MASTER

Design of a Bayesian networks risk diagnosing methodology release for innovation projects an exploration

Ruytenberg, N.J.

Award date:
2011

Eindhoven, July 2011

Design of a Bayesian Networks Risk Diagnosing Methodology Release for Innovation Projects

An exploration

By
N.J. Ruytenberg

Bachelor of Science in Electrical Engineering
Student identity number 0480043

in partial fulfilment of the requirements for the degree of

Master of Science
in Innovation Management

Supervisors:
dr. J.A. Keizer, TU/e, ITEM
dr. ir. K.E. van Oorschot, TU/e, ITEM

TU/e. Department of Industrial Engineering and Innovation Sciences
Series Master Theses Innovation Management

Subject headings: Risk, Risk Management, Bayesian Networks, Bayesian Belief, Risk Diagnosing, Project Management, Canonical, Noisy

Executive summary

Nowadays, the market is increasingly more competitive and globalizes fast. It is therefore important for companies to come up with high innovative products within a short time to market and within budget. This puts immense pressure on a company's R&D department and the New Product Development process. To assure a high project success rate, companies should have a sound risk management strategy, since a certain amount of risk is needed for successful radical innovations (Keizer and Halman, 2007; Delisle and St-Pierre, 2010). However, many companies do not have or do not implement a risk management strategy properly (Aloini et al., 2007; Delisle and St-Pierre, 2010; Skelton and Thamhain, 2005; Ricondo et al., 2010) with the consequence that the failure rate of the projects is high or the project is over budget (Choi and Ahn, 2010; Wang et al., 2010; Skelton and Thamhain, 2005; Aloini et al., 2007). Several authors state that improving the risk management process for a project within a firm, increases the new product/process project success rate (Caillaud et al., 1999) or as Choi and Ahn (2010) state that the critical explanations for the difficulty of this product development process are unexpected risks and their impact, and the inability of the firm to defend against those risks effectively and efficiently.

Risk management generally comes down to a four stage process: identification of the risks, prioritization of the risks identified, mitigation of the risks identified and tracking and control of the risks (Kayis et al., 2006, 2007; Thompson, 2000; Caillaud et al., 1999). The literature of the risk management tools can be divided into 4 classical risk management methodologies: Failure Mode and Effect Analysis (FMEA), databases, matrices and the Risk Diagnosing Methodology (RDM). Out of this literature it appeared however that these existing risk management directions generally have shortcomings in the different phases of the risk management process. Some do not have a risk tracking and control phase, they can suffer from groupdynamics' biases and other risk management tools do not take lessons learned from the past into account. What all classical risk management tools have in common is that they struggle with a list of risks and their effects without relating them at all or do not present them in a manageable way. The consequence is that the (multiple) cause and the (multiple) effect chains do not become clear.

The main contribution of this thesis is therefore an exploration to design an improved risk management tool that creates clear insight in cause and effect chains between risks and provides the option to build history in these cause and effect chains to make the tool more and more robust everytime it is executed. Building history in cause and effect chains is new and not shown in literature before.

This improved risk management tool is meant to be easy in use and to increase the success and the performance of a single radical product development project. The tool therefore considers risk management in the phases of a project. The exploration of the improved risk management tool is achieved by fulfilling the following research objectives:

Combine the best techniques of the classical risk management directions for the particular phases in risk management in one improved risk management tool.

Find a technique that provides a clear oversight of (multiple) cause and (multiple) effect chains between risks in order to detect the interaction-effects between the risks.

Find a technique that can be easily updated when new perceived risk level information is available.

Find a technique that is suitable to capture such knowledge that it is possible to make the tool more and more robust everytime it is used.

The improved risk management tool is called BNRDM. This name is chosen because the basis of the improved risk management tool is the original Risk Diagnosing Methodology (RDM) of Keizer et al. (2002). The RDM delivers the best identifying, prioritization and mitigation technique for a risk management tool because of the non-consensus principle that is used. The RDM shows which risks have the most variation in risk level and which risks are perceived as most risky individually. The technique Bayesian Networks (BN), which are acyclic causal graphs, deliver the possibility to model cause and effect chains of risks and built up history in its statistics.

The RDM identifies the risks in the coming project in the risk identification phase. In the risk prioritization phase, the RDM delivers all the main effects of the risks including the ones that have the most variation in probability. A Bayesian Network provides the answer in what magnitude this variation in probability will have a carry-over effect on other risks because of the cause and effect chains. The BN provides the insight in the interaction effects between the different risks. Both are needed to make a sound prioritization list. The RDM method together with a database and the BN delivers the best solution for the risk mitigation process. The database provides the lessons learned out of past projects to prevent reinventing the wheel, the RDM delivers the data when the situation is different than described by the database and the BN provides the answers which risks are best suited to mitigate in terms of time, resources, effectiveness and complexity due to the interaction-effects. In the risk tracking and control phase, a risk management plan of the original RDM is composed and describes who is responsible for each of the diagnosed risks, what the action plan is for mitigating each of the diagnosed risks, how much time and resources are needed to deal with these risks and how progress will be monitored and reported (Keizer et al., 2002). The action plans are drawn up by subgroups of the risk management team and the progress of the action plan, with its milestones, is documented in a risk tracking form. This risk tracking form provides a framework for each individual risk about the status and progress (Keizer et al., 2002). To gain insight in the interaction among the diagnosed risks, the project team leader fills the BN's with new evidence each time a milestone in the action plan is accomplished in the individual risk mitigation strategy. After the updating of the BN's, new data is added to the risk milestone charts of the individual risks to provide the perceived risk level progress over time. After completing a total risk mitigation strategy for a certain risk, the database is updated with the successes and failures of the risk mitigation strategy for that particular risk. Furthermore, the BN's statistical history is updated everytime a project is completed to make the tool more and more robust (see illustration 1).

The BN's are constructed out of the risk reference list with the same names of the original RDM (see appendix A). The commercial and organizational and project management risks are chosen for this exploration because of the generality of those risks and therefore a constructed BN (the qualitative connections) filled with these risks is widely applicable and mostly not limited to one organization. Other risks in the risk reference list do vary more and are expected more different for every company or even project. They are therefore less suited for constructing a general applicable exploration BN as is demonstrated in this master thesis. The Bayesian Networks design prototype, the structure of the network (qualitative part), is distilled out of the RDM method by selecting the most important parts of the commercial and organizational and project management risks of the risk reference list. The most important parts are selected and the qualitative connections among the variables are made in cooperation with the expert and author of the RDM: Dr. Keizer. The quantitative part of the BN needs to be filled with data that is derived out of interviews with experts from the company in question that use the risk management tool.

The verification of the improved risk management tool is tested empirically in interviews with 8 managers who dealt with or are dealing with risk management in innovation projects. In order for the BNRDM to work properly, statistical data is essential. This restrains the option whether this tool can be applied within SME's.

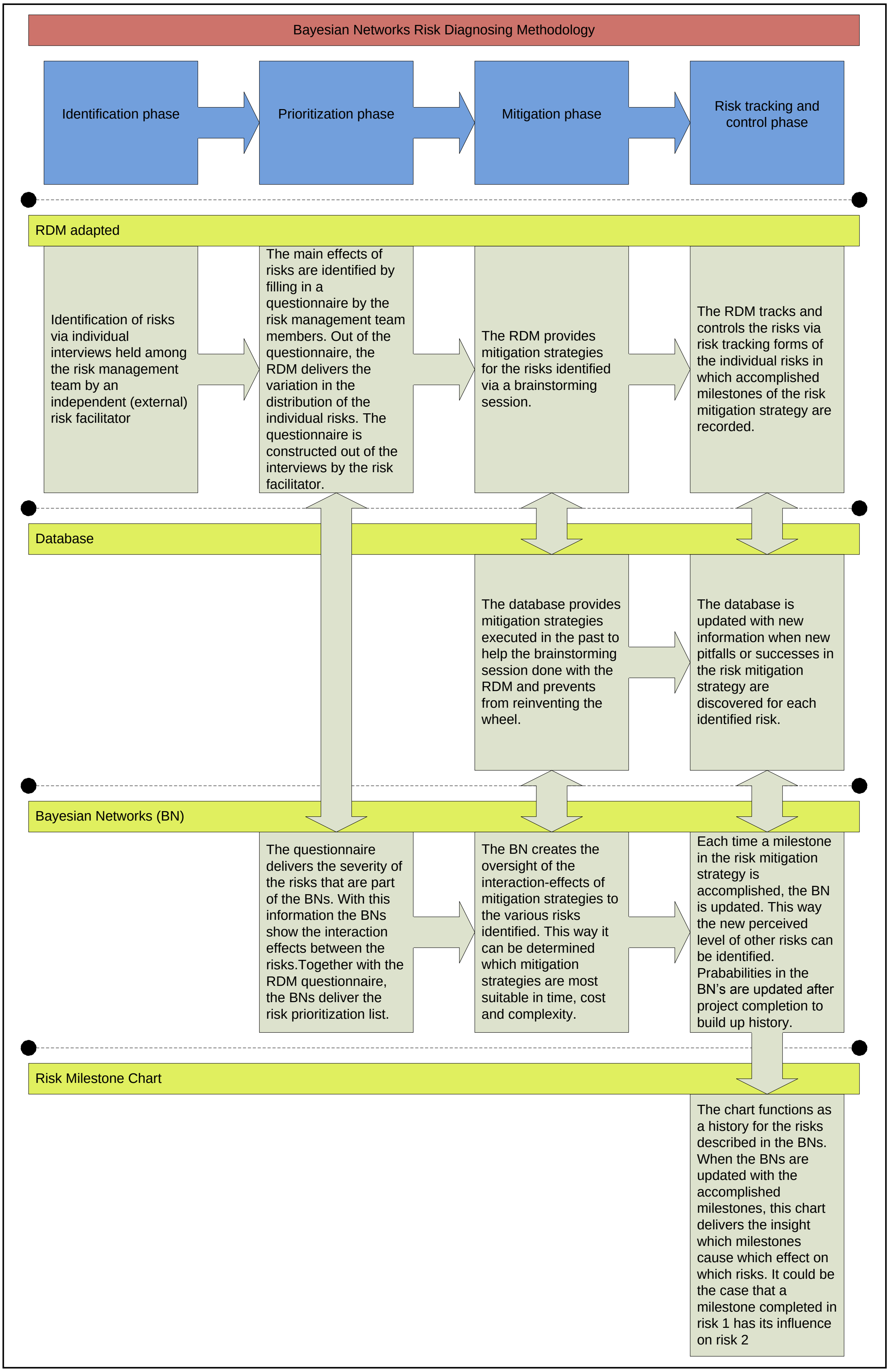


Illustration 1: Overview of the connections between the several techniques in the BNRDM

This page is intentionally left blank

Table of contents

List of abbreviations

BBN	Bayesian Belief Network
BN	Bayesian Network
BNRDM	Bayesian Networks Risk Diagnosing Methodology
CPT	Conditional Probability Table
DAG	Directed Acyclic Graph
FMEA	Failure Mode and Effect Analysis
GUI	Graphical User Interface
HHM	Hierarchical Holographic Model
ICI	Independence of Causal Influence
NPD	New Product Development
OS	Operating System
RPN	Risk Priority Number
SME	Small to Medium Enterprise
RDM	Risk Diagnosing Methodology
RFMEA	Project Risk Failure Mode and Effect Analysis

List of figures

List of tables

List of illustrations used in executive summary

This page is intentionally left blank

1.Introduction

Today we make sure we have a good insurance policy for our homes in the case of burglary, fire and flooding. The case of risk mitigation in domestic fire is twofold, one takes measures to prevent a fire and one insures himself against the high costs when a fire eventually destroys the property. Why don't have companies a good insurance policy for the outcomes of their development projects? Nowadays, the market is increasingly more competitive and globalizes fast. It is crucial for companies to come up with innovative solutions and new products in a short period of time. This puts high pressure on the New Product Development (NPD) process. It is therefore necessary that the new product development process is managed properly to ensure a high project success rate, since an innovation strategy based on risk avoidance cannot be an option because taking a certain amount of risk is inevitable for successful radical innovations (Keizer and Halman, 2007; Delisle and St-Pierre, 2010).). However, the day-to-day reality is different. Many companies do not have at all, do not have the right risk management strategy or do not implement a risk management strategy properly in their radical product development projects and therefore even exercise ad-hoc risk management (Aloini et al., 2007; Delisle and St-Pierre, 2010, Skelton and Thamhain, 2005; Ricondo et al., 2010). This ad-hoc risk management includes that not until the problem rises, an ad-hoc risk mitigation strategy is come up with and is applied. Because of the ad-hoc principle and not having the right risk management strategy, the failure rate of innovation projects is rather high (dependent on the branch of industry): 40% or even about 80% till 90% of the projects fail before project completion (Aloini et al., 2007; Choi and Ahn, 2010; Skelton and Thamhain, 2005; Wang et al., 2010) and 34% till 45% were late or over budget (Skelton and Thamhain, 2005; Aloini et al., 2007). Furthermore, there is less support when a project is cancelled by management because it is seen as a subjective decision rather than a rational decision based on sound data. Several authors state that improving the risk management process for a project within a firm, increases the new product/process project success rate (Caillaud et al., 1999) or as Choi and Ahn (2010) state that the critical explanations for the difficulty of this product development process are unexpected risks and their impact, and the inability of the firm to defend against those risks effectively and efficiently.

However, out of the literature review it appeared that today's new product development risk management tools have shortcomings in the different phases of the risk management process. Some do not have a risk tracking and control phase, they can suffer from groupdynamics' biases and other risk management tools do not take lessons learned from the past into account. What all classical risk management tools have in common is that they struggle with a list of risks and their effects without relating them at all or do not present them in a manageable way. The consequence is that the (multiple) cause and the (multiple) effect chains do not become clear.

The main contribution of this thesis is therefore an exploration to design an improved risk management tool that creates clear insight in cause and effect chains between risks and provides the option to build history in these cause and effect chains to make the tool more and more robust everytime it is executed. Building history in cause and effect chains is new and not shown in literature before.

This improved risk management tool is meant to be easy in use and to increase the success and the performance of a single radical product development project. The tool therefore considers risk management in the phases of a project. The exploration of the improved risk management tool is achieved by fulfilling the following research objectives:

Combine the best techniques for the particular phases in risk management in one improved risk management tool.

Find a technique that provides a clear oversight of (multiple) cause and (multiple) effect chains between risks in order to detect the interaction-effects between the risks.

Find a technique that can be easily updated when new perceived risk level information is available.

Find a technique that is suitable to capture such knowledge that it is possible to make the tool more and more robust everytime it is used.

To achieve the research objectives, this thesis presents the track to come to an improved risk management tool called BNRDM. It is called BNRDM, since the basis of the improved risk management tool is the Risk Diagnosing Methodology (RDM) of Keizer et al. (2002). This thesis is subdivided into 7 chapters. Chapter 2 provides the classical methodologies used in risk management. It gives an oversight of the techniques used in literature that are part of current risk management tools. Chapter 3 presents the methodology that is applied to come to an improved risk management tool. Furthermore, it provides the functional requirements of the improved risk management tool and the research objectives. Chapter 4 discusses the theory behind the Bayesian Networks used for the final design. It is a chapter that provides a deepening of this theory to provide an argumentation for the design of the Bayesian Networks in this thesis. This deepening is added since a large part of the improved risk management tool consists out of Bayesian Networks. Chapter 5 provides the design of the two Bayesian Networks and the design of the BNRDM. Chapter 6 delivers the validation of the improved risk management tool on the basis of interviews held with 8 managers who dealt with or are dealing with risk management in innovation projects. Finally, chapter 7 gives the conclusion of this thesis, suggests options for further research and presents the limitations of this improved risk management tool.

2.Classical risk management methods

This chapter provides a short description of the classical risk management tools as described in literature. The literature review was limited to risk management tools that were generally applicable on radical new product development projects, focussed on risk management in the different phases of a project and were published in the last decade (as from 1999). Therefore literature considering only construction projects, only software projects, incremental instead of radical innovation, considering the risk management process in project selection instead of risk management in phases of the project or when the date of publication was too old, was removed. The argument behind the time selection criteria is that when there is not written anything about a risk management tool (again) in the last ten years, the method is considered not value enough anymore (outdated) or interesting enough to write an update about and was therefore removed from the selection.

Out of this literature review it appeared that some risk management tools share a common underlying techniques like for example Fuzzy Theory, Analytic Hierarchical Process (AHP), Grey Theory and Bayesian Networks (BN). However, the focus of this master thesis lies not in the description of these underlying techniques unless it is used in the final risk management tool design. This chapter deals with a general overview of the four directions of classical risk management tools that can be roughly distinguished in literature.

The risk management tools have roughly the same four step structure. They have a risk identification phase, after the risk identification the risks are set in order of importance, mitigation plans are developed to reduce the effects of the identified risks and finally the risks are tracked and controlled. They differ however in the techniques they use for the different phases. Some use brainstorming sessions for the identification phase, others use individual interviews. The tools can also be distinguished in quantitative or qualitative techniques since some tools use particular calculations. In the end, however, all risk management tools have a qualitative part in the identification of the risks. Finally, what appeared from the literature review is that many risk management tools do not mention the definition of risk they use.

The different directions in this chapter include a short exposition of the methodology as well as a discussion on the shortcomings of the method. The techniques that are included are the Failure Mode and Effect Analysis (FMEA), databases, matrices and the Risk Diagnosing Methodology (RDM). The first section presents the oversight of the different phases in risk management. The second section presents the directions of the classical risk management tools and provides conclusions drawn from this literature overview.

2.1.The different phases in risk management

Risk management tools are integrated within project management to control different parameters of a project like schedule, costs and scope (Thompson, 2000) by making the risks on the particular project visible and thereby providing the possibility to take action on those risks. It appears that risk management tools generally consist of a four stage process: Identification of the risks, assessment/prioritization of the risks identified, treatment/mitigation of the risks identified and monitoring/tracking and control of those risks (Kayis et al., 2006, 2007; Thompson, 2000; Caillaud et al., 1999). In the literature some risk management tools do have a more stage process, these can however be summarized to these four stages (Kayis et al., 2007).

The first step in risk management is risk identification. It is the process of identifying the risks that can influence the outcome of the project during the entire project's lifecycle. A risk event is generally identified in the form of: "If x happens, then y will occur." (Carbone and Tippett, 2004). The risks can be identified with several techniques like fault-tree analysis, Failure Mode and Effect Analysis, test data, expert opinion, brainstorming with project team members and lessons learned from other projects or programs (Perera and Holsomback, 2004). These techniques use a predetermined set of risk categories which consist of technical, organizational, financial, schedule and operational matters. The most extensive list in literature used to identify the risks in certain categories is from Keizer et al. (2002) for their RDM risk management tool. They use in total 12 risk categories (see appendix A).

To identify project risks three activities are carried out (Halman and Keizer, 1994):

- There have to be a thorough understanding of the process or project under investigation and by reviewing this process or product, it ensures that everyone of the risk management team has the same understanding of the object being worked on (McDermott et al., 2009). More in detail, a systematic description is needed of the required product components, the processes necessary to make the production of the product components possible, the necessary equipment and tools that are requisite, as well as the relationships between these elements. In interviews, members of the new product development risk team are asked to describe these elements in general and their personal contribution (Halman and Keizer, 1994).
- Identification of technological gaps is needed on the basis of the description in step one. This can be achieved in a group session or in personal interviews. In interviews held with the risk team members, the interviewees are asked to indicate the gaps between available and required knowledge, skills and experience. The gaps are perceived as potential technical risks (Halman and Keizer, 1994).
- Identification of organizational and commercial gaps is needed which can be composed of internal (parent organization, holding organization) and external (customers, market, competitors, subcontractors) influences. These can be identified in individual interviews (Halman and Keizer, 1994) and/or a group session (McDermott et al., 2009).

Not all risks are equally relevant. The phase risk analysis/prioritization therefore analyses the risks determined in the first step and prioritizes the risks according to likelihood, impact, severity and the ability of the firm to influence the risk factors (Keizer et al., 2002). There are several techniques to analyze and prioritize risks. Examples are Failure Mode and Effect Analysis, GERT (Meredith and Mantel, 2006), Bayesian Networks (chapter 4) and the Analytic Hierarchical Process (Zahedi, 1986). Basically, the risk analysis methods can be divided into qualitative or quantitative analysis (Thompson, 2000).

Risk mitigation takes place when the risk analysis/prioritization phase is complete. The goal of this phase is to establish such measures that especially the high priority risk items reduce in likelihood, severity and impact. Cost, complexity, time, resources, ease of implementation and in which stage of the project the risk occurs, are the factors that affect the selection of which strategy is suitable (Thompson, 2000). Other possibilities than risk mitigation are risk transference to for example a third party (Thompson, 2000), avoidance and acceptance when a risk can fit within a company's tolerance level (Thompson, 2000; Carbone and Tippett, 2004).

The goal of the last phase, risk tracking and control, is the practice of assuring that the perceived risks are reviewed and updated throughout the project's lifecycle. Managers or risk owners monitor in this phase the risk management plans progress, evaluate the effectiveness of the risk responses and document it. When due to reassessment of the risks, new risks are discovered or it appears that the risk mitigation strategy does not work as planned, replanning and new mitigation measures are needed (Thompson, 2000; Pennock and Halmes, 2002).

2.2. Classical methods of risk management

As depicted in the previous section, risk management tools generally consist out of a four stage process. This section presents the four directions in risk management tools that are considered to be the classical risk management methods. Some do exist for already more than 40 years like the Failure Mode and Effect Analysis (FMEA). The directions that are presented consider the FMEA, databases, matrices and the RDM.

Failure Mode and Effect Analysis

The FMEA does not use statistics; it floats on project team members who put in data during the process. It is a systematic method designed to identify and prevent product and process problems before they occur. Or in other words: the objective is to find all ways in which a product or process can fail, the so called "failure modes". The failure mode has a potential effect with certain likelihood and this effect has a certain risk. Summarized is the FMEA a method to discover failures, effects and their associated risk within a certain process or product and the process and action to eliminate or reduce those risks (McDermott et al., 2009).

McDermott et al. (2009) describe the ten steps of the FMEA methodology as follows:

1) Review the process or product. Know which product or process is under investigation. By reviewing the process or product, it ensures that every project team member has the same understanding of the subject being worked on.
2) Brainstorm potential failure modes. Conduct a series of brainstorming sessions, with team members and/or experts with expertise in the particular process or product parts, in which a list of failure modes is made. This list is then organized in different categories in such a way that the modes are categorized by severity of the failure, the type of failure or where in the process or product the failure occurs.
3) List potential effects of each failure mode. Ask the following question: "If the failure mode occurs, then what are the consequences?"

4) Assign a severity ranking for each effect. Rank is given by the team based on a 10-point scale and it reflects the estimation of how serious the effects are if the failure occurs.
5) Assign an occurrence ranking for each failure mode. Rank is given by the team based on a 10-point scale and reflects the frequency in which the failure mode occurs. Best way is to use historical data.
6) Assign a detection ranking for each failure mode and/or effect. Rank is given by the team based on a 10-point scale and reflects the probability a failure or an effect of a failure is identified by current controls that may detect them. The detectability ranking is high when the likelihood of the detection is low.
7) Calculate the risk priority number (RPN) for each effect. The RPN is calculated by multiplying Severity Rank with the Occurrence Rank and the Detection Rank.
8) Prioritize the failure modes for action. The failure modes are ranked according to the magnitude of the RPN.
9) Take action to eliminate or reduce the high-risk failure modes. Use an organized problem-solving process to reduce the likelihood of occurrence and severity while increasing the detectability of the failure and thereby reducing the detection ranking.
10) Calculate the resulting risk priority number as the failure modes are reduced or eliminated. After taking action on the failure modes, a reduction of at least 50% should be expected in the total of RPN's.

During the years, other authors made extensions on or changes to the original FMEA to overcome some weaknesses in the methodology. Carbone and Tippett (2004) made the project risk FMEA (RFMEA) in which they added a scatter plot with the RPN value of the current risk and a RPN threshold on two axis. When the RPN reaches above a certain threshold level, mitigation of the risk is needed. This delivered a more graphical approach. Chang et al. (1999 and 2001) proposed a different approach for finding the risk priority number (RPN) by using the fuzzy method for "converting" the factors "occurrence", "severity" and "(non-)detection" and by using grey theory after the conversion. In the standard FMEA method, the RPN is calculated with the multiplication of occurrence, severity and detection. These factors however are each of different kind of scale. The factor chance is linear of scale and the factor non-detection is non-linear. After multiplication for the RPN it is unclear whether it is a sound result. To solve this problem, each of the factors is directly evaluated using fuzzy theory instead of using the converted scores. Wu et al. (2010) combined a database with the FMEA method and the GERT network. The database functions as a historical database in which success factors and failures are stored for input in the FMEA method. Together with experiences from the project team members, the database provide data about the failure mode, the severity the potential failure mode, the frequency of that failure, what the current controls are to detect this failure mode or its effects and the current prevent mechanisms and what the recommended actions are if the risk is prioritized in the FMEA tables. Out of the FMEA table and the product development plan, a GERT network is composed.

Although some shortcomings are solved in the extended versions of the methodology, others remain. The FMEA process takes only technical factors into account because of the definition of the failure mode: "A product failure occurs when the product does not function as it should or when it malfunctions in some way. ……. Ways in which a product or process can fail are called failure modes." (McDermott et al., 2009). Furthermore, every cause is only linked to its effects. This way cause and effect chains do not become clear. Finally, the used method to discover and prioritize the risks is sensitive to groupthink (Landy and Conte, 2007) and that can cause central tendency (Blumberg et al., 2005).

