem-solving'
- 'Job insecurity within the project team'
- 'Lack of team spirit and sense of mission within project team'
- 'Parent organization stable, non-dynamic, lacking strategic change'
- 'Poor rapport/coordination with the parent organization'
- 'Poor relations with the parent organization'
- 'Project more complex than the parent has completed before'
- 'Inability to freeze design early
- 'Inability to close out the effort'
- 'Unrealistic project schedules'
- 'Initial under-funding'
- 'New 'type' of project'
- 'Poor relations with public officials'
- 'Unfavourable public opinion'
- 'The company's reputation is damaged'

- 'Poor staff performance'
- 'Poor quality of the delivered system'

5.3 Identification of Opportunities

If risk is defined as entirely negative and opportunity as entirely positive then naturally we would need to look at project risk management and project opportunity management. Risk practitioners often find it easier to identify potential problems than to look for hidden advantages and upsides. Here indeed we list illustrative examples of common opportunities in large projects [60].

Typical opportunities

- 'There is commitment of the project team to a goal'
- 'The initial cost estimates are accurate'
- 'Project team has exceptional capability'
- 'There is exceptional funding to completion'
- 'There are exceptional planning and control techniques'
- 'There are minimal start-up difficulties'
- 'Absence of bureaucracy'
- 'There is an on-site project manager'
- 'There are clearly established success criteria'
- 'There is project manager commitment to: established schedules, budgets and technical performance goals'
- 'There is frequent feedback from the parent organization'
- 'There is frequent feedback from the client'
- 'There is client and parent commitment to: established schedules, budgets and technical performance goals'
- 'There is project team participation in determining schedules and budgets'
- 'There is slack in the schedule'
- 'There is slack in the budget'

- 'There is company enthusiasm'
- 'There are exceptional control procedures, especially for dealing with changes'
- 'Judicious use of networking techniques'
- 'Lack of excessive government red tape'

5.4 Definition of Risk includes Opportunities

Issues involving risk are often difficult to distinguish and misunderstood by those making vital decisions for projects. Risk is not tangible or visible, therefore, a manager's risk perceptions in a particular project vary by risk characteristics and the project's internal and external environment [47]. Are people more risk taking for risks or for opportunities? Indeed, what makes a risk risky is the possibility of loss, whether it be loss of current assets or loss of opportunity for more assets. However, few people could be expected to take risks if they did not perceive some element of opportunity associated with risk-taking behaviour. Thus, it seems clear that the degree to which people will engage in risk-taking behaviour is related to the degree to which they perceive risk taking as an opportunity for something. Therefore, it is important to first define risk.

The word risk generally has implications of negative or adverse results from an event [66, 174, 188, 25]. Therefore, there is no doubt that common usage of the word risk sees only the downside. Asking a man in the street if he would be willing to take a risk, will almost always result in a negative response. This is reflected in the traditional definitions of the word, both in standard dictionaries and some technical definitions. One dictionary defines 'risk' as: "*a situation involving exposure to danger, the possibility that something unpleasant will happen, loss, exposure to chance of injury or loss.*" [145].

However, some professional bodies and standards organisations have gradually developed their definitions of risk to include both the upside and the downside. COSO [34] defines a risk as an event that can have negative impact. Equally an event that can have a positive impact is an opportunity. A guide published by the UK Association for Project Management has adopted a broad view of risk. Their definition of risk is: "Risk – an uncertain event or set of circumstances that, should it occur, will have an effect on the achievement of the project's objectives. " [7] In this definition, the nature of the effect is undefined and could therefore implicitly include both positive and negative effects. The Australian/New Zealand Standard has a similar risk definition where once again the nature of the effect is undefined and hence could implicitly include both positive and negative effects. Others, for example, a guide published by

the US Project Management Institute, are explicit naming both positive and negative effects on the project objectives within their definition of risk. The PMBOK definition states: "Project risk is an uncertain event or condition that, if it occurs, has a positive or a negative effect on a project objective ... Project risk includes both risks to the project's objectives and opportunities to improve on those objectives."[151]

In traditional behavioural decision theory, the term risk is used interchangeably with the term uncertainty [115, 23, 46]. Decision makers are said to be risk-averse if they prefer a sure thing to an option whose outcome is uncertain (i.e. a risky option). Yates and Stone's [202] review of risk definitions in various arenas reveals that definitions of risk range from emphasis on risk of personal harm, found in medical and hazard research, to emphasis on possible opportunities, found in economic and business literature. A common theme in most definitions of risk is still the possibility of loss. However, each conceptualisation of risk also contains some component of opportunity, even if it is only the opportunity to avoid loss.

The fact that recent documentation now incorporates both opportunities and risks within their definition for risk, it is a clear recognition that both are equally important influences over project success [81].

5.5 Problems with the standard measure of risk

As discussed in 2.7.2 in organisations where risk is treated seriously, it is a standard that at the start of every project, managers discuss and list risks. Project managers are often expecting a number of risks to occur, which will be similar from project to project. Project managers can employ experiences gained through the course of one project to the next one.

When managers think about the risks that might cause the next project to fail, such as the risks listed in section 5.2; whether deliberately or not, they will have measured such risks. A liquidity crisis that destroys their company and forces it into administration would probably not appear on their list. Although its impact is more devastating than any of the others, the chances of it actually happening are so low that a project manager would probably have discounted it.

As discussed in 2.7.2 the *probability x impact* measure of risk is quite useful for prioritising risks (the bigger the number the 'greater' the risk). The problem is that, it is normally not possible to get the numbers needed to calculate it [59, 192, 31]:

• We cannot get the *Probability* number. It is only natural to be worried if, for example, we know there have been bad investments in mortgage back securities. This increases the risk of 'Liquidity crisis' and could result in the company going into administration. Does this make the probability of the liquidity crisis equal to one? Clearly not, because if it was

one then there would have been no point in trying to properly evaluate assets. The probability of the liquidity crisis is conditional on a number of other control events (like practising proper asset valuation to avoid the liquidity crisis) and trigger events (like bad investments in mortgage back securities). It makes no sense to assign a direct probability without considering the events it is conditional on. In general, it makes no sense (and would in any case be too difficult) for a risk manager to give the unconditional probability of every 'risk' irrespective of relevant controls, triggers and mitigants. This is especially significant when there are, for example, controls that are not used very often (like implementing proper asset valuation globally).

- We cannot get the Impact number. Just as it makes little sense to attempt to assign an (unconditional) probability to the event 'Liquidity crisis', so it makes little sense to assign an (unconditional) number to the impact of company goes into administration. This can literally mean anything from, for example, no job losses to 100% job losses. Apart from the obvious question "impact on what", we cannot say what the impact is without considering the possible mitigating events such as company searching for bailout. Hence, we simply discard having 1 10 point scale for impact. Mitigants can not only avoid the worst case scenario, but can even avoid administration altogether.
- Risk score is meaningless. Even if we could get round the two problems above what exactly does the resulting number mean? Suppose the (conditional) probability of the liquidity risk is 0.95 and, on a scale of 1 to 10, the impact of the crisis is 10 (even accounting for mitigants). The liquidity crisis 'risk' is 9.5, which is a number close to the highest possible 10. But it does not measure anything in a meaningful sense.
- It does not tell us what we really need to know. What we really need to know is the probability, given our current state of knowledge that the company will go into administration.

Shortcomings of *probability x impact* measure are discussed further in section 6.9.

5.6 Getting sensible risk measures with causal models (risk maps)

The rational way to think of risks is in terms of causal models (BNs) with trigger events, control events, risk events, mitigant events and consequence events. In the next section we will explain this in more detail. For the liquidity crisis risk, the relevant causal model is shown in Figure 5.1.

A risk is therefore characterised by a set of uncertain events. Each of these events has a set of outcomes. For simplicity here we will assume that these events have two outcomes — true

and false (in practice we can extend the outcomes to incorporate more states). For example, the criteria for consequence event are defined such that if 'Company goes into administration' is 'true', it means a probability of at least 80% that the company will not be rescued.

The 'uncertainty' associated with a risk is not a separate notion (as assumed in the classic approach). Every event (and hence every object associated with risk) has uncertainty that is characterised by the event's probability distribution.



Figure 5.1 Causal model for 'Liquidity crisis'

The sensible risk measures that we are proposing are simply the probabilities you get from running a BN. Of course, before you can run a BN, you still have to provide some probability values. But, in contrast to the classic approach, the probability values you need to supply are relatively simple and they make sense and you never have to define vague numbers for 'impact'.

To give you a feel of what you would need to do, in the risk map of Figure 5.1 the uncertain event 'Liquidity crisis' still requires us to assign a conditional probability distribution. But instead of second guessing what this event actually means in terms of other conditional events, the model now makes it explicit and it becomes much easier to define the necessary conditional probability. What we need to do is define the probability of the liquidity crisis given each combination of parent states as shown in Table 5.1.

Bad investment in mortgage back securities	False		True	
Proper asset valuation	False	True	False	True
False	1.0	1.0	0.0	0.8
True	0.0	0.0	1.0	0.2

Table 5.1 Conditional probability table for 'Liquidity crisis'

For example, if there are bad investments in mortgage back securities then the probability of liquidity crisis is 1, if there was no proper asset valuation, and 0.2, if there was proper asset valuation. In filling in such a table, we no longer have to try to 'factor in' any implicit conditioning events like investment type.

There are some events in the BN for which we do need to assign unconditional probability values. These are the nodes that have no parents; it makes sense to get unconditional probabilities for these because, by definition, they are not restricted by any conditions. Such nodes can generally be only triggers, controls or mitigants. An example is shown in Table 5.2.



Table 5.2 Probability table for 'Bad investment in mortgage back securities'

As discussed in chapter 3, we are not suggesting that assigning the probability tables in a BN is always easy. You will generally require expert judgement or data to do it properly. What is important is that it is easier than the classic alternative. At worse, when you have no data, purely subjective values can be supplied.

Once you have supplied the prior probability values a BN tool will run the model and generate all the measures of risk that you need. For example, when you run the model using only the prior probabilities i.e. no observations entered, the model computes the probability of the liquidity crises as just under 0.8 and the probability of company going into administration (meaning at least 80% chance that the company will not be rescued) is about 0.75 (Figure 5.2).



Figure 5.2 Liquidity crises - marginal state

In terms of the difference that proper asset valuation could make we can run two scenarios: One where there is proper asset valuation and one where there is not (Figure 5.3). The probability of 'Company goes into administration' being 'false' jumps from 0.09 (when there is no proper asset valuation) to 0.82 (proper asset valuation). This near tenfold increase in the probability of avoiding the liquidity crisis clearly explains why it is important to have a control.



Figure 5.3 Company goes into administration – different scenarios

5.7 Causal Framework for Risk

To develop responses to identified risks which are appropriate, achievable and affordable; we propose use of a causal framework for risk [60]. A risk is characterized by the following set of events (Figure 5.4):

- Trigger event a negative event that may or may not occur. If it occurs it may cause a risk event. Project manager has no impact on this node. There may be numerous trigger events for one risk event.
- Control event a positive event that may stop trigger event or reduce the size of its impact on the risk event in order to make it more acceptable to the project. There may be numerous control events for one risk event.
- Risk event a negative event that in turn may cause a negative consequence. This is the key node observed in the model.
- Mitigant event a positive event that may reduce the impact of risk event on further consequence event. There may be numerous mitigant events.
- Consequence event a negative event which is the result of a risk event occurring. There may be numerous consequence events caused by one risk event.

All the types of events in the model are completely interchangeable depending on the perspective. Hence, risk event in one model can be trigger event in another model or control event in one model can be trigger event in another model etc. This interchangeability stresses symmetry and simplicity of the causal approach. In addition, it is possible to extend the types of nodes when necessary. This might be especially useful for a consequence event node. Hence, we may define more than one level of consequence events in a model. We will demonstrate this in our model in chapter 6.



Figure 5.4 Causal framework for risk [60]

In a similar way an opportunity is characterized by the following set of events (Figure 5.5):

- Trigger event a positive event that may or may not occur. If it occurs it may cause an opportunity event. Project manager has no impact on this node. There may be numerous trigger events for one opportunity event.
- Danger event is the analogy of control event. A negative event that may stop trigger event or reduce the size of its impact on the opportunity event. There may be numerous danger events for one opportunity event.
- Opportunity event a positive event that in turn may cause a positive consequence. This
 is the key node observed in the model.
- Peril event is the analogy of mitigant event. A negative event that may reduce the impact of opportunity event on further consequence event. There may be numerous peril events.
- Consequence event a positive event which is the result of an opportunity event occurring. There may be numerous consequence events caused by one opportunity event.



Figure 5.5 Causal framework for opportunities

To implement our causal risk framework and demonstrate the synergy between risks and opportunities, we present the 'Developing system for client' example in Figure 5.6. On the left hand side is a causal chain characterising risk events; on the right hand side is a causal chain characterising opportunity events. We can clearly see how what some people regard as a risk, others might regard as a cause, a consequence, a control or a mitigant. Others still might even regard it as an opportunity.



Figure 5.6 Developing system for client

A causal framework shows not just that there is a synergy between risks and opportunities, but also that risks and opportunities can, and should be handled together. Therefore a single risk management process can effectively handle both opportunities and risks. Opportunities are given equal status with risks and seeking to manage them proactively can only benefit the project and the organisation.

5.8 Improved Causal Framework for Risk

Considering that our causal framework for risk and our causal framework for opportunities mirror each other; the natural way to handle this is to go for a uniform approach and have one qualitative model for risks and opportunities (Figure 5.7); where the values for the nodes could go from negative to positive. Which means instead of having, for example, a 'Trigger' node that can be only negative in the risk model or only positive in the opportunity model, this node can have a range from negative to positive, which means things can be better or worse than normal.



Figure 5.7 Causal framework for risks and opportunities

If we apply this new approach to our 'Developing system for client' model it will look as per Figure 5.8. Node names are now modified to suit this different approach and the nodes can take values from better to worse.



Figure 5.8 Developing system for client (new approach)

When risks are represented directly, a given risk can, at best, only take the value of zero. This is a problem, because the model would not be able to fully support the risk definition, and real life situations. For example, if 'Feedback during development' is known to be an active risk area and we think it could have a negative impact on 'Quality of delivered system', we might decide to investigate whether an improvement in 'Prototype delivery' could help to counteract this negative impact. This is not possible if 'Feedback during development' is represented directly.

Therefore, in the model shown in Figure 5.8 risks are no longer represented explicitly. Nodes that represented risks are now represented by scale attributes that underlie those risks, i.e. a node represents the quality of a risk. For example, before we had a node representing the 'Lack of feedback during development' risk, now we have a node representing the quality of 'Feedback during development'. For simplicity reasons in this example we use 3-point scale with low, medium and high states. Users can form a judgement from probabilities associated with a collection of outcomes.

