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INTELLIGENT DECISION SUPPORT SYSTEMS FOR COLLABORATION IN INDUSTRIAL PLANTS

Dissertação apresentada para obtenção do Grau de Doutor em Sistemas de Informação Industriais, Engenharia Electrotécnica, pela Universidade Nova de Lisboa, Faculdade de Ciências e Tecnologia.

Lisboa

2010

ACKNOWLEDGMENTS

I would like to acknowledge the consortiums of the projects PICK (IST-1999-10442), AIM (IST-2001-52222), FOKSai (COOP-CT-2003-508637), InLife (FP6-2005-NMP2-CT-517018), InAmI (FP6-2004-IST-NMP-2-16788) and K-NET (FP7-ICT-1-215584), all of which were partially funded by the Research Framework Programs of the European Union. The research partners of these projects always provided me useful insights and fruitful discussions about the research topics being developed. The industrial companies of these consortiums have contributed quite significantly to my experience in different domains and sectors. These industrial companies have given their time, experience and information that enabled me to learn about industrial environments and test the approaches presented in this thesis.

I would like to thank all the companies that answered my questionnaire about decision-making practices in industry. Their collaboration is invaluable for this thesis, particularly to provide an overview of how companies do make their decisions.

My ten years of professional life have been equally divided in two five-year periods, between two research institutes. ATB, Institut für angewandte Systemtechnik Bremen GmbH, in Bremen, Germany, was my first workplace. This institute provided me the opportunity of working in several European projects, gathering experience from working with international and multi-disciplinary teams. All the staff members helped me to grow professionally. However, I would like to highlight the special role of Dr. Dragan Stokic and Dr. Uwe Kirchhoff. Dr. Kirchhoff taught me relevant lessons in the areas of best practices and industry in general. Dr. Dragan Stokic was a true mentor for five years, teaching me a bit of everything from technical, writing, administrative and personal skills. I will always be thankful to them for the role they played in my life.

The latest five years, I have been working in UNINOVA, Instituto de Desenvolvimento de Novas Tecnologias, in Caparica, Portugal. I would like to thank the researchers of UNINOVA who have contributed to my work with productive conversations and insights about different topics and also contributed to increase and improve my experience in projects. Additionally, I would like to thank to Dr. Rui Neves-Silva, whom I profoundly respect and admire, and who accepted the difficult task of supervising this work and from whom I have learned in an immeasurable way. I will always be thankful to Dr. Neves-Silva for his support through this long and winding road.

SUMÁRIO

O principal objectivo desta dissertação é contribuir para um processo de tomada de decisão estruturado e sistemático em empresas industriais, permintindo que façam o melhor uso dos seus recursos.

Os paradigmas de operação das empresas industriais têm-se modificado nas duas últimas décadas. Este fluxo dinâmico e flexível de informação e pessoas entre empresas criou novos desafios para a indústria. Não é possível dissociar a empresa do conjunto dos seus recursos humanos e o conhecimento criado e utilizado por estes. As empresas enfrentam constantemente a necessidade de tomar decisões. Com a pressão do mercado e contextos empresariais em permanente mudança, as decisões são cada vez mais complexas, envolvendo pessoas com competências complementares e geograficamente dispersas.

Os processos do conhecimento serão eficientes apenas se os actores puderem ancorar e relacionar a informação manipulada com a empresa estendida. Assim, o modelo da empresa é um aspecto fundamental para suportar a tomada de decisão na indústria. Este trabalho inclui uma visão sobre metodologias de modelação e standards existentes. Seguidamente, propõe um modelo para representar a empresa virtual ou estendida, adequado a aplicações de tomada de decisão, entre outras.

A dissertação considera métodos e sistemas de suporte à decisão e analisa tipos e processos de decisão. Depois, apresenta algumas considerações sobre tomada de decisão na indústria, incluindo, uma revisão de critérios comummente usados. Dois dos métodos mais utilizados nas áreas mencionadas, *Case–Based Reasoning* e *Analytic Hierarchy Process*, foram usados no âmbito da resolução de problemas e tomada de decisão, respectivamente. A dissertação apresenta uma nova aproximação baseada na combinação destes dois métodos para suportar processos de inovação, em particular o projecto de produtos na indústria. Esta combinação permite ultrapassar as limitações dos dois métodos para fornecer o suporte mais adequado a equipas multi-disciplinares em processos de inovação. Além disso, o trabalho propõe um algoritmo para ajuste automático dos pesos dos actores no processo de decisão.

A dissertação inclui casos de estudo, desenvolvidos no âmbito de vários projectos de investigação, usados como aplicações práticas do trabalho desenvolvido. Esta aplicações incluem sete casos de teste (com duas empresas de manufactura, duas de montagem, duas de serviços de engenharia e uma de software) onde o modelo da empresa proposto e os métodos foram aplicados com o propósito de suportar decisões. Isto sublinha a aplicação versátil do modelo proposto, descrevendo as suas possíveis interpretações e o uso bem sucedido da aproximação ao suporte à decisão nas empresas industriais.

ABSTRACT

The objective of this thesis is to contribute for a structured and systematic decision-making process for industrial companies, particularly involving several actors, helping them make the best use of their resources.

The paradigms of how industrial companies operate have been progressively changing over the last two decades. The flexible and dynamic flow of information and persons over companies has created new challenges and opportunities for industry. It is not possible to dissociate an enterprise from its human resources and the knowledge they create and use. Companies face decisions constantly, involving several actors and situations. With the market pressure and rapid changing environments, decisions are becoming more complex, and involving more people with complementary expertise.

The knowledge processes are only efficient if the actors can anchor and relate the information handled to the extended enterprise. Therefore, an enterprise model is a fundamental aspect to support decision-making in industry. This work includes an overview of existing modelling methodologies and standards. Afterwards, it proposes an enterprise model to represent an extended or virtual enterprise, suitable not only for decision-making applications but also for others.