Databases

Databases are lists of risks that can occur during a new product development project. The databases contain captured knowledge from experts about these risks, which is stored and reused for preventing that the same pitfalls come up that earlier projects have suffered from. Each risk described is assigned to a managing organization and a specific risk owner who generates mitigation plans as appropriate (Perera and Holsomback, 2004; Caillaud et al., 1999). The database is updated when new knowledge or data becomes available during the new product development process, i.e. when a mitigation task is completed, the responsible managing organization records the completion of the task in the risk database and rescores the risk considering the tasks results. This way, the scores are kept up-to-date and the current top risks and risk exposure of the project can immediately be identified (Perera and Holsomback, 2004).

Another goal of use of the risk database is for example the eRisC tool from Delisle and St-Pierre (2003). It is a risk management web-based tool designed for expansion, innovation and export projects within Small-Medium Enterprises (SMEs). The goal of this tool is that when SMEs can make a clear formulated risk management assessment, lenders and investors can more precisely assess the real risks involved in funding a SME project, allowing them to offer more attractive financing terms. The tool consists of a questionnaire with several closed questions and sub-questions. Depending on the answers of the user, not all questions are applicable and are posed to the user. The final results include a numerical value which represents the risk rating for a specific SME project, the identification of at least five most important risk factors and their mitigation strategies to reduce the risk rating computed and a graphical pie representation showing the risk associated with every section and their respective weight in the computation of the global risk rating. The user can change these weights according to the projects characteristics or his personal views. All data provided by the users or entrepreneurs are recorded in a database and that makes it possible to establish statistically based weight models for every type of user. This provides the possibility for entrepreneurs to evaluate their projects with weight used by bankers and therefore better understand the bankers' viewpoint in evaluating the project.

Slightly different are risk registers, they are lists of risks described that can occur with its potential mitigation plans. The details of each risk stored contain the following categories (Williams, 1994):

- Event: Includes a description of the risk, its likelihood of occurrence and the person or department responsible for its removal or mitigation.
- Impact: Includes the severity of the impact and the object of the project on where the risk has its impact. This can be a time, cost or other performance measure.
- Actions: This includes the actions that have to be taken to lower the probability of the particular risk and the plans that have to be executed if the risk occurs.

The purpose of the risk register is twofold and has partly the same goal as the databases. The first is a repository of knowledge. Many today's projects are done in multidisciplinary teams. This causes that engineers, experts in one aspect of the project, does not know risks involved in another part of the project. Williams (1994) states that problems rise on the interfaces between the different disciplines are more severe than problems that rise within the discipline. Therefore the risk register provides a good overview because the project manager rapidly becomes one of the few people with a good overview of the project. Secondly, the risk register is to initiate cost, time and technical specification analysis to come to a total risk assessment in these categories and to assist the user to choose between research projects or project directions.

The next step is to consult the content of the risk register that contains management actions plans that cause the decrease of the probability of the risk occurring and actions plans that reduce the consequences of the risk if it does occur. These formal actions have to be taken during the development phase of the project. Because the actions to be taken are formal, the benefits are according to Williams (1994) that it stimulates thought on how to reduce the likelihoods and the impacts of risks. It shows senior management which of the key risk items have no risk reduction measures. Furthermore it delivers a checklist via the project definition report that the risk is managed and ensures that all activities are carried out.

The disadvantage of the risk registers and the databases is that they don't provide a clear overview because of the possible extensive list of described risks. Furthermore, they don't deliver the overview whether risks are linked together and their possible effects. With this overview, it could be determined if a particular risk perception changes, what kind of effects that information has on other perceived risks. The advantage of databases is that pitfalls and successes of past projects are recorded and it therefore serves as a lessons learned technique.

Matrices

The matrices are used to provide insight in the interdependencies between tasks in a multi-project environment. This approach enables the communication and prevents wrong assumptions between people from different disciplines in different geographical locations (Chen et al., 2003). Moreover, it delivers the tractability of dependencies, explores the information needed within and between different departments, projects and people (Danilovic and Sandkull, 2005). The most extensive tool based on matrices is from Pennock and Halmes (2002). Pennock and Halmes (2002) used the matrices not only as a communication device or as a tool to provide insight in the several task dependencies to overcome organizational boundaries in vertical, horizontal, external and geographic directions. They also provided a five step based process on risk filtering/prioritization using matrices. The goal of this five stage process is to determine which events are more risky. Risks are identified via brainstorming with domain experts to compose an Hierarchical Holographic Model (HHM). An HHM comes down to a list of risks which are logically and graphically arranged. The selected risks are in this process filtered through several steps (with a matrix) to pick out the risks that matter and are tested against redundancy, resiliency and robustness, which are the defensive attributes and are unique to every organization.

The defensive attributes consist of the following (Pennock and Halmes, 2002):
Redundancy consists of:

- Detectability of a particular event before it causes a problem to the project.
- The controllability of the event, the degree in which the event can be prevented to cause a problem to the project.
- Multiple paths to failure, the number of paths that lead to a problem.

Resiliency consists of:

- Irreversibility, the degree in which a scenario is reached in which the adverse condition cannot be returned to the initial condition.
- The duration of the adverse effects.
- Cascading effects, indicates the scenario in which the effects of an adverse condition propagates to other tasks.

Robustness consists of:

- The operating environment, in what degree is the project subject to external stressors.
- Wear and tear indicates a scenario that lead to degraded performance due to aging equipment for example.
- Hardware, Software, Human and Organizational interfaces. The degree to which the event is sensitive to interfaces among the subsystems.

- Complexity/emergent Behaviors, indicates a scenario of adverse effects because the knowledge of components and their interaction is partially known. An example is a complex supply network whose complex structure is only partially known.
- Design immaturity, the degree to which the adverse conditions can be subscribed to the newness of the technology involved.

When the risk filtering/priotitization process is completed, each remaining risk is extensively studied, interdependencies analysis is made with a matrix and the risk are ranked with a matrix. Finally a risk management plan is developed.

Pennock and Halmes (2002) described furthermore a risk tracking process in the form of a risk milestone chart (Figure 1) in which the level of risk exposure over time is displayed. It has the following important criteria (Pennock and Halmes, 2002):

- Each risk has its own chart with the exposed risk level on the y-axis and the time units on the x-axis. The y-axis can also be altered in for example costs.
- The vertical dotted lines indicate the milestones of the risk management plan, where each line represent a task that when it is finished, should lower the level of risk exposed to the project.
- The three dashed lines that are displayed horizontally divide that chart into three areas: the problem domain, the mitigation domain and the watch domain. When a risk reaches the problem domain, immediate action is necessary to fix the situation. When the mitigation domain is reached, a set of steps must be created to mitigate that risk. In the watch domain, no action is needed.
- The thick black vertical lines represent the measured risk values in which the top indicates the pessimistic case, the horizontal branch the most likely case and the bottom the optimistic case. These measured risk values compare the actual risk level with the predicted one. When the measured risk markers are higher than expected, a replan of the mitigation milestones is necessary as is done at the replan 1 to 4 indicators in the figure. The milestones in the risk management plan are revised in the replan phase and a new set of anticipated risk levels are developed.

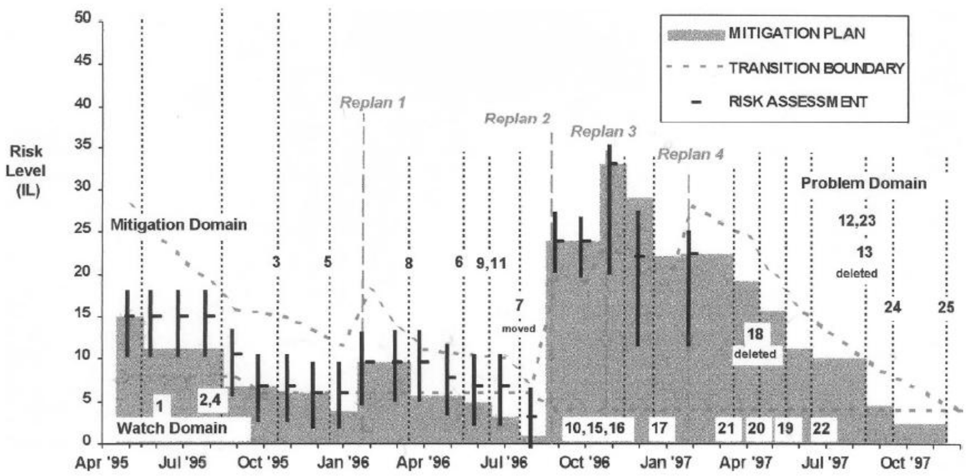


Figure 1: Risk milestone chart, adapted from Pennock and Halmes (2002).

The methodologies based on matrices described do not provide a prioritization procedure nor do they provide a mitigation strategy. The most extended matrices methodology of Pennock and Halmes (2002) is an exception and provided an extensive risk filtering/prioritization process. It is a time consuming methodology to get an updated version of the new perceived risks when new information becomes available. Although the dependency matrices provide some interaction between effects, it is not manageable for large series of risks. The matrices become at that point very large and/or multi-dimensional matrices have to be made and/or many matrices co-exist besides eachother. All options do not contribute to a clear oversight in (multiple) cause and (multiple) effect chains especially not when the perceived risks also have to updated in perceived risk level. Furthermore, the identification of the risks can suffer from groupthink. Although the HHM is composed by brainstorming by different domain experts, experts on practically the same domain can influence eachother. The risk milestone chart described by Pennock and Halmes (2002) (Figure 1) however, provides a clear overview of the progression of the perceived risk in time, after certain mitigation strategy accomplished milestones.

Risk Diagnosing Methodology
RDM is a risk management tool designed to initiate at the end of the feasibility phase of an innovation project. At this stage the transition to the actual product development and engineering takes place (Keizer et al., 2002). The tool is invented by Keizer, Halman and Song (2002) in cooperation with Philips Lighting and Unilever. It identifies risks on the basis of a risk reference list in 12 categories (appendix A). Risk is determined by its likelihood, its effects (impact) and the firm's ability to influence the risk factors. The risk management tool RDM is conducted in a 9-step process. Because the RDM is extensively described in chapter 5, only the main feature of the RDM is given in this section.

Risk identification
1) Initial briefing between project manager and risk facilitator. In this initial briefing the project manager and the risk facilitator make appointments about specific project related topics and some general topics. It is important that the risk facilitator is an individual who has no stake in the project and should be preferably a professional with knowledge about state-of-the-art product innovation. In this way the risk facilitator can ask questions unbiased by status, politics and what happened in earlier projects.
2) Kick-off meeting with the project manager, the project team members and the risk facilitator. In this meeting the expectations of and plans for the RDM process are displayed to the project team members.
3) Individual interviewing by the risk facilitator. Each project team member is individually interviewed to discover the potential risk issues in the project. An extensive risk reference list on twelve domains of risk issues in an innovation project is made by Keizer et al. (2002) which can serve as an aid in identifying specific risks during these individual interviews (see appendix A).

Risk assessment
4) Development of a risk questionnaire by the risk facilitator. Out of the interviews, a risk questionnaire is made by the risk facilitator in which the critical issues are transformed in positive statements of "objectives to be realized".
5) Answering of the risk questionnaire by the project team members. Each individual team member is asked to fill in the questionnaire with the positive risk statements. A team member fills in those questions they have expertise about. Each risk statement is composed of three sub-risk statements which are judged by the team members on a 5-point Lickert scale. The three sub-risk statements include: "The level of certainty that the objective formulated in the risk statement will be realized", "The ability of the team to reach an appropriate solution using the project's allocated time and resources" and "The relative importance of the objective to project performance".
6) Constructing of the risk profile by the risk facilitator. The risk profile that is made out of the questionnaires consist of the degree of risks perceived by the team members, a mark where at least 50% of the support for that particular risk lies on the 5-point scale and a distribution

of the perception of the team members. This last point prevents that an individual who perceives a high risk at a certain statement, is cancelled out by the mass. It indicates a lack of consensus in the group and it should be investigated. This is the most important feature in the RDM process.

Risk response development and control

7) Preparing of risk management session by the project manager and the risk facilitator.
8) Risk management session with the project manager, project team members and risk facilitator. This session is meant to provide answers to the risks identified in the previous steps. This is done in a two-way process in which the first is to create a common understanding of the risks and to provide general ideas of managing them. The second part consists of splitting the group up in sub-groups which develop action plans and work out the generated ideas.
9) Drawing up and execution of the risk management plan. The action plans, who is responsible for a particular action plan, how much time and resources a specific action plan will take and how the progress and reports of those plans are reported and their associated risks are documented in the risk management plan. The milestones of the action plans achieved in the risk mitigation strategy are recorded in a so-called risk tracking form. This provides the insight in the status and progress of each diagnosed risk. Senior management should provide formal approval of the risk management plan en verify the progress of the risk action plans in all subsequent gate reviews.

The RDM methodology is the only risk management method in which there is an emphasis on the variation in opinion about the risk perception. This method first investigates why there is no consensus before proceeding to the next step and prevents therefore groupthink in the team sessions (Keizer et al., 2002). An additional advantage of the RDM method is another possible groupdynamic bias. The procedure allows that every team member can speak up and it therefore allows a lot of issues that otherwise were festering under the surface during the project to be raised in a constructive manner. Because people like Michael could speak out their concerns and clarify their point of view in their perceived risk in the RDM, the issue is not kept under the surface during the project and strengthens the team's harmony and team ownership for the whole project (Keizer et al., 2002). Furthermore, the method has the most extensive risk list in literature. A disadvantage of the method however, is that it does not provide a direct overview of (multiple) risk and (multiple) effect chains and have no "lessons learned"-method for recording knowledge that came out of previous projects.

In table 1 a summarization of the classical risk management tool is made and shows whether the different phases of the tools are of quantitative or of qualitative nature. As is shown, in all tools the identification and the mitigation phase have a qualitative technique.

The advantages of a particular technique in a methodology compared to the other techniques used in the other methodologies presented in this section are summarized in table 2. The table provides the oversight of which type of risks are considered in the tool, whether the tool is sensitive to groupdynamics' biases, whether the tool considers only main effects of the risks (focuses on individual risks only) or also interaction effects (whether the tool gives an oversight in cause and effect chains), if the tool provides a "lessons learned" technique and what is considered to be the main advantage of the tool in which phase of the risk management process.

	Identification	Prioritization	Mitigation	Risk Tracking and Control
FMEA	Qualitative	Quantitative	Qualitative	Quantitative
Database	Qualitative	Qualitative	Qualitative	Qualitative
Matrices	Qualitative	Quantitative	Qualitative	Quantitative
RDM	Qualitative	Quantitative	Qualitative	Qualitative

Table 1: Phases of the classical risk management tools qualified

	Type of risks considered	Sensitive to groupdynamics' biases	Risk effects considered	Lessons learned technique	Particular advantages compared to other methodologies
FMEA	Technical	Groupthink, Central tendency	Main effect	Mainstream does not provide option	Builds on technical expertise.
Database	Technical, cost, time	Possible	Main effect	Yes	Pitfalls and successes of the risk mitigation strategy are recorded in the track and control phase and this record is reused as a "lessons learned" method in the mitigation phase of a new project.
Matrices	Technical, Cost and Time	Groupthink	Main effect and interaction - effects	No	The risk milestone chart described by Pennock and Halmes (2002) provides a clear overview of the progression of the perceived risk in time, after certain mitigation strategy accomplished milestones in the track and control phase.
RDM	Technical, Organizational and Business (market, commercial viability) in 12 domains	No	Main effect	No	In the identification and prioritization phase the tool is best considered in preventing biases from groupdynamics, has an emphasis on variation in perceived risk levels, accounts for prospect theory bias and has the most extensive risk reference list.

Table 2: Oversight classical risk management tools advantages

3.Methodology, functional requirements and research objectives

As stated in the introduction, risk management becomes more and more important for successful radical new product development and to be able to put innovative products in a short period of time on the market. However, a market that is increasingly more competitive due to fast globalization, makes product innovation without taking certain risks impossible. The Holy Grail is to know these risks and their impact and to mitigate these risks in time. This increases the new product success rate (Caillaud et al., 1999).

In order to know the risks, their impact and to be able to mitigate these risks effectively, a risk management tool is required. This risk management tool should not only be able to detect the likelihood, the (main) effect of the risk and the ability of the firm to influence these factors (Keizer et al., 2002), but should also provide a clear oversight of the interaction-effects between risks what can be easily updated, in order to get a sound risk picture the project is facing. The risk analysis should be directed towards as many domains as possible that have an effect on the radical new product development (supported by Skelton and Thamhain (2005) and Keizer et al. (2002) since risks in NPD occur in more domains than only technical, cost and time) and this analysis should not suffer from groupdynamics such as groupthink and central tendency. The mitigation step should be able to make the most out of knowledge gathered about risk management actions in the past and it should be able to combine this knowledge with new creative solutions from the current specialists and experts (partly from Keizer et al., 2002). Furthermore, the mitigation step should be able to consider the right actions to the right risks because of main and interaction-effects of these specific risks. A risk management tool should have a feedback loop that can be easily updated with new perceived risk level information when available in order to track and control the risks. Finally, the risk management tool should have such a feature, that every project that is executed with the risk management tool, also contributes to an ever increasing knowledge base in order to make the tool more and more robust for coming projects. This list delivers the functional requirements for the improved risk management tool.

To be able to fulfill the functional requirements needed for sound risk management, it is needed to explore which techniques satisfy these requirements and are therefore suited to implement in a phase of the improved risk management tool. Table 2 in the previous chapter provides the oversight of the advantages of the different phases of the methodologies. However, the preferred techniques for each risk management tool phase are divided over a couple of different risk management tools. The aim of this master thesis is therefore an attempt to combine the preferred techniques in one improved risk management tool. This delivers the first research objective:

Combine the best techniques available for the particular phases in risk management in one improved risk management tool.

This research objective delivers the following research question:

1.1. Which methodologies should be used in which phase of the new risk management tool?

The tools that use individual team member or expert interviews or brainstorming sessions with the project team members about which risks are perceived in the coming new product development project have subjective elements in the identification because they are based on team member or expert experience and/or can suffer from groupthink in the team sessions. Furthermore, the potential risks that are submitted have to survive a certain rather subjective selection process in order to proceed to the next phase. The only risk management tool that tries to avoid the rather subjective identification, selection process and groupthink is the RDM of Keizer et al. (2002). This method actively investigates first why there is no consensus before proceeding to the next step and accomplishes the individual interviews with the most extensive risk reference list existing in literature for identification of risks. The preferred method for the identification phase is therefore the RDM method.

The prioritization process is accomplished by brainstorming sessions with team members, individual questionnaires, via a rank provided to a particular risk in a database, via a questionnaire tool which prioritizes certain risks based on the answers provided by the user and the knowledge put in the question database. Another method of prioritization used, determines the factors severity, occurrence and detection of a particular risk and provide a risk ranking number by a mathematical calculation in which the factors are involved (FMEA).

The RDM is best in delivering in the identification phase, the list of identified risks and because of the emphasis on variation in opinion, it is also most suited to provide the main effect of the identified risks and prioritize the risks. Because of the variation in opinion a risk can evolve to a severe risk or a risk can be neglected. However, in the beginning of a project, it is not clear in what direction and magnitude the perceived risk will go and it is therefore important to first explore why there is no consensus. The RDM delivers in this phase all the main effects of the risks including the ones that have the most variation in probability.

The risk mitigation process in all risk management tools is a subjective process. Brainstorming with a risk management team, mostly the new product development team itself or by consulting experts, about the most efficient measures that should be taken to eliminate or decrease the risk is used. Another way of a risk mitigation strategy is delivered by the risk management tool database in which a history of past projects is recorded with its pitfalls and successes. The last strategy is a subjective way in the sense that the data in the database is put in via a brainstorming session with team members during previous projects or knowledge put in by consulting experts. It is less subjective in the sense that the database provides in this way a "lessons learned"-method about past projects what delivers accumulative knowledge and projects are in this way measured quantitatively as it were. The RDM method together with a database delivers the best solution for the risk mitigation process. The database provides the lessons learned in a qualitative way out of past projects to prevent reinventing the wheel, the RDM delivers the data by consulting specialists and experts for new creative solutions when the situation is different than described by the database or a better solution than described is available.

Most of those tools assign an owner to a specific risk in the risk tracking and control phase. The owner is responsible for executing the particular mitigation strategy and reports or updates information regarding the risk. The RDM describes an extensive risk tracking procedure. Each risk has a risk owner who is responsible for the mitigation of the particular risk and the reports that should be made to inform management. A graphical oversight to track risks is the risk milestone chart of Pennock and Halmes (2002) in which the progress of perceived risk levels of individual risks over time is set out. This method delivers the advantage that it is easily to assess and record the exposure of the project to individual risks after certain risk mitigation actions and therefore shows the progress over time. Finally, the best way to prevent reinventing the wheel in the future, is recording the pitfalls and successes of the risk mitigation strategy for each risk in a database.

The used techniques for the improved risk management tool can be summarized in figure 2.

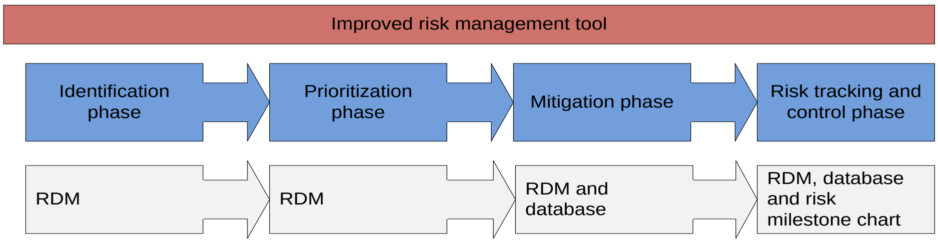


Figure 2: Overview of the classical techniques used in the improved risk management tool

However, one mayor problem is not solved with the combinations of the different techniques of the classical risk management tools. The tools do not take interaction effects into account at all or do not present them in a manageable way. This way (multiple) cause and (multiple) effect chains do not become clear. This oversight is needed since interaction-effects can have a huge influence on the final prioritization list. Stated hypothetically, it could be the case that two risks have such an influence on a third risk, that the risk level of this third risk becomes high and needs to be prioritized. This insight is crucial.

The (multiple) cause and (multiple) effect chains are also important in the risk mitigation phase to be able to mitigate the right risks. Stated hypothetically, it could be the case that it is cheaper or easier to mitigate two medium risks that have influence on a risk perceived as high, than trying to mitigate that particular high perceived risk. Another hypothetical example is that when two risks are perceived as high risks and should be mitigated, it could be the case that mitigation of one of those risks is enough and they don't have to be mitigated both. That way, the cheapest or easiest solution can be chosen.

Furthermore, the improved risk management tool should have a feedback loop that can be easily updated with new perceived risk level information when available in order to track and control the risks. The risk management tool should also have a feature, that when a project is executed with the risk management tool, each of those projects contributes to an ever increasing knowledge base in order to make the tool more and more robust for coming projects. These requirements are not fulfilled.

This delivers the second, third and fourth research objective of this thesis:

Find a technique that provides a clear oversight of (multiple) cause and (multiple) effect chains between risks in order to detect the interaction-effects between the risks.

Find a technique that can be easily updated when new perceived risk level information is available.

Find a technique that is suitable to capture such knowledge that it is possible to make the tool more and more robust everytime it is used.

The four research objectives deliver the following research questions:

2.1. Which technique(s) satisfy the remaining requirements?
2.1. How are the connections between the several methodologies established?

In order to achieve the last three research objectives, first a literature review has been done to search for the technique that delivers the clear oversight of the interaction-effects between risks and is able to make the tool more and more robust everytime it is used. The next chapter describes the promising technique to solve this matter: Bayesian Networks. In chapter 5 the result of the literature review is applied in the design of an improved risk management tool to fulfil the first research objective. In order to determine whether the design of this improved risk management tool is going into the right direction, whether it is useful in practice, interviews are held with 8 managers who dealt with or are dealing with risk management in innovation projects. The results of these interviews are set out in chapter 6.

4.The Bayesian (Belief) Networks Theory

Bayesian Networks (BN) and decision graphs became more and more popular in the 1990s to build frameworks that can handle uncertainty and not only in research institutions, but also in the industry. A good package of theoretical insight as well as practical experience is required in order to design these BNs (Jensen and Nielsen, 2007). Bayesian Networks are up to today more common in other disciplines like medical diagnosis and are rarely used for risk management of radical innovation projects. Only a couple of authors made a risk management system for innovation projects with Bayesian Networks: Fan and Yu (2004) and Chin et al. (2009). However, in the construction of BNs for risk management, no concrete, methodological approach has been found. Some papers only shortly discuss the consecutive steps towards a BN and do not provide a complete risk management tool. Also history building in BNs is not mentioned in literature and new in this thesis.

This chapter provides a deepening of the theory behind Bayesian Networks in order to provide an argumentation for the design of the Bayesian Networks in this thesis. This deepening is added since a large part of the improved risk management tool consists out of two Bayesian Networks.

Bayesian Belief Networks (BBN) or Bayesian Networks (BN) are causal visual graphs in which the nodes are the variables and these variables are connected with branches. These branches express the conditional probability between the nodes. When new information (“evidence”) of one of the variables is available, the network updates the probabilities of the other variables through “propagating” the new information through the network. This is called probabilistic inference (Neapolitan, 2004). They provide a powerful network to reason with uncertainty (Sigurdsson et al., 2001) and can combine heterogeneous data consisting of quantification of the opinion of experts, historical data (lessons learned) and new information that becomes available when the NPD projects proceeds; they combine statistical (hard) evidence and subjective evidence (Houben, 2010). The word “Belief” in the name of the methodology refers to beliefs of experts about the dependencies between the different variables (Neil et al., 2000). The term “Bayesian” is used for the network because it is based on Bayes’ theorem.

Arguments for adding Bayesian Networks to risk management tools are threefold (Fan and Yu, 2004): 1) Risk management should be done in a continuously feedback loop, so that problems can be dynamically detected and adjusted. 2) A Bayesian Network delivers a clear visual model, in which sources of risk can be easier determined. And 3) a Bayesian Network models uncertainties and provide probabilistic estimates which are updated when new data is available because of the feedback loop. In this way, BN can be used to identify, predict and estimate risks in a probabilistic way (Fan and Yu, 2004).