Risks are represented as the quality of risk and not directly (Figure 5.9), because the model should be able to support the risk definition and the real life situations, and it seems it is easier for people to have one model where things can be better or worse; than to have two separate models, one where things can be only positive and one where things can be only negative.



Figure 5.9 Developing system for client – nominal state

The root nodes in the model, i.e. they have no parent nodes are: 'Personal contacts', 'Prototype delivery', 'Staff performance', 'Cultivate personal contacts', 'Diversify clients' and 'Strategic planning'. Details of some nodes in the model are as follows:

- Feedback during development. This node represents the quality of the contribution that
 the feedback has on 'Quality of the delivered system' and ultimately 'Company state'.
 The node is dependent on 'Personal contacts' as well as 'Prototype delivery'. The state
 values of this node are: low, medium and high. Considering this is a ranked node, the
 distribution we have used is TNormal. The WMIN function is used as the mean of the
 TNormal. This means:
 - When 'Personal contacts' and 'Prototype delivered' are both 'high' the distribution of 'Feedback during development' is heavily skewed toward 'high' (Figure 5.10).



Figure 5.10 Feedback during development - high

- When 'Personal contacts' and 'Prototype delivery' are both 'low' the distribution of 'Feedback during development' is heavily skewed toward 'low'.
- When 'Personal contacts' is 'low' and 'Prototype delivery' is 'high' the distribution of 'Feedback during development' is centred toward 'low'.
- When 'Personal contacts' is 'high' and 'Prototype delivery' is 'low' the distribution of 'Feedback during development' is centred toward 'low'.

The nodes 'Quality of delivered system', 'Follow on work with the client' and 'Company state' are defined similarly using the wmin function. The node 'Profits' uses the wmean function.

5.9 Summary

In this chapter, we have identified some problems with the term risk as well as problems with how risk is quantified. Traditional definitions illustrate the term risk as negative. In any given decision situation both risks and opportunities are usually involved, and both should be managed. Relatively recent risk definitions incorporate opportunities into their risk definition.

To manage risk we propose a causal framework for risk. Risks and opportunities can sometimes be treated separately, but it is important to understand that they are not independent. Hence we use this framework to develop qualitative models where risks are no longer represented explicitly, but nodes that represent risk are now represented by scale attributes that underlie those risks. With this type of model, it is possible to fully support the risk definition and real life situations.

6. The Causal Risk Register Model

In chapter 2 we analysed standard project risk management tools; why they were often inadequate and provided no natural measure for risk analysis. We then went on to describe Bayesian nets in chapter 3 and explained why they provided a better platform for project risk analysis. Chapter 4 demonstrated the current BN project risk models and their limitations. New risk taxonomy was then presented in chapter 5. This chapter introduces the 'Causal Risk Register Model', a new model for large projects at the overall project level.

The main novel contribution of this chapter, and consequently of the whole thesis, is to implement and validate new risk framework using the Bayesian net model. This new model adopts the basic philosophy from the existing models whilst overcoming certain limitations. The model implicitly considers the trade-offs that may be made in the risk model, specifically time, cost and quality. We discussed project success and failure in section 2.5. At the end, the model gives a risk score in the form of the probability of the project failing.

6.1 Overview of the Causal Risk Register Model

The main goal of the Causal Risk Register Model (CRRM) is to offer an improvement on the standard risk measurement ($Risk = Probability \ x \ Impact$) and therefore enable improved project risk analysis. It captures the basic philosophy of the standard project risk analysis tool i.e. the risk register, but structurally it is very different.

As discussed previously, there are many problems with the standard measure of risk using the risk register. In chapter 5 we explained the rational way to think about risks in terms of causal models with trigger events, control events, risk events, mitigant events and consequence events. We have applied the causal framework to general top level risks and developed the risk model for an international leading defence company which we will refer to as 'company X'. Figure 6.1 shows the CRRM which is an improvement to the original model developed for 'company X'. This model illustrates how these risks affect 'Project Failure'.



Figure 6.1 Causal Risk Register Model

6.2 Summary of model variables

We identified the variables to be used in the model by analysing data provided by and collected from experts at 'company X'. There are a number of key level one consequence events

influencing the final project outcome: poor quality product, poor process quality, schedule overrun, project overspent and required functionality missing. We have extensively discussed the influence of these risk events with experts in project risk management. Table 6.1 summarizes all the variables of the CRRM including the original names and our names which in majority of cases are revised versions of the original names. We made more significant changes in the following consequence nodes:

- We divided 'operational' into 'poor process quality' and 'poor product quality'
- We defined 'performance' as 'required functionality missing'. These two terms have been used together and interchangeably in 'company's X' documentation. Considering the company's nature, we believe 'required functionality missing' is more specific and provides a better description.
- We believe that it is standard to have a risk score and therefore we have 'project failure' as consequence level 2. Originally 'company X' had 'reputation' here. We believe 'reputation' should not be included at this stage.

Node Type	Original Name from	Our Name	
	'company X'		
	Resources and motivation	Poor staff performance	
	Organisation and its	Organisation and its	
	effectiveness	ineffectiveness	
	Design solution – culture and	Poor design solution	
	acceptability		
	Functional and performance	Requirements creep	
	requirements		
	Planning and programme	Lack of programme	
Risk event	commitment	commitment	
	Process efficiencies	Process inefficiencies	
	Interfacing and integration	Rushed interfacing and	
	into the platform	integration into the platform	
	Procurement and sub-	Key sub-systems fail	
	contractor management		
	Obsolescence	Obsolescence	
	Business environment (order	Inadequate business	
	book, PR and legal)	environment	

	Availability of facilities	Inadequate facilities
	Budget constraints	Initial underfunding
	Operational	Poor product quality
Consequence event level 1	Operational	Poor process quality
	Schedule	Schedule overrun
	Cost	Project overspent
	Performance	Required functionality missing
Consequence event level 2	Reputation	Project Failure

Table 6.1 Summary of all Causal Risk Register Model variables

6.3 Improved Causal Risk Register Model

The structure of the CRRM follows the new risk framework discussed in chapter 5. At the moment the CRRM has risk events and consequence events, and these are clearly defined in the company's documentation. In addition, consequence events are divided into two levels. From the documentation, we can draw a conclusion on trigger events and control events, and add these to the CRRM. Considering the model is based on 'company X', the structure it has consists of trigger events, risk events, control events and consequence events, i.e. mitigant events are not included. Hence, we could make a parallel to the causal taxonomy of the Risk Control Self Assessment Model discussed in chapter 4 (Table 6.2).

Risk Control Self Assessment Model	Causal Risk Register Model
Issues with control	Trigger event
Action plan	Control event
Risk occurs	Risk event
Losses	Consequence event

Table 6.2 Risk control self assessment model and causal risk register model taxonomy

Based on 'company's X' documentation we believe that the trigger events and control events shown in Table 6.3 would be best suited to the type of top level risk events we have in the CRRM (Figure 6.2).

Trigger event	Associated control event				
Poor training scheme	Recruit adequately qualified staff				
Poor motivation	Flexible working hours and holidays				
	Good appraisal system and pay				
Dislocation from corporate	Change organisation structure				
--------------------------------------	------------------------------------	--	--	--	--
Business objectives not clear					
Inability to freeze design early	Specify maximum length for				
	negotiation/changes				
Poor management	Implement progress reports				
Technical novelty	Recruit adequately qualified staff				
Poor initial requirements	Follow-up procedures in place				
Lack of rapport with the client	Follow-up procedures in place				
Poor concurrent engineering strategy					
Poor change control					
Poor build strategy					
Important overridden by urgent	Key control checks must be passed				
important overhaden by urgent	Good planning				
Dependence on supplier deliveries					
Especially complex requirements	Recruit adequately qualified staff				
Poor image and PR	Market diversification				
Share price performance low	Focus on opportunity cost				
Inadequate testing and trials					
Rapidly changing technologies	Product diversification				
Small budget plan for order book	Good negotiating skills				
Poor cash flow analysis	Focus on opportunity cost				

 Table 6.3 Summary of trigger events and control events



Figure 6.2 Causal Risk Register Model with Trigger Events and Control Events

As established in chapter 5, it is possible for each risk event to have more than one trigger event and control event. If we observe the Causal Risk Register Model segment for 'Poor staff performance' risk event (Figure 6.3), we can see there are two trigger events ('Poor motivation' and 'Poor training scheme') and three control events ('Recruit adequately qualified staff', 'Flexible working hours and holidays' and 'Good appraisal system and pay'). Considering there are five parent nodes, we need to be careful not to end up with very complex NPTs.

To keep ease of use throughout the model and simple NPTs, we have taken the following steps: firstly, we introduced two dummy nodes for each of the trigger events, i.e. 'Poor staff performance with respect to training scheme' and 'Poor staff performance with respect to poor motivation'. Secondly, since there are two control events for 'Poor motivation', we introduced additional dummy node 'Control against poor motivation'. This node represents the combined contribution that all the control events put together have on the risk event with respect to a particular trigger event. For simplicity, this node is a Boolean node and we have used a noisyor comparative expression to define the NPT.

'Poor staff with respect to poor motivation' node is dependent on 'Poor motivation' and 'Control against poor motivation'. This node represents the impact that 'Poor motivation' has on 'Poor staff performance' when 'Control against poor motivation' taken into account. This is a Boolean node and the NPT is defined manually.

'Poor staff performance' node represents a risk event. It is dependent on 'Poor staff with respect to poor motivation' and 'Poor staff with respect to poor training scheme'. It directly influences 'Poor process quality' which is a consequence level 1 event. Hence, we could say 'Poor staff performance' is a trigger event for the 'Poor process quality' risk event. Hence, we can see how the types of events in the causal taxonomy of risk are all completely interchangeable.



Figure 6.3 'Poor staff performance' risk event

6.4 Structure of the Model

Trigger events and control events are root nodes and they don't have any parents; therefore we assign probability values to these nodes based on the information provided in 'company's X' documentation. Considering they are defined as Boolean nodes it is easy to enter their NPTs. Therefore, it is also easy to customize their NPTs, since companies typically gather some data from their past projects.

For all the nodes that have more than two parents we use a noisyor expression, for example 'Organisation and its ineffectiveness'. We use constants for weighting (Equation 6-1) and this will be discussed more in section 6.7.

Organisation and its ineffectiveness =

noisyor(org ineff bus obj,org ineff bus obj const,org ineff disloc cor,

org_ineff_disloc_cor_const, org_ineff_poor_mng,org_ineff_poor_mng_const, 0.1) (6-1)

Normally we will enter observations about risk events for the particular project being studied. As soon as we enter observations, these impact consequences level 1 and in turn the consequence level 2. Consequences are the main part of the model and they represent measurable quantities that managers can reason about. The combination of consequence outcomes determines if the overall project is going to fail or not.

A key feature of the Causal Risk Register Model is the trade-off part (Figure 6.4). The fact that the model indirectly models trade-off between time, cost and quality via:

- Poor product quality
- Poor process quality
- Schedule overrun
- Project overspent
- Required functionality missing.

Since 'Project failure' has more than two parents we use a noisyor expression. We use constants for weighting (Equation 6-2) and this will be discussed more in section 6.7.

Project failure =

noisyor(poor_prod_qual,poor_prod_qual_const,poor_proc_qual, poor_proc_qual_const, sched_overrun,sched_overrun_const, proj_overspent, proj_overspent_const, req_func_missing, req_func_missing_const, 0.1) (6-2)



Figure 6.4 Trade-off part

6.5 Issues arising from model development

One of the initial requirements was for the model to be used by practitioners who have no mathematical/statistical background. Hence, all the variables in the model are Boolean and NPTs for them are defined manually.

In some cases, where there are more than one trigger event and control event; what we had in the model, by following the risk register approach, was a list of trigger events that can trigger the risk event and then a list of control events for the combination of all triggers. If we analyse a segment of the model in Figure 6.5, we can see that we have 'Poor training scheme' and 'Poor motivation' as trigger events for 'Poor staff performance' on one side and 'Pay increase', 'Flexible working hours' and 'Longer holidays' as control events on the other side.





Using this structure we cannot clearly see which control event relates directly to which trigger event. What we have is a set of combined control events for the set of combined trigger events. What we want to do is to separate the trigger events and control events. We need a different model structure in order to achieve this. We need a model structure whereby we will take the first trigger event and then list all the control events for a risk event with respect to the first trigger event; then take the second trigger event and list all the control events for a risk event with respect to the second trigger event.

In practice, looking at Figure 6.6, we will first take the 'Poor motivation' trigger event and list all the control events for 'Poor staff performance' with respect to the 'Poor motivation'; then we will take the second trigger event 'Poor training scheme' and list all the controls for 'Poor staff performance' with respect to the 'Poor training scheme'. You can see what the same model segment looks like using the new model structure in Figure 6.6.



Figure 6.6 Modelling trigger events and control events

6.6 Model validation

6.6.1 Internal Validation

We will first validate the model internally, based on priors that we had supplied and probabilities for the outcomes. Ideally we would have liked to have information on which triggers happened during this project, but unfortunately considering the nature of the project, this information was too confidential.

Internal validation is followed with two cases of external validation by two independent project managers. In the first case of external validation we look at a small software company.

Case 1 – No observations entered

First we validate the model internally and analyse if the model predictions are consistent with the initially assumed distributions. We execute the model without any observations. Table 6.4 illustrates the predicted probabilities for 'consequence level 1' and 'consequence level 2'.

	Product	Process	Schedule	Project	Required	Project failure
	quality	quality	overrun	overspent	functionality missing	
False	81%	70%	63%	65%	83%	63%
True	19%	30%	37%	35%	17%	37%

Table 6.4 Predictions when no observations are entered

We can observe that the predicted probabilities are reasonable and consistent with what 'company X' was expecting at the time. For example, the model correctly predicts a higher probability of failure for 'Schedule overrun' and 'Project overspent'. This is historically correct for 'company X'; as well as many other companies.

Case 2 – Observation 'false' is entered for 'Project failure'

We execute the model when observation 'false' is entered for 'Project failure'. This results in back propagation and Table 6.5 illustrates the revised probabilities for 'consequence level 1' nodes.

	Product	Process	Schedule	Project	Required
	quality	quality	overrun	overspent	functionality missing
False	87%	77%	69%	71%	88%
True	13%	23%	31%	29%	12%

Table 6.5 Predictions when observation 'false' is entered for 'Project failure'

The model correctly revises probability distributions and predicts a higher probability of 'consequence level 1' nodes being 'false'. For example, the probability for 'Product quality' being 'false' is revised and it increases from 81% (Figure 6.4) to 87% (Figure 6.5).

Case 3 – Observation 'false' is entered for 'Schedule overrun'

We execute the model when observation 'false' is entered for 'Schedule overrun'. This results in back propagation and Table 6.6 illustrates the revised probabilities for relevant risk event nodes.