This thesis considers methods and systems to support decision and analyses decision types and processes. Afterwards, the thesis presents some considerations on decision-making in industry and a generic decision-making process, including, a review of decision criteria commonly used in industry. Two of the methods widely used in some of the mentioned areas, case-based reasoning and the analytic hierarchy process, have been used in the scope of problem solving and decision-making, respectively. This thesis presents an approach based on a combination of case-based reasoning and analytic hierarchy process to support innovation, particularly product design in industry. The combination overcomes shortcomings of both methods to provide the most adequate decision support for multi-disciplinary teams in innovation processes. Moreover, the work presented proposes an algorithm for automatic adjustment of the weight of the actors in the decision process.

This thesis includes case studies, developed in the scope of several research projects, used as practical applications of the work developed. These practical applications include seven test cases (with two manufacturing companies, two assembling companies, two engineering services companies and one software company) where the proposed enterprise model and methods have been applied with the purpose of supporting decisions. This highlights the wide application of the proposed model, describing its possible interpretations and the successful use of the decision support approach in industrial companies.

Symbol	Description
$\mathrm{A_i}$	Alternative i
$\mathbf{B}^{(k)}$	Matrix of pairwise judgements of all criteria by actor k
C_i	Criteria i
$\mathrm{count_A}(l_i)$	The number of times l_i occurs in collection A
$\mathbf{F}_i^{(k)}$	Matrix of pairwise judgements of all alternatives, for criterion i, given by actor k
$\boldsymbol{\phi}$	Data vector in recursive least squares
H_i	Human actor i
$\mathbf{K}$	Kalman matrix in recursive least squares
L	Number of actors in the team
$\mathrm{LCA}(l_1, l_2)$	Lowest Common Ancestor, i.e. the node of greatest depth that is an ancestor of both l_1 and l_2
λ	Eigenvalue of a matrix or forgetting factor in recursive least squares
M	Number of alternatives in the decision situation
N	Number of criteria under consideration in the decision situation
$\mathbf{p}$	Vector of weight of actors in the team, for aggregation of criteria weights
$\mathbf{p}^*$	Optimal solution vector of actors' weights in the team, for aggregation of criteria weights
$\mathbf{P}$	Co-variance matrix in recursive least squares
$\mathbf{q}$	Vector of weights of actors in the team, for aggregation of alternatives ratings
$\mathbf{s}_i^{(k)}$	Vector of ratings for all alternatives considering criterion i, provided by actor k
$\mathbf{S}^{(k)}$	Matrix of ratings for all alternatives for all criteria, provided by actor k
$\mathbf{S}$	Matrix of aggregated ratings of all alternatives for all criteria
$\mathrm{sim}(\mathrm{A}, \mathrm{B})$	Similarity between two entities A and B
$\mathbf{U}$	Matrix of ratings for all alternatives for all criteria, provided by the market
$\mathbf{v}^{(\mathrm{E})}$	Vector of rankings of the alternatives in the market
$\mathbf{w}^{(k)}$	Vector of weights for all criteria, defined by actor k
$\mathbf{w}$	Vector of aggregated weights for all criteria, provided by all actors
$\mathbf{W}$	Matrix of weights for all criteria, provided by each actor (one column per actor)
$\mathbf{w}^{(\mathrm{E})}$	Vector of weights for all criteria, provided by the market
$\hat{\mathbf{w}}^{(\mathrm{E})}$	Vector of best estimative of market's weights for all criteria
$\mathbf{Y}$	Matrix of rankings of all alternatives provided by each actor (one column per actor)
$\mathbf{y}$	Vector of rankings of the alternatives to make the decision

ACRONYMS AND ABBREVIATIONS

Acronym	Description
AHP	Analytic Hierarchy Process
ARIS	Architecture of Information Systems
CAD	Computer-Aided Design
CBR	Case-Based Reasoning
CDM	Collaborative Decision Making
CEN	European Committee for Standardization
CEO	Chief Executive Officer
CIMOSA	Computer Integrated Manufacturing Open System Architecture
CORBA	Common Object Request Broker Architecture
CRM	Customer Relationship Management
DSS	Decision Support System
ebXML	eXtensible Markup Language
GDSS	Group Decision Support System
GERAM	Generalised Enterprise Reference Architecture and Methodology
GRAI	Groupe de Recherche en Automatisation Intégrée
GRAI-GIM	Groupe de Recherche en Automatisation Intégrée – Integrated Methodology
IDSS	Intelligent Decision Support System
IEC	International Electrotechnical Commission
IFAC	International Federation of Automatic Control
IFIP	International Federation for Information Processing
ISO	International Organization for Standardization
MDA	Model Driven Architecture
OASIS	Organisation for the Advancement of Structures Information Standards
OMG	Object Management Group
PERA	Purdue Enterprise Reference Architecture
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management
RBR	Rule-Based Reasoning
RLS	Recursive Least Squares
SCOR	Supply Chain Operations Reference Model
STEP	Standard for Product Data Representation and Exchange
STEP	Standard for the Exchange of Product Model Data
TOVE	Toronto Virtual Enterprise
UML	Unified Modelling Language
UN/CEFACT	United Nations Centre for Trade Facilitation and Electronic Business

active decision-making support systems. Intelligent decision-making support systems that take the initiative without getting specific orders.

collaborative decision making. Process of decision making in a collaborative environment where problems can be addressed through argumentative discourse and collaboration among the users involved.

collaborative decision support systems. Technologies or systems that enable or enhance the ability of the participants involved in collaborative decision-making processes.

craft production. Production focused on craft, where highly skilled people transformed materials to produce something, using mostly inexpensive tools.

decision. Choice, which is to realise a certain goal by analysing subjective-objective conditions, generating alternatives, and choosing the most appropriate one among them.

decision-making. Process of reaching a conclusion after considering several alternatives.

decision support systems. Interactive computer-based information systems designed to help human decision makers, by processing data and models in order to identify, structure, and solve semi-structured or unstructured problems.

enterprise model. Abstraction of an enterprise domain that represents enterprise entities, their interrelationships, their decomposition and detailing to the extent necessary to convey what it intends to accomplish and how it operates.

enterprise modelling. Conceptual modelling techniques to describe the structure and business processes of an enterprise, its missions and objectives with the way these objectives may be operationalised onto systems components.

extended enterprise. Formation of closer co-ordination in the design, development, costing and the co-ordination of the respective manufacturing schedules of co-operating independent manufacturing enterprises and related suppliers.

group decision support systems. Interactive computer-based systems that facilitate the solution of ill-structured problems by a set of decision makers that work together as a team.

intelligent decision support systems. Information systems to generate knowledge to support decision-making, combining the research fields of decision support, artificial intelligence and knowledge management.

knowledge acquisition. Process of gathering information from any source.

knowledge elicitation. Sub-task of knowledge gathering that deals with gathering knowledge from human experts.

lean production. Combination of craft and mass production, using multi-skilled workers and flexible automated machines.

mass production. Production of inexpensive goods, using highly sophisticated machines operated by relatively unskilled operators

virtual enterprise. Temporary alliance of enterprises that come together to share skills or core competencies and resources in order to better respond to business opportunities, and whose cooperation is supported by computer networks.