This chapter is divided into three parts. The first part deals with a general method of building a Bayesian Network according to Sigurdsson et al. (2001). The second part consists of section 2, 3 and 4 in which the mentioned method of Sigurdsson et al. (2001) is explained in more detail. The third part, section 5, finally provides some definitions about the analysis done within Bayesian Networks.

4.1.Building a network

Bayesian Networks are directed acyclic graphs (DAG) in which the variables represent a countable or continuous finite or infinite set of possible states. A variable is considered to be in exactly one of these states which may be unknown. The graphs are acyclic; feedback cycles are not allowed in BN because no calculus have been developed that can cope with feedback cycles in causal models. As depicted, Bayesian Networks are used to follow how a change of certainty in one variable may change the certainty in one or more other variables (Jensen and Nielsen, 2007; Stein, 2003). This master thesis considers only the discrete finite set of possible states because this is used for the improved risk management tool design.

Sigurdsson et al. (2001) provide a general approach for constructing a BN. The approach consists of a three-stage process in which seven steps can be distinguished (see figure 3).

The first stage consists of problem structuring (the qualitative part of the BN) and describes three steps. The first and third steps include the identification of the relevant variables and express them in such a manner that the statistical connections between the variables can be expressed probabilistically. The design of the connections between the variables is step two in this stage. The degree of effort required to build a Bayesian Network increases dramatically with the amount of variables.

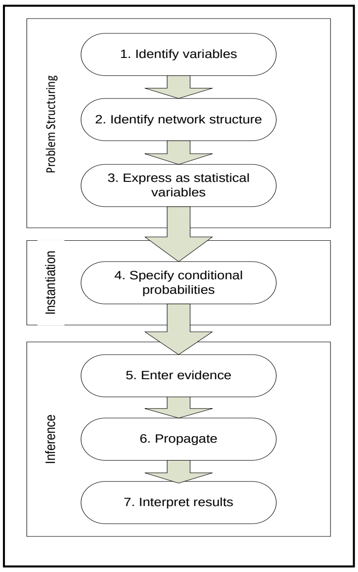


Figure 3: Method of building a BN according to Sigurdsson et al. (2001).

The second stage, instantiation or quantification consist of one step: specify the conditional probabilities of the variables. These probabilities can be derived from databases or expert opinions. This quantitative part of building a BN can be a hard task, especially when variables have many states and have many connections with other variables. A solution for this problem is described in section 4.4.

The third and final stage "inference" includes three steps. Variables can be filled with "evidence". This is a form of knowledge or information about the state of a certain variable or variables which is put in by the user. With this new information, the probabilities of the states of other nodes change when the information is "propagated" through the network. This is called "belief propagating" or "probabilistic inference" and when it is done, the Bayesian Network is "updated". With different sets of evidence "what if" analyses can be conducted or revised outcomes can be generated as new evidence becomes available over time (Sigurdsson et al., 2001).

To define a Bayesian Network, a Bayesian Network consists of the following (Jensen and Nielsen, 2007; Holmes and Jain, 2008):

- It consists out of a set of variables and a set of directed arcs between variables.
- Each variable has a finite set of mutually exclusive states.
- The variables and their directed arcs form an acyclic directed graph.
- Each variable Y with parents $X_1,\ldots., X_n$ has a conditional probability table $P(Y|X_1,\ldots., X_n)$.

4.2.The qualification of Bayesian Networks and the propagation of information

This section deals with the qualification or the arcs of a BN. Furthermore it describes how information is propagated through the network.

Bayesian Networks exist of different type of nodes. The nodes represent the variables and the arcs connecting the nodes represent the relations between these variables. The network begins with parent nodes which are connected to one or more several child nodes. One parent node can be connected to several child nodes and one child node can be connected to several parent nodes. When a child node has no descendant it is called a leave of the network and when a parent has no predecessor, it is called a root node (Sigurdsson et al., 2001) or ancestor (Díez and Drudzel, 2007). The combination of nodes, the parents and its child, is called a family (Díez and Drudzel, 2007). In figure 4 an example of a BN is illustrated graphically. In this figure, A, B, C and D are the root nodes of the network. Node G is a parent of H while nodes C and D are parent nodes of G. G is therefore the child of nodes C and D, while H is the child of G. Since H doesn't have a descendant, it is a leave of this network.

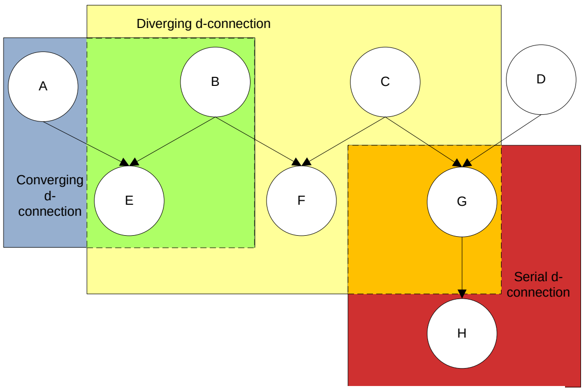


Figure 4: An example of a BN

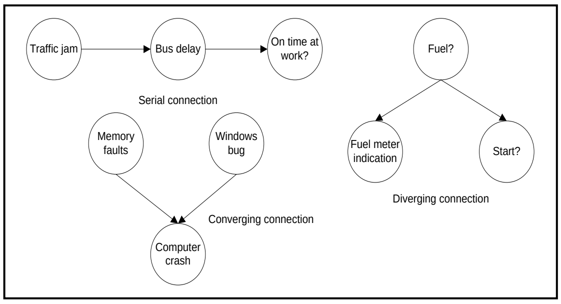


Figure 5: The different possible connections in a BN

In figure 4 and 5 the different possible dependence connections (d-connections) in a BN are displayed. "Dependent" because the state of the child node can only be determined when the state of the parent node(s) are known or vice versa. The examples are inspired by Jensen and Nielsen (2007) and Houben (2010). The possible states for all the nodes in figure 5 are {*yes,* no}, indicating whether the event occurs or not, except for the *fuel meter indication.* The possible states for the *fuel meter indication* are {*full, ½, empty*}.

In the serial connection, the traffic jam has an impact whether the bus will be late which in turn has its influence whether John will arrive on time at work since John always travels by bus to his employer. The same holds in the opposite direction. Evidence about whether John is on time at work influences the certainty of the traffic jam through whether the bus is delayed. When the bus delay is known however, the other two nodes become conditionally independent. This phenomenon is called that the "*traffic jam"*-node and the "*on time at work?"*-node are d-separated (dependence separated) from eachother given the "*bus delay*"-node. When it is known that the bus is delayed and that John is late at work, the fact that John is late at work, does not add new information about whether there was a traffic jam in this case. The variable is called instantiated or evidence is put into the variable, when the state of a variable is known.

In the diverging connection, when the node "*Fuel?"* is filled with evidence, it blocks communication between its children. Otherwise, evidence can be transmitted freely. The story is about a car. The fuel level has impact on the fuel meter indication and whether the engine starts. When it is known that the *fuel meter indication* is *full* and the *fuel?* is not given, the certainty that there is fuel increases. This gives also more certainty about the *yes* for whether the engine will start. However, when it is known that there is fuel, information about the fuel meter indication gives no extra information about whether the engine starts.

In the converging connection only when something is known about the consequences, then information about one possible cause may tell something about the other causes. To illustrate this, assume that is it known that a computer has crashed. The possible causes are faults in the hardware memory (defect capacitors) of the computer or software bugs (faults) in windows. If it is known that there are no faults in the memory, the certainty that there are bugs in windows increase given the computer crashed.

Another example inspired by the example given by Stein (2003), in which some of the connections mentioned are combined, is provided in figure 6. A person who has skin irritation is taken to a doctor. The doctor identifies the skin irritation caused by a fungus. The question is whether the fungus only lives at the home of the patient or whether the fungus also lives outside somewhere. In the last case, there will maybe more persons in the vicinity who suffer from the skin irritation. When the fungus only lives at the home of the patient, this has indirectly impact on the probability of the node "*outside*" via the "*one person*" node. The "*outside*" node has influence on the probability of the "*multiple persons*" node. In this example, when the fungus is only at the home of the patient, it excludes the option that the fungus lives outside and therefore excludes that multiple persons may have skin irritation.

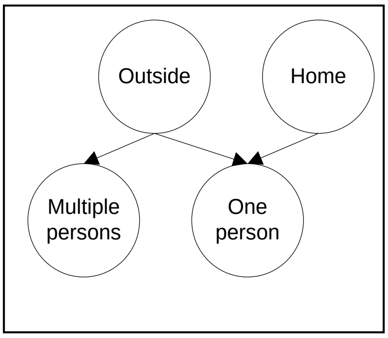


Figure 6: Example of skin irritation BN

The examples above provide the following definition (Jensen and Nielsen, 2007):
Two distinct variables A and B in a causal network are d-separated if for all paths between A and B, there is an intermediate variable V such that either 1) the connection is serial or diverging and V is instantiated or 2) the connection is converging and neither V nor any of V's descendants have received evidence. If A and B are not d-separated, they are d-connected.

To illustrate the propagation of evidence in a larger network, see figure 7 (Jensen and Nielsen, 2007). Jensen and Nielsen (2007) defined: "The Markov blanket of a variable A is the set consisting of the parents of A, the children of A, and the variables sharing a child with A." Neapolitan (2004) stated something similar. This definition provides that although the nodes C, D, G and H are instantiated, node E is still d-connected to nodes F, B and A (Jensen and Nielsen, 2007). Since node F shares a child with node E and F is not instantiated, F and E are connected (when the state of E changes, the state of F changes since the state of H is fixed). B is not instantiated, therefore F is connected to B since B is the parent of F. Through F, E is connected to B. Finally, B shares a child with A, which is not instantiated. Therefore B is connected with A and E is connected with A. When F is also instantiated, node E is d-separated.

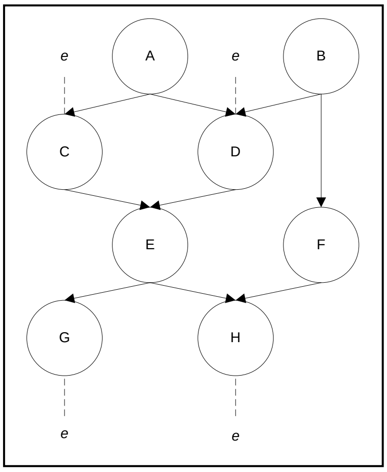


Figure 7: Example of propagation through a larger BN (Jensen and Nielsen, 2007)

4.3.The quantification of Bayesian Networks (1) and the propagation of information

The structure of a Bayesian Network is the qualitative part of the graph design (see previous section). With the information of the qualitative part of a BN, two mathematical formulas and when the network is filled quantitatively, Bayesian Networks can update the probabilities of the network when new evidence is entered and propagated.

The two mathematical formulas used in Bayesian Networks are:
Bayes' theorem: $P(A\,|B) = \frac{P(B\,|A)P(A)}{P(B)}$
and the total probability function: $P(A) = P(A|B)P(B) + P(A|\bar{B})P(\bar{B})$

Bayesian Networks use these formulas to propagate the effect of "evidence" or new information in a node in the network on the probability distribution of other nodes in the network either by forward (from cause to consequence) or backward (from consequence to cause) reasoning (Houben, 2010).

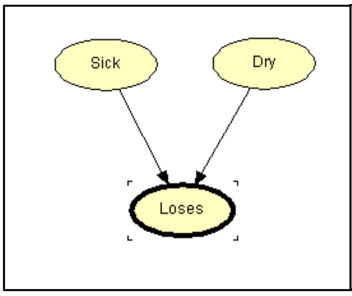
When B is the parent of A, the so called "strength" is defined by $P(A\,|B)$. When C is also a parent of A, the two conditional probabilities $P(A\,|B)$ and $P(A\,|C)$ alone do not give information about the interaction between B and C. B and C can co-operate or counteract in several ways. Therefore the theorem can be extended with more variables (Stein, 2003; Houben, 2010):

$$P(A\,|B,C) = \frac{P(B\,|A,C)P(A|C)}{P(B|C)}$$

To illustrate the calculations done in Bayesian Networks see appendix F where an example given by Neapolitan (2004) is provided.

Software, in which Bayesian Networks can be modeled, does the above mentioned computations automatically as is illustrated below.

The conditional probability of a node is displayed in a so-called Conditional Probability Table (CPT). This table is filled with probabilities; the probability of the variable in each possible state is indicated (see Figure 8, with CPT's for the nodes "Sick", "Dry" and "Loses"). Consider the example of figure 8. This example is adapted from the Hugin software tutorial (see reference 1) and from Kjaerulff and Madsen (2008). Hugin is a software package that can be used to model BN. The story behind the example BN is that a tree can lose its leaves because of sickness or the ground in which the tree stands is dry. This delivers the qualitative part of the BN, which node is connected to which other node.



Sick

Sick	0.1
Not	0.9

Dry

Dry	0.1
Not	0.9

Loses

Dry	Dry		Not	
Sick	Sick	Not	Sick	Not
Yes	0.95	0.85	0.9	0.02
No	0.05	0.15	0.1	0.98

Figure 8: Tree is losing leaves example.

The CPT of the node *Loses* shows that the probability of that the tree is losing its leaves, given the ground is dry and the tree is not sick, is 0.85. When the node *Loses* is in the "No" state, the probability is 0.15. The definition of BN restricts that the probability of all the states of a node added have to be always 1.

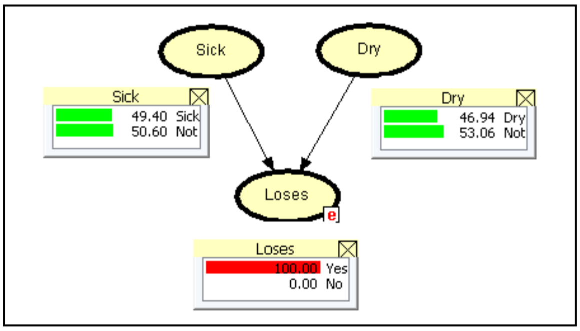


Figure 9: BN propagated with evidence

By putting in the evidence that the tree is losing its leaves, the probability that the cause is due to sickness is 49.40 and the probability that the reason is dryness of the ground is 46.94. This shows the propagation of evidence through the network (see figure 9).

The second example is based on the diverging connection network in figure 5 in the previous section and shows the probabilities calculated when no evidence is entered. The possible states for all the nodes in the figure are {*yes,* no}, indicating whether the event occurs or not, except for the *fuel meter indication.* The possible states for the *fuel meter indication* are {*full, ½, empty*}. The probabilities for the different variables with their different states are given in table 3. Assume it is not known in what state the variable *fuel?* is. This last means that the probability of the variable *start?* is distributed among the states *yes* and *no* of the variable *fuel?* and leads to $P(start? = yes) = 0.48$ and $P(start? = no) = 0.52$. To explain, see the most right table in table 2. When the state of variable *fuel?* is unknown, the probability of the state *yes* of variable *start?* is the calculation: $0.6 * 0.8 + 0.4 * 0 = 0.48$.

Fuel meter indication	Fuel?=yes	Fuel?=no
Full	0.6	0
Half	0.4	0.1
Empty	0	0.9

Fuel?	
Yes	0.6
No	0.4

Start?	Fuel?=yes	Fuel?=no
Yes	0.8	0
No	0.2	1

Table 3: Probabilities of the different variables in their different states

The size of the CPT depends on the number of states of the parent nodes (s_p), the number of parents (*p*) and the number of states of the child node (*s*) (Gerssen, 2004):

$$size_{CPT} = s * (s_p)^p$$

This formula indicates that problems arise quickly when the number of states or the number of parents grow. As an example, it can be determined that the CPT in figure 8 of the node *Loses*, the probabilities that have to be entered manually by two parents with two states and with a child that has two states are already 8 spots. To indicate the problem: when two parent nodes each have 5 states and the child have 5 states (for example: Very low, Low, Medium, High, Very High), 125 possible probabilities have to be filled in. For every variable a number of parameters is required that is exponential in the number of its parents in the graph. Since the probabilities have to be filled in mostly by experts, not only the problem arises that those experts have limited time available, but there is also a possibility that certain combinations may have never been seen by the experts. The solution lies in so-called "canonical models" like Noisy OR/MAX or Noisy AND/MIN. These models allow probability distributions from a small number of parameters (Jensen and Nielsen, 2007; Díez and Drudzel, 2007; Gerssen, 2004) and are described in the next section.

4.4.The quantification of Bayesian Networks (2) using canonical models

To be able to deal with the practical problem of large Conditional Probability Tables due to many parents and/or many states per variable, literature describes the existence of canonical models in the form of Noisy-OR/MAX, Noisy-AND/MIN and Noisy-XOR (Pradhan et al., 1994; Jensen and Nielsen, 2007; Díez and Drudzel, 2007; Gerssen, 2004; Galán and Díez, 2000; Korb and Nicholson, 2011). Other models like the Noisy adder (Heckerman, 1993) are also possible but are not a subject in this thesis. The canonical models consist of an extension of an original BN with virtual auxiliary nodes. This causes that only the CPT's of the parent nodes have to be filled in with expert data. The canonical parameters of the child node contain the same data as the parents' CPT's. The CPT of the child node can be easily calculated by means of these canonical parameters. How this calculation precisely works, is explained in this chapter. This section first sets out the theory behind the canonical models and secondly explains the models on the basis of some examples.

The theory of canonical models provides the knowledge engineer with a powerful solution to the large CPT's problem. However, although it looks like a simplification of the original mathematical methodology, it appears that the performance of the Bayesian Network does not degrade in performance when canonical models are used (Bolt and Van der Graag, 2010).

The term "noisy" consigns to the possibility that some of the causes fail to produce an effect even when they are present (Díez and Drudzel, 2007), this is explained later on in this section. Consider the Noisy-OR BN illustrated in figure 10, with *n* binary input variables X_n, *n* auxiliary variables Z_n, x_n the states of the variables X_n, z_n the states of the variables Z_n and an output variable Y (with *n* ϵ N). The binary variables only have the states *presence* and *absence* which means that *presence* of a variable X_n indicates an observation where x_n=1 and *absence* indicates x_n=0. The variables X_n "represent" the variables of the "OR-truth table" with their binary states, see table 4. For example, X_1 can be A, X_2 can be B and X_3 can be C with their associated states x_n=1 and x_n=0.

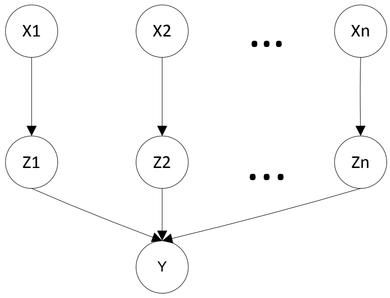


Figure 10: General Noisy-OR BN scheme

When the variable X_n has an observation of x_n=1, the probability between that parent and its child Y is "let through" to the node Y. Contrary, when the variable X_n has an observation of x_n=0, the probability between the child and the parent is "blocked" to the node Y. Summarized this yields the following for binary models, with *i* ϵ N (Díez and Drudzel, 2007; Galán and Díez, 2000):

- $c_i = P(+z_i|+x_i)$ with c_i as the probability that X_i produces Y when it is present. $c_i > 0$ because if c_i is zero, then X_i would not be a possible cause of Y and should therefore not be included as a parent.
- $P(+z_i|\bar{x}_i) = 0$, because when X_i is absent it cannot cause Y.
- The probability that the output node is *absent* is the product of the noise parameters / inhibitors for all the input nodes that are *present*:
  $P(\bar{y}|x) = \prod_{i \in T_x}(1 - c_i)$ with T_x the subset of causes that Y is present.

Furthermore, there are restrictions or assumptions in canonical models called independence of causal influence (ICI), which inhibits that there are no interactions among the causal mechanisms and inhibitors (Díez and Drudzel, 2007):

- Each cause has an independent chance of causing the effect.
- Inhibitors are independent. In which an inhibitor is defined as the inverse of the probability that the parent X causes child Y.

To be able to model a noisy gate in a modeling program like GeNie, the following definitions are needed (Gerssen, 2004; reference 2; Pradhan et al., 1994):

- The lowest value of x_i is assumed to be the "absent" state, therefore Z_i is absent if X_i is absent. This comes down to that the right column of the canonical parameters table of a node should contain a 1 at the bottom row and all the other rows contain the value 0. This is achieved with the *absent* state.
- The outcomes of the child node are ordered from the highest to the lowest. The outcomes of the parent nodes need also be ordered from the highest to the lowest (in

term of causal influence on the child node); from the one that influences the child most to the one that influences it least.

- The BN cannot model every possible case. The explanation is that any knowledge differs from reality and therefore suffers from incompleteness. To enable the closed-world assumption, the leak-variable represents the causes that are not modeled explicitly. In this thesis, any case is modeled and the leak-variable is therefore not needed. It is assigned to the state *absent* without any change of occurring (see figure 12 most right table).

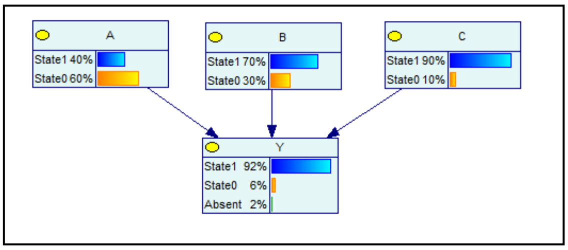


Figure 11: Noisy-OR BN example

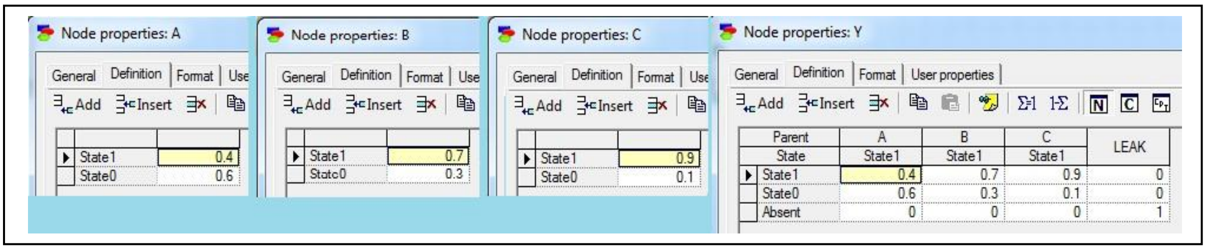


Figure 12: CPT's of the parent nodes A, B and C and the canonical parameter table of Y.

As an example of the binary canonical models, consider the Bayesian Network with Noisy-OR given in figure 11. In this network, the probabilities of the parent nodes are indicated: $P(Y|A) = 0.4$, $P(Y|B) = 0.7$ and $P(Y|C) = 0.9$, this delivers the canonical parameter table of the child Y indicated right in figure 12. The figure shows that the probabilities of the CPT's of the parents are filled in the child's canonical parameter table. To note the difference between a CPT and a canonical parameter table, compare the lowest table in figure 8 with the most right table in figure 12. In the first figure for every possible combination of states a probability has to be filled in, for example, the combination of states *sick*, *dry* and *yes* is 0.95 and the combination of states *sick*, *dry* and *not* is 0.85 (with the inverse state of the variable *Loses*). In figure 12, only the combination that the parent A is in state 1 and the child Y is in state 1 has to be filled in and not the inverse states and not the combination of states of other variables. As already stated, the CPT of the child node can be calculated out of this canonical parameter table. It can however be calculated with different functionality. To illustrate the possibilities and the easy adaptation of a node to create another function, the OR, AND and XOR (any odd-number of inputs "1" gives output "1") "truth-tables" with three parents are given in table 4, 5 and 6 respectively.

As defined above, the inverse output of the child node consists of multiplying the inverse probabilities when the particular parent nodes are in *state1* (see tables 7, 8 and 9). The output can be calculated by applying the inverse rule on the inverse output. As an example in table 6, the last row is calculated through the multiplication of the inverse probabilities between A and Y, B and Y, C and Y. These inverse probabilities are multiplied because at each of the variables, the table indicates a state "1".

Output	A	B	C
0	0	0	0
1	1	0	0
1	0	1	0
1	1	1	0
1	0	0	1
1	1	0	1
1	0	1	1
1	1	1	1

Output	A	B	C
0	0	0	0
0	1	0	0
0	0	1	0
0	1	1	0
0	0	0	1
0	1	0	1
0	0	1	1
1	1	1	1

Output	A	B	C
0	0	0	0
1	1	0	0
1	0	1	0
0	1	1	0
1	0	0	1
0	1	0	1
0	0	1	1
1	1	1	1

Left:
Table 4: OR truth table

Centre:
Table 5: AND truth table

Right:
Table 6: XOR truth table

Bottom left:
Table 7: Noisy-OR CPT of Y

Bottom centre:
Table 8: Noisy-AND CPT of Y

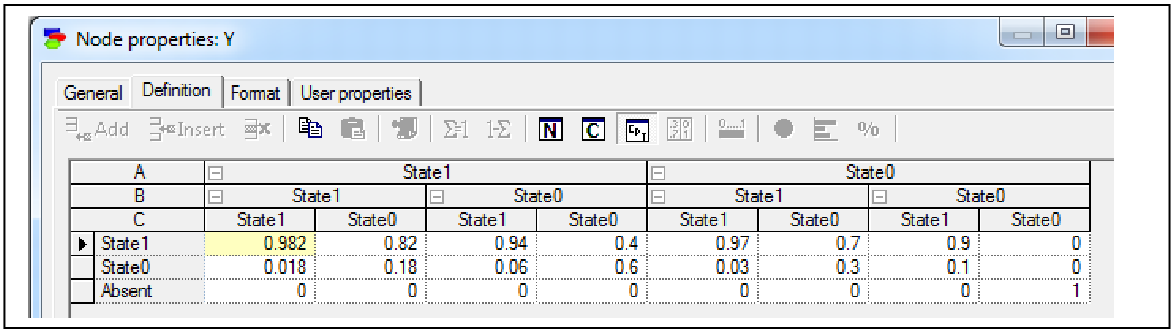
Bottom right:
Table 9: Noisy-XOR CPT of Y

P(Y)	P($\overline{Y}$)	A	B	C
0	1	0	0	0
0.4	0.6	1	0	0
0.7	0.3	0	1	0
0.82	0.6*0.3 = 0.18	1	1	0
0.9	0.1	0	0	1
0.94	0.6*0.1 = 0.06	1	0	1
0.97	0.3*0.1 = 0.03	0	1	1
0.982	0.6*0.3*0.1 = 0.018	1	1	1

P(Y)	P($\overline{Y}$)	A	B	C
0	1	0	0	0
0	1	1	0	0
0	1	0	1	0
0	1	1	1	0
0	1	0	0	1
0	1	1	0	1
0	1	0	1	1
0.982	0.6*0.3*0.1 = 0.018	1	1	1

P(Y)	P($\overline{Y}$)	A	B	C
0	1	0	0	0
0.4	0.6	1	0	0
0.7	0.3	0	1	0
0	1	1	1	0
0.9	0.1	0	0	1
0	1	1	0	1
0	1	0	1	1
0.982	0.6*0.3*0.1 = 0.018	1	1	1

Which function of X is selected in a Bayesian Network depends on the purpose of the child-node. When it is desired that not only one parent can influence the probability of a child when the parent state is *state1* then the Noisy-AND fulfills this need (table 8). With the Noisy-XOR the parents only influences the child when the quantity of the parents that are in state *state1*, is odd. Finally, with the Noisy-OR any parent can influence the state of the child node, independent of the state of other parents with the same child. These examples provide the insight that the function of the node can be simply altered by replacing the truth table of the virtual X-node.