	Poor design	Lack of programme	Rushed interfacing and
	solution	commitment	integration into the platform
False	92%	93%	91%
True	8%	7%	9%

Table 6.6 Predictions when observation 'false' is entered for 'Schedule overrun'

The model correctly revises probability distributions and predicts a higher probability of relevant risk events being 'false'. For example, the probability for 'Poor design solution' being 'false' is revised and it increases from 77% (Figure 6.7) to 92% (Figure 6.6).

	Poor design	Lack of programme	Rushed interfacing and
	solution	commitment	integration into the platform
False	77%	87%	84%
True	23%	13%	16%

Table 6.7 Predictions when no observations are entered

Case 4 – Observation 'true' is entered for all trigger events

We execute the model when observation 'true' is entered for all trigger events. Table 6.8 illustrates the predicted probabilities for 'consequence level 1' and 'consequence level 2'.

	Product	Process	Schedule	Project	Required	Project failure
	quality	quality	overrun	overspent	functionality missing	
False	61%	54%	31%	53%	65%	48%
True	39%	46%	69%	47%	35%	52%

Table 6.8 Predictions when observation 'true' is entered for all trigger events

For example, the model correctly predicts a higher probability of 'consequence level 1' and consequence level 2' events being 'true'. For example, the probability for 'Product quality' being 'true' increases from 19% (Figure 6.4) to 39% (Figure 6.8).

Case 5 – Observation 'true' is entered for all trigger events and observation 'false' is entered for all control events

We execute the model when observation 'true' is entered for all trigger events and observation 'false' is entered for all control events. Table 6.9 illustrates the predicted probabilities for 'consequence level 1' and 'consequence level 2'.

	Product	Process	Schedule	Project	Required	Project failure
	quality	quality	overrun	overspent	functionality missing	
False	43%	42%	17%	33%	47%	37%
True	57%	58%	83%	67%	53%	63%

Table 6.9 Predictions when observation 'true' is entered for all triggers and observation 'false' is entered for all controls

For example, the model correctly predicts an even higher probability of 'consequence level 1' and consequence level 2' events being 'true'. For example, the probability for 'Product quality' being 'true' increases even further from 39% (Figure 6.8) to 57% (Figure 6.9).

Case 6 – Observation 'true' is entered for all trigger events and observation 'true' is entered for all control events

We execute the model when observation 'true' is entered for all trigger events and observation 'true' is entered for all control events. Table 6.10 illustrates the predicted probabilities for 'consequence level 1' and 'consequence level 2'.

	Product	Process	Schedule	Project	Required	Project failure
	quality	quality	overrun	overspent	functionality missing	
False	67%	58%	36%	61%	71%	53%
True	33%	42%	64%	39%	29%	47%

Table 6.10 Predictions when observation 'true' is entered for all trigger events and observation 'true' is entered for all control events

For example, the model correctly predicts lower probability of 'consequence level 1' and consequence level 2' events being 'true'. For example, the probability for 'Product quality' being 'true' decreases from 57% (Figure 6.9) when control events were 'false' to 33% (Figure 6.10).

Case 7 - Observation 'true' is entered for 'Poor management'

We execute the model when observation 'true' is entered for 'Poor management'. This is the key risk event that has impact on all 'consequence level 1' events. Table 6.11 illustrates the predicted probabilities for 'consequence level 1' and 'consequence level 2'.

	Product	Process	Schedule	Project	Required	Project failure
	quality	quality	overrun	overspent	functionality missing	
False	69%	66%	45%	62%	73%	56%
True	31%	34%	55%	38%	27%	44%

Table 6.11 Predictions when observation 'true' is entered for 'Poor management'

For example, the model correctly predicts a higher probability of 'consequence level 1' and consequence level 2' events being 'true'. For example, the probability for 'Product quality' being 'true' increases from 19% (Figure 6.4) to 31% (Figure 6.11).

6.6.2 External Validation

Case 1 – External validation for 'company Y'

We have asked the project manager for a small software company, which we will refer to as 'company Y', to enter values for the triggers and controls for two projects. The entries for the triggers are shown in Figure 6.7 and the entries for controls are shown in Figure 6.8. These entries are completed in a 'Risk table' which is the feature of AgenaRisk and allows observations to be entered in a similar way as in a spreadsheet.

	Project1	Project2	Prior
Triggers			
Poor motivation	False 👻	True 👻	No Answer 👻
Poor training scheme	True 👻	True 👻	No Answer 👻
Dislocation from corporate	False 👻	True 👻	No Answer 👻
Business objectives not clear	True 👻	True 👻	No Answer 👻
Inability to freeze design early	True 👻	True 👻	No Answer 👻
Technical novelty	True 👻	True 👻	No Answer 👻
Poor management	False 👻	True 👻	No Answer 👻
Poor initial requirements	False 👻	True 👻	No Answer 👻
Lack of raport with the client	False 👻	True 👻	No Answer 👻
Poor concurrent engineering strategy	False 👻	True 👻	No Answer 👻
Poor change control	False 👻	False 👻	No Answer 👻
Poor build strategy	False 🗸	False 👻	No Answer 👻
Important overriden by urgent	False 👻	True 👻	No Answer 👻
Dependence on supplier deliveries	False 🗸	True 👻	No Answer 👻
Especially complex requirements	True 🗸	True 👻	No Answer 👻
Poor image and PR	False 🗸	False 👻	No Answer 👻
Share price performance low	False 🗸	False 👻	No Answer 👻
Inadequate testing and trials	True 🗸	True 👻	No Answer 👻
Rapidly changing technologies	True 🗸	True 👻	No Answer 👻
Small budget plan for order book	False 👻	False 🗸	No Answer 👻
Poor cash flow analysis	False 🗸	False 🗸	No Answer 🗸 👻

Figure 6.7 Project manager's entries for triggers for 'company Y'

	Project1	Project2	Prior
Controls			
Recruit adequatly qualified staff	True 👻	False 👻	No Answer
Flexible working hours and holidays	True 👻	True 👻	No Answer
Good appraisal system and pay	True 👻	False 👻	No Answer
Change organisational structure	False 👻	False 👻	No Answer
Implement progress reports	False 👻	False 👻	No Answer
Specify maximum length for negotiation/changes	False 👻	False 👻	No Answer
Follow-up procedures in place	True 👻	False 👻	No Answer
Key control checks must be passed	False 👻	False 👻	No Answer
Good planning	True 👻	False 👻	No Answer
Market diversification	False 👻	False 👻	No Answer
Product diversification	False 👻	False 👻	No Answer
Good negotiating skills	False 👻	False 👻	No Answer
Focus on opportunity cost	False 🗸	False 🗸	No Answer

Figure 6.8 Project manager's entries for controls for 'company Y'

'Project 1' was a reasonably successful project. Therefore, we can see that there are some triggers that are 'true', but also the relevant controls are mainly 'true'. 'Project 2' was a bit of a failure. Hence, there are many triggers that are 'true', but also many relevant controls are 'false'. The model correctly predicted the risk events and these probabilities were more or less spot on. Figure 6.9 shows some examples of risk events.



Figure 6.9 Predicted probabilities for risk events

We can observe that the model predicts a higher probability of 92% for 'Poor staff performance' being false for 'project 1' which is a successful project. The probability for 'Poor staff performance' being false drops to 46% for 'project 2' which is an unsuccessful project. Similarly the model predicts a higher probability of 71% for 'Poor design solution' being false for 'project 1' and this drops to 29% for 'project 2'.

The model's predictions for 'consequences level 1' and 'consequences level 2' are showed in Figure 6.10.





Figure 6.10 Predicted probabilities for consequences

The predictions for 'consequence level 1' are pretty good. There are small inaccuracies and reasons for this are as follows:

- These projects were different in nature, had different sizes and were done in a different environment to the original project environment for which the model was built.
- There were certain risk events that were not at all relevant; for example, 'Lack of programme commitment', 'Inadequate business environment' and 'Inadequate facilities'. The way the model handles this is to (correctly) assert that these particular risk events have a low probability of occurring. The problem is that the model does not distinguish between them being 'unlikely' and being 'irrelevant'. Therefore, it treats them as unlikely, but still relevant. Hence, they impact in a positive way on the subsequent predictions.

The predictions for 'Project failure' are very good. The model predicts there is a 63% probability that 'project 1' will be successful and a 58% probability that 'project 2' will be a failure.

Case 2 – External validation for 'company Z'

We have asked the project manager for a large construction company, which we will refer to as 'company Z', to enter values for the triggers and controls for two projects. The entries for the triggers are shown in Figure 6.11 and the entries for controls are shown in Figure 6.12.

	Baseline	Project 1	Project 2
Triggers			
Poor motivation	No Answer 👻	True 🗸	False 🗸
Poor training scheme	No Answer 👻	True 👻	False 👻
Dislocation from corporate	No Answer 🗸 👻	True 🗸	False 👻
Business objectives not clear	No Answer 👻	True 👻	False 👻
Inability to freeze design early	No Answer 🗸 👻	True 👻	False 👻
Technical novelty	No Answer 👻	True 🗸	False 👻
Poor management	No Answer 🗸 👻	True 🗸	False 👻
Poor initial requirements	No Answer 👻	True 👻	False 👻
Lack of raport with the client	No Answer 🗸 👻	True 👻	False 👻
Poor concurrent engineering strategy	No Answer 👻	True 👻	False 👻
Poor change control	No Answer 🗸 👻	True 👻	False 👻
Poor build strategy	No Answer 👻	True 👻	False 👻
Important overriden by urgent	No Answer 🗸 👻	True 👻	True 👻
Dependence on supplier deliveries	No Answer 👻	True 👻	True 👻
Especially complex requirements	No Answer 👻	True 👻	False 👻
Poor image and PR	No Answer 👻	True 👻	False 👻
Share price performance low	No Answer 👻	True 👻	False 👻
Inadequate testing and trials	No Answer 👻	False 👻	False 👻
Rapidly changing technologies	No Answer 👻	False 👻	False 👻
Small budget plan for order book	No Answer 👻	True 🗸	False 🗸
Poor cash flow analysis	No Answer 🗸 🗸	True 🗸	True 🗸

Figure 6.11 Project manager's entries for triggers for 'company Z'

Baseline	Project 1	Project 2
No Anewer 🔶 👻	True -	True -
No Anewer 🔶 👻	False -	True -
No Answer 🔶 👻	False -	True -
No Anewer 🔶 👻	False -	True -
No Answer 🚽	False -	True -
No Answer 🔶 👻	False -	False +
No Answer 🔶 👻	False -	True -
No Answer 🔶 👻	False -	True -
No Anewer 🔶 👻	False -	False -
No Anewer 🔶 👻	False -	True -
No Anewer 🔶 👻	False -	True -
No Anewer 🔶 👻	False -	True -
No Answer 🔹 👻	False -	True -
	Baseline Na Anawer – Na Anawer –	Baseline Project 1 No. Answer - Tua - No. Answer - False - No. Answer - No. A

Figure 6.12 Project manager's entries for controls for 'company Z'

'Project 1' was a bit of a failure. Hence, there are many triggers that are 'true', but also many relevant controls are 'false'. 'Project 2' was a reasonably successful project. Therefore, we can see that there are some triggers that are 'true', but also the relevant controls are mainly 'true'. The model correctly predicted the risk events and these probabilities were more or less spot on. Figure 6.13 shows some examples of risk events.



Figure 6.13 Predicted probabilities for risk events

We can observe that the model predicts a higher probability of 88% for 'Organisation and its ineffectiveness' being false for 'project 2' which is a successful project. The probability for 'Organisation and its ineffectiveness' being false drops to 29% for 'project 1' which is an unsuccessful project. Similarly the model predicts a higher probability of 90% for 'Poor design solution' being false for 'project 1' and this drops to 35% for 'project 2'.

The model's predictions for 'consequences level 1' and 'consequences level 2' are showed in Figure 6.14.





The predictions for 'consequence level 1' are pretty good. Small inaccuracies and reasons for this are same as in the previous case and they are due to:

- Projects were different in nature, had different sizes and were done in a different environment to the original project for which the model was built.
- There were certain risk events that were not at all relevant; for example, 'Lack of programme commitment' and 'Inadequate business environment'.

The predictions for 'Project failure' are very good. The model predicts there is a 59% probability that 'project 1' will be failure and a 69% probability that 'project 2' will be a success.

6.7 CRRM Ease of Use and Tailoring

The model (Figure 6.3) is easy to use and it is possible for the project manager to go directly to the Risk Table and enter observations for all the nodes. The Risk Table is more like a questionnaire and it is useful for entering many observations at once. A sample risk table is shown in Figure 6.15. In addition, the model can still be easily tailored to different projects.

	Support
Triguese	
Post materian	the bolt and
Post instruments	
Dislocation from companie	Di Attanti
Exclusion objections and clear	No Alterna
Inshifts in franze design early	The Articleum
Technical newty	No Avenue
Poer management	Di Colori
Poor initial requirements	The Annual
Lack of raport with the client	Ba Antone
Poor concurrent engineering strategy	Ro Antoni
Poer change control	By Annual
Poor build strategy	Its Attack
Important overriden by urgent	Ra Antiver
Dependence on supplier deliveries	Ro Artivel
Especially complex requirements	The ADDIVITY
Poer image and PR	Its Annual
Share price performance low	Ra Annum
Inadequate testing and Irials	No Alterna
Rapidly changing technologies	Its Anti-ent
Small budget plan for order book	Ra Annuer
Poer cash flow analysis	Ba Antone
	Scenato 1
Risk events	
Poor staff performance	the Annual
Organisation and its ineffectiveness	Its Annual
Poor design solution	No Avenue
Requirements creep	Ina Anawer

Figure 6.15 CRRM Risk Table

The managers with a non-mathematical background can easily tailor the model to different projects. Trigger and control events don't have any parents and they are Boolean nodes. Therefore it is easy to change their priors in accordance with different projects (Figure 6.16).

2	Node Probabi	lity Table	
Node Details	NPT Editing Mode	Manual 👻	
	False	0.75	
	True	0.25	
Node States			
#			

Figure 6.16 Example NPT for root node 'Poor training scheme'

A CRRM is created for a specific company. If we want to have a more general model, we could define the probability for all triggers and all controls as P('True') = 0.5 and P('False') = 0.5. In this case, project managers can enter priors directly into the risk table as soft evidence (Figure 6.17) and there is no need to change the NPTs.

Hisk Scenarios	G
Rick Map Rick Table	
	Scenario 1
Triggers .	
- Pour methyation	Buff Cyldense w
GPTM / Poor multivation / Observation	
Hew Notio	
0.0 944	1

Figure 6.17 Soft evidence example

As mentioned in section 6.4 noisyor expression involves constants. This enables the user to change the weighting directly from the risk table (Figure 6.18) without the need to access and change NPTs.