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1. INTRODUCTION

The main objective of this thesis is to contribute for a structured and systematic decision-making process for industrial companies, helping them make the best use of their resources.

This first chapter of the thesis describes the motivation for the work performed, how it was structured and the main original contributions proposed.

1.1. MOTIVATION

People have always used information in any aspect of their daily lives. It is not possible to think, act, decide or even feel without having information processed by our brains. In business companies, the same happens. Companies have been using information to handle the business. Until not long ago, companies' information was the people's information. This means that the only source of knowledge within a business was its employees. This was possible because businesses were less complex and the majority of people stayed their complete productive life in the same job and company. The structure of the society and economy encouraged and permitted the "job for life". However, this situation does no longer hold.

The phenomenon of globalisation, which appeared in the 80s, has changed our world in a very significant way. The overall education of people around the world has increased and the jobs have changed. Local, regional and even national companies have been transformed into global business, operating in multiple countries. As people change jobs several times in their productive working life, they accumulate knowledge, but also move this knowledge from one place to another. Businesses have been losing information and knowledge, and not only employees. Therefore, companies started noticing the need to retain information in a way that did not entirely depend on the employees.

The paradigms of how companies, and especially manufacturing companies, operate have changed deeply over the last century. Before World War I, production focused on craft, where highly skilled people transformed materials to produce something, using mostly inexpensive tools. The process was expensive and extensive. After World War I, two automotive companies, Ford and General Motors, were responsible for introducing the paradigm of mass production. The objective was to produce inexpensive goods, using highly sophisticated machines operated by relatively unskilled operators. However, the expensive and highly specialised machines were somehow less tolerant to modifications, which required companies to produce vast amounts of the same product, for as long as possible. Henry Ford described the process best with his sentence "*Any customer can have a car painted any colour that he wants so long as it is black.*" After World War II, another automotive company, Toyota, pioneered the paradigm of lean production. This paradigm combines craft and mass production, using multi-skilled workers and flexible automated machines. The objective was to use less human efforts, fewer tools, less manufacturing space and less investment, when compared to mass production.

The need for flexibility made companies analyse their internal structures and hierarchies, which were very pyramid-like. Businesses discovered several layers of middle management that were involved neither in any decision-making process nor in leading the companies. In fact, some of these middle layers were only relaying information, representing filters that were retaining some information, representing loss of information. The re-structuring of companies, cutting down the middle management, represented the movement of lean production (Womack and Jones, Lean Thinking 1996).

More recently, globalisation brought an immense increase in relations among businesses. Companies seldom represent a complete supply chain to deliver any product to market. Global market demands for high quality, customised but inexpensive products, which have forced companies to establish short, medium and long-term relations with others. Emerging information and communication technologies foster the specific characteristics of this paradigm: collaboration, decentralisation and inter-organisational integration (O'Neill and Sackett 1994). In this context, two main concepts have emerged, to classify alliances: extended enterprise and virtual enterprise. Extended enterprise is the formation of closer co-ordination in the design, development, costing and the co-ordination of the respective manufacturing schedules of co-operating independent manufacturing enterprises and related suppliers (Jagdev and Browne 1998). This allows a company to take advantage of competencies and resources without owning them. A virtual enterprise is a temporary alliance of enterprises that come together to share skills or core competencies and resources in order to better respond to business opportunities, and whose cooperation is supported by computer networks (Camarinha-Matos, Afsarmanesh and Garita, et al. 1998). It is commonly agreed that the extended enterprises focus on long-term relationships across the value chain, while the virtual enterprises suggest a more dynamic environment where individual companies work together for a relatively short time to satisfy a specific market demand quickly (Browne and Zhang 1999) (Camarinha-Matos and Afsarmanesh, Virtual Enterprise Modeling and Support Infrastructures: Applying Multi-agent System Approaches 2006). In addition, extended enterprises centre their core competencies in one dominant company, while virtual enterprises have core competencies distributed over the participating companies (Jagdev and Browne 1998).

Increasing relations brought two main challenges for companies: flexibility and exchange of information. This made companies focus more on their information and knowledge, where to get it from and especially how to represent it. Exchanging information is only possible and efficient from the organisation viewpoint if a formal structuring is in place.

The recent advances in information and communication technologies have moved the industrial world from highly data-driven environments to a more cooperative information/knowledge-driven environment, taking into account more of the enterprise know-how, common-sense, and application semantics (Vernadat 2002).

The way people work has changed together with the operation paradigms of companies. Individuals not only work for several companies during their productive life, but the way people and companies are connected has also adjusted. Market constraints for companies to decrease their costs, and individual requirements of people who need to balance personal and professional lives, fostered the appearance of new ways of work, which are highly facilitated by technology, especially information and communication technologies, and particularly the Internet. Concepts such as freelancer, e-lancing, e-work, telework and telecommute are quite often nowadays. The number of freelancers, for example, reached 12 million in the end of 2009, in the United States, and the number of web sites to support e-lancing is also growing (Working in the digital age: a clouded future 2010).

This flexible and dynamic flow of information and persons over companies has created new challenges for industry. It is not possible to dissociate an enterprise from its human resources and the knowledge they create and use. A company can be seen as just a processor of information created by the individuals (Simon, Administrative Behaviour 1997), or the amplifier of knowledge created by the individuals (Nonaka and Takeuchi 1995). In any of the situations, what companies make with the knowledge they have is of key importance.