A	State1				State0			
B	State1		State0		State1		State0	
C	State1	State0	State1	State0	State1	State0	State1	State0
State1	0.982	0.82	0.94	0.4	0.97	0.7	0.9	0
State0	0.018	0.18	0.06	0.6	0.03	0.3	0.1	0
Absent	0	0	0	0	0	0	0	1

Figure 13: CPT of child node Y

To complete the example, the CPT-table of the Noisy-OR child Y of figure 12 becomes as is demonstrated in figure 13 (compare with figure 8). GeNie does the calculations automatically, the only tables the user has to fill in are the ones in figure 12. Figure 14 finally provides the graphical prove of when the nodes A, B and C are filled in with the evidence that they are in *state1*. The chance that Y is in *state1* is 98% and in *state0* 2% as it is in table 7 in the last row.

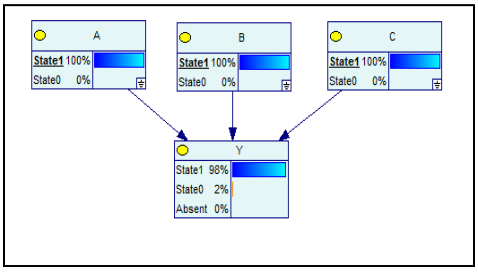


Figure 14: Noisy-OR BN filled with evidence

To complete this section, the Noisy-MAX theory is set out. The Noisy-MAX and the Noisy-MIN are generalizations of the nodes Noisy-OR and Noisy-AND respectively (Galán and Díez, 2000; Pradhan et al., 1994; Díez and Drudzel, 2007). The binary Noisy-MAX is another name for the Noisy-OR (Gerssen and Rothkrantz, 2004) with the difference between the two gates that the Noisy-OR is limited with two states per variable. When the number of states per variable exceeds two, it is called a Noisy-MAX gate. This allows that non-binary variables can be used with the following restrictions (Gerssen, 2004; Díez and Drudzel, 2007; Galán and Díez, 2000):

- The states of the variables should be ordinal, not nominal.
- The variables should have an equal number of states.
- The variables should be graded variables.

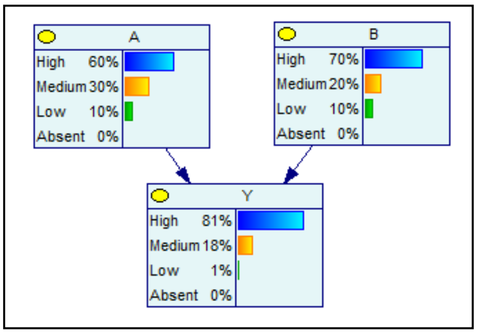
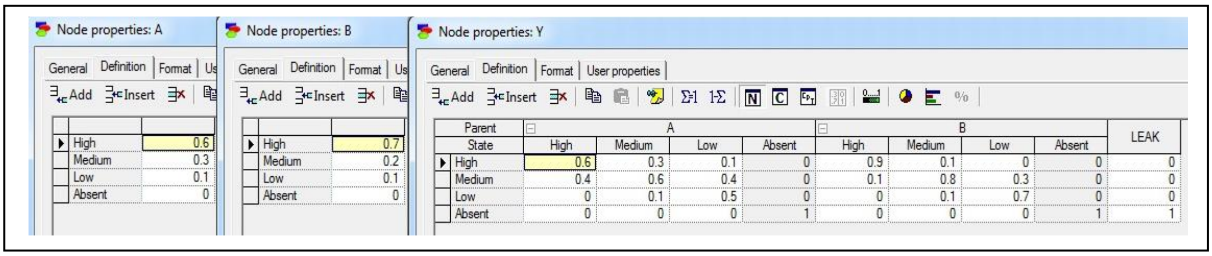


Figure 15: Noisy-max BN example

See again figure 10. In a noisy MAX node, each Z_i represents the value of Y produced by X_i. $y = f_{MAX}(z)$ as the value produced by the individual X_is. Explained in another way: each Z_i causes that X_i raise the value of Y to a certain value and the maximum of that value of Y is the maximum of the Z_is (Díez and Drudzel, 2007). A Noisy-MAX gate follows the next equations (Díez and Drudzel, 2007):

1) $c_y^{x_i} = P(Z_{i=y}|x_i)$ as the probability that each variable X_i, when it is in state x_i, raises the value of Y to y.
2) $P(Y \leq y|x) = \prod_i \sum_{z_{i<y}} c_{z_i}^{x_i}$
3) With $C_y^{x_i} = \sum_{z_{i \leq y}} c_{z_i}^{x_i}$
4) delivers $P(Y \leq y|x) = \prod_i C_y^{x_i}$
5) Each value of the Noisy-MAX CPT can be obtained with:

$$P(y|x) = \begin{cases} P(Y \leq y|x) - P(Y \leq y-1|x) \; for \; y \neq y_{min} \\ P(Y \leq y|x) \; for \; y = y_{min} \end{cases}$$



Node properties: A	
High	0.6
Medium	0.3
Low	0.1
Absent	0

Node properties: B	
High	0.7
Medium	0.2
Low	0.1
Absent	0

Parent	A				B				LEAK
State	High	Medium	Low	Absent	High	Medium	Low	Absent	
High	0.6	0.3	0.1	0	0.9	0.1	0	0	0
Medium	0.4	0.6	0.4	0	0.1	0.8	0.3	0	0
Low	0	0.1	0.5	0	0	0.1	0.7	0	0
Absent	0	0	0	1	0	0	0	1	1

Figure 16: CPT's of the parent nodes A and B and canonical parameter table of Y.

As an example consider the Noisy-MAX BN in figure 15, with the CPT's of the parent nodes and the canonical parameter table of Y in figure 16. The C-parameters are calculated with equation 3 from the Noisy-MAX formalization as is indicated in tables 10, 11 and 12. Note that the leak variable is not used as mentioned earlier. It is just added to complete the example.

	A		
C_y^a	High	Medium	Low
Y=High	1.0	1.0	1.0
Y=Medium	1-0.6=0.4	1.0-0.3=0.7	1.0-0.1=0.9
Y=Low	1-0.6-0.4=0	1.0-0.3-0.6=0.1	1.0-0.1-0.4=0.5
Y=Absent	0	1.0-0.3-0.6-0.1=0	1.0-0.1-0.4-0.5=0

Left:
Table 10: C parameters from node A

Bottom left:
Table 11: C parameters from node B

Bottom right:
Table 12: C parameters of leak variable

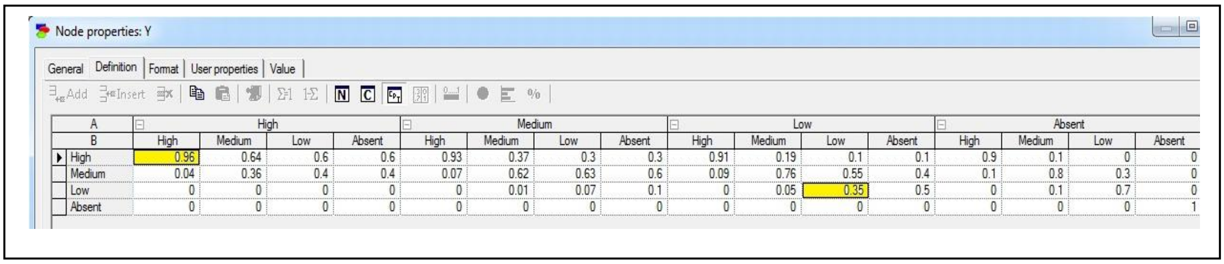
	B		
C_y^b	High	Medium	Low
Y=High	1.0	1.0	1.0
Y=Medium	1-0.9=0.1	1.0-0.1=0.9	1.0-0.0=1
Y=Low	1-0.9-0.1=0	1.0-0.1-0.8=0.1	1.0-0.3=0.7
Y=Absent	0	1.0-0.1-0.8-0.1=0	1.0-0.3-0.7=0

	Leak
C_y^L	
Y=High	1.0
Y=Medium	1.0
Y=Low	1.0
Y=Absent	1.0

The probabilities of the CPT of node Y are calculated with equations 4 and 5. Consider the next two calculations as an example:

1) $P(Y \leq High|A = High, B = High) = 1 * 1 * 1 = 1$ (with the last "1" as the leak-variable)
   $P(Y \leq Medium|A = High, B = High) = 0.4 * 0.1 * 1 = 0.04$
   $$P(Y = High|A = High, B = High) = P(Y \leq High|A = High, B = High) - P(Y \leq Medium|A = High, B = High) = 1 - 0.04 = 0.96$$
2) $P(Y \leq Low|A = Low, B = Low) = 0.5 * 0.7 * 1 = 0.35$
   $P(Y \leq Absent|A = Low, B = Low) = 0 * 0 * 1 = 0$
   $$P(Y = Low|A = Low, B = Low) = P(Y \leq Low|A = Low, B = Low) - P(Y \leq Absent|A = Low, B = Low) = 0.35 - 0 = 0.35$$

These calculations are made for the cells as indicated in figure 17. To complete the example, consider the evidence as noted in calculation 1, this delivers the graphical proof of figure 18. For more examples see appendix E.



Node properties: Y

General | Definition | Format | User properties | Value

A	High				Medium				Low				Absent			
B	High	Medium	Low	Absent	High	Medium	Low	Absent	High	Medium	Low	Absent	High	Medium	Low	Absent
High	0.96	0.64	0.6	0.6	0.93	0.37	0.3	0.3	0.91	0.19	0.1	0.1	0.9	0.1	0	0
Medium	0.04	0.36	0.4	0.4	0.07	0.62	0.63	0.6	0.09	0.76	0.55	0.4	0.1	0.8	0.3	0
Low	0	0	0	0	0	0.01	0.07	0.1	0	0.05	0.35	0.5	0	0.1	0.7	0
Absent	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure 17: CPT of Noisy-MAX node Y

In advance of the explanation of the design in chapter 5: for the design of the Bayesian Network part in the BNRDM, only the Noisy-MAX is used since all parent nodes must be able to influence the child node independent of the state of another parent node with the same child.

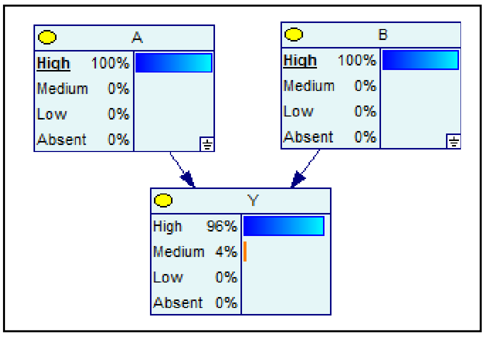


Figure 18: Noisy-MAX BN filled with evidence

4.5. Analysis within Bayesian Networks

Bayesian provides two types of analysis of which each consist out of two variants. This section explains what the difference is between the different types of analysis and how they can contribute to risk analysis. Some analyses are already used in this chapter. This section is therefore solely used to formalize them and indicate what other types of analyses exist.

The first analysis tool is scenario analysis which can be subdivided in two forms (Houben, 2010):

1) Prognosis: The outcome (value of the child node) can be calculated as a result of the inputs (values of the parent nodes) into the model. This is done with "forward reasoning".
2) Diagnosis: Given a certain outcome (value of the child), the most likely conditions (values of the parents) can be computed under which the outcome is obtained. This is a calculation made in the other direction and is called "backward reasoning".

The second analysis tool, sensitivity analysis, can be used to compare the effect of the different parent nodes on their child nodes. With this analysis it is possible to detect the most effective way to influence the target variable via other variables since changes in the value of the output variable may be small compared to changes in the input variables (Houben, 2010).

There are two methods of sensitivity analysis (Kjaerulff and Madsen, 2008; Houben, 2010):

1) In evidence sensitivity analysis the effect of changing values (providing evidence) of the different input variables (the parents) on the value of the output node (the child) is computed. This can be achieved by varying the value of one input variable with extreme changes, for example from 0 to 1 and vice versa.

   As an example, a scenario with a medical practitioner considers a treatment of a patient given the probability of a disease variable. The sensitivity analysis provides the practitioner the opportunity to investigate the distribution of the outcome variable (the hypothesis variable) with the collected information. Given a set of findings and a hypothesis, the analysis presents which sets of findings are in favor, against or irrelevant for the hypothesis (Kjaerulff and Madsen, 2008).

The disadvantage of sensitivity analysis is that so called 'influence diagrams' have to be created. In simple words, of each input node the user wants to analyze what the effects of the different inputs are on the outcome, a special node has to be added to the model. This node does nothing more than specifying each time that a particular input node is in a specific state. Other programs like Netica (see reference 3) can provide a sensitivity analysis without adding 'influence nodes', but this program has the disadvantage of that a license has to be purchased and GeNie is free of charge.

2) In parameter sensitivity analysis the effects of changing the value of a parameter in the model compared to the changes in the outcome (the values of the child) are considered.

In advance of the explanation of the design in chapter 5, the evidence sensitivity analysis is not used as a feature in the BNRDM because the evidence of the input nodes is provided by the interviewees and is not subject to a choice making process. In other words: the evidence of the input nodes is not "chosen" because the effect on the outcome is more favorable. The parameter sensitivity analysis is not used because this analysis simulates the effect of changes in the structure of the model. The structure of the model is designed as far as possible to model reality and the aim is to provide the end user with a tool that can be used for risk analysis and not with a design that has to be 'redesigned', therefore the parameter sensitivity analysis is not used either.

5.The design

This chapter contains the actual design part of this master thesis. It shows first which technique from which risk management methodology is used in the improved risk management tool. To be able to do this, an updated version of table 2 is made in which the Bayesian Networks are added. The second section of this chapter presents how the Bayesian Networks of the improved risk management tool are constructed and how these networks are filled with company specific data. It is required before conducting the actual improved risk management tool, that these Bayesian Networks are filled. The specific data represents the "history" of the firm in risk management and this procedure to fill the BNs has to be executed one time only. The "history" in these networks is updated when a project is completed to get a more and more robust tool everytime it is carried out. The third section in this chapter presents the actual improved risk management process as it has to be executed during a single project.

In chapter 3 a summarization was made to show which techniques should be combined in which phase of the improved risk management tool. However, with the techniques of the classical risk management tools, it was not possible to make a clear oversight of the interaction-effects between risks and make the tool more and more robust everytime it is executed. The previous chapter provided the technique that makes both possible. An updated version of table 2 is made in table 13 in which the Bayesian Networks technique is added. Since the Bayesian Networks is a technique that is able to make cause and effect chains and is not a risk management tool by itself, not all categories in the table in which the classical risk management tools are subdivided, are applicable.

As can be determined by examining the table, the Bayesian Networks solve the remaining not fulfilled functional requirements as described in chapter 3. In the four phases of the improved risk management tool, the Bayesian Networks appear in the risk prioritization, mitigation and risk tracking and control phase. The phases of the improved risk management tool become as is described below.

	Type of risks considered	Sensitive to groupdynamics' biases	Risk effects considered	Lessons learned technique	Particular advantages compared to other methodologies
FMEA	Technical	Groupthink, Central tendency	Main effect	Mainstream does not provide option	Builds on technical expertise.
Database	Technical, cost, time	Possible	Main effect	Yes	Pitfalls and successes of the risk mitigation strategy are recorded in the track and control phase and this record is reused as a "lessons learned" method in the mitigation phase of a new project.
Matrices	Technical, Cost and Time	Groupthink	Main effect and interaction -effects	No	The risk milestone chart described by Pennock and Halmes (2002) provides a clear overview of the progression of the perceived risk in time, after certain mitigation strategy accomplished milestones in the track and control phase.
RDM	Technical, Organizational and Business (market, commercial viability) in 12 domains	No	Main effect	No	In the identification and prioritization phase the tool is best considered in preventing biases from groupdynamics, has an emphasis on variation in perceived risk levels, accounts for prospect theory bias and has the most extensive risk reference list.
Bayesian Networks	Not applicable	Not applicable	Main and interaction -effects	Possible	Makes the interaction-effects between risks visible in a clear graphical oversight for the prioritization, mitigation and risk tracking and control phase and provides an option for history keeping.

Table 13: Oversight risk management techniques advantages and disadvantages

The improved risk management tool is named BNRDM. That name is chosen because the foundation of the improved risk management tool consists for the largest part out of the original RDM from Keizer et al. (2002).

To get into more detail of the improved risk management tool, the RDM itself also has to be adapted for the identification phase when the Bayesian Networks are added. During the identification phase, the interviewees should not only be posed the questions of the original RDM. They also need to be interviewed about “evidence” for the Bayesian Networks. This “evidence” is needed for providing insight in which risks need to be prioritized due to the interaction-effects in the next phase.

In the risk prioritization phase, the RDM delivers all the main effects of the risks including the ones that have the most variation in probability. A BN provides the answer in what magnitude this variation in probability will have a carry-over effect on other risks because of the cause and effect chains. The BN provides the insight in the interaction effects between the different risks. Both are needed to make a sound prioritization list.

The RDM method together with a database and the BN delivers the best solution for the risk mitigation process. The database provides the lessons learned out of past projects to prevent reinventing the wheel, the RDM delivers the data when the situation is different than described by the database and the BN provides the answers which risks are best suited to mitigate in terms of time, resources, effectiveness and complexity due to interaction-effects.

In the risk tracking and control phase, a risk management plan of the original RDM is composed and describes who is responsible for each of the diagnosed risks, what the action plan is for mitigating each of the diagnosed risks, how much time and resources are needed to deal with these risks and how progress will be monitored and reported (Keizer et al., 2002). The action plans are drawn up by subgroups of the risk management team and the progress of the action plan, with its milestones, is documented in a risk tracking form. This risk tracking form provides a framework for each individual risk about the status and progress (Keizer et al., 2002). To gain insight in the interaction among the diagnosed risks, the project team leader fills the BN’s with new evidence each time a milestone in the action plan is accomplished in the individual risk mitigation strategy. After the updating of the BN’s, new data is added to the risk milestone charts of the individual risks to provide the perceived risk level progress over time. After completing a total risk mitigation strategy for a certain risk, the database is updated with the successes and failures of the risk mitigation strategy for that particular risk. Furthermore, the BN’s statistical history is updated everytime a project is completed to make the tool more and more robust.

The used techniques for the BNRDM can be summarized in figure 19.

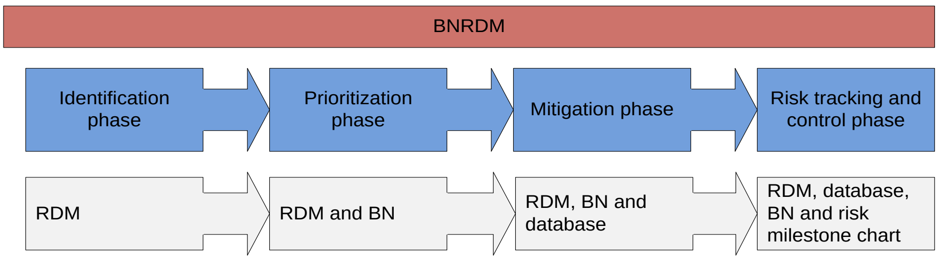


Figure 19: Overview of the techniques used in the improved risk management tool

5.1.The two Bayesian Network design

At the core of the extension of the original RDM are the two Bayesian Networks. Since they are the largest and most complicated part of the new risk management tool, this separate section deals with the design of the two BN’s. The original RDM shows which risks have the most variation in risk level and which risks are perceived as most risky individually (the main effect of risks). The two BN design make the original RDM procedure more robust since it shows the interaction effects between the separate risks. Because of these interaction effects, an original low risk level perceived risk can appear to be a high level perceived risk due to the interaction with other high level perceived risks. This insight is created with the BN's in the most important risks in the organizational and project management and commercial viability setting.

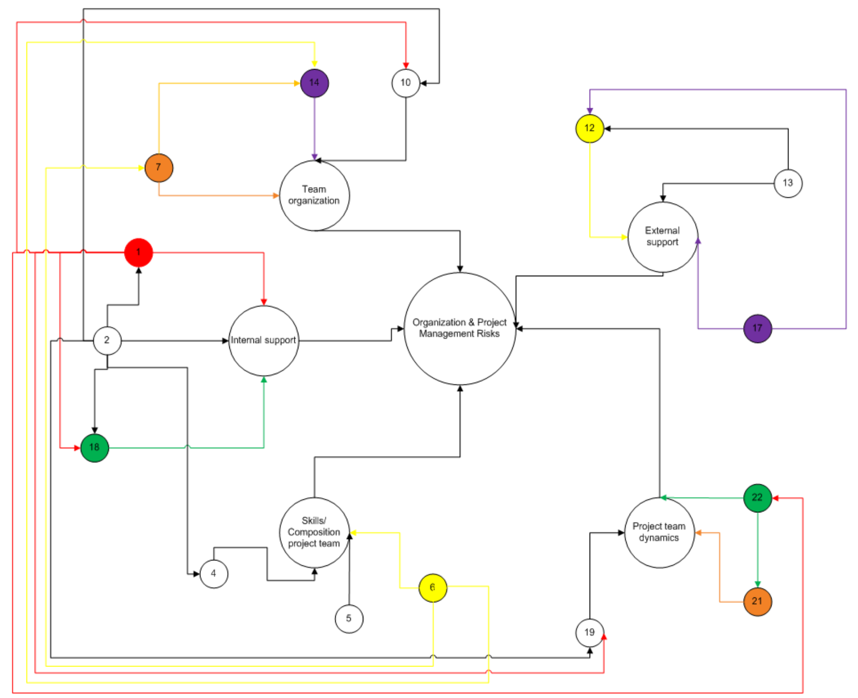
The first part of this section deals with the qualification part of the Bayesian Networks in which variables are selected and in which connections among the variables are made. The second part of this section deals with the quantification, how the CPT's of the BN's supposed to be filled. The CPT's are filled with that kind of data that reflects the current state of the company in risk management. This quantification of the Bayesian Networks is the preliminary work that has to be completed before a BNRDM procedure can be executed.

5.1.1.The qualification of the two Bayesian Networks design

The qualification part of the Bayesian Network deals with the determination of the variables and the identification of the connections between those variables (see chapter 4). This section describes the procedure taken to construct the qualitative part of the two Bayesian Networks that are part of the extension of the RDM.

The BN's are constructed out of the risk reference list with the same names of the original RDM (see appendix A). The commercial and organizational and project management risks are chosen for this exploration because of the generality of those risks and therefore a constructed BN (the qualitative connections) filled with these risks is widely applicable and mostly not limited to one organization. Other risks in the risk reference list are expected to vary more and are expected to have different a different set of variables and connections between these variables for every company or even project. They are therefore less suited for constructing a general applicable exploration BN for this exploration. The design prototype, the structure of the network (qualitative part), is distilled out of the RDM method by selecting the most important parts of the commercial and organizational and project management risks of the risk reference list. The total list in the appendix of the organizational and project management risks and the commercial viability risks are divided into sub-risk-topics to make it possible to indicate in a more detailed way the influence of those risks. The commercial viability risks are divided into the four sub-risk topics: market knowledge, capital requirements, supplier and risk mitigation/strategy (see figure 21) and the organizational and project management risks are divided into the five sub-risks: Internal support, Skills / composition project team, team organization, external support and team dynamics (see figure 20). Per sub-risk topic are the three most important risks selected in cooperation with the expert and author of the RDM: Dr. Keizer. The risks selected, are indicated in the figures. The most important risks are selected to keep things manageable for this exploration of the extension of the RDM. The connections between the variables are also made in cooperation with Dr. Keizer's expertise.

Note: The figures provided in this section are not screenshots of the actual BN's that are used in the BNRDM, but are made in another program to be able to clearly indicate the connections between the variables. Screenshots of the actual BN's can be found in the figures 25 and 26.