	Fish Map Fish Table	
۵	Risk events Poer staff performance	na Annon 🔹
2	Organisation and its ineffectiveness	Ra Antana 🗸 🗸
J	org_bodf_bus_obj_const CERtALLOrganization and to contractive tracking to org_bodf_bus_obj_const	
	org_inett_distoc_cor_const	
	GMMM / Departure and to instruction and / Constant for org_hruff_dolor_cor_content	
	org_ineff_poor_mog_const CRRMI Diglocation and REINSTRICtoneers (Declare the org_ineff_poor_mog_const	

Figure 6.18 Constant example

6.8 CRRM Features

The causal taxonomy approach satisfies the minimalist requirements described by Chapman and Ward in [34] where they recommend that any approach to risk quantification:

"should be so easy to use that the usual resistance to appropriate quantification based on lack of data and lack of comfort with subjective probabilities is overcome".

Moreover, the approach ensures that:

- A project manager can easily change priors for triggers and controls, either by directly changing NPTs or by entering soft evidence into the risk table.
- Every aspect of risk measurement is meaningful in the context the risk map tells a story that makes sense. This is an improvement on "risk = probability x impact" approach where not one of the concepts has a clear unambiguous interpretation.

- Every aspect of uncertainty is fully quantified since at any stage we can simply read off the current probability values associated with any event.
- It provides a visual and formal mechanism for recording and testing subjective probabilities. This is especially important for a risk event about which you do not have much or any relevant data.
- Enables us to perform trade-off analysis.
- Provides an overall risk 'score' in terms of 'Project failure'.
- Prioritisation of risk events can be achieved in ways that are much more meaningful and rigorous. For example, we could:
 - Simply read off the marginal probability values for each risk event given your current state of knowledge. This will rank the risks in order of probability of occurrence. (This tells you which are most likely to happen given your state of knowledge of controls and triggers);
 - Set the value of each risk event in turn to be true and read off the resulting probability values of the appropriate consequence nodes. This will provide the probability of the consequence given that each individual risk definitively occurs. The risk prioritisation can then be based on the consequence probability values.
 - Introduce 'dashboard' type features by identifying key consequences, setting thresholds below which they should not fall and then building traffic light components based around that.

6.9 Further enhancements to the model

In organisations where risk is treated seriously, at the start of every project, project managers discuss and list risks. Hence, most such projects will have a risk register. As discussed in section 2.7.2 when creating a risk register, we first identify risks. Then we give each risk a probability and the impact it can have. At the end, we add up all the risks to get the risk score. The more the risk register expands, the more the risk score increases and the more the manager thinks that the overall probability of the project failing increases. This is the paradox. The fact is that at the start of the project, the process of identifying risks cannot possibly increase the risk of the project failing.

This is supported by classical subjectivist view of the probability. Suppose you ask your friend Naomi to roll a die without letting you see the result, but before she rolls it you have to answer the following:

Question 1: What is the probability the number rolled will be a 4?

Having rolled the die Naomi must write down the number rolled on a piece of paper (without showing you) and place it in an envelope.

Now answer:

Question 2: What is the probability the number written down is a 4 (i.e. was the number rolled a 4)?

From your perspective it is rational to answer 1/6 in both cases. If Naomi informs Hannah that the number written down is even, then the rational answer to Question 2 from Hannah's perspective is 1/3. So different information about the same unkown event can rationally lead to different subjective probabilities about that event. But from Naomi's perspective there is no uncertainty at all about the event. The answer to question 2 is either 1 (if it is a 4) or 0 (if it is not) and it is this situation that leads (wrongly) to the 'no such thing as probability' argument. This argument says that there is no uncertainty about the number because it is a 'fact' - it is even written down (and is known to Naomi). But, if YOUR knowledge about the number after it is thrown (i.e. if you are not Naomi or even Hannah) is as incomplete as it was before, then your uncertainty about it remains the same. Hence it is irrational to argue that the probability has changed from your perspective.

For example, we could look at the probability of a terrorist attack from two perspectives [2]; the perspective of a random school child and the perspective of an MI5 officer. Imagine they were both given authority to make decision about the risk of a terrorist attack. We can say that what is known to the decision maker in the first case will be less than what is known to the decision maker in the second case (at least we hope this would be the case). However, the probability of the terrorist attack is clearly independent of probability assign to it by decision makers.

Therefore, the key in this example is that the probability of the 'terrorist attack' is the same in both cases. This probability does not change. What changes is that the random school child will probably know less 'known terrorist groups' than the MI5 officer who will hopefully know more. The fact that the MI5 officer will simply list many more 'known terrorist groups' does not increase the probability of a 'terrorist attack'. Hence, the prior for 'terrorist attack' should not change, because what changes is only our knowledge about the risks and not the risks themselves. Following the risk register approach, the random school child and the MI5 officer would end up with two different risk scores. The MI5 officer would end up with a higher risk score, because he would simply list many more terrorist groups; and the random school child

would end up with a lower risk score, because he/she would list less terrorist groups. This is the paradox.

However, there has been little discussion about this paradox. Therefore, we need a new approach to improve risk classification. The key point is that in the beginning when we do a risk assessment, the probability of a project failing does not change. However, the probability margins between the known knowns and the known unknown are probably different. This is the key technical point that most project managers miss out on. We will discuss risk classification more in the next section.

6.9.1 The Risk Classification Framework

The United States military was the first one to use the term 'unknown unknowns'. The earliest use comes from a paper entitled 'Clausewitz and Modern War Gaming: losing can be better than winning' [68]. Almost a decade later, the software engineering community has adopted the term and used it as basis to propose one of the ways to classify risks. A 1993 paper by Carnegie Mellon's Software Engineering Institute proposed grouping risks into three basic categories. Risks can be known, unknown or unknowable. "Known risks are those that one or more project personnel are aware of – if not explicitly as risks, at least as concerns. The unknown risks are those that would surface (i.e. become known), if the project personnel were given the right opportunity, cues, and information. The unknowable risks are those that, even in principle, "none could foresee." [169] In 1997 Chapman and Ward's [32] text book on project management adopted this approach of classifying risk. In 2002 Donald Rumsfeld [165], the American secretary of defence at the time, was ridiculed by media for his famous 'known unknowns' remark, then defended as clear. Media coverage did not reveal he was simply quoting accepted project management theory.

Most commonly used standards for project risk management in organisations e.g. Project Management Institute, Project Management Body of Knowledge, Chapter 11 [151], UK Association for Project Management Project Risk Analysis and Management (PRAM) Guide [7], AS/NZS 4360 Standard [9]; do not at all mention known, unknown and unknowable risk. The World Economic Forum 2006 [179] Global risk report's suggestion is to classify risks into three categories: known, unknown and unknowable. Clearly there are ambiguities here; the cases of tsunamis, hurricanes, the severity of an epidemic, terrorism attacks are a few to mention.

Let us take, for example, the terrorist attacks in the United States on September 11th 2001. Here we can identify the risk event as "Terrorists hijack and crash large civilian aircraft into major buildings". The question now is whether this risk event was known, unknown or

unknowable. We can certainly say that it was definitely not an unknowable risk event, because there were many examples before whereby terrorists have hijacked planes. The real question is whether this risk event was known or unknown. We are not able to answer this question using the classification framework proposed in 1993 and still in use. The reason for this is that the risk event in question was known to the US intelligence, but it was unknown to the key decision makers at the time. Using this example we can clearly see what is wrong with the risk classification framework currently in use. It fails to account for information and knowledge available to particular decision makers.

Part of the initial purpose of our new risk classification framework was to define known, unknown and unknowable in more detail and to provide simple descriptions and terminology to fit these ambiguities. The key is that these ambiguities do not fit in the World Economic Forum 2006 Global risk report framework, because the risk event from the above example is not just unknown. Generally speaking people knew about it, but the problem was that at the time decision makers did not know. Hence, in our new risk event classification framework, we will introduce this new idea of the decision maker and the information and knowledge available to them (Table 6.12).

There are known knowns; these are things we know we know. A known known is when we know the risk and we have seen it happen sufficiently many times before. Hence, we are able to make an empirical probabilistic judgement of the risk occurring and its consequence. We also know there are known unknowns; that is to say we know there are some things we do not know. A known unknown is when we know the risk event, but we have rarely observed it or we have never had the opportunity to observe it. Hence, we can only make a subjective probabilistic judgement about it and we are not able to make an empirical probabilistic judgement. Hence, the probability of the risk occurring and its consequence is based only on our subjective probabilistic judgement.

Level observation of known risk events Decision maker knowledge of risk event	Risk event observed sufficiently many times to make an empirical probabilistic judgement or subjective judgement	Rarely or never observed risk event and it is only possible to make subjective judgement
Risk event known to decision maker	Known known	Known unknown
Risk event unknown to decision maker	Unknown known	Unknown unknown

Table 6.12 Risk classification framework

The key concept we introduce in our framework is the decision maker knowledge of the risk event. It is possible for both risk groups, known knowns and known unknowns, to be known to the decision maker or not to be known to the decision maker. If a known known is not known to the decision maker than it is unknown known from the decision maker's point of view. If a known unknown is not known to the decision maker then it is an unknown unknown.

The unknowable risks are those ones we don't know we don't know. Which means there are facts that are unknown by anyone and others that will never be known. These are not worth addressing in this thesis since it is impossible to quantify them and hence we omitted them from our new risk classification framework.

6.9.2 The Risk Classification Framework Example

We can use the example of a submarine to demonstrate our new risk classification framework (Table 1). In 2010 'Attack by submarine' is a known known risk event to any competent naval officer since it has been used sufficiently many times during the wars until today for the decision maker to be able to make an empirical probabilistic judgement about it. The same risk event would be an unknown known to any incompetent naval officer who because of his incompetence would not be able to identify 'Attack of submarine' as a risk event and consequently would not be able to make an empirical probabilistic judgement about it.

In 1776, during the American Revolution, 'Attack by submarine' was a known unknown risk event for the American army. The reason for this is that the concept of a submarine existed.

The fact that it had not been used in warfare before meant that the decision makers at the time were not able to make an empirical probabilistic judgement. However, they were still able to make a subjective probabilistic judgement about it. Since the decision makers were able to make a subjective judgement about the risk event, we can put the above risk event into the known unknown category.

The first published description for the submarine was in 1578. William Bourne, a former Royal Navy gunner, designed a completely enclosed boat that could be submerged and rowed beneath the surface. His creation was a wooden framework bound in waterproofed leather. It was to be submerged by using hand vices to contract the sides and decrease the volume. In 1776, the submarine was used in warfare for the first time. Because of this we can say that before 1776 'Attack by submarine' was an unknown unknown risk event.

The key to improving the risk register is using our new risk classification framework and looking at how dividing line between the known knowns, known unknowns, unknown knowns and unknown unknowns changes. As the project progresses what changes is our knowledge about risks and not the risk events themselves. What is a known unknown can become a known known. In some situations, the list of things that are known knowns and known unknowns can be altered. There are some things that could be known knowns, but sometimes the costs of knowing them may exceed the potential benefits. Risk management in general tries to shift risks that are considered known unknowns into the category of known knowns and tries to mitigate the costs associated with things that remain known unknowns. Known unknowns can appear at any time during the execution of the project. We need to create a strategy to deal with such possibilities.

The real dilemma is what to do with risks that seem unknowable. In a crisis, information inevitably will be highly imperfect. The very nature of a crisis means that the ratio of the unknown and unknowable will be especially large relative to the known, and this, in turn, can influence how decision makers judge risks. It is important to mention that the only way for the overall probability of failure to change is if an unknowable risk becomes at least an unknown unknown.

The challenge is how to complete priors for this type of model. Maybe it would be possible to elicit them from experienced managers. We would have to ask them to say something about what they don't know. An unknowable risk cannot be modelled. The only way to incorporate unknowable risks is to add additional nodes when unknowable risks become at least unknown unknowns. Hence, in terms of quantitative project risk management, it would be possible to concentrate on known knowns and known unknowns. Ideally what we would like to achieve in a model is to somehow automatically change between known knowns and known unknowns without changing the overall probability. This complex causal relationship is important, but it is beyond the scope of this thesis.

6.10 Summary

The new Causal Risk Register Model discussed in this chapter applies risk framework developed in chapter 5. The model is developed based on top level risks provided by an international leading defence company. The internal and external validation performed on the CRRM showed its great potential in providing useful information for project risk assessment. The model provides reasonable explanations in a number of different scenarios. We identified some issues and possible future improvements notably the risk classification framework. The next chapter discusses the extension to the model in order to explicitly address project trade-offs.

7. Generic Trade-off Model

In chapter 4 we provided examples of previous BN models and how they indirectly addressed trade-offs. The Causal Risk Register Model developed in chapter 6 also addresses trade-offs indirectly. Therefore, this chapter focuses on extending the Causal Risk Register Model with a sub-model able to explicitly model trade-offs. The Generic Trade-off Model considers the trade-offs that may be made during a project, specifically time, cost and quality. For example, if asked to estimate the probability of a project overrunning by various lengths of time, a manager may respond by contending that such a risk can be reduced to virtually zero if he is given a larger budget. This implies that, in such a case, there is a trade-off between the time and the cost.

Novel contributions of this chapter include a list of assumed rules that satisfy project trade-offs and reflect relationships between key project variables and the BN model that satisfies all the assumed rules identified. The Generic Trade-off Model is one of the main contributions to the whole thesis. **The earlier version of this work has been published [64].**

7.1 The Project Trade-offs

As mentioned in section 2.5, successful project risk management attempts to control resources within the constraints of time, cost and quality. In the traditional cost, time and quality model; quality is a euphemism for the features of the end project which is delivered. This clearly has two attributes: functionality (amount of useful features delivered to end users) [107] and product quality (how good is the product delivered) [104]. Clearly it is possible to deliver less or more functionality; and lower or higher product quality. This breakdown of quality is really important, since it brings the causal aspect into the model. In addition, we introduce a new dimension – process quality (how good is the process during delivery). This is important because from a risk management perspective this is something the project manager can control/improve.

For the purpose of assumed rules simplification, we have grouped cost and time into resources. If cost and time are observed independently, then anything that applies to resources applies to cost and time. The model itself preserves cost and time separately; considers process quality and both attributes for quality.

Trade-offs are always determined by the constraints of the project. The types of constraints commonly imposed are illustrated in Table 7.1 [97]. Situations with one or two elements fixed at a given time are the typical trade-offs encountered in project management. Situations where three elements are fixed or variable portray some research and development projects. The quality of research and development projects, for example, is usually well defined,

and it is cost and time that may be allowed to go beyond budget and schedule. The decision on which element to sacrifice is based on the available alternatives.