Many tasks in an industrial environment relate to reaching a conclusion after considering several alternatives, i.e. making a decision. Companies face decisions constantly, involving several actors and situations (e.g. developing a new product, fixing a machine, hiring a new employee). With the market pressure and rapid changing environments, decisions are becoming more and more complex, and involve more people with complementary expertise, not necessarily from the same company or geographical location. Quite often, decision-making processes involve different actors within the extended or virtual enterprise, with diverse backgrounds and expertise and located in disperse places. This thesis aims at contributing to support decision-making processes, particularly involving several actors, which are designated by collaborative decision-making.

The recent economic downturn, which started in 2007, has led companies to cut their costs and many have underinvested in their information infrastructure. A recent study by the American consultant Gartner (Schlegel, et al. 2008) stated, “most organisations find they do not have the information, processes and tools needed by their managers to make informed, responsive decisions.” The same report estimates that through 2012, more than 35% of the top 5000 global companies will fail to make insightful decisions about significant changes in their business and markets due to underinvestment in their information infrastructure and business user tools.

Companies need a systematic approach to support decision-making processes, which enables traceability and accountability. Companies need the best information and rules to make a decision, but they also need to learn from what went right and what went wrong. Being able to replicate a successful situation and avoid a downfall has to be part of a company’s strategic thinking.

Many sciences have studied topics relevant for decision-making, including neuro-sciences, psychology, management science, operations research, control, artificial intelligence, business intelligence and the recent behavioural economics. Already more than twenty years ago, Nobel Prize laureate Herbert Simon had said (Simon, Two heads are better than one: collaboration between AI and OR 1987):

> JOINING HANDS WITH ARTIFICIAL INTELLIGENCE, MANAGEMENT SCIENCE AND OPERATIONS RESEARCH CAN ASPIRE TO TACKLE EVERY KIND OF PROBLEM-SOLVING TASK THE HUMAN MIND CONFRONTS.

There has been a convergence among the research fields of decision support, artificial intelligence and knowledge management, developing a number of information systems to generate knowledge to support decision-making. Collectively, these systems can be called intelligent decision support systems (Hans and Peter 1992). These systems integrate the functions of decision support systems and knowledge-based systems to assist decision makers in performing decision analysis, and explain conclusions and recommendations (Hunsaker and Hunsaker 1981) (Tansley and Hayball 1993) (Sensiper 1998) (Silverman 1994).

The research has produced impressive results in the area of decision-making, as described in Chapter 3, Decision support in industrial environments, but often failed at focusing the application of its results to industrial companies. One of the main issues has been segmentation between information, knowledge and their application. Companies invest heavily in expert systems for specific applications within the enterprise. Often, companies have several systems, which are completely independent, and are not able to communicate and use different and sometimes redundant information. The extended and virtual enterprises need tailored support for decision-making, which includes:

- Full use of the enterprise's information and knowledge. Companies need to have one model independent of the applications, which means only one knowledge base.
- Efficient and methodical procedure to model and acquire knowledge in an extended or virtual enterprise. Companies need to be able to identify and select the knowledge relevant for the desired applications.
- Systematic and clear approach to support decision-making processes involving complex teams with diverse expertise and geographical dispersed. Companies need to be able to review past decisions and learn from them.

The objective of this thesis is to contribute to minimise these state-of-the-art gaps, in order to help industrial companies in having an appropriate approach for decision support. The work presented has the objective of modelling extended enterprises for decision-making applications, and contribute to providing a systematic procedure to support accountable and repeatable decisions in industrial companies.

1.2. ORIGINAL CONTRIBUTIONS

The main objective of this thesis is, in general terms:

Develop a systematic methodology to support industrial companies in making and revisiting decisions, using the best resources available.

The work developed includes the following main original contributions:

1. An **enterprise model**, considering state-of-the-art methodologies and standards, to represent an extended or virtual enterprise, enabling decision support applications, among others. The model includes the necessary constructs for companies to model their physical elements, operations and resources to anchor dynamic information related to decision situations. The enterprise model includes a modelling methodology to support industrial companies in modelling their enterprises with limited use of external knowledge modelling experts. This modelling methodology details a set of phases for companies to follow in the process of knowledge acquisition and includes some tools to support knowledge elicitation from human actors (e.g. questionnaire for semi-structured interviews).

2. A **combination of case-based reasoning and the analytic hierarchy process** to support decision-making situations in industrial enterprises, particularly in the scope of innovation processes. This combination overcomes the bottlenecks of each method individually, namely how to adapt the most similar case suggested by case-based reasoning and how to identify and formulate the hierarchy to use in the analytic hierarchy process. This proposed approach is tightly connected to the enterprise model and comprehends a hierarchy of criteria that can be applied in diverse decision situations in industrial environments.

3. An **algorithm to adapt actor's weights in a team** by considering market ranking feedback and enterprise strategy. This method uses information about the implementation of decisions to potentiate the role of actors that systematically take decisions aligned with the company's strategy. The proposed algorithm is presented as a possible approach to support companies in learning from the implementation of decisions and adapting their decision making process to reinforce the most successful decisions.

4. A collection of **case studies** that represent tests of parts of the work presented in this thesis in industrial environments. The seven test cases include two manufacturing companies, two assembling companies, two services engineering companies and one software company. The enterprise model was applied in the seven test cases proving its diversity and showcasing different interpretations to the set of constructs proposed. The case-based reasoning method was also tested in the seven companies, allowing to show its successful application and enabling its continuous development. One of the test cases was used to perform a preliminary study on the analytic hierarchy process approach, providing results that supported the refinement of the approach.

1.3. ORGANISATION OF THE THESIS

This thesis is organised in six chapters, as described in the following text.

Chapter 1, Introduction, presents the motivation for the work developed, describing the background that led to the topic, namely in a business and industrial perspective. This chapter also describes the structure of the thesis and identifies its main original contributions.

Chapter 2, Enterprise model, discusses the structure used to represent an enterprise. This chapter starts with an overview of existing modelling methodologies and standards, and afterwards details the model developed to represent an extended or virtual enterprise for the purpose of decision-making applications.

Chapter 3, Decision support in industrial environments, introduces the topic of decision-making with a particular industrial focus. The chapter begins with a review of different systems to support decision, followed by a definition of decision types and the process of making a decision. Afterwards, the chapter presents some considerations on decision-making in industry and a generic decision-making process. This chapter finalises with a review of criteria commonly used in decision-making in industry.