<u>Organizational & project management risks</u>

<u>Internal support</u>

1.Internal political climate is in favor of this project
2.Top management actively supports project
18.Collaboration between project team and the parent organization is effective

<u>Skills / composition project team</u>

4.Project team is sufficiently authorized and qualified for the project
5.Project team will effectively utilize the knowledge and experience of (internal) experts
6.Roles, tasks and responsibilities of all team members are defined and appropriate

<u>Team organization</u>

7.Decission making process in project is effective
10.Adequate money, time and (human) resources will be available when required
14.Collaboration within the project team is effective

<u>External support</u>

12.External development partners will deliver in time, conform budget and technical specifications
13.Sound alternatives are available to external development partners
17.Collaboration with external parties is effective

<u>Team dynamics</u>

19.Project team is highly motivated and committed
21.Project team has an effective planning and contingency planning
22.Project team is learning from past experiences

Figure 20: The connections between the organizational & project management risks

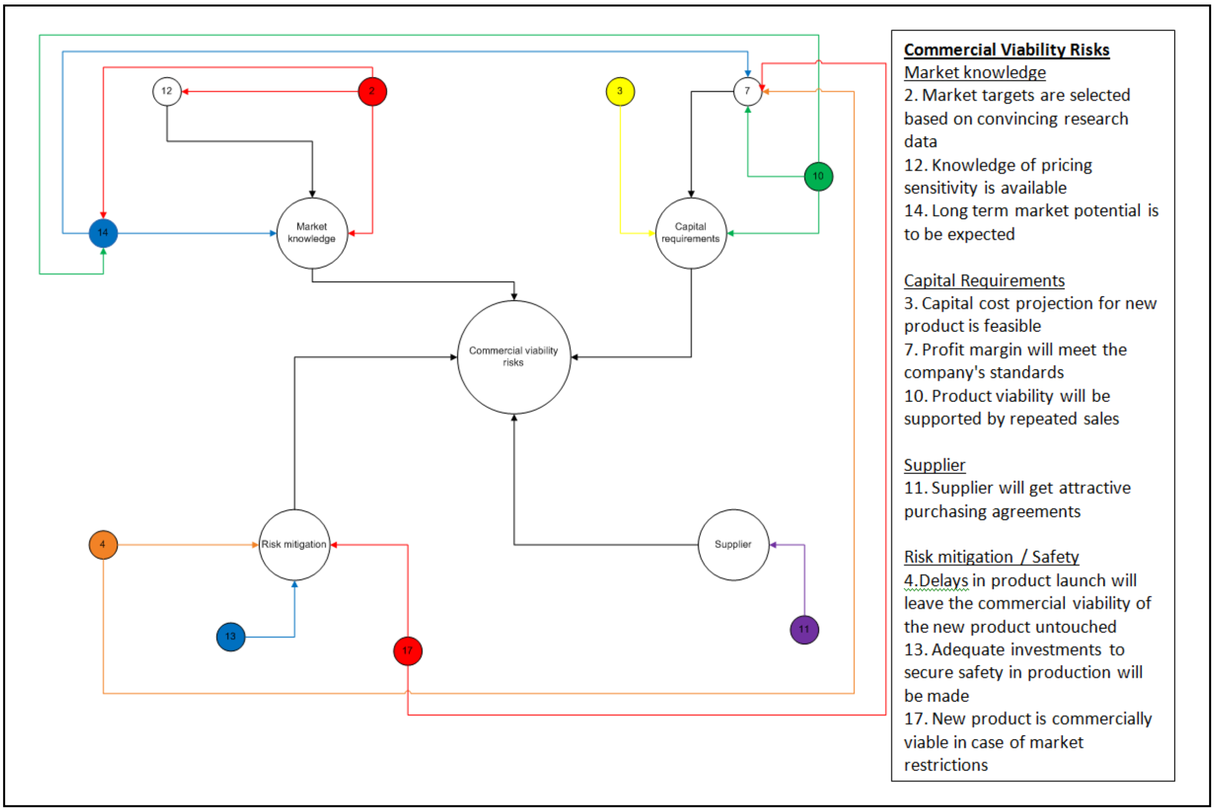


Figure 21: The commercial viability risks connections

5.1.2.The quantification of the two Bayesian Networks design

The quantification part of the Bayesian Network assigns probabilities to the states of the variables (see chapter 4). This section discusses the process to build the quantitative part of the two Bayesian Networks. The quantitative filling of the Bayesian Networks with company specific data is needed before a BNRDM procedure can be executed. It has to be done one time only. The data is updated everytime a BNRDM procedure is used for a project.

To be able to fill the Bayesian Networks with data to use for the BNRDM procedure, the questions that need to be asked are shown below in two examples of the Commercial Viability risks. The first set of example questions are for root nodes of the network, the second set provided is for nodes that have parent nodes, but have also child nodes themselves. The questions for other nodes in the network are similar. It is a daunting task, but it needs to be done for each project-category and have to consist of measurements over 10 different projects in the same project category to be reliable (with multiple interviews per project). This number is however an indication and there is no proof yet that this amount is sufficient. Nevertheless, the amount of measurements increases when after each conducted BNRDM procedure, the new acquired evidence is recorded in the probabilities of the nodes (see next section, step 11). The measurements done via the interviews, carried out by an external risk facilitator, are considered as a basis for the BN's and delivers the current state of the company in risk management. It is with the limitation that the more persons are interviewed by the external risk facilitator to fill the BN's, the better the basis. The external risk facilitator should have the same characteristics as the facilitator used for the RDM (Keizer et al., 2002). The external risk facilitator should have no direct stake in the projects for where the BNs are used for and is therefore relative independent. This way the risk facilitator can ask the questions unbiased by status, politics and what happened in earlier projects. Project members will be more likely to confide their worries to such a facilitator.

Note that the questions are negatively framed compared to the risk points stated in figure 20 and 21. This is due to the fact that the Bayesian Networks measure risks. For example, the risk of whether the "internal political climate will be in favor of this project" becomes "what is the level that the internal political climate will not be in favor of this project". This design choice is made despite the fact that positively framed questions are in favor of risk discovering (Keizer et al., 2002). It would not be a workable situation when all the answers given need to be inverted before the probabilities are added to the CPT's. Especially for large tables the invert-procedure would be rather complex and far more prone to mistakes as a result.

All questions are of the order: "In what state is Y given Xi = xi and all the other causes of Y are absent?", instead of: "What is the probability that Y=y given Xi = xi and all the other causes of Y are absent". It is considered easier for the interviewee to give an indication whether the risk perceived is low, medium or high than giving the chance that the low, medium or high state occurs.

The first set of example questions are for root node 2 of the Commercial Viability Risks:

- What is the state that the market targets selected are not based on convincing research data, low, medium or high? This delivers data for the CPT of node 2 (see figure 22, the green area).
- The following question will be: "When the market targets selected are not based on convincing research data have the state as the interviewee answered, how large will be the negative effect on the knowledge of the pricing sensitivity. Will this be low, medium or high?" This delivers data for the canonical parameter table of node 12 (see figure 22, the yellow area).
- The third question: "When the market targets selected are not based on convincing research data have the state as the interviewee answered, how large will be the negative effect on the long-term market potential? Will this be low, medium or high?" This delivers part of the answers needed to construct the canonical parameter table of node 14 (see figure 22, the orange area).
- The fourth question: "When the market targets selected are not based on convincing research data have the state as the interviewee answered, what will be the negative effect on the total market knowledge? Will this be low, medium or high?" This delivers 1/3 of the data needed for the canonical parameter table of the node "Market Knowledge" (see figure 22, the pink area).

The second set example questions are for a non-root node, in this example for node 14:
When the states of 1) "the product viability won't be supported by repeated sales" and 2) of "market targets are not selected based on convincing research data" are as indicated by the interviewee have on the state of the market potential (data of the orange and light blue area of figure 22), what will be the negative effect that this market potential has on:

1) The market knowledge (see figure 22, the red area)
2) Whether the profit margin will not meet the company's standards (node 7, see figure 22, the purple area.)

in terms of low, medium and high?

The question to complete the table of node 14: "When the product viability won't be supported by repeated sales with the state as indicated, what will the level be of the negative effect of this on the long term market potential?" This delivers the second part of the answers needed to construct the canonical parameter table of node 14 (see figure 22, the light blue area).

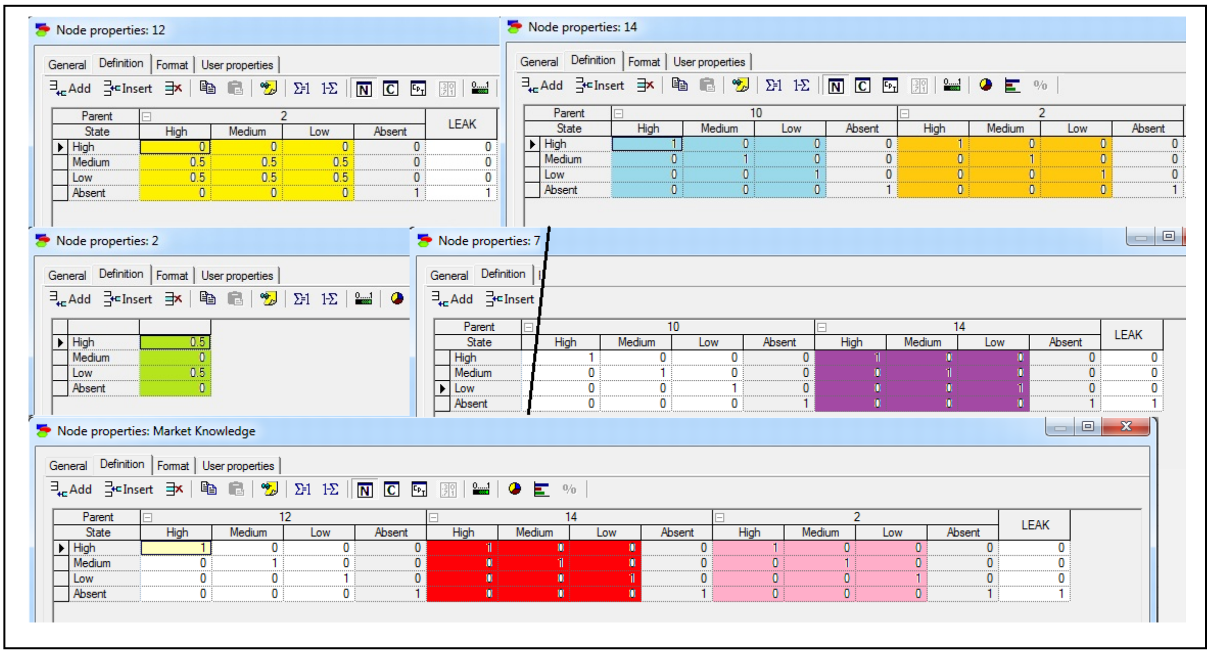


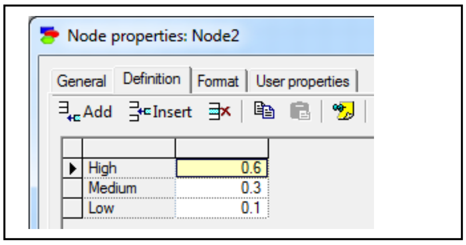
Figure 22: Areas of CPT's and canonical parameter tables

Basically, every arc or relation between two variables is given a weight in the form of low, medium or high and the probability that a particular node is in a particular state, is calculated by the amount of persons that voted for that particular state divided by the total amount of persons that voted a state on that specific node. For a non-root-node holds something similar, but with the addition of the probability of the previous node: the probability that a particular node is in a particular state, is calculated by the amount of persons that voted for that particular state divided by the total amount of persons that voted a particular state on the previous node. With the questions, as indicated in the example sets, answered by multiple persons, you get a distribution needed to fill the CPT's or canonical parameter tables of the nodes. An example of the procedure to come from data to a table with probabilities is shown below. It contains fictional data.

--**Example**--

Assume the following data comes out of 100 interviews, divided over multiple projects in the same project-category.

The state selection of root-node 2 of the Commercial Viability Risks is achieved by asking the question (question 1 of the root node questions): "What is the probability that the market targets selected are not based on convincing research data, low, medium or high?" This question delivers the data of table 14.



Magnitude	# persons voted for this state
High	60
Medium	30
Low	10

Figure 23: CPT for root-node 2 of the Commercial Viability Risks

Table 14: State partition of node 2 of the Commercial Viability Risks

Out of the data of table 14, the following can be calculated:
The state *High* has a chance of occurring: 60/100=0.6
The state *Medium* has a chance of occurring: 30/100=0.3
The state *Low* has a chance of occurring: 10/100=0.1
These calculations deliver the CPT for node 2 as indicated in figure 23.

The state selection of node 14 of the Commercial Viability Risks, given the state chosen by the interviewee of node 2 is achieved by asking a form of question 2 of the root node questions. As an example, an interviewee voted as a chance that the market targets selected are not based on convincing research data as *high*. The question for this table 15 will be: "what is the chance that a long term market potential is not to be expected when the market targets selected that are not based on convincing research data is *high*?"

	# persons voted for the states		
States of node 14, given states voted by node 2	States voted by the interviewees by node 2		
	High	Medium	Low
High	50	5	0
Medium	10	20	4
Low	0	5	6
Total persons	60	30	10

Table 15: State partition of node 14 given the data of node 2 of the Commercial Viability Risks

When the table is filled in correctly, note that the numbers in the last row are the same as in the previous table 14. The data provided in table 15 delivers the probabilities as indicated in table 16. This is the data needed to fill the orange area of figure 22.

	# probabilities voted for the states corrected		
States of node 14, given state voted by node 2	States voted by the interviewees by node 2		
	High	Medium	Low
High	50/60 = 0.83	5/30 = 0.17	0
Medium	10/60 = 0.17	20/30 = 0.66	4/10 = 0.4
Low	0	5/30 = 0.17	6/10 = 0.6

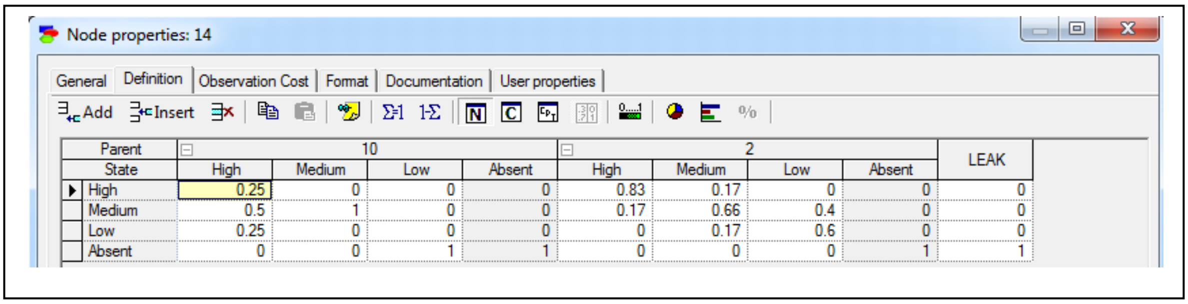
Table 16: Probabilities of the data provided in table 12

The state selection of node 14 of the Commercial Viability Risks, given the state chosen by the interviewee of node 10 is achieved by asking a form of question 2 of the root node questions. This question delivers the data provided in table 17.

	# persons voted for the states		
State of node 14, given state voted by node 10	States voted by the interviewees by node 10		
	High	Medium	Low
High	20	0	0
Medium	40	20	0
Low	20	0	0
Total persons	80	20	0

Table 17: State partition of node 14 given the data of node 10 of the Commercial Viability Risks

The data of table 15 and 16 delivers the canonical parameter table of node 14 as is indicated in figure 24.



Parent	10				2				LEAK
State	High	Medium	Low	Absent	High	Medium	Low	Absent	
High	0.25	0	0	0	0.83	0.17	0	0	0
Medium	0.5	1	0	0	0.17	0.66	0.4	0	0
Low	0.25	0	0	0	0	0.17	0.6	0	0
Absent	0	0	1	1	0	0	0	1	1

Figure 24: The canonical parameter table of node 14

---End of example---

The qualification procedure described in the previous section and the quantification method set out in this chapter delivers the two Bayesian Networks as in the figures 25 and 26. The probabilities in the figures are not displayed.

For the design of the two Bayesian Networks extensions of the BNRDM, only the Noisy-MAX is used since all parent nodes must be able to influence the child node independent of the state of another parent node with the same child (see chapter 4). Furthermore, the variables have three states but can be extended to five. The usage of three states is chosen because the CPT values have to be reliable. When five states are added, the experts are also divided over five states and the “reliability power” of a state is decreased. Of course when the number of interviewees is sufficient, add the states “Very Low” and “Very High” to the possibilities (see appendix C and D for the 5 states BN designs).

A final remark in quantifying the two Bayesian Networks: the appropriate number of persons to fill in a BN to make the outcomes reliable is unclear. Literature is not consistent, several studies speak of “experts” (Díez and Drudzel, 2007; Gerssen, 2004; Korb and Nicholson, 2011; Bolt and Van der Graag, 2010; Sigurdsson et al., 2001) while others even about one “expert” (Galán and Díez, 2000; Pradhan et al., 1994; Heckermann, 1993).

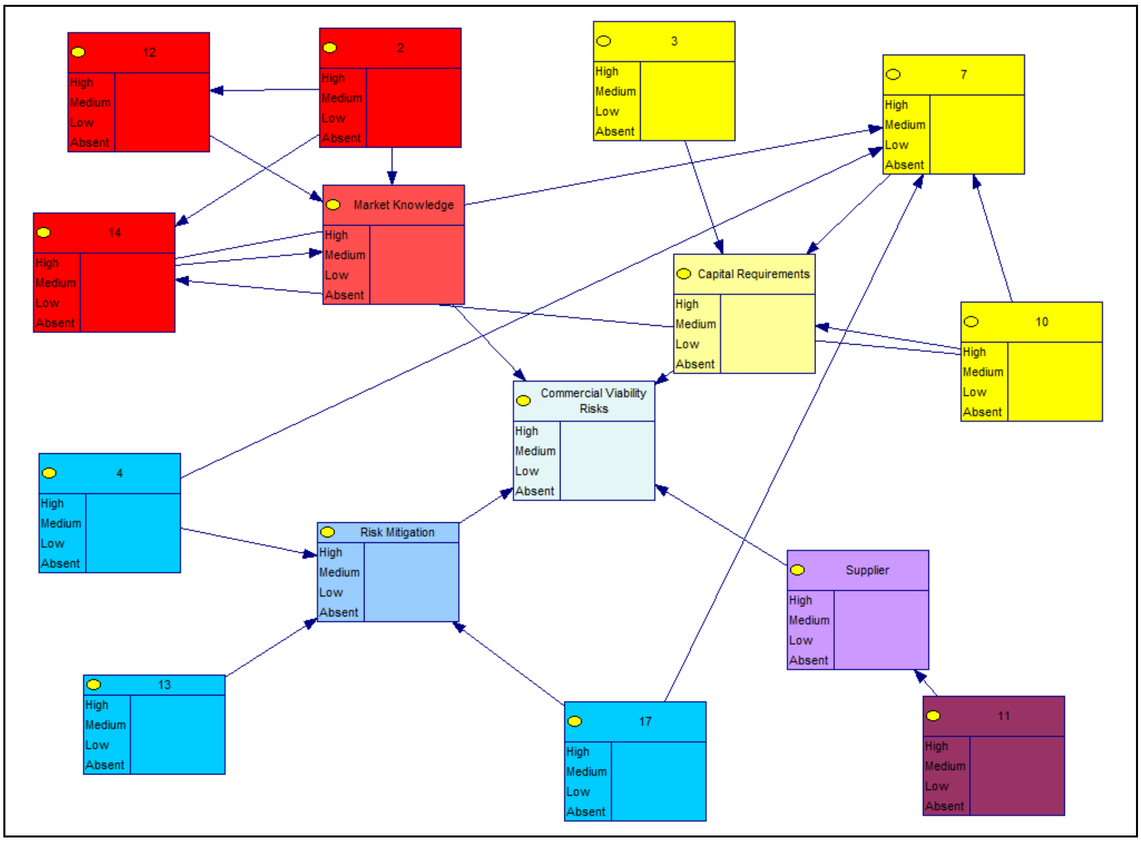


Figure 25: The Commercial Viability Risks BN

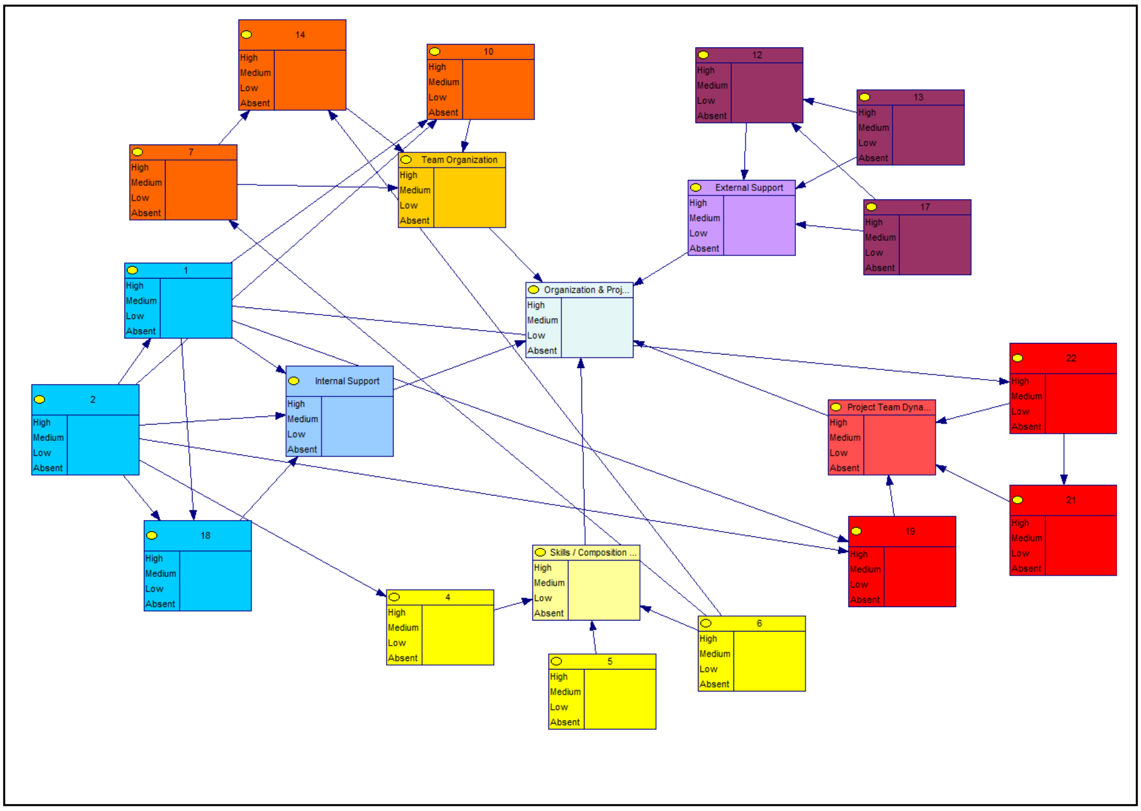


Figure 26: The Organizational & Project Management Risks BN

5.2.The Bayesian Networks Risk Diagnosing Methodology

As it is already stated in the name, the BNRDM is an extension of the original RDM developed by Keizer et al. (2002). It is an extension of the RDM since that technique is present in all the four phases of the improved risk management tool. To make this master thesis self-contained and complete as possible, parts described in this chapter are taken from the original RDM paper as far as needed. Furthermore, a sole description of the extension would be rather complex, cluttered and the oversight would be lost since the extension is intertwined in the original RDM and it alters the original methodology in different steps and in various areas. This chapter describes the improved risk management tool designed to manage risks in a single radical innovation project.

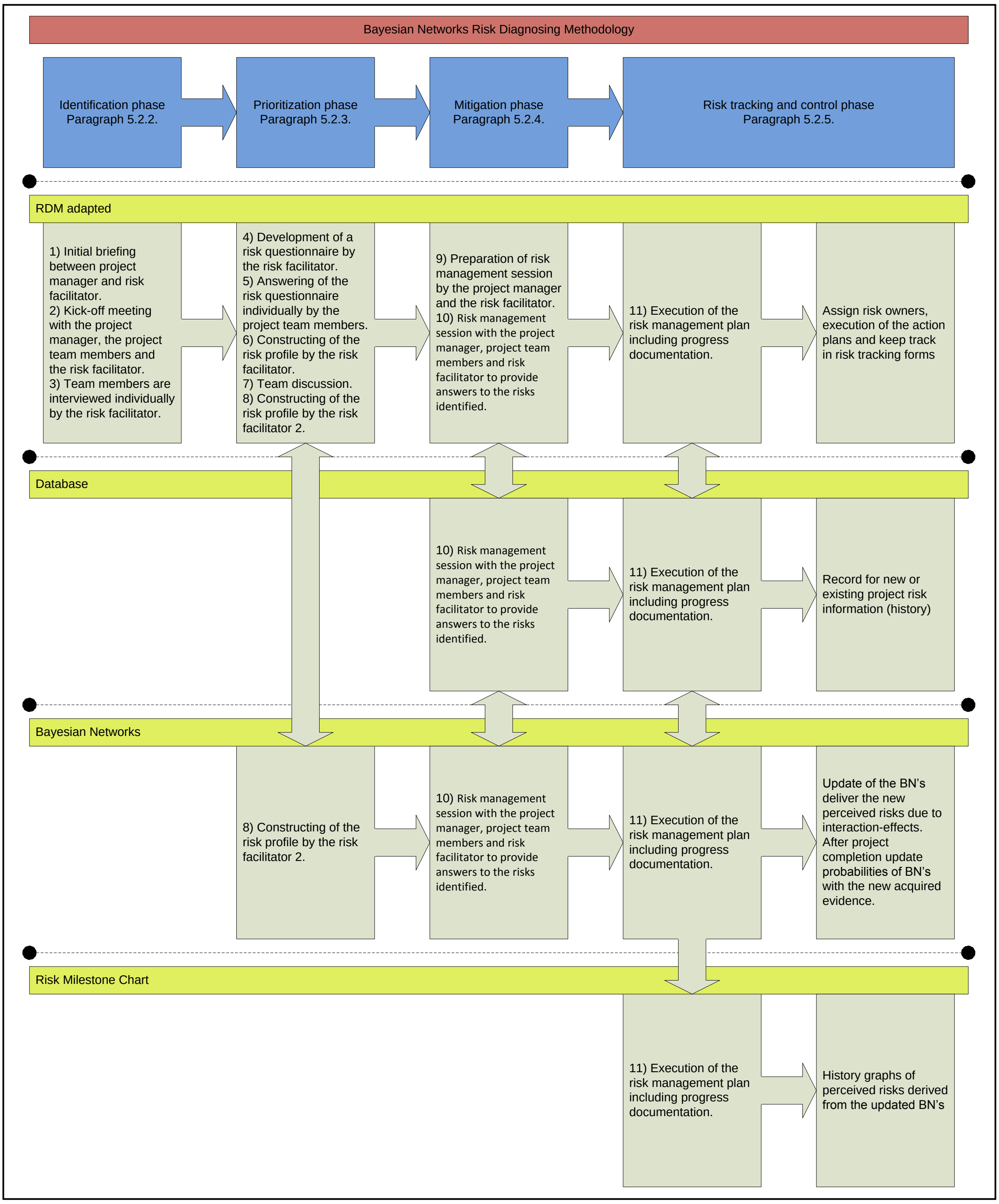


Figure 27: Schematic overview of the Bayesian Networks Risk Diagnosing Methodology

As presented earlier, the BNRDM is subdivided into four phases: the risk identification phase, the prioritization phase, the mitigation phase and the risk tracking and control phase. An oversight of the BNRDM is given in figure 27. This figure describes which techniques and which steps are used in which phase of the improved risk management tool. Furthermore, it provides which section deals with which phase of the tool. A section describes the different steps to be taken in that particular risk management phase. The steps are taken from the original RDM and extended when needed for the BNRDM.