Time	Cost	Quality
One element fixed at the	time	
Fixed	Variable	Variable
Variable	Fixed	Variable
Variable	Variable	Fixed
Two elements fixed at the	e time	
Fixed	Fixed	Variable
Variable	Fixed	Fixed
Fixed	Variable	Fixed
Three elements fixed or w	variable	
Fixed	Fixed	Fixed
Variable	Variable	Variable

Table 7.1 Trade-off constraints categories [97]

Most capital equipment projects will eventually reach a stage where time is of the essence, i.e. time is fixed and cost and quality are variable. The sooner the piece of equipment gets into production, the sooner the return on investment can be realised. In addition markets are entered early and it is possible to grow those markets quickly. In pharmaceutical product development, the Tufts Centre for the Study of Drug Development estimates an average of \$30 000 in direct costs is added for each day's delay [70]. Often performance constraints exist which determine the profit potential of the project. If the project potential is determined to be great, after all the constraints have been considered, cost will be the slippage factor hence time and performance will be fixed whereas cost will be variable.

Non-process-type equipment, such as air pollution control equipment, usually result in the situation where time is variable and cost and quality are fixed. Quality is fixed by the Environmental Protection Agency. The deadline for compliance can be delayed through litigation, but if the lawsuits fail, most firms then try to comply with the least expensive equipment that will meet the minimum requirements.

Professional consulting firms operate primarily with fixed time and cost constraints and variable quality constraints. In the situation where all three elements are fixed there is no room for error as none of the elements can be changed yet the project is managed with a view to success; if all elements are variable, there are no constraints and thus no trade-offs.

7.2 Assumed rules for Generic Trade-off Model

Before discussing the assumed rules we make a number of simplifying assumptions:

- Cost and time are combined into resources in order to keep the assumed rules simple. Resources represent total effort allocated for a project.
- 2. Quality is separated into:
 - a) process quality overall measure of process quality aggregating various organizational factors,
 - b) functionality size or quantity of a product,
 - c) product quality how good the delivered product is.

With these assumptions, we propose the following assumed rules summarised in Table 7.2.

Assumed	Observed	Expected	
rule No.	variables*	outcome*	
1	if R↑	then F^{\uparrow} or Q^{\uparrow}	
2	if P↑	then F^{\uparrow} or Q^{\uparrow}	
3	if F↑	then $P\uparrow$ or $R\uparrow$	
4	ifQ↑	then P^{\uparrow} or R^{\uparrow}	
5	if $F\uparrow$ and $R=$	then P [↑] or Q [↓]	
6	if F↑ and P=	then R [↑] or Q [↓]	
7	if Q^{\uparrow} and $R=$	then P \uparrow or F \downarrow	
8	if Q↑ and P=	then R \uparrow or F \downarrow	
* 'R' – resources, 'P' – process quality,			
F' – functionality, Q' – project quality			
' \uparrow ' – increase, ' \downarrow ' – decrease, '=' – no change			

Table 7.2 Summary of assumed rules in project management

Assumed rule 1. If the only information that we have about the project is that the resources have increased (i.e. more time and budget allocated to the project), then it is reasonable for us to expect that either the functionality delivered and/or the product quality will increase.

Assumed rule 2. If the only information that we have about the project is that the process quality has increased, then it is reasonable for us to expect that either the functionality delivered or the product quality will increase.

Assumed rule 3. If the only information that we have about the project is that the functionality delivered has increased, then it is reasonable for us to expect that this increase was an effect of the increase in either the process quality and/or the resources being allocated to the project.

Assumed rule 4. If the only information that we have about the project is that the project quality has increased, then it is reasonable for us to expect that this increase was an effect of the increase in either the process quality and/or the resources being allocated to the project.

Assumed rule 5. If the functionality delivered increases and if the resources being allocated for the project remain unchanged, then it is reasonable for us to expect either:

- 1) If the process quality increases the project quality remains unchanged.
- 2) If the process quality remains unchanged the project quality will decrease.

Assumed rule 6. If the functionality delivered increases and if the process quality remains unchanged, then it is reasonable for us to expect either:

- 1) If the resources being allocated for the project increase the project quality will remain unchanged.
- If the resources being allocated for the project remain unchanged the project quality will decrease.

Assumed rule 7. If the quality of the project increases and if the resources allocated for the project remain unchanged, then it is reasonable for us to expect that either:

- 1) If the process quality increases the functionality will remain unchanged.
- 2) If the process quality remains unchanged the functionality will decrease.

Assumed rule 8. If the quality of the project increases and if the process quality remains unchanged, then it is reasonable for us to expect that either:

- Functionality delivered will decrease if the resources being allocated for the project remain unchanged.
- If functionality delivered remains unchanged then the resources being allocated for the project will increase.

While these assumed rules are uncontroversial, it turns out that it is remarkably difficult to construct a causal BN model in which they are all satisfied. A major challenge therefore was to consider how and why previous attempts failed to preserve all the assumed rules and how we built a model that satisfied them.

7.3 Issues arising from model development

7.3.1 Modelling trade-off based on SIMP model

Initially we looked at the SIMP model discussed in chapter 4. We concentrated on percentage increase or decrease in cost, schedule and performance based on the risk score. The reason being, as previously mentioned in chapter 4, the project manager can determine percentage increase or decrease when analysing the trade-off between budget and time. Therefore in order to

build our model, we tried to improve the original SIMP model. To be able to use the SIMP model more generally in the core of it we distinguished four nodes: *Risk Score, Actual Resources, Quality Produced* and *Functionality Delivered*; as shown in Figure 7.1.



Figure 7.1 Initial core of the SIMP model

For example, when risk increases quality and functionality decrease. At the moment the model in Figure 7.1 does not predict this correctly since there is no link between functionality and quality. This link is crucial for the assumed rules to be satisfied. Hence, we have introduced it in our model (Figure 7.2).



Figure 7.2 Improved core of the SIMP model

Details of the nodes in the model are as follows:

- *Risk score*. This node summarizes all risks into one score. The node type is discrete real. It has a numeric value in the range from -5 to 5. This range allows risks to be positive and not only negative things in the model.
- *Actual Resources.* This node represents available resources. The node type is a continuous interval. It has a numeric value in the range minus infinity to plus infinity.
- *Quality Produced.* This is the extent to which the quality delivered in the final project satisfies the project specification. This node has three parents *Risk Score, Actual Resources* and *Functionality Delivered.* The node essentially takes account of the impact of the three parents onto the final *Quality Produced.* The node type is continuous interval. It is calculated using the normal distribution and its value is numeric in the range minus infinity to plus infinity.
- *Functionality Delivered.* This is the extent to which the functionality delivered in the final project satisfies the project specification. This node has two parents: *Risk Score* and *Actual Resources.* The node essentially takes account of the impact of the two parents onto the final *Functionality Delivered.* The node type is continuous interval. It is calculated using the normal distribution and its value is numeric in the range minus infinity to plus infinity.

The problem with this model is when for example we know there are a lot of risks and *Risk Score* value increases; both *Quality Produced* and *Functionality Delivered* decrease. It is only when we fix either variable at nominal i.e. zero, the decrease in the other variable is worse. This leads us to another problem, for example, if we put that *Functionality Delivered* is zero, then the model assumes that this affects *Quality Produced*, as well as *Actual Resources*. Hence, both *Actual Resources* and *Quality Produced* decrease. This means we have to fix *Actual Resources* as well for the model to work. From this we see that the model only works if *Actual Resources* and either *Quality Produced* or *Functionality Delivered* are fixed.

We tried to solve our problem by introducing the delta function. The delta represents percentage change in the model. For example consider the situation in Figure 7.3.



Figure 7.3 Delta function segment

The delta represents proportional change in *Resulting functionality* given *Risk score*. The delta function was a good idea when applied to one node or maybe even two nodes. The problem emerged when we tried to apply it to all four nodes in our model. The model became complicated and we concluded that the delta function was not the simple solution we were looking for.

7.3.2 Revised SIMP trade-off model

In the revised model we made the following changes:

- Instead of 'Risk score' we introduced 'Process quality'.
- 'Process quality' and 'Resources' are combined into 'Effective resources'.
- 'Quality' and 'Functionality' have only one parent and that is 'Effective resources'.
- We introduced a constraint node which we called '*balanced f and q*'. In essence, the normal constraint is that this node is set to '*balanced between attributes*' and this means that we expect there to be a balance between functionality and quality. Please note that the observation entered for the node *balanced f and q* is *both attributes*. This is done because as said earlier we expect to have a balance between functionality and quality. This observation shouldn't be changed when you run the model.



Figure 7.4 Revised generic trade-off model

Details of the nodes in the revised model are as follows:

- *Process quality.* This node represents the quality of all processes. The node type is ranked. It has a 7 point scale: lowest, very low, low, medium, high, very high and highest.
- *Resources.* This node represents available resources. The node type is ranked and it has a 7 point scale.
- *Effective resources.* This node is simply a weighted average of *process quality* and *resources.* The node type is ranked and it has a 7 point scale.
- *Quality.* This node represents the quality produced. It is proportional to *effective resources*. The node type is ranked and it has a 7 point scale.
- *Functionality*. This node represents the functionality delivered. It is proportional to *effective resources*. The node type is ranked and it has a 7 point scale.
- *Balanced f and q*. This node is simply the average of quality and functionality. The node type is ranked. Possible observations you can enter are: neither attributes, balanced between attributes, both attributes. In order to satisfy our requirements, this node is set to balanced between attributes.

The revised SIMP trade-off model works when the node *balanced* f and q is set to *balanced between attributes* and it is possible to put constraints on one or two attributes and have

the model predict the third one. For example, if you know you have high resources you can have the model predict what quality and functionality you can expect. You can also put constraints on two nodes, for example, if you know you have medium resources and you want high quality, you can get the model to predict what will happen with functionality.

7.3.3 Internal Validation

This section explores different scenarios of the revised SIMP trade-off model. The main objective is to establish whether the model satisfies all the assumed rules and therefore is suitable for trade-off analysis. By entering various evidence (observations) to the model, it is possible to analyse project trade-offs from different aspects and in comparison to the 'Nominal' scenario. Our 'Nominal' scenario is when we run the model where 'balanced f and q' is set to 'balanced between attributes' and no other evidence is entered into the model.

Assumed rule 1. This assumed rule is indicative of a case where a project manager has the 'highest' resources to deliver a project. The model predicts that for such a project the functionality will increase (Figure 7.5 a) or the quality will increase (Figure 7.5 b).



Figure 7.5 Predicted probabilities for Assumed rule1

Assumed rule 2. This assumed rule is indicative of a case where a project manager has the 'highest' process quality to deliver a project. The model predicts that for such a project the functionality will increase (Figure 7.6 a) or the quality will increase (Figure 7.6 b).



Figure 7.6 Predicted probabilities for Assumed rule 2

Assumed rule 3. This assumed rule is indicative of a case where a project manager wishes to find an answer on: How to deliver the 'highest' functionality in a project? The model predicts that for such a project there has to be an increase in the process quality (Figure 7.7 a) or an increase in the resources (Figure 7.7 b).



Figure 7.7 Predicted probabilities for Assumed rule 3

Assumed rule 4. This assumed rule is indicative of a case where a project manager wishes to find an answer on: How to deliver the 'highest' quality in a project? The model predicts that for such a project there has to be an increase in the process quality (Figure 7.8 a) or an increase in the resources (Figure 7.8 b).



Figure 7.8 Predicted probabilities for Assumed rule 4

Assumed rule 5. This assumed rule is indicative of a case where a project manager has to deliver the 'highest' functionality in a project, but he cannot afford an increase in resources. The model predicts that for such a project there has to be an increase in the process quality (Figure 7.9 a) to keep the quality unchanged (Figure 7.9 b) or the quality will decrease if process quality remains unchanged.



Figure 7.9 Predicted probabilities for Assumed rule 5

Assumed rule 6. This assumed rule is indicative of a case where a project manager has to deliver the 'highest' functionality in a project, but he cannot afford an increase in process quality. The model predicts that for such a project there has to be an increase in the resources (Figure 7.10 a)
to keep the quality unchanged (Figure 7.10 b) or the quality will decrease if resources remain unchanged.



Figure 7.10 Predicted probabilities for Assumed rule 6

Assumed rule 7. This assumed rule is indicative of a case where a project manager has to deliver the 'highest' quality in a project, but he cannot afford an increase in resources. The model predicts that for such a project there has to be an increase in the process quality (Figure 7.11 a) to keep the functionality unchanged (Figure 7.11 b) or the functionality will decrease if process quality remains unchanged.



Figure 7.11 Predicted probabilities for Assumed rule 7

Assumed rule 8. This assumed rule is indicative of a case where a project manager has to deliver the 'highest' quality in a project, but he cannot afford an increase in process quality. The model

predicts that for such a project there has to be an increase in the resources (Figure 7.12 a) to keep functionality unchanged (Figure 7.12 b) or the functionality will decrease if resources remain unchanged.



Figure 7.12 Predicted probabilities for Assumed rule 8

Based on internal validation we can conclude that revised generic trade-off model overall performs well. In some cases, for example Assumed rule 1 movements are not as high as expected, but the model does indicate movement in the right direction. Main drawbacks of the model are:

- Need to fix the 'balance f and q' node.
- The cost and time are combined into resources, therefore the model does not preserve them separately.

In the next section we present final generic trade-off model that solves the problem in a much more practical way.

7.4 Overview of the Generic Trade-off model

The BN used to model project trade-offs is shown in Figure 7.13. The main goal for the Generic Trade-off Model was to develop a conceptual model which contains only the lowest possible set of variables and satisfies the assumed rules discussed in the previous section in order to improve project risk assessment in comparison to the previous models discussed in chapter 4. Table 7.3 summarizes the model variables for the BN.



Figure 7.13 Generic Trade-off Model

Name	Туре	Description						
Cost	2 A	This node represents cost of a project. It leads						
		to resources.						
Schedule		This node represents schedule of a project. It						
		leads to resources.						
Process Quality	Ranked	This node represents level of process quality.						
	Kalikeu	It leads both to quality and functionality.						
Resources		This node represents total resources available						
		for a project.						
Quality		This node represents total product quality.						
Functionality		This node represents total project						
		functionality.						
Percent on	Continuous interval	This is a dummy node that represents						
quality		percentage of resources spent on quality. It						
		leads to both quality and percentage spent on						
		functionality.						
Percent on		This is a dummy node that represents						
functionality		percentage of resources spent on						
		functionality. It leads to functionality.						
Prod_prior_ratio		This is a dummy node that calculates ratio of						
		functionality and product quality.						
Functionality_B		This is an input node that is linked to						
		'Required functionality missing' output node.						
Product		This is an input node that is linked to 'Poor						

quality_B	Continuous interval	product quality' output node.					
Schedule_B		This is an input node that is linked to					
		'Schedule overrun' output node.					
Cost_B		This is an input node that is linked to 'Project					
		overspent' output node.					
Process quality_B		This is an input node that is linked to 'Poor					
		process quality' output node.					