Chapter 4, Problem solving and innovation in industry, focus on decision-making applications in industrial companies. This chapter describes several systematic approaches to support industrial decision-making, namely based on case-based reasoning, the analytic hierarchy process and a combination of both. Additionally, this chapter proposes an algorithm to automatically adjust actors' weights in a team using information about the success of the implemented decisions.

Chapter 5, Case studies, presents the experimental part of this thesis, with detailed descriptions of practical applications of the model and methods developed.

Chapter 6, Conclusions and future work, finalises this thesis summarising the work performed and identifying future directions.

2. ENTERPRISE MODEL

Providing decision support for industrial companies requires the ability of modelling the extended enterprise and the decision process. This chapter proposes an enterprise model to represent an extended enterprise, suitable not only for decision-making applications but for others as well. The concept's foundation is that any application in an extended enterprise involves handling and exchanging knowledge. The knowledge processes are only efficient if the actors can anchor and relate the information handled to the extended enterprise.

With the increased relations among companies, the concern of representing information in a formal and structured way soon became a major concern (Nagarajan, Whitman and Cheraghu 1999). Companies started storing all bits of data and information, even if not relevant at all. Another aspect is also that each system inside the company (CRM, CAD, PLM etc.) uses its own information structure, making for a lot of redundancy in a less positive sense. However, the efficiency of a virtual or extended enterprise, once formed, is greatly determined by the speed and efficiency with which information can be exchanged and managed among business partners (Browne and Zhang 1999). Sharing information among partners of a supply chain will not only reduce the operation costs of each of the partners, but the efficiency of this 'trust' based business transaction will give rise to a sense of 'customer satisfaction' along the value chain (Jagdev and Browne 1998).

There are situations where extended and/or virtual organisations include competitors. Even in these situations, companies should not see as a disadvantage sharing information and knowledge, as it is an essential feature. Knowledge, even if public, may not be an obvious source of competitive advantage; what each company does with the knowledge, in terms of applying it to value-creating tasks, matters more than its public availability (von Krogh, Ichijo and Nonaka 2000).

Companies in an extended or virtual enterprise need to coordinate their processes, and efficiently exchange information and knowledge. All things to be integrated and coordinated need to be modelled to some extent (Vernadat 2002). The goal of an enterprise modelling approach is not to model the entire enterprise in all of its details, although it might be theoretical possible. The size and scope of the model must be decided by the business users, according to finality to be achieved.

Most industrial companies have a main concern in problem solving, because unsolved problems cause delays, increases waste and consumes resources ineffectively. In addition, companies want to extend their products by incorporating in them knowledge and expertise from all participants of the value chain (Sorli, et al. 2006). This added-value knowledge often comes from what it is possible to learn during the product lifecycle, especially from solving problems. Industrial companies usually use accumulated knowledge, especially from what went wrong (i.e. from solving problems) to innovate their products and processes. This thesis introduces a model to represent industrial enterprises, especially targeting problem-solving applications. The need for such a model came when developing problem-solving approaches for manufacturing industry, using methods such as reasoning. Companies lack an overview of their products, processes and resources, needed to document any problems occurring in the manufacturing processes. Additionally, companies were involved in extended and virtual enterprises and needed to document problems occurring all over the supply chain, i.e. in process of distinct companies.

2.1. EXISTING MODELLING TECHNOLOGIES

Enterprise knowledge modelling, or enterprise modelling, is a generic name that refers to a collection of conceptual modelling techniques for describing the structure and business processes of an enterprise, its missions and objectives with the way these objectives may be operationalised onto systems components (Loucopoulos and Kavakli 1999).

The majority of enterprise modelling techniques provides concise descriptions of what an enterprise “does” in order to operate. To this end, they usually involve two kinds of sub-models: an entity (or data, or information) model and a process (or functional) model.

There are several methodologies and tools that facilitate business process management, from the enterprise integration perspective, trying to support the life-cycle stages of the integrated manufacturing enterprise (Szegheo and Andersen 1999) (Kosanke, Comparison of Enterprise Modelling Methodologies 1996).

Computer integrated manufacturing open system architecture (CIMOSA) provides a process oriented modelling concept that captures both the process functionality and the process behaviour (Kosanke, CIMOSA: enterprise engineering and integration 1999). CIMOSA consists on a generic and a partial modelling and supports three modelling levels of the complete life cycle of enterprise operations: requirements definition, design specification and implementation description. Each modelling level supports different views on the particular enterprise model. CIMOSA has defined four different modelling views: function, information, resource and organisation (CIMOSA: A Primer on key concepts, purpose and business value n.d.).

Purdue Enterprise Reference Architecture (PERA), developed at Purdue University, recognises the fact a computer cannot implement many human functions, especially innovative ones (Williams and Li 1998). Therefore, the focus of PERA is to separate human based functions in an enterprise from those with a manufacturing or information perspective. PERA separates enterprise tasks in three categories: information system tasks, manufacturing system tasks, and human based (organisational) tasks. PERA considers two views of the enterprise: a functional view and a manufacturing functional model view.

The Architecture of Information Systems (ARIS), developed at the University of Saarland, has an overall structure very similar to CIMOSA. However, instead of focusing on computer-integrated manufacturing systems, it deals with more traditional and business-oriented issues of enterprises, such as order processing, production planning and control, inventory etc. The focus is essentially on software engineering and organisational aspects of integrated enterprise system design (Szegheo and Andersen 1999).

The GRAI method (Doumeingts, et al. 1987), developed in the University of Bordeaux, deals with the decisional aspects of manufacturing systems. Based on the GRAI models, two formalisms were developed to model the macro decision structure and the micro decision centre; the GRAI grid and the GRAI nets. The GRAI method was extended to GRAI-GIM (GRAI Integrated Methodology) within the framework. GRAI-GIM contains two methods: one is user-oriented and the other is technical-oriented. The user-oriented method transforms user requirements into user specification in terms of function, information, decisions and resources. The technical-oriented method transforms the user specification into technical specifications in terms of information and manufacturing technology components and the organisation.