5.2.1.BNRDM Introduction

The Bayesian Networks Risk Diagnosing Methodology (BNRDM) is a risk management tools designed to initiate at the end of the feasibility phase of an innovation project. It identifies and evaluates risks in technological, organizational and business categories. The main effect of a risk is determined by its likelihood, its effects (impact) and the firm's ability to influence the risk factors in the following categories (Keizer et al., 2002):

1) *Technological risk*: product design and platform development, manufacturing technology and intellectual property.
2) *Market*: consumer and trade acceptance, public acceptance and the potential actions of competitors.
3) *Finance*: commercial viability.
4) *Operational risk*: internal organization, project team, co-development with external parties and supply and distribution.

The main question that resides from these risk categories is: what is new or different in the knowledge and skills this project or the company requires in general and the project team in particular (Keizer et al., 2002)?

The BNRDM is conducted in an 11-step process. These steps are described in the coming sections.

5.2.2.Risk Identification phase

Step 1: Initial briefing

The BNRDM is preferably executed with the help of an outside risk facilitator who has state-of-the-art knowledge about product innovation. The advantage of an outside risk facilitator is that he has no direct stake in the project and is therefore seen as relative independent. The responsibility for the actual risk management of the project should stay nevertheless with the project leader. Because of the relative independence, the risk facilitator can ask questions unbiased by status, politics and what happened in earlier projects. Project members will be more likely to confide their worries to such a facilitator. The initial briefing step consists of a meeting between the project manager and risk facilitator in which they make appointments about specific project related topics and some general topics. Project-specific topics include its objectives, its unique characteristics and its stakeholders. The outcome of this meeting should be agreements between project manager and risk facilitator on actions to be taken and send invitations for a "kick-off" meeting for participants in the RDM process. It is important that the participants in this RDM-team have expertise in a various range of areas like technology, business and marketing. These experts can also be from outside the company. A RDM process team usually consists of 10 - 20 participants (Keizer et al., 2002).

Step 2: kick-off meeting

The participants for kick-off meeting are the project manager, the RDM team members and the risk facilitator. In this meeting the expectations of and plans for the RDM process are displayed to the project team members. It is to make sure that the team members know of what is expected from them in subjects like the expected input, level of involvement and amount of time it takes from the participants. Above all it is important to stress the confidentiality of the interviews and information provided by the participants (Keizer et al., 2002).

Step 3: individual interviewing of the participants
Each project team member is individually interviewed by the risk facilitator to discover the potential severe risk issues in the project. They are interviewed individually with intend because it provides the participant the freedom of speech in what they perceive as the most risky aspects of the project. It furthermore prevents groupthink (Landy and Conte, 2007) and it prevents central tendency (Blumberg et al., 2005).

Each interviewee is asked to study the project innovation charter, the project plan, the extensive risk reference list on twelve domains of potential risk issues in an innovation project (see appendix A), the list of potential risk issues in the two Bayesian Networks and the relations between the risks. In each new interview, the preceding interviews are taken into account, without mentioning a name, to verify the completeness and correctness of the already gathered risk issues (partly Keizer et al., 2002).

The protocol for the interviews is as follows (Keizer et al., 2002, adapted):

- An introduction by the participant and the risk facilitator. In addition, the risk facilitator sets out the objective of the interview and underlines the confidentiality of the interview and the information provided by the interviewee again.
- First a general introduction about the participants position in the organization and his link to the project.
- Let the interviewee provide the "gaps" in the project according to his opinion. "What do you see as gaps in knowledge, skills and experience for this project?" and "Can these gaps be bridged within time and resource constraints of the project?"
- Referring to the extensive risk list of appendix A and the two Bayesian Networks: "what other gaps might be difficult to bridge?" The goal is to find out whether there might be "evidence" for the parents 2, 3, 4, 7, 10 to 14 and 17 of the "Commercial Viability Risks" BN and/or for the parents 1, 2, 4 to 7, 10, 12 to 14, 17 to 19, 21 and 22 of the "Organizational and Project Management Risks" BN. When the participant is pointed at the BN's he might get inspiration of potential risks described in those risk lists and a question can be developed around this potential risk in the next step.
- By closing the interview, the risk facilitator should pose the question: "Did we forget something?"
- Final steps of the interview: the risk facilitator briefly explains again what the interviewee can expect next, namely the risk questionnaire and the risk management session.

5.2.3.Risk Prioritization phase

Step 4: Development of a risk questionnaire by the risk facilitator
Out of the results of the interviews, a risk questionnaire is made by the risk facilitator in which the critical issues are transformed in positive statements of "objectives to be realized". For example when an interviewee notes: "We will be using a new ingredient in our product solution, and I have read in a journal that this material sometimes causes skin irritations", the statement should be transformed in: "The new product formula will be safe to use also for people with a sensitive skin." As mentioned earlier, the prospect theory of Kahneman and Tversky (1979) states that negative framing of risks induces more positive perceptions than positive framing. In risk identification it is important that risks are not accepted easily, therefore positive statements are preferred. For example, people tend to respond to negative statements with: "It is not that bad", while they respond to a positive statement with: "They may suppose so, but I am not that sure." The critical issues are clustered according to the risk categories distinguished in the risk reference list (Keizer et al., 2002).

Step 5: Answering the risk questionnaire by project team members.
Each individual team member is asked to fill in the questionnaire with the positive risk statements. Each risk statement is composed of three sub-risk statements which are judged by the team members on a 5-point Likert scale. The three sub-risk statements include: "The level of certainty that the objective formulated in the risk statement will be realized", "The ability of the team to reach an appropriate solution using the project's allocated time and resources" and "The relative importance of the objective to project performance" (see figure 28).

Risk Statements:	What is the *level of certainty* that the statement will be true?					*Ability of team to influence* course of actions within time & resource limits					*Relative importance* of statement for obtaining project success				
	Very Low				Very High	Very Low				Very High	Very High				Very Low
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1. The new product will be safe to use for people with a sensitive skin.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2. With the trade customer clear after sales arrangements have been agreed.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. For localized dye damage we have an appropriate solution.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Figure 28: Example of part of a risk questionnaire, adapted from Keizer et al. (2002).

The questions should be answered as completely as possible by the participants, but they should not fill in issues they have no idea or opinion about. A typical questionnaire consist of 50-60 questions and the average time to complete it is 45-60 minutes (Keizer et al., 2002).

Step 6: Constructing of the risk profile by the risk facilitator.
The risk profile that is made out of the questionnaires by the risk facilitator consists of the degrees of the risks perceived by the majority of the participants (the "cum %"-line in figure 29) and a distribution of their perceptions (the "50%"-line in figure 29). The score is marked where there is at least 50% of the support for that particular risk on the 5-point scale (see the dot in figure 29). This dot provides a first glimpse of the thinking of the majority of respondents. The next task of the risk facilitator is to classify the risk statements in two ways. The first stage is the classification of every risk statement along the three parameters: "The level of certainty that the objective formulated in the risk statement will be realized", "The ability of the team to reach an appropriate solution using the project's allocated time and resources" and "The relative importance of the objective to project performance" by following the rules (Keizer et al., 2002):

("*"): At least 50% of the scores are 1 or 2 on the 5-point scale (1 being "very risky"), and there are no scores of 5 on the 5-point scale.
("0"): At least 50% of the scores are 4 or 5 on the 5-point scale, and there are no scores of 1 on the 5-point scale.
("m"): At least 50% of the scores are 3 on the 5-point scale, and there are no scores of 1 or 5 on the 5-point scale.
("?"): For all remaining cases. There exists a lack of consensus, visible in a wide distribution of opinions. After discussion with the interviewees, the "?" scores may be changed to one of the other three.

Risk Statements:		What is the *level of certainty* that the statement will be true? 'C'					*Ability of team to influence* course of actions within time & resource limits 'A'					*Relative importance* of statement for obtaining project success 'I'					Score for each dimension of risk			Risk class
		Very Low				Very High	Very Low				Very High	Very High				Very Low				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	*C*	*A*	*I*	
1. The new product will be	N resp.	0	0	1	3	5	0	0	1	3	5	0	2	5	2	0				
safe to use for people with a	Cum %	0	0	11	44	100	0	0	11	44	100	0	22	78	100	100	0	0	m	**L**
sensitive skin.	□ 50%				●						●			●						
2. With the trade customer	N resp.	3	2	4	0	0	0	2	5	2	0	3	5	1	0	0				
clear after sales arrangements	Cum %	33	56	100	100	100	0	22	78	100	100	33	89	100	100	100	*	m	*	**H**
have been agreed.	□ 50%		●						●				●							
3. For localized dye damage	N resp.	1	3	2	0	2	2	2	0	4	0	4	0	1	1	2				
we have an appropriate	Cum %	13	50	75	75	100	25	50	50	100	100	50	50	63	88	100	?	*	?	**L-F**
solution.	□ 50%		●					●				●								

N resp: Number of team members who scored in certain column
Cum %: Cumulative percentage of team respondents
□ 50%: Column in which at least 50% of team response is first met
'*': At least 50% of the scores are 1 or 2 on the five point scales and there are no scores of 5
'0': At least 50% of the scores are 4 or 5 on the five point scales and there are no scores of 1
'm': At least 50% of the scores are 3 on the five point scales and there are no scores of 1 or 5
'?': Lack of consensus: There is a wide distribution of opinions.
Risk Classes used: **S** = Safe; **L** = Low Risk; **M** = Medium Risk; **H** = High Risk and **F** = Fatal risk.

Figure 29: Part of a project risk profile, adapted from Keizer et al. (2002).

The second stage is the classification of each risk statement by the risk facilitator into a so-called "risk class" by examining the three parameters of each risk statement. The following risk classes are used or a combination of them to extend the scale in more detail: S = safe, L = low, M = medium, H = High, F = fatal (see table 18). When a particular risk statement scores "*,*,*", (the three parameters of this risk statement) this results in the highest risk class and yields that when this risk is not taken care of, it would be fatal for the project. The combination of scores in the three parameters and their corresponding risk class is presented in appendix B. In case of a non-consensus in opinions of a risk statement, the risk score is represented by a combination of a high risk class with a low risk class letter. See for example the third risk statement in figure 29: L-F. This lack of consensus should be solved after discussion and clarification only in another letter, for example from L-F to F, when the team as a whole is convinced about the new classification. The mayor contribution of this feature is that one team member can have a different opinion and is not cancelled out by the mass. What would be the case when the average score was taken (Keizer et al., 2002).

RDM
F
H-F
M-F
L-F
S-F
H
M-H
L-H
S-H
M
L-M
S-M
L
S-L
S

Table 18: RDM classification table (adapted from Keizer et al. (2002)

Step 7: Team discussion.

The risks identified in step 6 that reached a non-consensus need to be discussed in a group session with the RDM participants, the project team leader and the risk facilitator. The goal of this meeting is to achieve a consensus, after a <u>thorough</u> discussion and clarification, about those risks and to change the risk classification in another letter when the whole team is convinced about this new classification.

Step 8: Constructing of the risk profile by the risk facilitator 2.

This first stage of this step consists of identifying which significant risks identified in the second stage of step 6 and step 7 are also risks described in the BN's. The risk classes of these risks have to be converted in risk states that can be used to fill the BN's. In table 19 the risk classes of the RDM are described at the left and the corresponding risk state is set out at the middle and the right of the table for the 5-state BN's and 3-state BN's respectively. The risk classes are converted for the 3-state BN in such a way that when the risk class is H or S, the risk is "promoted" a risk degree higher with *high* and *low* respectively. It is better to set the risk on the risk prioritization list with a slightly too high risk indication and to prevent that the risk will go to a higher perceived risk due to a good mitigation strategy than to neglect that the perceived risk can evaluate to that and set the risk initial to a lower state.

RDM	5-state BN	3-state BN
F	Very High	High
H	High	High
M	Medium	Medium
L	Low	Low
S	Very Low	Low

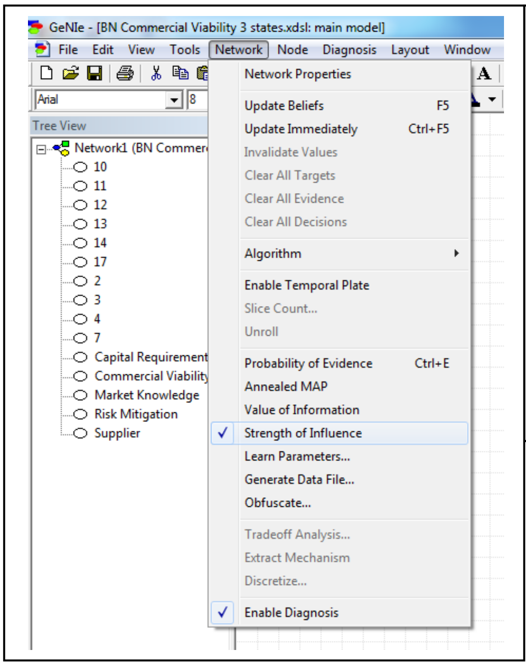
Table 19: Conversion table

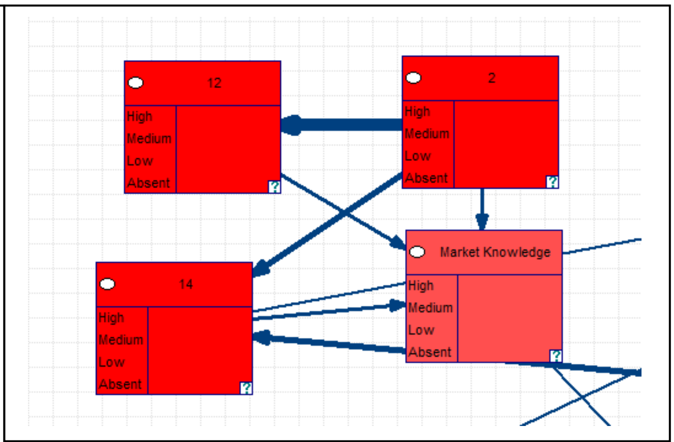
The second stage is the analysis of the two Bayesian Networks by the project manager and the risk facilitator by filling in the evidence in the parent nodes gathered by the conversion in stage 3. Filling in the evidence in the BN's can make the insight that risks that were not perceived medium, high or very high by the participants can become medium, high or very high through interaction-effects among the risks. The new project threatening risks should be added together with the threatening risks identified in step 6 and 7 on the risk prioritization list.

5.2.4.Risk Mitigation phase

Step 9: Preparing of risk management session by the project manager and the risk facilitator.
This step is the preparation of the risk management session by the project manager and the risk facilitator. The aim of this meeting is setting up an agenda for the risk management session and discuss whether the risks should be tackled in a plenary session or in sub-groups (Keizer et al., 2002).

Step 10: Risk management session with the project manager, RDM team and risk facilitator.
This session is meant to provide answers and actions to the risk identified in the previous steps. This is done in a two-way process in which the first is to create a common understanding of the risks and





Above:
Figure 30: part of a Bayesian Network with strengths of the nodes displayed

Left:
Figure 31: the option in GeNie "strength of influence"

to provide general ideas of managing them and set out which risks should be managed. Which risks should be managed depends on the interaction-effects among the risks perceived. Stated hypothetically, it could be the case for example that it is cheaper or easier to mitigate two medium risks that have influence on a risk perceived as high, than trying to mitigate that particular high perceived risk. That way, the cheapest or easiest solution can be chosen. Another hypothetical example is that when two risks have such an influence on another risk that the perceived risk level of that risk becomes high and should be mitigated, it could be the case that mitigating of one of those risks is enough and they don't have to be mitigated both. To help to decide which risks should be mitigated, GeNie provides an oversight in which is indicated how much parent nodes influences one child node (see part of a network in figure 30). The thicker the arc is drawn, the fewer parents influence the child node. This oversight can be easily created by choosing the option "strength of influence" in GeNie in the menu "network" (see figure 31).

The general idea cultivation consists out of brainstorming sessions and out of consulting the database. The database ensures that knowledge of risks built in the past do not disappear when certain experts leave the organization. Furthermore, the consultation of the database prevents that failures and pitfalls made in the past are not made again and success factors are repeated. New ideas or adaptations can be generated and when proven successful at the end of the project, added to the database.

The database consists out of the following data (inspired by Williams (1994), see chapter 3):

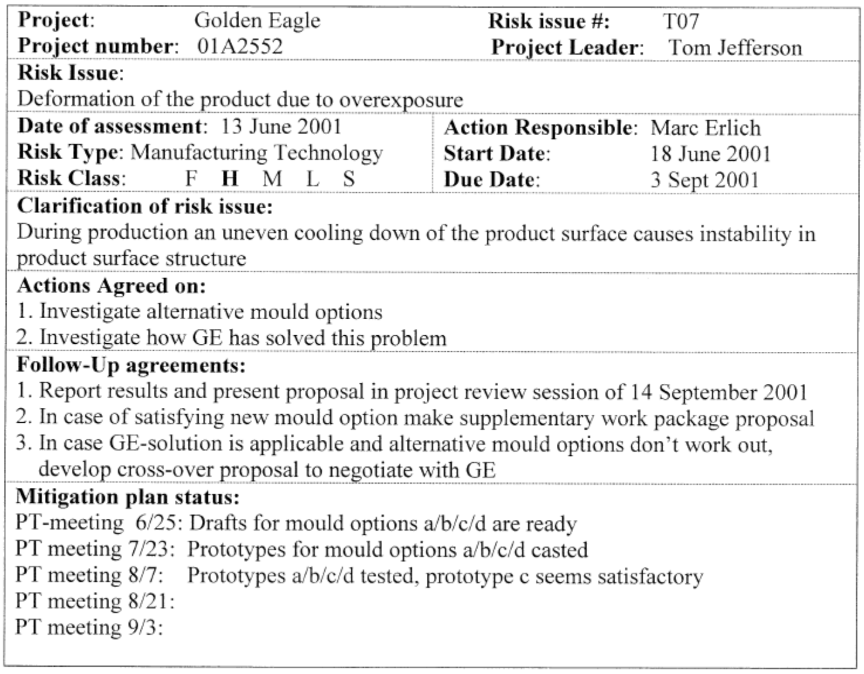
- Event: Includes a description of the risk and its likelihood of occurrence.
- Impact: Includes the severity of the impact and the object(s) of the project on where the risk has its impact (including other risks).
- Actions taken:
  - Success factors: Mitigation strategies those were successful in handling the particular risk.
  - Failures: Mitigation strategies that failed to handle the particular risk or weren't that successful.

The second part consists of splitting up the group into sub-groups of which each sub-group develops an action plan and work out the generated ideas for a particular risk. In the action plan should be formulated what needs to be done, by whom and when (Keizer et al., 2002). The sub-groups are most effective when composed of an odd number of members and are made up of five or seven persons. Research states that groups with an odd number of team members and the mentioned group size have the best elements of both small and large groups. An odd number of members eliminate the possibility of ties when votes are taken. The group size is large enough to form a majority and allow for diverse input, but small enough to avoid negative outcomes of large groups like domination by a few group members, development of subgroups and needed excessive time to reach a decision (Robbins, 2003).

5.2.5. Risk Tracking and Control phase

Step 11: Drawing up and execution of the risk management plan.

The risk management plan consists of the risks identified, the action plans for each of the diagnosed risks, who is responsible for each of those risks, how much time and resources a specific action plan will take and how the progress and reports of those plans are reported. This plan creates the insight for management in the feasibility phase of the project and makes them able to decide upon a "go/no go"-decision. The action plans made by the subgroups are documented in risk tracking forms (see figure 32) in which information about the status and progress of each individual risk is captured.



Project: Golden Eagle **Risk issue #:** T07
Project number: 01A2552 **Project Leader:** Tom Jefferson

Risk Issue:
Deformation of the product due to overexposure

Date of assessment: 13 June 2001
Risk Type: Manufacturing Technology
Risk Class: F **H** M L S

Action Responsible: Marc Erlich
Start Date: 18 June 2001
Due Date: 3 Sept 2001

Clarification of risk issue:
During production an uneven cooling down of the product surface causes instability in product surface structure

Actions Agreed on:
1. Investigate alternative mould options
2. Investigate how GE has solved this problem

Follow-Up agreements:
1. Report results and present proposal in project review session of 14 September 2001
2. In case of satisfying new mould option make supplementary work package proposal
3. In case GE-solution is applicable and alternative mould options don't work out, develop cross-over proposal to negotiate with GE

Mitigation plan status:
PT-meeting 6/25: Drafts for mould options a/b/c/d are ready
PT meeting 7/23: Prototypes for mould options a/b/c/d casted
PT meeting 8/7: Prototypes a/b/c/d tested, prototype c seems satisfactory
PT meeting 8/21:
PT meeting 9/3:

Figure 32: Example of a risk tracking form, adapted from Keizer et al. (2002)

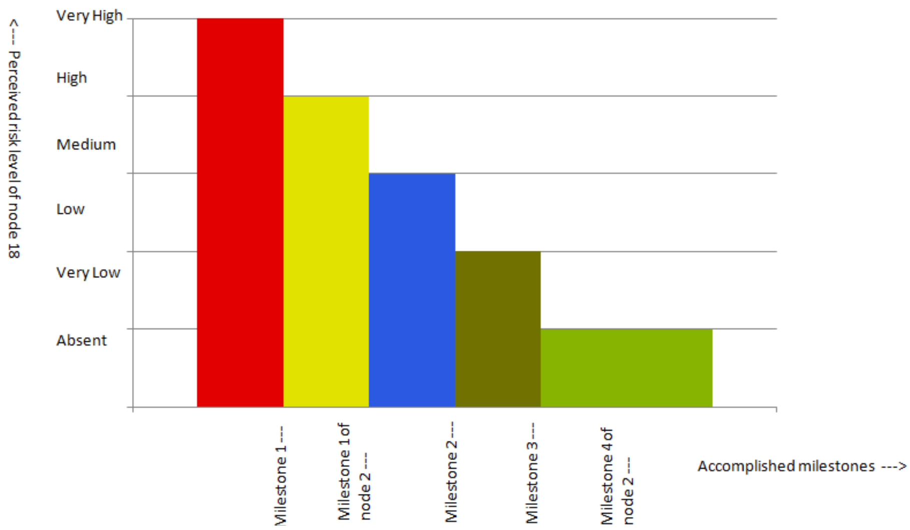


Figure 33: Risk milestone chart

To gain insight in the remaining total project risk, the project team leader fills the BN's with new evidence (perceived risk according to the sub-group) each time a milestone in the action plan is accomplished in the individual risk mitigation strategy. The perceived risk level in the sub-group is determined by measuring the perceived risk level of each sub-group team member. This perceived risk level should consist out of the parameters to what degree each sub-group member will be able to complete his task for the next milestone in time. It is important that the results of this little questionnaire should not be mediated but should be treated as the results of the large questionnaire in distribution. The argument for measuring the distribution is that when a sub-group team member notices that the chance of not fulfilling his task on time is very high, that this reflects the whole schedule of the milestone and not only the schedule of his task.

After the updating of the BN's with the new evidence, the new data is added to the modified risk milestone charts of Pennock and Halmes (2002) of the individual risks. Because of the interaction-effects in the BN's, it can therefore be possible that a milestone reached in the risk mitigation strategy of a certain risk that is completed, has its effects on another risk. This milestone appears therefore not only on the risk milestone chart of the first risk, but also on the chart of the other risk. Suppose there are two identified risks, node 2 and node 18 of the organization and project management risks that need to be mitigated. In figure 33 a milestone in the action plan of node 2 has its influence on the risk perceived in node 18.

After completing a total risk mitigation strategy for a certain risk, the database is updated with the successes and failures of the risk mitigation strategy for that particular risk and the risk milestone charts deliver the history of that particular risk with the milestones of the risk mitigation strategy.

As a final task, the BN's *probabilities* are updated each time a project is complete. This way a history is also built up in the *probabilities* of the BN's what make them more reliable each time a BNRDM procedure is executed. The "original" probabilities delivered the basis for the BN's and delivered the current state of the company at that moment in risk management. With updating the probabilities, the progress of the company in risk management is recorded. The evidence that is collected in step 8 is added after project completion to the *probabilities* of the particular risks. The evidence is added the same way as the "base" Bayesian Networks are built up as explained in section 5.1.2. As an example consider the tables below. The left table is the same as table 14 in section 5.1.2. and the right table is the adapted form after adding evidence of a new project. Suppose that the number of participants that filled in the questionnaire is 10. In step 8 they decided that the perceived risk level of the risk mentioned in the table is of *medium* level. This evidence is put in the Bayesian Networks and after project completion it is added to the probabilities of the Bayesian Network.