Table 7.3 Variables in Generic Trade-off Model

The BN shown in Figure 7.13 is best thought of as consisting of three fragments. Fragment 1 contains the trade-off nodes (Figure 7.14). 'Available cost' and 'available schedule' determine 'Resources', which represent the total effort allocated for a project. Increase or decrease in 'available cost' and 'available schedule' influence 'Resources' in equal measure. 'Resources' are calculated using the formula in Equation (7-1)

Resources = TNormal (wmean (1.0, cost, 1.0, schedule), 5.0E-3)(7-1)

The TNormal expression has a mean that is the weighted mean of 'available cost' and 'available schedule', which both carry equal weighting in this expression, with a variance of 5.0E-3. 'Resources' in turn influence both 'Quality' and 'Functionality'. Hence, for example an increase in 'available cost' would lead to an increase in 'Resources' which in turn would lead to an increase in 'Quality' and 'Functionality'.



Figure 7.14 Fragment 1- Trade-off nodes

Quality is separated into:

- a) 'Process quality' which represents the overall measure of process quality aggregating various organizational factors. The value of the 'Process quality' is just the 'Poor process quality' value from the Causal Risk Register Model. 'Process quality' influences both 'Quality and 'Functionality'. High 'Process quality' means high 'Quality' and 'Functionality'.
- b) 'Quality' represents how good the delivered product is. 'Quality' is influenced by 'Process quality', 'Resources' and 'percent on quality'. We will discuss 'percent on quality' more in Fragment 2. 'Quality' is calculated using the formula in Equation (7-2).

```
Quality =
```

TNormal (wmean (1.0, percent_quality/100, 1.5, pq, 1.5, res), 0.05) (7-2)

c) 'Functionality' represents the size or quantity of a product. 'Functionality' as well as quality is influenced by 'Process quality', 'Resources' and naturally 'percent on func'. We will discuss 'percent func' in Fragment 2. 'Functionality' is calculated using the formula in Equation (7-3).

Functionality =

TNormal (wmean (1.0, percent_func/100, 1.5, pq, 1.5, res), 0.05) (7-3)



Figure 7.15 Fragment 2 – Percentage nodes

Fragment 2 contains the "percentage" nodes that are lightly shaded in Figure 7.15. There are two "percentage" nodes and they are dummy nodes in the BN model. It is impossible to build the model satisfying all the assumed rules without introducing the "percentage" nodes. It is reasonable to assume if resources need to be divided between quality and functionality then there should be an equitable distribution of resources. The model shown in Fragment 1 works based on this principle. The problem arises when we would like to specify that we want to spend more resources on, for example, quality. Therefore, we want to have high quality.

To achieve this it is necessary to introduce "percentage" nodes:

1. 'Percent on quality' represents percentage of resources out of 100% spent on quality. Quality can be viewed as time spent on testing.

2. 'Percent on func' represents percentage of resources out of 100% spent on functionality. Functionality can be viewed as time spent on development.

For any project time spent on development and time spent on testing can be checked from time sheets. Using "percentage" nodes that are hidden from the user is really crucial in making the model work. They allow us to allocate a certain percentage of total resources we would like to spend on quality and functionality. For example, if we would like to achieve very high quality, we may wish to spend 70% of resources on quality. In that case, we have only 30% left for functionality assuming we are not going over resources. Hence, we would have to be satisfied with low to medium functionality. Hence, percentage spent on functionality is calculated using the formula in Equation (7-4).

Percentage spent on functionality =
$$Max(0, 100 - percent_quality)$$
 (7-4)

We are using the maximum arithmetic function and simply saying that the value for functionality is 100% minus the percentage we spent on quality.



Figure 7.16 Fragment 3 – Linked nodes

Fragment 3 contains the "link" nodes that are darkly shaded in Figure 7.16. These nodes are dummy nodes in the BN model. 'Process Quality_B', 'Cost_B' and 'Schedule_B' use constants. They pass values directly from the Causal Risk Register Model from 'Poor process quality' to 'Process quality'; 'Project overspent' to 'available cost' and 'Schedule overrun' to 'available schedule'. We established earlier discussing Fragment 2 that 'percent on func' is dependent on 'percent on quality'. Therefore, 'Product quality_B' and 'Functionality_B' are joined together into 'prod_prior_ratio' that passes value to 'percent on quality' (this sentence doesn't quite make sense). 'Prod_prior_ratio' is calculated using a TNormal expression where 'product quality' is divided by the sum of 'product quality' and 'functionality' with variance 0.1.

7.5 The Object Oriented framework

As mentioned at the beginning of this chapter, the Generic Trade-off Model is an extension to the Causal Risk Register Model. The two models are linked together using an object oriented framework. The AgenaRisk tool provides numerous facilities for building Object Oriented Bayesian Networks (OOBNs). As defined in section 3.4.4, a Bayesian object is a fragment of a BN that encapsulates the internal nodes and is linked to other objects through

interfaces. AgenaRisk provides the easy linking of predefined BNs, forward only inference algorithm and the mixing of discrete and continuous approximation nodes.

Figure 7.13 shows five input nodes (shown by the dashed ellipse: 'Process quality_B', 'Cost_B', 'Schedule_B', 'Product quality_B' and 'Functionality_B'. These nodes take their value from other objects. 'Poor process quality', 'Project overspent', 'Schedule overrun', 'Poor product quality' and 'Required functionality missing' variables from the Causal Risk Register Model are output nodes that send their values to input nodes. Figure 7.17 shows the resulting OOBN.



Figure 7.17 The Generic Trade-off Model using object oriented framework

7.6 Model Validation

7.6.1 Internal Validation

This section explores different scenarios of the revised generic trade-off model. The main objective is to establish whether the model satisfies all the assumed rules and therefore is suitable for trade-off analysis. By entering various observations to the model it is possible to analyse project trade-offs from different aspects and in comparison to 'Nominal' scenario. Our 'Nominal' scenario is when we run the model with no evidence entered into the model.

Assumed rule 1. This assumed rule is indicative of a case where a project manager has the 'highest' resources to deliver a project. The model predicts significant increase in functionality (Figure 7.18 a) and quality (Figure 7.18 b).



Figure 7.18 Predicted probabilities for Assumed rule 1

As mentioned previously cost and time are grouped together into resources in order to simplify the assumed rules. The model preserves cost and time separately. Therefore we observe that if a project manager has 'highest' available cost, the model predicts increase in functionality (Figure 7.19 a) and quality (Figure 7.19 b).



Figure 7.19 Predicted probabilities for Assumed rule 1 when 'Available cost' is highest

As seen in the previous example for available cost, we can in a similar way observe that if a project manager has 'highest' available schedule, the model predicts increase in functionality (Figure 7.20 a) and quality (Figure 7.20 b).



Figure 7.20 Predicted probabilities for Assumed rule1 when 'Available schedule' is highest

Assumed rule 2. This assumed rule is indicative of a case where a project manager has the 'highest' process quality to deliver a project. The model predicts significant increase in functionality (Figure 7.21 a) and quality (Figure 7.21 b).



Figure 7.21 Predicted probabilities for Assumed rule 2

Assumed rule 3. This assumed rule is indicative of a case where a project manager wishes to find an answer on: How to deliver the 'highest' functionality in a project? The model predicts that for such a project there has to be an increase in process quality (Figure 7.22 a) and resources (Figure 7.22 b).



Figure 7.22 Predicted probabilities for Assumed rule 3

Assumed rule 4. This assumed rule is indicative of a case where a project manager wishes to find an answer on: How to deliver the 'highest' quality in a project? The model predicts that for such a project there has to be an increase in process quality (Figure 7.23 a) and resources (Figure 7.23 b).



Figure 7.23 Predicted probabilities for Assumed rule 4

Assumed rule 5. This assumed rule is indicative of a case where a project manager has to deliver the 'highest' functionality in a project, but he cannot afford an increase in resources. The model predicts that for such a project there has to be a significant increase in process quality (Figure





Figure 7.24 Predicted probabilities for Assumed rule 5

Assumed rule 6. This assumed rule is indicative of a case where a project manager has to deliver the 'highest' functionality in a project, but he cannot afford an increase in process quality. The model predicts that for such a project there has to be a significant increase in resources (Figure 7.25 a) to keep quality unchanged (Figure 7.25 b) or quality will decrease if resources remain unchanged.



Figure 7.25 Predicted probabilities for Assumed rule 6

Assumed rule 7. This assumed rule is indicative of a case where a project manager has to deliver the 'highest' quality in a project, but he cannot afford an increase in resources. The model

predicts that for such a project, there has to be a significant increase in process quality (Figure 7.26 a) to keep functionality unchanged (Figure 7.26 b) or functionality will decrease if process quality remains unchanged.



Figure 7.26 Predicted probabilities for Assumed rule 7

Assumed rule 8. This assumed rule is indicative of a case where a project manager has to deliver the 'highest' quality in a project, but he cannot afford an increase in process quality. The model predicts that for such a project, there has to be a significant increase in resources (Figure 7.27 a) to keep functionality unchanged (Figure 7.27 b) or functionality will decrease if resources remain unchanged.



Figure 7.27 Predicted probabilities for Assumed rule 8

7.6.2 External Validation

External validation should be used in combination with internal validation. Projects were chosen based on success and failure factors identified and discussed in sections 2.5 and 2.6. Advantages of external evaluation and using the real life projects are:

- 1. It is possible to convey key information about project.
- 2. Fully depicts client's experience throughout project which represents powerful means to portray project to outsiders.

Disadvantage of this approach is difficulty to generalize from a single successful project observed and a single failed project observed.

Case 1 – External validation for 'company Y'

We observe the model for the scenarios entered for 'company Y' and used for external validation of the CRRM. All parameter passing from CRRM to GTOM is correct (Figure 7.28). 'Project 2' was failure and probabilities for 'consequence level 1' to be 'true' were higher and this is reflected in GTOM. For example, probability for 'Process quality' is lower than average.





Figure 7.28 Parameter passing for 'company Y'

Case 2 – External validation for 'company Z'

We observe the model for the scenarios entered for 'company Z' and used for external validation of the CRRM. All parameter passing from CRRM to GTOM is correct (Figure 7.29). 'Project 2' was a success and probabilities for 'consequence level 1' to be 'false' were higher and this is reflected in GTOM. For example, probability for 'Process quality' is higher than average.





Figure 7.29 Parameter passing for 'company Y'

7.7 Further enhancements to the model

If we want deliberately to focus on 'functionality' or 'quality', then the weighting in the model should be changed. The model could be extended in a way that instead of changing weighting by directly accessing NPTs, we somehow change weighting automatically.

An extension to the Generic Trade-off Model could be finding a way of including reputation in the trade-off model potentially extending quality prediction. We have demonstrated how to solve the problem of cost/schedule/quality trade-offs. The next step could be to address cost/schedule/quality/reputation trade-offs.

7.8 Summary

The Generic Trade-off Model discussed in this chapter is an extension to the CRRM presented in chapter 6. This model focuses explicitly on project trade-offs between time, cost and quality. The model satisfies the assumed rules identified for trade-off analysis. The validation performed on the model showed that the model can be a useful extension to the CRRM, but it can also be a standalone model. This model is especially powerful because it is truly generic and it can be used for a number of various projects. The model has great potential in providing useful information for trade-offs for any project. The model provides reasonable explanations in a number of different scenarios.

8. Conclusions

The main hypothesis stated in chapter 1 was that we can provide an approach and template model that satisfies all of the following requirements needed by decision makers for effective project risk management:

- Able to model and measure trade-offs between time, cost and quality; in such a way as to be able to answer questions such as those provided in chapter 1. Supported by 7.2 and 7.4. A list of assumed rules that satisfy project trade-offs between time, cost and quality has been developed. The assumed rules reflect relationships between key project variables and the Generic Trade-off Model satisfies all the assumed rules identified.
- 2. Able to produce an overall risk score for the project which: a) takes into account the overall success criteria and b) is available at any stage of the project life cycle and not just at the end of the project. Supported by 6.1 and 6.3. The Causal Risk Register Model illustrates how top level risks affect time, cost, quality and consequently project failure at any stage of a project.
- 3. Is dynamic, i.e. able to take into account new information in order to revise its predictions and assessments for the overall risk score. Supported by 7.5. The Generic Trade-off Model is an extension to the Causal Risk Register Model. The two models are linked together using object oriented framework.
- 4. Is able to capture notions of cause and effect such as the possibility of avoiding risks by using controls and mitigants. Ideally also be able to capture opportunities as well as risks since these will have an impact on the overall success of the project. Supported by 5.6, 5.7 and 6.3.
- 5. Able to quantify unavoidable uncertainty in all of this. Supported by 3.3, 3.4, 5.6, 6.3 and 7.4. It was discussed that BNs offer a general and flexible approach for modelling risk and uncertainty. The models developed in this thesis applied BNs to incorporate uncertainty in project risk analysis.
- 6. The approach can be used by practitioners who have no mathematical/statistical background. Supported by 6.7. It is possible to use Risk Table in the Causal Risk Register Model to enter observations and also soft evidence in order to change probabilities for different projects without the need to directly change NPTs.

I claim novelty for the models developed in points 1 and 2. They are a significant improvement on the previous BN models that are already in use in the commercial environment. Although, there is still room for further improvements, I discussed the need to extend the causal risk register to deal with the issue of unknown knowns in 6.8 and the scope for improving the trade-off model in 7.7, I believe that the contributions provided by the new models will lead to a better understanding of project trade-offs between time, cost and quality; better project risk analysis and consequently better project delivery.

The best (and possibly only realistic) way to ensure proper practical use and exploitation of this model is to make it web enabled, with different users having access to the parts of the model relevant to them. Different users would enter evidence into the model on one or more nodes during project duration. This would enable the model to be used for bottom-up as well as top-down reasoning. The users could find out the reasoning behind the model outputs as interactions between variables are clearly displayed. This would provide clarity to users and increase the transparency of project risk management decision making. In addition it may be appropriate to link a database to the system and store different scenarios in order to enhance future forecasts and analysis for different projects. This would show that it is possible to deploy large and complex probabilistic models in practice.

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Appendix A, Risk Factors for Large Projects

Project	t Name for an area in which projects might be done, with risk factors in this table general						
Domain	found in this type of project.						
Factor ID	A sequentially assigned number for risk factors in this domain. When new factors are added, they get the next available sequential number, thus items within a category may not be in numerical order.						
Risk Category	Header that names the category in which the following risk factors belong.						
Risk Factors	Named areas of potential risk to projects in this domain.						
Low Risk Cues	Characteristics of this factor when it can be considered low risk to a project.						
Medium Risk Cues	Characteristics of this factor when it provides a medium risk to a project.						
High Risk Cues	Characteristics of this factor when it should be considered high risk to a project.						
Rating	Level of risk you think is true of this project.						
Low (L)	This project exhibits the low risk cue, or appears to have no risk in this area.						
Medium (M)	This project exhibits the medium risk cue, or something similar in threat.						
High (H)	This project exhibits the high risk cue, or something similar in threat.						
Not Applic (NA)	This factor is not applicable to this project.						
Need Info							
(NI)	We need information from someone else (perhaps an expert) to make a judgment.						
TBD	The project is not far enough along to make a rating; we need to review this later.						
Notes	Space for notes during rating, for later reference on reasons a rating was chosen.						