The Generalised Enterprise Reference Architecture and Methodology (GERAM) framework was defined by a task force from the International Federation of Automatic Control and the International Federation on Information Processing, starting from the evaluation of CIMOSA, GRAI/GIM and PERA. GERAM is about those methods, models and tools needed to build and maintain the integrated enterprise, be it a part of an enterprise, a single enterprise or a network of enterprises (virtual or extended enterprises) (IFIP-IFAC Task Force on Architectures for Enterprise Integration 1999). GERAM defines a toolkit of concepts for designing and maintaining enterprises for their entire life history.

This section mentions some of the main existing modelling methodologies. In addition, there is also work developed in the area of ontology for business processes, including Toronto Virtual Enterprise (TOVE) (Grüninger, Atefi and Fox 2000) and ontology to support extended enterprises (Kuczynski, Stokic and Kirchhoff 2006). Despite the wide range of modelling technologies, their application in industrial environments is quite limited. Most of the models referred in this section are quite complex or general to make their application possible in an industrial environment, by the actors of the extended enterprise. When the models are applicable in industry, they are usually very resource consuming, because they imply long hours not only from staff within the extended enterprise but also outsourced resources as knowledge experts.

2.2. EXISTING MODELLING STANDARDS

There has been significant work developed in trying to develop standards to unify approaches in enterprise engineering and integration. The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) on the international level and the European Committee for Standardization (CEN) on the European level have produced an important set of standards. However, there is still significant work to do, especially regarding human-related aspects. Recently, these organisations have joint efforts to produce comprehensive standards, unifying their previous work.

Some important standards lay important rules and concepts in a general perspective. In this category, it is important to refer ISO 14258, Concepts and Rules for Enterprise Models, and ISO IS 15704, Requirements for Enterprise Reference Architectures and Methodologies. These two documents describe fundamental concepts and objectives to be met by enterprise models.

In addition, there are standards defining framework that aim to improve business process interoperability, and standards structuring languages that provide languages for modelling different perspectives of enterprises. In the framework section, three standards are relevant: CEN/ISO 19439 Framework for Modelling, ISO 15745 Framework for Application Integration and ISO 15288 Life Cycle Management. Regarding languages, three other standards appear: CEN/ISO 19440 Constructs for Modelling, ISO 18629 Process Specification Language and ISO/IEC 15414 ODP Enterprise Language.

In addition to standards to model enterprises, there has also been considerable work in achieving interoperability among systems and companies. Interoperability between systems depends on standards to represent data, knowledge and services. The Object Management Group (OMG) develops enterprise integration standards that include the Unified Modelling Language (UML), Model Driven Architecture (MDA) and the Common Object Request Broker Architecture (CORBA), all of which are highly used in various domains. ISO developed the ISO 10303 standard, known as STEP, Product Data Representation and Exchange, and the Organisation for the Advancement of Structures Information Standards (OASIS), together with the United Nations Centre for Trade Facilitation and Electronic Business (UN/CEFACT), developed the Electronic Business using eXtensible Markup Language (ebXML). The work of interoperability among services has gained major relevance because of the changes in computing paradigms (e.g. service-oriented architecture, web services). Some research work has been developing combinations of existing standards to improve interoperability among companies (Jardim-Gonçalves, Grilo and Steiger-Garção 2006).

For the work presented, the most interesting standard is CEN/ISO 19440 because it is, not only the most recent, but defines a general set of constructs that are considered essential when modelling an enterprise. As described below, this standard was used as basis for the model proposed.

2.3. PROPOSED MODEL

The work presented was realised in the context of developing a comprehensive approach for problem solving applications in industry, initially with manufacturing companies. The starting point was the need of some companies to quickly solve problems occurred in their shop-floor, while avoiding waste of resources. However, these companies recognised that about 95% of the problems occurred were repetitions of previous situations. This means that only 5% of the problems represented new situations in the machines. Therefore, the simple possibility of accessing what maintenance staff had done in a previous situation could enhance the problem solving approach in the companies. This simple fact uncovered the problem that companies do not record occurred problems in a structured way, enabling its future use.

The research work of how to represent and model problems occurred in a manufacturing shop floor cannot be isolated from the enterprise. Problems occur in specific machines, registering precise measures and conditions, and are handled in an exact way by employees. Therefore, all this information had to be part of describing a problem.

Companies also lack an overview of their structure and operation. They are missing an enterprise model, which is defined as an abstraction of an enterprise domain that represents enterprise entities, their interrelationships, their decomposition and detailing to the extent necessary to convey what it intends to accomplish and how it operates (ISO 2006).

This work presents an enterprise model appropriate for the context of problem solving in manufacturing enterprises. As will be described later (see chapter 5 Case studies), this model was also applied in companies not related to manufacturing with satisfactory results. Because the objective was to develop a model for a wide application, it was necessary to consider existing standards. The first basis for this model was the European Pre-Standard ENV12204, and later updated to comply with ISO 19440 (ISO 2007). Table 2.1 shows a mapping between the constructs indicated in the international standard ISO 19440 and the constructs of the model proposed. The main objective is to show that the model developed complies with all aspects of the standard, while extending it to cover additional aspects of problem solving. This means that companies that already have an enterprise model following ISO 19440 could easily extend it to have additional problem solving features.

TABLE 2.1. MAPPING ISO19440 TO THE PROPOSED MODEL.

ISO 19440 Constructs	Proposed Model Constructs
Domain	Business Unit
Business process	Process Step
Enterprise activity	Process Step
Event	Actual State Item
Enterprise Object	Generic
Enterprise Object View	Production Unit Process Step Product Part
Order	Problem
Product	Product Part
Capability	Technology
Operational Role	Technology
Resource	Resource
Functional Entity	Production Unit
Person Profile	Actor
Organisational Role	Actor
Organisation Unit	Business Unit
Decision Centre	Business Unit

The knowledge model developed includes two modules: the static data and the dynamic data (see Figure 2.1). The implementation of the model in an enterprise is designated as common knowledge base (Campos, Stokic and Neves-Silva 2004). The static data comprehends all the information about the physical and process model of the dynamic virtual enterprise, i.e. it is used to store data about product parts, production units, process steps, technologies, resources, states etc., as well as all the interactions among these elements. In addition, the static data also includes types of problems. This information describes all the processes in the enterprise, and although these will suffer modifications, their information is considered static because it represents components, characteristics and/or parameters, therefore attributes of existing items in the enterprise.