Magnitude	# persons voted for this state
High	60
Medium	30
Low	10

Magnitude	# persons voted for this state with evidence
High	60
Medium	40
Low	10

Table 20: Left, original probabilities of a risk node. Right, probabilities of a risk node after project completion

5.2.6.Time commitment for conducting a BNRDM

The time commitment for conducting a full BNRDM is slightly different than the original RDM. The difference in time commitment is primarily adjusted to the extra step in the BNRDM: step 7. The team discussion committed in step 7 is meant to solve the discrepancy in the perceived risks with large variance. This is needed to be able to fill the BN's in step 8. The team discussion will take about a half day. This causes a time commitment for project team members, invited stakeholders and experts of 2 days, 3 days for the project manager and about 7-8 working days for the risk facilitator. The BNRDM can therefore be conducted in 1-2 weeks (timeframe from Keizer et al. (2002) adapted for the BNRDM).

6.Evaluation and validation

The goal of the validation of the BNRDM was to get feedback if this design exploration provides managers with the right answers to make a sound decision about the "go/no go" -option for a project in the feasibility phase. Furthermore, the validation was meant to determine the "user experience" with the design. i.e. whether the design was easy to use and in what kind of situation the user would use the BNRDM. The answers provided would make a sound argumentation whether the exploration of the BNRDM should be continued in this direction.

The interviews consisted out of a presentation of how the BNRDM works. After this presentation the interviewee was asked what the advantages or disadvantages were according to their experience in risk management when they would apply this methodology. They were also asked whether they would apply the BNRDM in their own organization or what adaptations were needed to make it suitable. To prevent that the interviewee was thinking in the same direction as previous interviewees, the points made by previous interviewees were not mentioned in order to make a completely new set of points possible compared to other interviews. Only when the interviewee was by him or herself going in the same direction as a previous interviewee, the points made by the previous interviewee(s) were exposed. These interviews were not held to verify points made by other managers in previous interviews since every point that a manager remarks and sounds plausible is considered as important. Furthermore, it would not be a doable situation due to the limitate time of the researcher, to verify all points made again so a distribution can be made out of it. In that case the first 7 managers have to be interviewed again after the 8th interview is completed. Therefore a distribution of how they think about each point is not supplied.

The interviews are held with 8 managers who have dealt with or are dealing with risk management in innovation projects. For their experience see appendix G. The next section summarizes the points that came out of the interviews without providing the name and company of the manager since it would add no further valuable information when known.

6.1.Validation

Out of the interviews the following points were made:

- High opportunities are expected about the tool in the case of a company that needs to be restructured because of ongoing unprofitable high innovative products. This is due to a lack of proper communication between R&D and upper management and the failure to make what the market demands. The BNRDM is that analytic that it may convince upper management to change the direction of the company. The BNRDM does not only provide information about the project itself, but displays also a reflection of the company as a whole and thereby showing what might be wrong about certain procedures (5 managers agree with this point).

- It is remarked that when there was a non-consensus about a perceived risk level, it could be the case that management analyses why there was no consensus about that particular risk and comes to the conclusion that it should be “Michael” that has the different opinion. Because Michael is seen (known) by management as the person that is always recalcitrant and the consequence is that management dismisses that opinion. The solution at this point is that the risk management tool should be supported by upper management whatever the outcome is. The experience of Keizer et al. (2002) with this groupdynamic bias is that the RDM procedure allowed a lot of issues that were festering under the surface to be raised in a constructive manner. Because people like Michael could speak out their concerns and clarify their point of view in their perceived risk in the RDM, the issue is not kept under the surface during the project and strengthens the team’s harmony and team ownership for the whole project (based on the experiences by Dr. Keizer and confirmed by 3 managers).

- It appears that the BNRDM might be very well suited to be used within a couple of companies. Many managers are very interested. However, some plead for a slightly adapted form that enables the possibility to use general applicable BN’s for all the product categories that the company is in instead of a specific BN for each product category. This way, the model would be easier to maintain. The slightly adapted form should also have its impact on the step 4 and 5 of the BNRDM process in the sense that 75% of the questionnaire should be the same for all projects and about 25% project specific, in order to speed up the RDM process and make it more suitable for smaller projects (7 managers agree with this point).

This master thesis describes the general rules of the game for conducting a BNRDM. With adaptations by making it less general and more company specific it is possible to fulfill the needs.

- The FMEA is used in two companies to discover in detail the technical issues around the project. One manager believes that there are no interaction-effects in technical risks. However, whether or not there are interaction-effects between technical risks is a non-consensus among the managers. (Three managers think interaction-effects exist in technical risks, one disagrees.)

- To be able to track risks, the risk and control phase should have a small questionnaire for each sub-group team member in which the perceived risk level for that particular risk can be tracked. This small questionnaire should contains questions like: "To what degree the sub-group team member understands his tasks" and "to what degree the sub-group team member is able to complete his task in time". The team members should be able to complete this small questionnaire within 15 minutes. (Two managers agree with this point.)

  The small questionnaire in the tracking and control phase is needed, but it is another research project to understand and investigate which questions should fulfill the need.

- Step 10 should be automated. Instead of exploring the options manually which risks are best to mitigate to obtain the most optimal result, the program should provide the options which risks should be mitigated to show the answer which variation in risk delivers the most variation in another risk that should be mitigated. For example, see figure 26, the program should deliver that when risk 10 needs to be mitigated, it is best to first mitigate risk 1 to the low perceived risk level. After that is achieved, it is best in time, resources and complexity to mitigate risk 2 to the low perceived risk level to further decrease the perceived risk level 10 compared to trying to mitigate risk 1 to the very low perceived risk level. (One manager remarked this point.)

  Part of this answer can be achieved by applying so-called "influence diagrams" in the model. The draw-back of these influence diagrams are explained in chapter 4: "of each input node the user wants to analyze what the effects of the different inputs are on the outcome, a special node has to be added to the model." This special node has to be filled with an utility function consisting out of parameters like cost, complexity and resources and the effect has to be determined of which utility is gained when the risk is lowered one level. Even more, like the probabilities of the BN, all the utility functions of these nodes also have to be updated. Since it alters many aspects in the Bayesian Networks physically, it needs to be further investigated what would be the appropriate solution. Another solution is using another program to model Bayesian Networks. Instead of using GeNie of which the license is free of charge, it should be considered whether it is profitable to purchase a license of for example the program Netica. Netica can do sensitivity analysis without creating influence diagrams and therefore might have the right solution for this problem.

- The BNRDM obliges the manager to structurally work on risk management instead of applying risk management in "ad hoc"-mode and act upon the "feeling" of a manager. Since the tool provides statistical history and does not follow the feeling of one manager by a "go/no go"-decision of a project, the final decision can be better accepted by people who are involved in the project in the sense that not one person makes the conclusion that their project should be ended. (Three managers agree with this point.)

- Not every risk has the same influence on another risk. Different risks should have a weighted influence on another risk. As an example see figure 26. Risk 1 and 2 have in this picture the same weighted influence on risk 10. (Two managers remarked this point.)

  The weights of the arcs can be easily adapted in GeNie. Further research for this option should contain the question what should be the parameters to determine the weight of the different arcs. Or in other words: what parameter delivers the importance of an influence on another risk. It is however not needed. The influence of a risk on another risk is already secured in the probabilities and the risk levels of the variable. When a node has a parent, the influence of the parent node on the child is already defined in the CPT of that child node. It reflects the chance (influence) that the child node will be in a certain state (weight), dependent on the state of the parent node.

Some final remarks: all managers stress the high importance of applying a risk management tool and were very enthusiastic when I explained my design. One very experienced manager noted: "*The design is a fantastic beginning of something of such great importance and the final design will be that big that you can fill your promotion research with it and eventually have work in designing until you are going to retire. The tool is explained in the radical innovations projects setting, but I can mention many other disciplines where they should use this."*

6.2.Evaluation

The managers were very enthusiastic when the tool was explained. They see further possibilities and provide new ideas to add to the exploration design to make it a complete tool. Some are even interested about co-developing the complete BNRDM. Out of the interviews, there can only be concluded that the exploration in this master thesis provide a very good base track to build upon for the eventually complete Risk Diagnosing Methodology Plus.

6.3.Implementation

Since the BNRDM takes a reasonable amount of resources in the form of man hours, the tool is mostly suited for breakthrough projects or projects that have significant impact on the business of the firm and therefore costs a lot of money. It might therefore also be recommended to commit a complete RDM procedure more than one time (Keizer et al., 2002). As remarked by the managers, when the large questionnaire is altered in that 75% of the questionnaire is the same for all projects and about 25% is project specific it is possible to speed up the RDM process and make it more suitable for smaller projects.

The presented design is suitable for SME projects only when one bears to mind that the design becomes more and more statistically robust when more data of more different persons is entered. As stated earlier, it is at this point not clear what would be a sufficient amount of persons that have to fill in the BN's history to be reliable.

7.Conclusions, further research options and limitations

The aim of this thesis was the following main research objective:
Combine the best techniques for the particular phases in risk management in one improved risk management tool.

And the following research objectives:
Find a technique that provides a clear oversight of (multiple) cause and (multiple) effect chains between risks in order to detect the interaction-effects between the risks.

Find a technique that can be easily updated when new perceived risk level information is available.

Find a technique that is suitable to capture such knowledge that it is possible to make the tool more and more robust everytime it is used.

These objectives are fulfilled in this exploration research by combining the Risk Diagnosing Methodology of Keizer et al. (2002), a database, the modified risk milestone charts of Pennock and Halmes (2002) and the construction of two Bayesian Networks. The RDM shows which risks have the most variation in risk level and which risks are perceived as most risky individually. The two BN's make the original RDM procedure more robust since they show the interaction effects between the risks. This insight is created with the BN's in the most important risks in the organizational and project management and commercial setting. Furthermore, the database prevents reinventing the wheel by recording the pitfalls and successes of past projects and therefore delivers part of the knowledge for a successful mitigation strategy. The risk milestone charts fulfills the need for a clear oversight of the perceived risk level after accomplished milestones in the risk mitigation strategy. Finally, the results obtained by each BNRDM session are recorded in the Bayesian Networks to build up history and make the tool more and more robust everytime the BNRDM procedure is executed.

Out of the validation it appears that with the exploration done in this thesis, the right direction for extending the RDM is chosen. The managers do not only determine possibilities for the risk management tool in risk management per project. But also emphasize the possibilities for identifying problems on a higher level in the company or even for risk management in other disciplines. The validation delivered also some further research options:

1) It appeared that step 10 should be automated. Instead of exploring options manually which risk should be mitigated to get the optimal solution, the model should provide these answers. Part of this can be achieved by adding "influence diagrams" to the Bayesian Network or design the Bayesian Networks in another program. It should however be investigated how the influence diagrams should be added to the model and whether this will deliver the desired solution or that the design of the networks has to put in another program.
2) To make the update of the perceived risk of the sub-group of a particular risk in step 11 more reliable, this perceived risk should be determined by a more detailed "sub-questionnaire" for each sub-group team member. Items that should be in that questionnaire should be investigated but one can think of items like: "Does the team member understand the (sub-)task for the next milestone he should accomplish?", "Does the team member accomplish his task for that next milestone within time and resources?".
3) In order to speed up the RDM procedure and to make it more suitable for smaller projects, 75% of the large questionnaire should be the same for all projects and 25% should be project specific. It should be investigated whether this is feasible. It would be a nice discussion because a statement against this 75% would be that it might block new risks to be discovered.

Other research options that did not directly come out of the validation are summarized below. Point 2 and 3 can be considered as further research options that can speed up the BNRDM procedure:

1) An extension of the two BN's described in this thesis can be made. The two BN's consist out of the most important parts of the Commercial Viability Risks and the Organizational and Project Management Risks. Even more, it may be possible to construct BN's for all the other domains in the risk reference list. All these other domains can be connected under the node: "Project risk", in order to get one clear score of the total risk the project is facing. This way, the risk identification can be limited to searching for evidence to fill the BN's. With the inter-action effects, a risk prioritization list can be made out of the different BN's.
2) Chapter 5.2 can be partly automated. It would be a discussion whether the risk identification phase can also be automated by a web-based questionnaire. When this phase would be done via a web-based questionnaire, new risk items might not be discovered. The questionnaire is at that time solely based on risks identified in the past and whether they also occur in the coming project. The questions come at that time out of a database. If we leave the identification phase not automated and automate the prioritization, mitigation and risk tracking and control phase, it can be built as follows. The risk identification phase is still done via interviews. The risk facilitator develops the risk questionnaire in a web-based design. This has the advantage that results that come out of the questionnaire are calculated by the computer and do not have to be calculated by hand. By those risks there is non-consensus about the risk level, a discussion session with the risk facilitator, project manager and the team members takes place (step 7). After this session, the risk facilitator is able to change only the risk perceived values of those "original non-consensus perceived risks" and fills in the risk perceived level as agreed on in step 7. Assuming that BN's are constructed for all the risk domains, the web-based questionnaire "fills in" the evidence in the BN's. The BN's are constructed in a programming language called "SMILE". Where GeNie is the Graphical User Interface (GUI) in where you can drag-and-drop nodes, arcs and construct CPT's, SMILE is the platform independent library of C++ classes of GeNie. C++ is one of the most used programming languages in the world. To name a few, Microsoft Windows and all Linux and Unix based operating systems (OS) have been built in this programming language. This way, the web-based questionnaire can fill the programmed BN's with evidence and the inter-action effects can be studied. It is even possible to program that the risk milestone charts will be updated when new evidence is filled in the Bayesian Networks.
3) Chapter 5.1 can also be automated. For example, when chapter 5.1.1. would be done via a web-based questionnaire, this questionnaire can generate as it were the variables (risk items) and draws the connections (arcs) between them by posing the right questions. This leaves out the variables and connections that are not applicable for this kind of projects or this sort of companies. This web-based questionnaire contains the suitable variables and their connections and can generate the C++-code for the construction of the BN's (the qualitative part). Via another web-based questionnaire constructed out of the results of the first questionnaire (because the questions have to be based on the variables selected in the first questionnaire) which is posed to interviewees over multiple projects in the same category, the CPT-values are extracted (chapter 5.1.2.). The program that holds the values of this questionnaire "searches" in the code generated by the first questionnaire, where the CPT's should be placed and generates and places a C++-code in these spots.

Finally, the limitation of this study is that I was unable to find arguments of what would be the appropriate number of persons to fill in a BN to make the outcomes most reliable. Literature is not consistent, several studies speak of "experts" (Díez and Drudzel, 2007; Gerssen, 2004; Korb and Nicholson, 2011; Bolt and Van der Graag, 2010; Sigurdsson et al., 2001) while others about one "expert" (Galán and Díez, 2000; Pradhan et al., 1994; Heckermann, 1993). Further research has to be done on this matter. Furthermore, the BNRDM uses a reasonable amount of man hours. Therefore, the tool might not be appropriate for innovation projects which do not exceed a certain amount of budget and time. The BNRDM is therefore most suited for breakthrough projects or projects with a significant impact on the business of the firm (Keizer et al., 2002).

Literature

- Aloini, D., Dulmin, R., Mininno, V. Risk Management in ERP project introduction: Review of the literature. *Information and Management*, 44, pp. 547-567, 2007.

- Bolt, J.H., Van der Graag, L.C. An Empirical Study of the Use of the Noisy-OR Model in a Real-Life Bayesian Network. *Information Processing and Management of Uncertainty in Knowledge-Based Systems. Theory and Methods.* Springer Berlin Heidelberg, 2010.

- Blumberg, B., Cooper, D.R., Schindler, P.S. Business Research Methods. *McGraw-Hill Education*, second European edition, 2005.

- Caillaud, E., Gourc, D., Garcia, L.A., Crossland, R., McMahon, C. A framework for a Knowledge-Based System for Risk Management in Concurrent Engineering. *Concurrent Engineering*, 7, pp. 257-267, 1999.

- Carbone, T.A., Tippett, D.D. Project Risk Management Using the project risk FMEA. *Engineering Management Journal*, Vol.16, No.4, Dec 2004.

- Chang, C.L., Wei, C.C., Lee, Y.H. Failure mode and effects analysis using fuzzy method and grey theory, *Kybernetes*, Vol. 28 Iss: 9, pp.1072 – 1080, 1999.

- Chang, C.L., Liu, P.H., Wei, C.C. Failure mode and effects analysis using grey theory. *Integrated Manufacturing Systems*, 12/3, pp. 211-216, 2001.

- Chen, C.H., Ling, S.F., Chen, W. Project scheduling for collaborative product development using DSM. *International Journal of Project Management,* 21, pp. 291-299, 2003.

- Chin, K.S.,Tang, D.W., Yang, J.B., Wong, S.Y., Wang, H. Assessing new product development project risk by Bayesian network with a systematic probability generation methodology. *Expert Systems with Applications,* 36, pg. 9879-9890, 2009.

- Choi, H.G., Ahn, J. Risk analysis models and risk degree determination in new product development: A case study. *Journal of Engineering and Technology Management,* 27, pp. 110-124, 2010.

- Danilovic, M., Sandkull, B. The use of dependence structure matrix and domain mapping matrix in managing uncertainty in multiple project situations. *International Journal of Project Management,* 23, pp. 193-203, 2005.

- Delisle, S., St-Pierre, J. SME Projects: A Software for the Identification, Assessment and Management of Risks, *48th World Conference of the International Council for Small Business (ICSB- 2003)*, Belfast (Ireland), CD-ROM proceedings, 15-18 June 2003.

- Díez, F.J., Drudzel, M.J. Canonical Probabilistic Models for Knowledge Engineering. *Technical Report CISIAD-06*-01. Version 0.9, April 28 2007.

- Fan, C.F., Yu, Y.C. BBN-based software project risk management. *The Journal of Systems and Software*, 73, pp. 193–203, 2004.

- Galán, S.F., Díez, F.J. Modelling Dynamic Causal Interactions with Bayesian Networks: Temporal Noisy Gates. *The 2nd International Workshop on Causal Networks and the*

14th European Conference on Artificial Intelligence, Berlin, Germany, pages 1-5, August 2000.

- Gerssen, S. Bayesian Networks in Credit Rating. *Msc. Thesis, Delft University of Technology*, 2004.

- Gerssen, S.G., Rothkrantz, L.J.M. Bayesian Network Learning for Rare events. *Delft University of Technology*, March 5, 2004.

- Halman, J.I.M., Keizer, J.A. Diagnosing risks in product-innovation projects. *International Journal of Project Management*, 12 (2), pp. 75-80, 1994.

- Heckerman, D. Causal Independence for Knowledge Acquisition and Inference. *Uncertainty in Artificial Intelligence, Proceedings of the Ninth Conference.* Morgan Kaufmann, San Mateo, CA. pp.122-127, 1993.

- Holmes, D.E., Jain, L.C. Innovations in Bayesian Networks: Theory and Applications. *Springer-Verlag Berlin Heidelberg*, 2008.

- Houben, M.J.H.A. Using Bayesian Belief Networks for Reliability Management – construction and evaluation: a step by step approach. *University of Technology Eindhoven*, 2010 (Phd. Thesis).

- Jensen, F.V., Nielsen, T.D. Bayesian Networks and Decision Graphs. *Springer science + Business Media*, Feb. 2007.

- Kayis, B., Arndt, G., Zhou, M., Savci, S., Khoo, Y.B., Rispler, A. Risk Quantification for New Product Design and Development in a Concurrent Engineering Environment. *CIRP Annals, Manufacturing Technology (Elsevier)*, Volume 55, Issue 1, pp. 147-150, 2006.

- Kayis, B., Zhou, M., Savci, S., Khoo, Y.B., Ahmed, A., Kusumo, R., Rispler, A. IRMAS – development of a risk management tool for collaborative multi-site, multi-partner new product development projects. *Journal of Manufacturing Technology Management*, Vol. 18 No. 4, pp. 387-414, 2007.

- Kahneman, D. and Tversky A., Prospect Theory: An analysis of decision under risk. *Econometrica* 47, pp.263-291, 1979.

- Keizer, J.A., Halman, J.I.M., Song, M. From experience: applying the risk diagnosing methodology. *The Journal of Product Innovation Management,* 19, pp. 213-232, 2002.

- Keizer, J.A., Halman, J.I.M. Diagnosing risks in radical innovation projects. *Research Technology Management*, September-October, 2007.

- Kjaerulff, U.B., Madsen, A.L. Bayesian Networks and Influence Diagrams: a guide to construction and analysis. *Springer*, New York, 2008.

- Korb, K.B., Nicholson, A.E. Bayesian Artificial Intelligence. *Chapman & Hall/CRC Press*, 2nd edition, 2011.

- Landy, F.J. and Conte, J.M. Work in the 21th century: An introduction to industrial and organizational psychology. *Blackwell Publishing Ltd*, second edition, 2007.

- McDermott, R.E., Mikulak, R.J., Beauregard, M.R. The basics of FMEA. *Productivity press, Taylor & Francis Group*, 2009.

- Meredith, J.R., Mantel, S.J. Project Management: A managerial approach. *Wiley international student version*, sixth edition, 2006.

- Neapolitan, R.E. Learning Bayesian Networks. *Pearson education, Inc.* 2004.

- Neil, M., Fenton, N., Nielsen, L. Building Large-Scale Bayesian Networks. *The knowledge engineering review*, Vol. 15, Iss. 3, pp. 257-284, 2000.

- Pennock, M.J., Halmes, Y.Y. Principles and guidelines for project risk management. *Systems Engineering*, Vol. 5, No. 2, 2002.

- Perera, J., Holsomback, J. An integrated Risk Management Tool and Process. *IEEEAC,* Version 3, updated November 29, 2004.

- Pradhan, M., Provan, G., Middleton, B., Henrion, M. Knowledge Engineering for Large Belief Networks. *Proceedings of the Conference on Uncertainty in Artficial Intelligence*, 1994.

- Ricondo, I., Arrieta, J.A., Aranguren, N. NPD Risk Management: Proposed implementation to increase new product success, retrieved 5-4-2010, URL: http://www.ip-ecospace.org/projects/408/ICE%202006/Product%20development/p45-41.pdf

- Robbins, S.P. Organizational behavior. *Pearson Education International, Prentice Hall.* 10th international edition, 2003.

- Sigurdsson, J.H., Walls, L.A., Quigley, J.L. Bayesian Belief Nets for managing expert judgement and modeling reliability. *Quality and reliability engineering international,* 17, pp. 181-190, 2001.

- Skelton, T.M., Thamhain, H.J. User-Centered Design as a Risk Management Tool in New Technology Product Development. *IEEE*, 2005.

- Stein, A. Proceedings of the Frontis workshop on Bayesian statistics and quality modelling in the agro-food production chain. Chapter 9. Wageningen, The Netherlands 11 - 14 May 2003.

- Thompson, T. Risk Management Solutions for New Product Technologies in the Semiconductor Industry. *IEEE*, 2000.

- Wang, J., Lin, W., Huang, Y.H. A Performance-oriented risk management framework for innovative R&D Projects. *Technovation*, 30, pp. 601-611, 2010.

- Williams, T.M. Using a risk register to integrate risk management in project definition. *Intemational Journal of Project Management,* 12 (1), pp. 17-22, 1994.

- Wu, D.D., Kefan, X., Gang, C., Ping, G. A Risk Analysis Model in Concurrent Engineering Product Development. *Risk Analysis*, Vol. 30, No. 9, 2010.

- Zahedi, F. The Analytic Hierarchy Process - A Survey of the Method and Its Applications. *Interfaces,* Vol. 16, Iss. 4, pp. 96- 109, 1986.

References

1) http://www.hugin.com/developer/tutorials/biuld-bn, accessed April 12, 2011
2) http://genie.sis.pitt.edu/GeNIeHelp/Elements_of_GeNIe/Diagrams/NoisyOR.htm, accessed April 26, 2011
3) http://www.norsys.com/netica.html, accessed July 7, 2011

Acknowledgements

I want to thank my parents, brother and my girlfriend for their love, support and understanding during the past years of my study. Therefore I want to dedicate this master thesis to them.

I want to thank my mentor Dr. Keizer for his support and help in making my design in this master thesis project with my own argumentations. He gave me also a glimpse of the role as a university researcher within company projects (WS Energia) and within the university with his interesting stories. He gave me the feeling that I was not “another student as in many”, but provided me with the feeling as an individual colleague researcher.

My second mentor, Dr. Ir. Van Oorschot, I would like to thank her for the comforting words when I experienced my about 20th barrier from preventing to understand the theory behind Bayesian Networks.

Furthermore, I want to thank I. Chivata Cardenas, Phd. student of the University of Twente for his patience in answering my questions about Bayesian Networks.

Last but not least, I want to thank the following managers who delivered the validation for my design (in random order): P. van Binsbergen of Van Binsbergen Beheer, A.J. van Kranenburg of Dunes, J. Van Lammeren and L. van de Laar of Prodrive, M. Dierselhuis of Pentri, J. Van Balen-De Greef of dICTum fACTum Inforegie, L. van Roozendaal of TomTom and L. Strijbosch of ASML.