					Rating (check one)							
Factor	Risk Factors	Low Risk Cues	Medium Risk	High Risk	L	М	H	NA	NI	TBD	Notes	

ID			Cues	Cues			
Mission	1 and Goals						
1	Project Fit to Customer Organization	directly supports customer organization mission and/or goals	indirectly impacts one or more goals of customer	does not support or relate to customer organization mission or goals			
2	Project Fit to Provider Organization	directly supports provider organization mission and/or goals	indirectly impacts one or more goals of provider	does not support or relate to provider organization mission or goals			
3	Customer Perception	customer expects this organization to provide this product	organization is working on project in area not expected by customer	project is mismatch with prior products or services of this organization			
4	Work Flow	little or no change to work flow	will change some aspect or have small affect on work flow	significantly changes the work flow or method of organization			
Progra	m Management (if project is part	of a program)				
5	Goals Conflict	goals of projects within the program are supportive of or	goals of projects do not conflict, but provide little direct support	goals of projects are in conflict, either directly or indirectly			
		complimentary to each other					
----	----------------------------------	--	---	---			
6	Resource Conflict	projects within the program share resources without any conflict	projects within the program schedule resources carefully to avoid conflict	projects within the program often need the same resources at the same time (or compete for the same budget)			
7	Customer Conflict	multiple customers of the program have common needs	multiple customers of the program have different needs, but do not conflict	multiple customers of the program are trying to drive it in very different directions			
8	Leadership	program has active program manager who coordinates projects	program has person or team responsible for program, but unable to spend enough time to lead effectively	program has no leader, or program manager concept is not in use			
9	Program Manager Experience	program manager has deep experience in the domain	program manager has some experience in domain, is able to leverage subject matter experts	program manager is new to the domain			
10	Definition of the Program	program is well-defined,	program is well-defined,	program is not well-defined			

with a scope	but unlikely to	or carries
that is	be handled by	conflicting
manageable by	this	objectives in
this	organization	the scope
organization		

Decision Drivers

11	Political	no particular	project has	project has a
	Influences	politically-	several	variety of
		driven choices	politically	political
		being made	motivated	influences or
			decisions, such	most decisions
			as using a	are made
			vendor selected	behind closed
			for political	doors
			reasons, rather	
			than	
			qualifications	
12	Convenient	date for	date is being	date is being
	Date	delivery has	partially driven	totally driven
		been set by	by need to	by need to
		reasonable	meet marketing	meet
		project	demo, trade	marketing
		commitment	show, or other	demo, trade
		process	mandate not	show, or other
			related to	mandate; little
			technical	consideration
			estimate	of project
				team estimates
13	Use of	technology	project is being	project is
	Attractive	selected has	done in a sub-	being done as
	Technology	been in use for	optimal way, to	a way to show
		some time	leverage the	a new
			purchase or	technology or
			development of	as an excuse
			new	to bring a new

			technology	technology
				into the
				organization
14	Short Term	project meets	project is	project team
	Solution	short term need	focused on	has been
		without serious	short-term	explicitly
		compromise to	solution to a	directed to
		long term	problem, with	ignore the
		outlook	little	long term
			understanding	outlook and
			of what is	focus on
			needed in the	completing
			long term	the short term
				deliverable

Organization Management

15	Organization	little or no	some	management
	Stability	change in	management	or
		management or	change or	organization
		structure	reorganization	structure is
		expected	expected	continually or
				rapidly
				changing
16	Organization	individuals	individuals	many in the
	Roles and	throughout the	understand	organization
	Responsibilities	organization	their own roles	are unsure or
		understand	and	unaware of
		their own roles	responsibilities,	who is
		and	but are unsure	responsible
		responsibilities	who is	for many of
		and those of	responsible for	the activities
		others	work outside	of the
			their immediate	organization
			group	
17	Policies and	development	development	no policies or
	Standards	policies and	policies and	standards, or

		standards are defined and carefully followed	standards are in place, but are weak or not carefully followed	they are ill- defined and unused
18	Management Support	strongly committed to success of project	some commitment, not total	little or no support
19	Executive Involvement	visible and strong support	occasional support, provides help on issues when asked	no visible support; no help on unresolved issues
20	Project Objectives	verifiable project objectives, reasonable requirements	some project objectives, measures may be questionable	no established project objectives or objectives are not measurable
Custon	ners/Users			
21	User Involvement	users highly involved with project team, provide significant input	users play minor roles, moderate impact on system	minimal or no user involvement; little user input
22	User Experience	users highly experienced in similar projects; have specific ideas of how needs can be met	users have experience with similar projects and have needs in mind	users have no previous experience with similar projects; unsure of how needs can be

23	User	users accept	users accept	users do not
	Acceptance	concepts and	most of	accept any
		details of	concepts and	concepts or
		system;	details of	design details
		process is in	system; process	of system
		place for user	in place for	
		approvals	user approvals	
24	User Training	user training	user training	requirements
	Needs	needs	needs	not identified
		considered;	considered; no	or not
		training in	training yet or	addressed
		progress or	training plan is	
		plan in place	in development	
25	User	user	user	no satisfactory
	Justification	justification	justification	justification
		complete,	provided,	for system
		accurate, sound	complete with	
			some questions	
			about	
			applicability	

Project Characteristics

26	Project Size	small, non-	medium,	large, highly
		complex, or	moderate	complex, or
		easily	complexity,	not
		decomposed	decomposable	decomposable
27	Reusable	components	components	components
	Components	available and	available, but	identified,
		compatible	need some	need serious
		with approach	revision	modification
				for use
28	Supplied	components	components	components
	Components	available and	work under	known to fail
		directly usable	most	in certain

met

			circumstances	cases, likely to be late, or incompatible with parts of approach
29	Budget Size	sufficient budget allocated	questionable budget allocated	doubtful budget is sufficient
30	Budget Constraints	funds allocated without constraints	some questions about availability of funds	allocation in doubt or subject to change without notice
31	Cost Controls	well established, in place	system in place, weak in areas	system lacking or nonexistent
32	Delivery Commitment	stable commitment dates	some uncertain commitments	unstable, fluctuating commitments
33	Development Schedule	team agrees that schedule is acceptable and can be met	team finds one phase of the plan to have a schedule that is too aggressive	team agrees that two or more phases of schedule are unlikely to be met
Produc	t Content			
34	Requirements Stability	little or no change expected to approved set (baseline)	some change expected against approved set	rapidly changing or no agreed- upon baseline
35	Requirements Completeness and Clarity	all completely specified and clearly written	some requirements incomplete or	some requirements only in the

			unclear	head of the
				customer
36	Testability	product	parts of	most of
		requirements	product hard to	product hard
		easy to test,	test, or minimal	to test, or no
		plans	planning being	test plans
		underway	done	being made
37	Design	well defined	unclear how to	interfaces not
	Difficulty	interfaces;	design, or	well defined
		design well	aspects of	or controlled;
		understood	design yet to be	subject to
			decided	change
38	Implementation	content is	content has	content has
	Difficulty	reasonable for	elements	components
		this team to	somewhat	this team will
		implement	difficult for	find very
			this team to	difficult to
			implement	implement
			I · · · ·	
39	System	clearly defined	some elements	no clear plan
39	System Dependencies	clearly defined dependencies	some elements of the system	no clear plan or schedule
39	System Dependencies	clearly defined dependencies of the project	some elements of the system are well	no clear plan or schedule for how the
39	System Dependencies	clearly defined dependencies of the project and other parts	some elements of the system are well understood and	no clear plan or schedule for how the whole system
39	System Dependencies	clearly defined dependencies of the project and other parts of system	some elements of the system are well understood and planned; others	no clear plan or schedule for how the whole system will come
39	System Dependencies	clearly defined dependencies of the project and other parts of system	some elements of the system are well understood and planned; others are not yet	no clear plan or schedule for how the whole system will come together
39	System Dependencies	clearly defined dependencies of the project and other parts of system	some elements of the system are well understood and planned; others are not yet comprehended	no clear plan or schedule for how the whole system will come together
39 Deploy	System Dependencies ment	clearly defined dependencies of the project and other parts of system	some elements of the system are well understood and planned; others are not yet comprehended	no clear plan or schedule for how the whole system will come together
39 Deploy 40	System Dependencies ment Response or	clearly defined dependencies of the project and other parts of system readily fits	some elements of the system are well understood and planned; others are not yet comprehended	no clear plan or schedule for how the whole system will come together
39 Deploy 40	System Dependencies ment Response or other	clearly defined dependencies of the project and other parts of system readily fits boundaries	some elements of the system are well understood and planned; others are not yet comprehended operates occasionally at	no clear plan or schedule for how the whole system will come together operates continuously
39 Deploy 40	System Dependencies ment Response or other Performance	clearly defined dependencies of the project and other parts of system readily fits boundaries needed;	some elements of the system are well understood and planned; others are not yet comprehended operates occasionally at boundaries	no clear plan or schedule for how the whole system will come together operates continuously at boundary
39 Deploy 40	System Dependencies ment Response or other Performance Factors	clearly defined dependencies of the project and other parts of system readily fits boundaries needed; analysis has	some elements of the system are well understood and planned; others are not yet comprehended operates occasionally at boundaries	no clear plan or schedule for how the whole system will come together operates continuously at boundary levels
39 Deploy 40	System Dependencies ment Response or other Performance Factors	clearly defined dependencies of the project and other parts of system readily fits boundaries needed; analysis has been done	some elements of the system are well understood and planned; others are not yet comprehended operates occasionally at boundaries	no clear plan or schedule for how the whole system will come together operates continuously at boundary levels
39 Deploy 40	System Dependencies ment Response or other Performance Factors Customer	clearly defined dependencies of the project and other parts of system readily fits boundaries needed; analysis has been done requires little	some elements of the system are well understood and planned; others are not yet comprehended operates occasionally at boundaries	no clear plan or schedule for how the whole system will come together operates continuously at boundary levels
39 Deploy 40 41	System Dependencies ment Response or other Performance Factors Customer Service Impact	clearly defined dependencies of the project and other parts of system readily fits boundaries needed; analysis has been done requires little change to	some elements of the system are well understood and planned; others are not yet comprehended operates occasionally at boundaries	no clear plan or schedule for how the whole system will come together operates continuously at boundary levels requires major changes to

		service	service	service
				approach or
				offerings
40	Data Mianatian	1:441		
42	Data Migration	nutle of no data	much data to	much data to
	Required	to migrate	migrate, but	migrate;
			good	several types
			descriptions	of data or no
			available of	good
			structure and	descriptions of
			use	what is where
43	Pilot Approach	pilot site (or	pilot needs to	only available
	11	team) available	be done with	pilot sites are
		and interested	several sites	uncooperative
		in participating	(who are	or in crisis
			willing) or with	mode already
			one who needs	
			much help	

Development Process

44	Alternatives	analysis of	analysis of	analysis not
	Analysis	alternatives	alternatives	completed, not
		complete, all	complete, some	all alternatives
		considered,	assumptions	considered, or
		assumptions	questionable or	assumptions
		verifiable	alternatives not	faulty
			fully	
			considered	
45	Commitment	changes to	changes to	changes to
45	Commitment Process	changes to commitments	changes to commitments	changes to commitments
45	Commitment Process	changes to commitments in scope,	changes to commitments are	changes to commitments are made
45	Commitment Process	changes to commitments in scope, content,	changes to commitments are communicated	changes to commitments are made without
45	Commitment Process	changes to commitments in scope, content, schedule are	changes to commitments are communicated to all involved	changes to commitments are made without review or
45	Commitment Process	changes to commitments in scope, content, schedule are reviewed and	changes to commitments are communicated to all involved	changes to commitments are made without review or involvement
45	Commitment Process	changes to commitments in scope, content, schedule are reviewed and approved by all	changes to commitments are communicated to all involved	changes to commitments are made without review or involvement of the team

46	Quality	QA system	procedures	no QA process
	Assurance	established,	established, but	or established
	Approach	followed,	not well	procedures
		effective	followed or	
			effective	
47	Development	correct and	some	nonexistent
	Documentation	available	deficiencies,	
			but available	
48	Use of Defined	development	process	no formal
	Development	process in	established, but	process used
	Process	place,	not followed or	
		established,	is ineffective	
		effective,		
		followed by		
		team		
49	Early	peer reviews	peer reviews	team expects
	Identification	are	are used	to find all
	of Defects	incorporated	sporadically	defects with
		throughout		testing
50	Defect	defect tracking	defect tracking	no process in
	Tracking	defined,	process	place to track
		consistent,	defined, but	defects
		effective	inconsistently	
			used	
51	Change Control	formal change	change control	no change
	for Work	control process	process in	control
	Products	in place,	place, not	process used
		followed,	followed or is	
		effective	ineffective	
Develop	pment Environm	ent		
52	Physical	little or no	some	major
	Facilities	modification	modifications	modifications
		needed	needed; some	needed, or
			existent	facilities