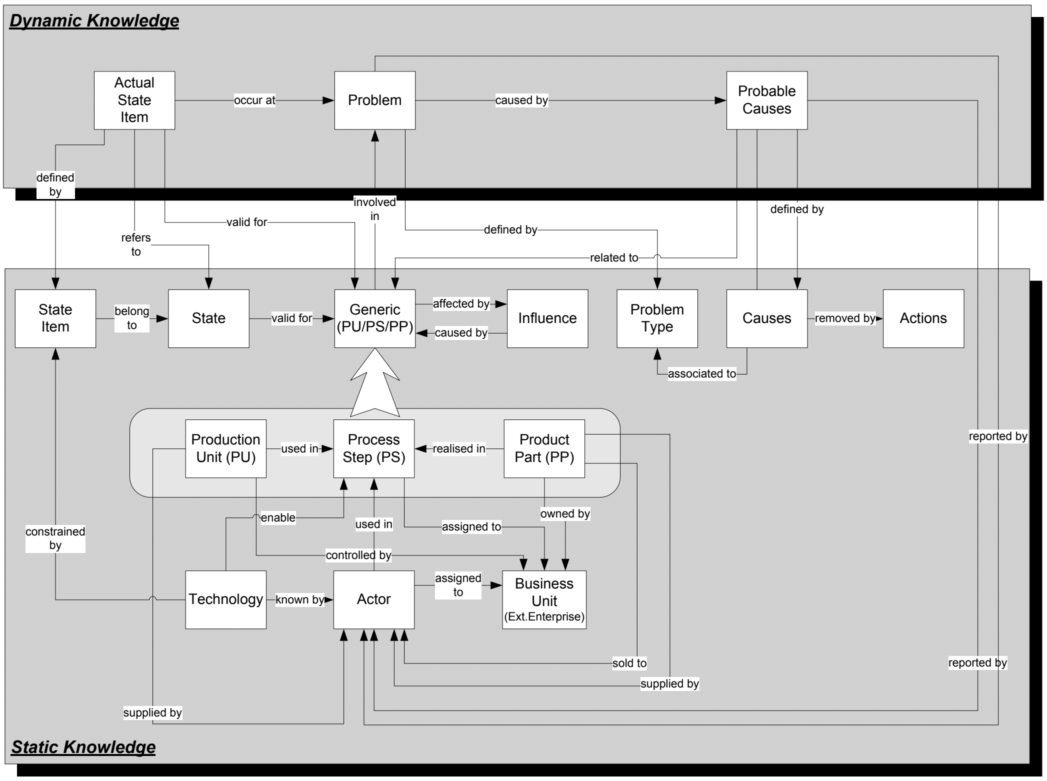


FIGURE 2.1. PROPOSED ENTERPRISE MODEL.

The dynamic data comprises information about actual data for a specific instant of time, i.e. specific values for any element, attribute or relation defined in the common knowledge base. This set of information represents problems, process deviations, specific values of machine states, probable causes for problems and actions.

The static data of the common knowledge base represents the complete infrastructure of the enterprise, and its modification reflects a business decision. The dynamic data of the common knowledge base contains information on the actual state of the enterprise's variables, which is described using components from the static set of the common knowledge base.

The model comprehends many relationships that enable to save interactions among elements, which constitute a major source of information in the enterprises.

Following the application of the ISO 19440 standard, the constructs that define the proposed enterprise model are described using a common structure and template. Each model construct is described, according to ISO 19440, by (ISO 2007):

- a textual description consisting of brief text defining the modelling language construct in terms of a purpose, its description and its intended usage, and
- a construct template, which organises and defines the attributes for the modelling language construct.

- The template is described in an informal manner but using a common pro forma. In turn, the construct template shall have the form described below:
  a) Header part having the same attributes for each modelling language construct and containing attributes relating to the identity of a construct instance and to its context. It shall be structured as follows:
     1) construct label (a literal string denoting the kind of construct);
     2) identifier (a literal string that is unique for each occurrence of the modelling language construct within the model);
     3) name (the name of the instance of the modelling language construct);
     4) authority for model design (i.e. the identifier of the Organisational Role or Organisational Unit responsible for the design of this construct): for all construct and for all attributes concerned with authorities or responsibilities, the identifier or name of the Organisational Unit may be omitted in the Concept Identification and Requirements Definition modelling phases.
  b) Body part containing the particular attributes that are specific to each construct and whose description is derived from the particular modelling language construct definition. Body parts shall then be structured ion two further partitions as follows:
     1) descriptives, containing descriptive attributes that comprise
        – construct-identifying description in textual form,
        – construct attributes that are predefined,
        – additional construct attributes that may be defined by the user to meet particular needs, such as those required by additional model views, and
        – attribute qualifications – statements that are made about whether attribute values are mandatory or optional, when they are applicable, etc.
     2) relationships, containing relationship attributes that can include
        – Operational relationships, that are responsibility and authority for model operation (i.e. the identifier of the Organisational Role and Organisational Unit responsible for the operational usage of this construct or authorised to change its usage),
        – *Specialisation_of* relationships, representing relationships between a specialisation and its generalisation,
        – *Part_of* relationships, representing relationships between this construct instance and the whole aggregated from such instances,
        – *Consists_of* relationships, representing relationships between this construct instance and its constituent parts, and
        – Association relationships for other forms of relationships, either predefined or user-defined (such as provision or usage of a Capability instance by Resource or Enterprise Activity instances).

The work done includes a full specification of the proposed model following this structure, to be compliant to the standard. However, this structure is not very suitable to present the proposed constructs in this thesis. Therefore, the following sections include a textual description of the model, presenting the same information requested by the standard template, while the standard-compliant forms are in Annex A, Model Specification.

2.3.1. STATIC KNOWLEDGE

The static knowledge represents a model of the product and process models of the enterprise. Figure 2.2 represents the main objects in the static knowledge. Several inheritance relationships mark the model, which represent the complete hierarchy of the industrial companies, and especially the manufacturing processes. The hierarchy enables the representation of repeatable similar objects, with unique characteristics. This is a key aspect for the companies, which helped to ease the knowledge acquisition process.