Appendices

Appendix A: Risk reference list of the Risk Diagnosing Methodology (Keizer et al., 2002)

Reference list with potential risk issues in the innovation process

I Product Family & Brand Positioning risks

1. New product helps to achieve business strategy
2. Project is important for project portfolio
3. New product contributes to brand name position
4. Project includes global roll out potential and schedule
5. New product fits within existing brand
6. New product fits with brand image
7. New product enhances potential of product family development
8. New product provides opportunities for platform deployment
9. New product supports company reputation
10. New product has brand recovery potential
11. New product has brand development potential
12. New product's platform will be accepted by consumers

II. Product technology risks

1. New product's intended functions are known and specified
2. New product fulfils intended functions
3. In-use conditions are known and specified
4. Interactions of product in-use with sustaining materials, tools etc. are understood
5. Components' properties, function and behavior are known
6. Correct balance between product components is established
7. Assembled product meets safety and technical requirements
8. Alternatives to realize intended product functions available
9. New product shows parity in performance compared to other products
10. New product shows stability while in storage (factory, shop/warehouse, transportation, at home)
11. New Product format meets functional requirements

III. Manufacturing Technology Risks

1. Raw materials available that meet technical requirements
2. Process steps to realize the new product are known and specified
3. Conditions (temperature, energy, safety, etc.) to guarantee processing of good product quality known and specified
4. Production means (equipment and tools) necessary to guarantee good product quality are available
5. Scale up potential is possible according to production yield standards
6. Production system requirements (quality & safety standards, training of human resources, facilities etc.) will be met
7. Product packaging implications are known and specified
8. Manufacturing efficiency standards will be met
9. Alternative approaches to process the intended product will be available
10. Adequate production capacity available
11. Adequate Production Start Up assured
12. Reusability of rejects in production foreseen

Appendix A (continued)

IV. Intellectual property Risks

1. Original know-how will be protected
2. Required external licenses or know how known and available
3. Relation to legal and patent rights of competitors known and arranged
4. Relevant patent issues are understood
5. Patent crossing potential known and arranged
6. Trade mark registration potential known and arranged

V. Supply chain & Sourcing risks

1. Suppliers will meet required quality
2. Capacity available to meet peak demands
3. Appropriate after sales services available
4. Contingency options available for each of the selected suppliers
5. Financial position of each supplier is sound
6. Past experiences with each of the suppliers are positive
7. Suppliers are ready to accept modifications if required
8. Supply contracts can be canceled
9. Each supplier will be reliable in delivering according to requirements
10. Required quantities will be produced against acceptable prices
11. Appropriate contract arrangements with suppliers will be settled

VI. Consumer Acceptance Risks

1. Product specifications meeting consumer standards and demands
2. New product fits consumer habits and/or user conditions
3. New product offers unique features or attributes to the consumer
4. Consumers will be convinced that they get value for money, compared to competitive products
5. New product appeals to generally accepted values (e.g. health, safety, nature, environment)
6. New product offers additional enjoyment, compared to competitive products
7. New product will reduce consumer's costs, compared to competitive products
8. Non-intended product use by consumers is adequately anticipated
9. Target consumer's attitudes will remain stable during the development period
10. New product will be communicated successfully with target consumers
11. New product will provide easy-in-use advantages, compared to competitive products
12. Primary consumer requirements are known
13. Target consumers will accept the new product's key product ingredients
14. Niche marketing capabilities available if required
15. Communication about new product is based on realistic product claim
16. Advertising will be effective
17. Product claims will stimulate target consumers to buy
18. New product has repeat sales potential

Appendix A (continued)

VII. Trade Customer Risks

1. Product specifications will meet trade customer standards and demands
2. Trade customers will welcome the new product from the perspective of potential sales
3. Trade customers will welcome the new product from the perspective of profit margin
4. Trade customers will welcome the new product given required surface and volume on shelf and storage facilities
5. Trade customer's attitude will remain stable during the development period
6. New product will be communicated successfully to trade customers
7. Right distribution channels will be used
8. Trade will give new product proper care
9. Trade supporting persons will endorse the new product
10. Stock demands will be met

VIII. Competitor Risks

1. Product will provide clear competitive advantages
2. Introduction of new product will change existing market share positions
3. Introduction of the new product will have impact on market prices
4. New product will be launched before competitors launch comparable product
5. Response actions towards public and media expected from competitors will be anticipated
6. New product enables the creation of potential barriers for competitors
7. Implications of being technology leader or follower for this project have been identified
8. Competitor's actions will be monitored and followed with adequate response
9. Competitor's challenges will be monitored adequately

IX. Commercial Viability Risks

1. The market target is clearly defined and agreed
2. Market targets are selected based on convincing research data
3. Capital cost projection for new product is feasible
4. Delays in product launch will leave the commercial viability of the new product untouched
5. Sales projections for new product are realistic
6. Estimated profit margin are based on convincing research data
7. Profit margin will meet the company's standards
8. The estimated return on investment will meet the company's standards
9. Volume estimates are based on clear and reliable estimates
10. Product viability will be supported by repeat sales
11. Supplier will get attractive purchasing agreements
12. Knowledge of pricing sensitivity is available
13. Adequate investments to secure safety in production will be made
14. Long term market potential is to be expected
15. Financing of capital investment is secured
16. Fall back to prior product concept is feasible
17. New product is commercially viable in case of market restrictions

Appendix A (continued)

X. Organizational & Project Management Risks

1. Internal political climate is in favor of this project
2. Top management actively supports project
3. Project goals and objectives are feasible
4. Project team is sufficiently authorized and qualified for the project
5. Project team will effectively utilize the knowledge and experience of (internal) experts
6. Roles, tasks and responsibilities of all team members are defined and appropriate
7. Decision making process in project is effective
8. Communication between members in the project team is effective
9. Required money, time and (human) resources estimations are reliable and feasible
10. Required money, time and (human) resources will be available when required
11. Project team will be informed in time about project progress
12. External development partners will deliver in time, conform budget and technical specifications
13. Sound alternatives are available to external development partners
14. Collaboration within the project team is effective
15. Sponsor's interest for the project is secured
16. Project will effectively be organized and managed
17. Collaboration with external parties is effective
18. Collaboration between project team and the parent organization is effective
19. Project team is highly motivated and committed
20. Project team is paying attention to the right issues
21. Project has an effective planning and contingency planning
22. Project team is learning from past experiences

XI. Public Acceptance Risks

1. It is clearly understood who is responsible for PR of the project
2. The key opinion formers for the new product are known
3. Support of key opinion formers will be assured
4. Legal and political restrictions will be adequately anticipated
5. Environmental issues will be adequately anticipated
6. Safety issues will be adequately anticipated
7. Possible negative external reactions will be effectively anticipated
8. In case of new technology prior (external) experience will be consulted

XII. Screening & Appraisal

1. New product performance targets will be tested and measured adequately
2. Trade customer appreciation will be tested and measured adequately
3. Consumer appreciation will be tested and measured adequately
4. Adverse properties as a consequence of the technological change will be tested and measured adequately
5. Credibility of the (internal) measures to external agencies is warranted
6. Tests will provide reliable evidence

Appendix B: Score list with the translation into risk classes (Keizer et al., 2002)

Score:
- * = At least 50% of the scores is found in 1st and/or 2nd column and none in 5th column;
- 0 = At least 50% of the scores is found in 4th and/or 5th column and none in de 1st column;
- M = At least 50% of the scores is found in 3rd column;
- ? = For all the remaining cases (wide distribution in opinions or remarkably deviating opinions). This score may eventually lead to a '*', '0' or 'm', after examinations and discussions between members in the risk team.

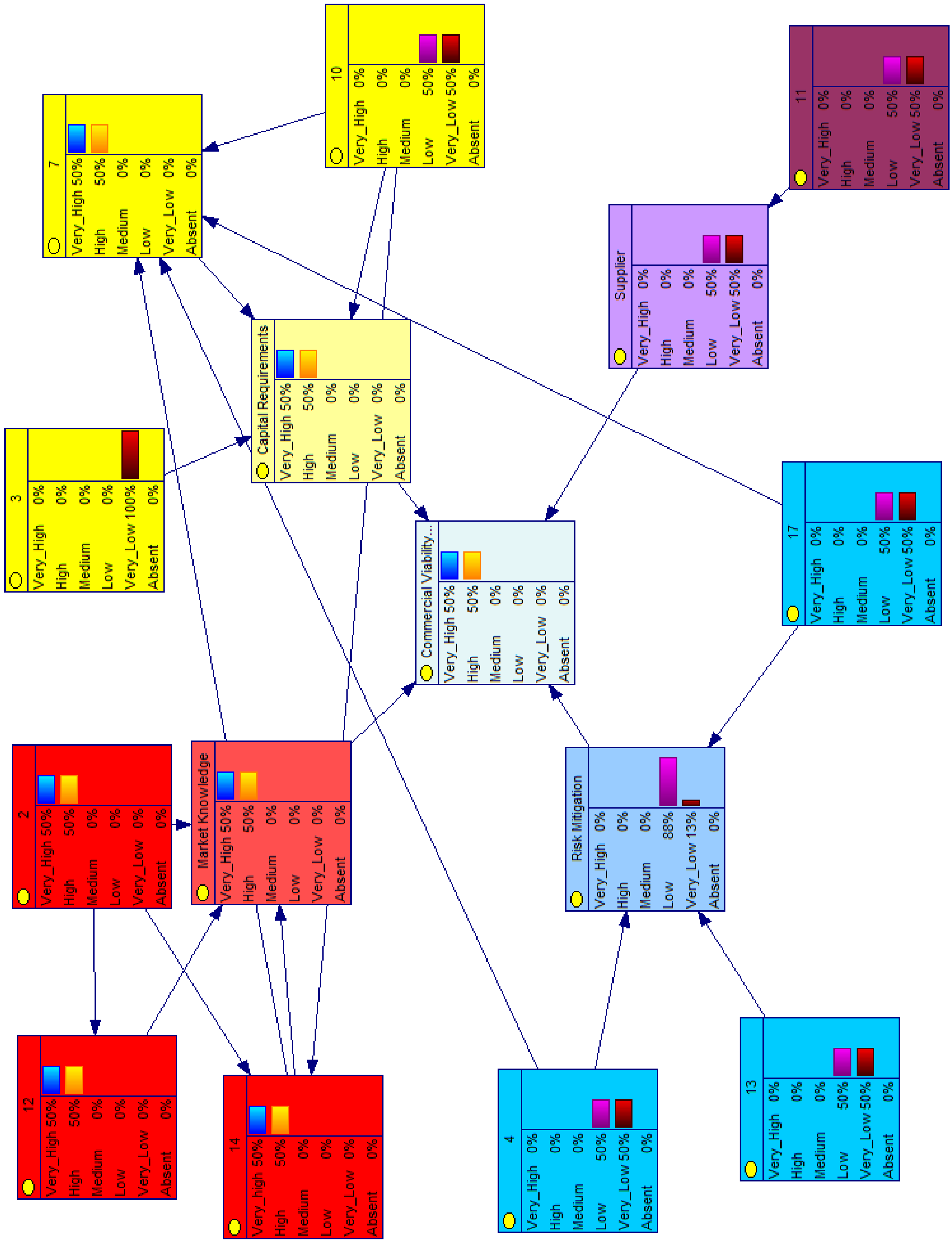
SCORE			RISK CLASS	SCORE			RISK CLASS
Certainty	Ability of team to influence course of action	Relative importance to project success		Certainty	Ability of team to influence course of action	Relative importance to project success	
*	*	*	F	*	*	?	M-F
*	*	0	L	*	?	*	H-F
*	0	*	M	?	*	*	M-F
0	*	*	H	*	?	?	L-F
0	0	*	L	?	*	?	L-F
0	*	0	L	?	?	*	L-F
*	0	0	L	?	?	?	S-F
0	0	0	S	?	0	0	L
*	*	m	H	0	?	0	L
*	m	*	H	0	0	?	L
m	*	*	H	?	?	0	S-M
*	m	m	M	?	0	?	S-H
m	*	m	M	0	?	?	S-M
m	m	*	M	*	?	0	L-M
m	m	m	M	*	0	?	L-H
0	*	m	M	0	*	?	L-M
*	0	m	M	0	?	*	L-M
0	m	*	M	?	0	*	L-H
*	m	0	M	?	*	0	L-M
m	*	0	M	*	?	m	M-H
m	0	*	M	*	m	?	M-H
0	0	m	L	m	?	*	M-H
0	m	0	L	m	*	?	M-H
m	0	0	L	?	m	*	M-H
0	m	m	M	?	*	m	M-H
m	m	0	M	m	?	0	L-M
m	0	m	M	m	0	?	L-M
				0	?	m	L-M
				0	m	?	L-M
				?	0	m	L-M
				?	m	0	L-M
				?	m	m	L-M
				m	?	m	M
				m	m	?	M
				?	?	m	L-H
				?	m	?	L-H
				m	?	?	L-H

mean of the risk classification:

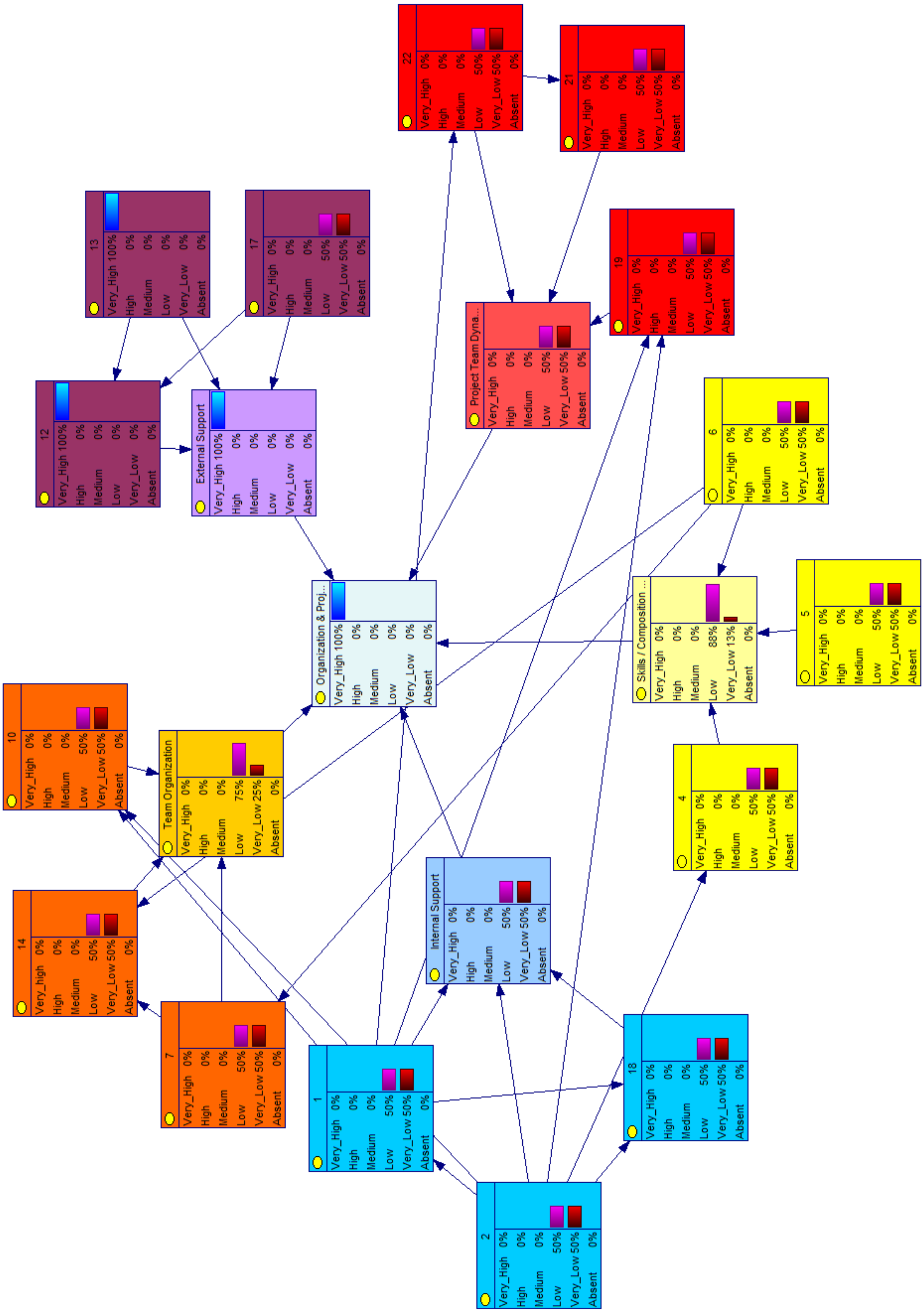
- F = Fatal risk;
- H = High risk;
- M = Medium risk;
- L = Low risk;
- S = Safe, no risk.

A combination of classes means that the risk team should work out whether the disagreement can be resolved and hence a single risk classification can be achieved. If consensus can't be achieved the worst possible case should be assumed.

Appendix C: The two Bayesian Network of the Commercial Viability Risks with five states



Appendix D: The two Bayesian Network of the Organizational and Project Management Risks with five states



Appendix E: Noisy-MAX calculation examples

Example 1:

	A	B
High	0.2	0.8
Medium	0.1	0.1
Low	0.7	0.1
Absent	0	0

	A		
	High	Medium	Low
Y=High	0.2	0.1	0
Y=Medium	0.1	0.1	0.1
Y=Low	0.7	0.8	0.9
Y=Absent	0	0	0

	B		
	High	Medium	Low
Y=High	0.3	0.4	0.7
Y=Medium	0.2	0.3	0.3
Y=Low	0.5	0.3	0
Y=Absent	0	0	0

	A		
C_y^a	High	Medium	Low
Y=High	1.0	1.0	1.0
Y=Medium	1-0.2=0.8	1.0-0.1=0.9	1.0-0.1=0.9
Y=Low	1-0.2-0.1=0.7	1.0-0.1-0.1=0.8	1.0-0.1-0.9=0
Y=Absent	1-0.2-0.1-0.7=0	1.0-0.1-0.1-0.8=0	0

	B			Leak	
C_y^b	High	Medium	Low	C_y^L	
Y=High	1.0	1.0	1.0	Y=High	1.0
Y=Medium	1-0.3=0.7	1.0-0.4=0.6	1.0-0.7=0.3	Y=Medium	1.0
Y=Low	1-0.3-0.2=0.5	1.0-0.4-0.3=0.3	1.0-0.7-0.3=0	Y=Low	1.0
Y=Absent	1-0.3-0.2-0.5=0	1.0-0.4-0.3-0.3=0	0	Y=Absent	1.0

1) $P(Y \leq High|A = High, B = High) = 1 * 1 * 1 = 1$
$P(Y \leq Medium|A = High, B = High) = 0.8 * 0.7 * 1 = 0.56$
$$P(Y = High|A = High, B = High) = P(Y \leq High|A = High, B = High) - P(Y \leq Medium|A = High, B = High) = 1 - 0.56 = 0.44$$
2) $P(Y \leq Low|A = Low, B = Low) = 0 * 0 * 1 = 0$
$P(Y \leq Absent|A = Low, B = Low) = 0 * 0 * 1 = 0$
$$P(Y = Low|A = Low, B = Low) = P(Y \leq Low|A = Low, B = Low) - P(Y \leq Absent|A = Low, B = Low) = 0 - 0 = 0$$
3) $P(Y \leq Medium|A = Medium, B = High) = 0.9 * 0.7 * 1 = 0.63$
$P(Y \leq Low|A = Medium, B = High) = 0.8 * 0.5 * 1 = 0.40$

$$P(Y = Medium|A = Medium, B = High)$$
$$= P(Y \leq Medium|A = Medium, B = High)$$
$$- P(Y \leq Low|A = Medium, B = High) = 0.63 - 0.40 = 0.23$$

Example 2:

	A	B
High	0.9	0.1
Medium	0.1	0.2
Low	0	0.7
Absent	0	0

	A		
	High	Medium	Low
Y=High	0.2	0.1	0
Y=Medium	0.1	0.1	0.1
Y=Low	0.7	0.8	0.9
Y=Absent	0	0	0

	B		
	High	Medium	Low
Y=High	0.9	0.8	0.7
Y=Medium	0.1	0.2	0.3
Y=Low	0	0	0
Y=Absent	0	0	0

	A		
C_y^a	High	Medium	Low
Y=High	1.0	1.0	1.0
Y=Medium	1-0.2=0.8	1.0-0.1=0.9	1.0-0.1=0.9
Y=Low	1-0.2-0.1=0.7	1.0-0.1-0.1=0.8	1.0-0.1-0.9=0
Y=Absent	1-0.2-0.1-0.7=0	1.0-0.1-0.1-0.8=0	0

	B		
C_y^b	High	Medium	Low
Y=High	1.0	1.0	1.0
Y=Medium	1-0.9=0.1	1.0-0.8=0.2	1.0-0.7=0.3
Y=Low	1-0.9-0.1=0	1.0-0.8-0.2=0	1.0-0.7-0.3=0
Y=Absent	0	0	0

Leak	
C_y^L	
Y=High	1.0
Y=Medium	1.0
Y=Low	1.0
Y=Absent	1.0

1) $P(Y \leq High|A = High, B = High) = 1 * 1 * 1 = 1$
   $P(Y \leq Medium|A = High, B = High) = 0.8 * 0.1 * 1 = 0.08$
   $$P(Y = High|A = High, B = High)$$
   $$= P(Y \leq High|A = High, B = High)$$
   $$- P(Y \leq Medium|A = High, B = High) = 1 - 0.08 = 0.92$$
2) $P(Y \leq Low|A = Low, B = Low) = 0 * 0 * 1 = 0$
   $P(Y \leq Absent|A = Low, B = Low) = 0 * 0 * 1 = 0$

$$P(Y = Low|A = Low, B = Low)$$
$$= P(Y \leq Low|A = Low, B = Low)$$
$$- P(Y \leq Absent|A = Low, B = Low) = 0 - 0 = 0$$

3) $P(Y \leq Medium|A = Medium, B = High) =$ 0.9 * 0.1 * 1 = 0.09
$$P(Y \leq Low|A = Medium, B = High) = 0.8 * 0 * 1 = 0$$
$$P(Y = Medium|A = Medium, B = High)$$
$$= P(Y \leq Medium|A = Medium, B = High)$$
$$- P(Y \leq Low|A = Medium, B = High) = 0.09 - 0 = 0.09$$

Appendix F: Calculations done in BN

This appendix shows an example of the calculations done in Bayesian Networks when the effect of "evidence" is propagated in the network either by forward or backward reasoning.

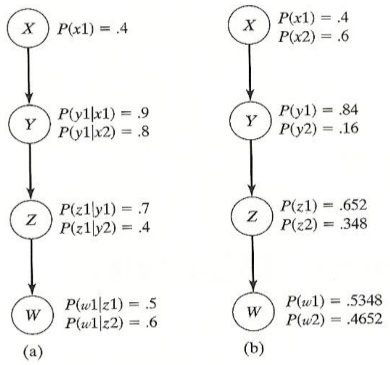


Figure 34: Example of Bayesian Network shown in a, adapted from Neapolitan (2004).

The prior probabilities of the variables in the network are shown in b. Each variable has only two values, therefore the probability of only one is shown in a.

With the given network and probabilities (figure 33), the examples of inference can be provided. The forward propagation of all variables are calculated as follows:
In general, the total probability is: $P(A) = P(A\,|B)P(B) + P(A\,|B')P(B')$

$$P(y1) = P(y1\,|x1)P(x1) + P(y1|x2)P(x2) = (0.9)(0.4) + (0.8)(0.6) = 0.84$$
$$P(z1) = P(z1\,|y1)P(y1) + P(z1|y2)P(y2) = (0.7)(0.84) + (0.4)(0.16) = 0.652$$
$$P(w1) = P(w1\,|z1)P(z1) + P(w1|z2)P(z2) = (0.5)(0.652) + (0.6)(0.348) = 0.5348$$

This computation clearly shows that calculation of each variable needs information from its parent. This is called the message passing algorithm in which each node passes to its child a message needed to calculate the probabilities of that child.

Suppose that X is instantiated for x1, the following calculations can be made:
$$P(y1\,|x1) = 0.9$$

$$P(z1\,|x1) = P(z1\,|y1, x1)P(y1|x1) + P(z1|y2, x1)P(y2|x1)$$
$$= P(z1\,|y1)P(y1\,|x1) + P(z1\,|y2)P(y2\,|x1)$$
$$= (0.7)(0.9) + (0.4)(0.1) = 0.67$$

$$P(w1\,|x1) = P(w1\,|z1, x1)P(z1|x1) + P(w1\,|z2, x1)P(z2\,|x1)$$
$$= P(w1\,|z1)P(z1\,|x1) + P(w1\,|z2)P(z2\,|x1)$$
$$= (0.8)(0.67) + (0.6)(0.33) = 0.734$$

These calculations show how downward propagation of messages is used to calculate the conditional probabilities of variables below the instantiated variable.

Suppose that W is instantiated for w1, then backwards propagation is used:

$$P(z1\,|w1) = \frac{P(w1\,|z1)P(z1)}{P(w1)} = \frac{(0.5)(0.652)}{0.5348} = 0.6096$$

$$P(y1\,|w1) = \frac{P(w1\,|y1)P(y1)}{P(w1)}$$

Appendix G: Managers' specifics

This appendix gives more detail about the current and past occupations of the managers that provided the validation of the design. The past occupations of a manager are listed only when there can be made a reasonable assumption that the occupation added experience in project risk management.

Profile 1
Current: Program Manager at an electronics manufacturer
Past:

- Program/Project Manager in the telecom industry
- Marketing Manager & Manager Development at an electronics manufacturer
- Researcher at laboratory

Profile 2
Current: Owner of company
Past:

- CEO of actuary at a bank
- Head Project Management and Quality Assurance at an electronics manufacturer
- Marketing Manager Europe of a division of an electronics manufacturer

Profile 3
Current: Owner of a company that does project management of innovation projects
Past:

- Project Manager at diverse innovation based companies
- Information Manager

Profile 4
Current: Project Leader/Manager Finance at an electronics manufacturer

Profile 5
Current: Manager R&D group at an electronics manufacturer
Past:

- Unknown

Profile 6
Current: Managing Director of a consultancy in technology
Past:

- CTO at a micro process technology manufacturer
- CEO at an electronics manufacturer
- Managing Director

Profile 7
Current: Owner of a company that improves project management within other companies
Past:

- Director and Project Manager
- Senior Consultant

- Project Leader and head of department at a university

Profile 8
Current: Program Manager at an electronics manufacturer
Past:

- Project Leader at an electronics manufacturer