4	50	T 1-	:		
:	55	10015	in place,	available,	unvalidated,
		Availability	documented,	validated, some	proprietary or
			validated	development	major
				needed (or	development
				minimal	needed; no
				documentation)	documentation
4	54	Vendor Support	complete	adequate	little or no
			support at	support at	support, high
			reasonable	contracted	cost, and/or
			price and in	price,	poor response
			needed time	reasonable	time
			frame	response time	
4	55	Contract Fit	contract with	contract has	contract has
			customer has	some open	burdensome
			good terms,	issues which	document
			communication	could interrupt	requirements
			with team is	team work	or causes extra
			good	efforts	work to
					comply
4	56	Disaster	all areas	some security	no security
		Recovery	following	measures in	measures in
			security	place; backups	place; backup
			guidelines;	done; disaster	lacking;
			data backed	recovery	disaster
			up; disaster	considered, but	recovery not
			recovery	procedures	considered
			system in	lacking or not	
			place;	followed	
			procedures		
			followed		
Proj	ect	Management (P	M)		
4	57	PM Approach	product and	planning and	weak or
		rpprouon	process	monitoring	nonexistent
			r	B	

nonexistent

		planning and monitoring in place	need enhancement	planning and monitoring
58	PM Experience	PM very experienced with similar projects	PM has moderate experience or has experience with different types of projects	PM has no experience with this type of project or is new to project management
59	PM Authority	has line management or official authority that enables project leadership effectiveness	is able to influence those elsewhere in the organization, based on personal relationships	has little authority from location in the organization structure and little personal power to influence decision- making and resources
60	Support of the PM	complete support by team and of management	support by most of team, with some reservations	no visible support; manager in name only
Team N	Aembers			
61	Team Member Availability	in place, little turnover expected; few interrupts for fire fighting	available, some turnover expected; some fire fighting	high turnover, not available; team spends most of time fighting fires
62	Mix of Team Skills	good mix of disciplines	some disciplines inadequately	some disciplines not represented at

			represented	all
63	Team Communication	clearly communicates goals and status between the team and rest of organization	team communicates some of the information some of the time	rarely communicates clearly within team or to others who need to be informed
64	Application Experience	extensive experience in team with projects like this	some experience with similar projects	little or no experience with similar projects
65	Expertise with Application Area (Domain)	good background with application domain within development team	some experience with domain in team or able to call on experts as needed	no expertise in domain in team, no availability of experts
66	Experience with Project Tools	high experience	average experience	low experience
67	Experience with Project Process	high experience	average experience	low experience
68	Training of Team	training plan in place, training ongoing	training for some areas not available or training planned for future	no training plan or training not readily available
69	Team Spirit and Attitude	strongly committed to	willing to do what it takes to	little or no commitment

		success of	get the job	to the project;
		project;	done	not a cohesive
		cooperative		team
70	Team	all milestones	milestones met,	productivity
	Productivity	met,	some delays in	low,
		deliverables on	deliverables,	milestones not
		time,	productivity	met, delays in
		productivity	acceptable	deliverables
		high		
Techno	ology			
71	Technology	technology	some of the	selected
	Match to	planned for	planned	technology is
	Project	project is good	technology is	a poor match
		match to	not well-suited	to the problem
		customers and	to the problem	or customer
		problem	or customer	
72	Technology	good level of	some	no experience
72	Technology Experience of	good level of experience	some experience	no experience with the
72	Technology Experience of Project Team	good level of experience with	some experience with the	with the technology
72	Experience of Project Team	good level of experience with technology	some experience with the technology	no experience with the technology
72	Experience of Project Team Availability of	good level of experience with technology technology	some experience with the technology experts	no experience with the technology will need to
72 73	Experience of Project Team Availability of Technology	good level of experience with technology technology experts readily	some experience with the technology experts available	no experience with the technology will need to acquire help
72 73	Experience of Project Team Availability of Technology Expertise	good level of experience with technology technology experts readily available	some experience with the technology experts available elsewhere in	no experience with the technology will need to acquire help from outside
72 73	Experience of Project Team Availability of Technology Expertise	good level of experience with technology technology experts readily available	some experience with the technology experts available elsewhere in organization	no experience with the technology will need to acquire help from outside the
72 73	Technology Experience of Project Team Availability of Technology Expertise	good level of experience with technology technology experts readily available	some experience with the technology experts available elsewhere in organization	no experience with the technology will need to acquire help from outside the organization
72 73 74	Technology Experience of Project Team Availability of Technology Expertise	good level of experience with technology technology experts readily available technology has	some experience with the technology experts available elsewhere in organization technology is	no experience with the technology will need to acquire help from outside the organization technology is
72 73 74	Technology Experience of Project Team Availability of Technology Expertise Maturity of Technology	good level of experience with technology technology experts readily available technology has been in use in	some experience with the technology experts available elsewhere in organization technology is well	no experience with the technology will need to acquire help from outside the organization technology is leading edge,
72 73 74	Technology Experience of Project Team Availability of Technology Expertise Maturity of Technology	good level of experience with technology technology experts readily available technology has been in use in the industry for	some experience with the technology experts available elsewhere in organization technology is well understood in	no experience with the technology will need to acquire help from outside the organization technology is leading edge, if not
72 73 74	Technology Experience of Project Team Availability of Technology Expertise Maturity of Technology	good level of experience with technology technology experts readily available technology has been in use in the industry for quite some	some experience with the technology experts available elsewhere in organization technology is well understood in the industry	no experience with the technology will need to acquire help from outside the organization technology is leading edge, if not "bleeding
72 73 74	Technology Experience of Project Team Availability of Technology Expertise Maturity of Technology	good level of experience with technology technology experts readily available technology has been in use in the industry for quite some time	some experience with the technology experts available elsewhere in organization technology is well understood in the industry	no experience with the technology will need to acquire help from outside the organization technology is leading edge, if not "bleeding edge" in
72 73 74	Technology Experience of Project Team Availability of Technology Expertise Maturity of Technology	good level of experience with technology technology experts readily available technology has been in use in the industry for quite some time	some experience with the technology experts available elsewhere in organization technology is well understood in the industry	no experience with the technology will need to acquire help from outside the organization technology is leading edge, if not "bleeding edge" in nature

75	Design	easily	certain aspects	extremely
	Complexity	maintained	difficult to	difficult to

			maintain	maintain			
76	Support Personnel	in place, experienced, sufficient in	missing some areas of expertise	significant discipline or expertise			
77	Vendor Support	number complete support at reasonable price and in needed time frame	adequate support at contracted price, reasonable	hittle or no support, high cost, and/or poor response time			
		Total Categories	14		r		
		Total Factors	77				

Source: http://www.dir.state.tx.us/eod/qa/risk/risklist.htm

Appendix B, Risk Factors for Large Projects as Attributes

	Adequacy of PM	Good	Bad
Μ	lission and Goals		
1	Project Fit to Customer Organization	directly supports customer organization mission and/or goals	does not support or relate to customer organization mission or goals
2	Project Fit to Provider Organization	directly supports provider organization mission and/or goals	does not support or relate to provider organization mission or goals
3	Customer Perception	customer expects this organization to provide this product	project is mismatch with prior products or services of this organization
4	Work Flow	little or no change to work flow	significantly changes the work flow or method of organization
5	Goal commitment of project team	High goal commitment of project team	Low goal commitment of project team
Pı	rogram Management (if Project is part of a program	1)
5	Goals Conflict	goals of projects within the program are supportive of or complimentary to each other	goals of projects are in conflict, either directly or indirectly
6	Resource Conflict	projects within the program share resources without any conflict	projects within the program often need the same resources at the same time (or compete for the same budget)
7	Customer Conflict	multiple customers of the program have common needs	multiple customers of the program are trying to drive it in very different directions
8	Leadership	program has active program manager who coordinates projects	program has no leader, or program manager concept is not in use
9	Program Manager	program manager has deep	program manager is new to the

	Experience	experience in the domain	domain
8	Project manager location	On-site project manager	Off-site project manager
1 0	Definition of the Program	program is well-defined, with a scope that is manageable by this organization	program is not well-defined or carries conflicting objectives in the scope
D	ecision Drivers		
1 1	Political Influences	no particular politically- driven choices being made	project has a variety of political influences or most decisions are made behind closed doors
1 2	Convenient Date	date for delivery has been set by reasonable project commitment process	date is being totally driven by need to meet marketing demo, trade show, or other mandate; little consideration of project team estimates
1 3	Use of Attractive Technology	technology selected has been in use for some time	project is being done as a way to show a new technology or as an excuse to bring a new technology into the organization
1 4	Short Term Solution	project meets short term need without serious compromise to long term outlook	project team has been explicitly directed to ignore the long term outlook and focus on completing the short term deliverable
0	rganisation manageme	ent	
1 5	Organization Stability	little or no change in management or structure expected	management or organization structure is continually or rapidly changing
1 6	Organization Roles and Responsibilities	individuals throughout the organization understand their own roles and responsibilities and those of others	many in the organization are unsure or unaware of who is responsible for many of the activities of the organization
1	Policies and	development policies and	no policies or standards, or they

7	Standards	standards are defined and carefully followed	are ill-defined and unused
1 8	Management Support	strongly committed to success of project	little or no support
1 9	Executive Involvement	visible and strong support	no visible support; no help on unresolved issues
2 0	Project Objectives	verifiable project objectives, reasonable requirements	no established project objectives or objectives are not measurable
C	ustomers/Users		
2 1	User Involvement	users highly involved with project team, provide significant input	minimal or no user involvement; little user input
2 2	User Experience	users highly experienced in similar projects; have specific ideas of how needs can be met	users have no previous experience with similar projects; unsure of how needs can be met
2 3	User Acceptance	users accept concepts and details of system; process is in place for user approvals	users do not accept any concepts or design details of system
2 4	User Training Needs	user training needs considered; training in progress or plan in place	requirements not identified or not addressed
2 5	User Justification	user justification complete, accurate, sound	no satisfactory justification for system
Pı	oject Characteristics		
2 6	Project Size	small, non-complex, or easily decomposed	large, highly complex, or not decomposable
2	Reusable	components available and	components identified, need
7	Components	compatible with approach	serious modification for use
2 8	Supplied Components	components available and directly usable	components known to fail in certain cases, likely to be late, or incompatible with parts of

approach

9	Accuracy of initial cost estimates	High accuracy of initial cost estimates	Low accuracy of initial cost estimates
2 9	Budget Size	sufficient budget allocated	doubtful budget is sufficient
3 0	Budget Constraints	funds allocated without constraints	allocation in doubt or subject to change without notice
3 1	Cost Controls	well established, in place	system lacking or nonexistent
3 2	Delivery Commitment	stable commitment dates	unstable, fluctuating commitments
3 3	Development Schedule	team agrees that schedule is acceptable and can be met	team agrees that two or more phases of schedule are unlikely to be met
P	roduct Content		
3 4	Requirements Stability	little or no change expected to approved set (baseline)	rapidly changing or no agreed- upon baseline
3 5	Requirements Completeness and Clarity	all completely specified and clearly written	some requirements only in the head of the customer
3 6	Testability	product requirements easy to test, plans underway	most of product hard to test, or no test plans being made
3 7	Design Difficulty	well defined interfaces; design well understood	interfaces not well defined or controlled; subject to change
3 8	Implementation Difficulty	content is reasonable for this team to implement	content has components this team will find very difficult to implement
3 9	System Dependencies	clearly defined dependencies of the project and other parts of system	no clear plan or schedule for how the whole system will come together

Deployment

4	Response or other	readily fits boundaries	operates continuously at
0	Performance Factors	needed; analysis has been done	boundary levels
4 1	Customer Service Impact	requires little change to customer service	requires major changes to customer service approach or offerings
4 2	Data Migration Required	little or no data to migrate	much data to migrate; several types of data or no good descriptions of what is where
4 3	Pilot Approach	pilot site (or team) available and interested in participating	only available pilot sites are uncooperative or in crisis mode already
D	evelopment Process		
4 4	Alternatives Analysis	analysis of alternatives complete, all considered, assumptions verifiable	analysis not completed, not all alternatives considered, or assumptions faulty
5	Adequacy of planning and control techniques	High adequacy of planning and control techniques	Low adequacy of planning and control techniques
4 5	Commitment Process	changes to commitments in scope, content, schedule are reviewed and approved by all involved	changes to commitments are made without review or involvement of the team
4 6	Quality Assurance Approach	QA system established, followed, effective	no QA process or established procedures
4 7	Development Documentation	correct and available	nonexistent
4 8	Use of Defined Development Process	development process in place, established, effective, followed by team	no formal process used
4	Early Identification	peer reviews are incorporated	team expects to find all defects

9	of Defects	throughout	with testing			
5 0	Defect Tracking	defect tracking defined, consistent, effective	no process in place to track defects			
5 1	Change Control for Work Products	formal change control process in place, followed, effective	no change control process used			
Development Environment						
5 2	Physical Facilities	little or no modification needed	major modifications needed, or facilities nonexistent			
5 3	Tools Availability	in place, documented, validated	unvalidated, proprietary or major development needed; no documentation			
6	Start-up difficulties	Low start-up difficulties	High start-up difficulties			
5 4	Vendor Support	complete support at reasonable price and in needed time frame	little or no support, high cost, and/or poor response time			
5 5	Contract Fit	contract with customer has good terms, communication with team is good	contract has burdensome document requirements or causes extra work to comply			
5 6	Disaster Recovery	all areas following security guidelines; data backed up; disaster recovery system in place; procedures followed	no security measures in place; backup lacking; disaster recovery not considered			
7	Bureaucracy	Absence of bureaucracy	High bureaucracy			
Project Manager (PM)						
5 7	PM Approach	product and process planning and monitoring in place	weak or nonexistent planning and monitoring			
5 8	PM Experience	PM very experienced with similar projects	PM has no experience with this type of project or is new to project management			
5	PM Authority	has line management or	has little authority from location			

9		official authority that enables project leadership effectiveness	in the organization structure and little personal power to influence decision-making and resources				
7	PM Influence	High PM influence	Low PM influence				
8	PM Technical skills	High PM technical skills	Low PM technical skills				
9	PM Human skills	High PM human skills	Low PM human skills				
6 0	Support of the PM	complete support by team and of management	no visible support; manager in name only				
1	Project manager commitment to established schedules						
1	Project manager commitment to established budgets						
1	Project manager commitment to technical performance goals						
Team Members							
6 1	Team Member Availability	in place, little turnover expected; few interrupts for fire fighting	high turnover, not available; team spends most of time fighting fires				
6 2	Mix of Team Skills	good mix of disciplines	some disciplines not represented at all				
6 3	Team Communication	clearly communicates goals and status between the team and rest of organization	rarely communicates clearly within team or to others who need to be informed				
6	Application	extensive experience in team	little or no experience with				
4	Experience	with projects like this	similar projects				
6 5	Expertise with	good background with	no expertise in domain in team,				
J	(Domain)	development team	no avanaomity of experts				

6 6	Experience with Project Tools	high experience	low experience			
6 7	Experience with Project Process	high experience	low experience			
6 8	Training of Team	training plan in place, training ongoing	no training plan or training not readily available			
6 9	Team Spirit and Attitude	strongly committed to success of project; cooperative	little or no commitment to the project; not a cohesive team			
7 0	Team Productivity	all milestones met, deliverables on time, productivity high	productivity low, milestones not met, delays in deliverables			
Technology						
7 1	Technology Match to Project	technology planned for project is good match to customers and problem	selected technology is a poor match to the problem or customer			
7 2	Technology Experience of Project Team	good level of experience with technology	no experience with the technology			
7 3	Availability of Technology Expertise	technology experts readily available	will need to acquire help from outside the organization			
7 4	Maturity of Technology	technology has been in use in the industry for quite some time	technology is leading edge, if not "bleeding edge" in nature			
Maintenance and Support						
7 5	Design Complexity	easily maintained	extremely difficult to maintain			
7 6	Support Personnel	in place, experienced, sufficient in number	significant discipline or expertise missing			
7 7	Vendor Support	complete support at reasonable price and in needed time frame	little or no support, high cost, and/or poor response time			