The following text describes briefly each object of the static knowledge model. All the main objects of this model include attributes for identifier, name, description and documents.

A **business unit** represents the organisational structure of the enterprise, according to its decomposition. A business unit can represent one company or one of its departments or units. The business unit corresponds to a domain, i.e. the boundary and the content of an enterprise or a portion of an enterprise for which an enterprise model is to be created. The business units are leading elements in the model because they control the production elements, i.e. process steps, product parts and production units. Business units are defined using attributes for identifier, name, description, documents and responsible. This last attribute characterises the person responsible for the business unit and is an actor. Business units have two relationships defined among themselves. A hierarchy defines a *parent_of* relation that represents a generalisation between two elements. A decomposition relationship defined by *consists_of* and *part_of* indicates the organisational chart of the company. When modelling a multi-site company, it is possible to have one business unit “maintenance department” which is the parent of “maintenance city A” and “maintenance city B”. The two children are a specialisation of the parent business unit. On the other hand, it would be possible to define that business unit “maintenance city A” *consists_of* two different business units called “routine maintenance” and “emergency response”.

An **actor** describes an employee of the extended or virtual enterprise, using attributes for identifier, surname, name, username, password, email, and phone. Actors always belong to one business unit, providing the information of which organisational structure (department or even company) the person represents. This is registered in the attribute belongs to business unit.

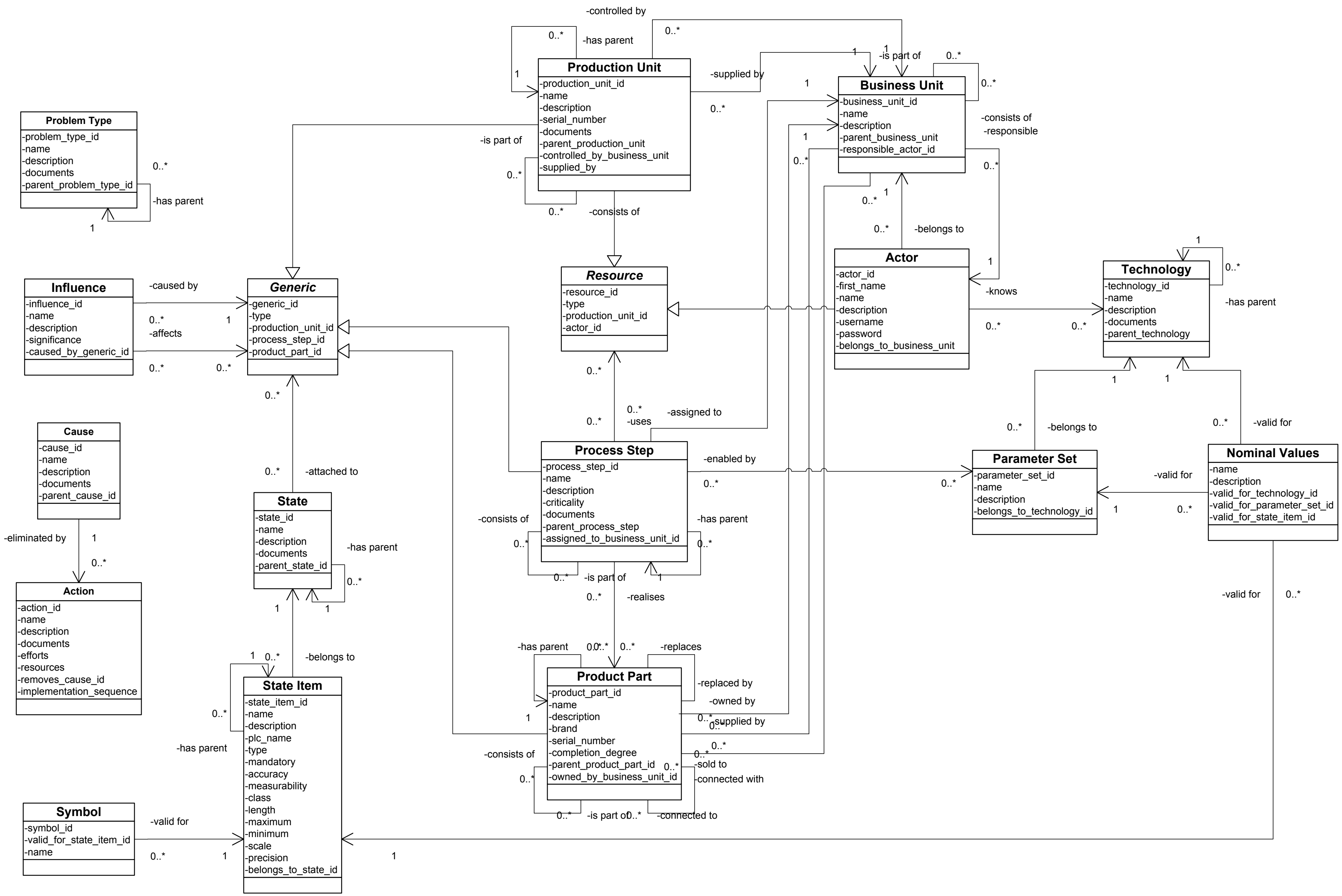


FIGURE 2.2. OVERVIEW OF MODEL’S STATIC KNOWLEDGE.

A **technology** represents application of scientific knowledge or techniques in the company's operational life. It describes all the techniques used in assembling or manufacturing and services, and for which knowledge is needed within the enterprise. This object comprehends attributes for identifier, name, description, equation and documents. There is a relationship between technologies and actors, since technologies represent actors' expertise, i.e. actors know technologies. In addition, technologies have a relationship among themselves, representing a hierarchy of scientific subjects, through the *parent_of* relation.

A **production unit** describes a physical resource of the enterprise used to realise an activity. In most cases, a production unit is some kind of machine used to produce something. Production units include attributes for identifier, name, description, and serial number. Each production unit belongs to one business unit, through the attribute *controlled_by*, providing information about its location and responsibility. Production units relate to business units, through relation *supplied_by*, since some organisational structure supplies each production unit, being a department within the company or another company in the extended enterprise. Production units have two relationships defined among themselves: a hierarchy defines a *parent_of* relation that represents a generalisation between two elements; and a decomposition relationship is defined by *consists_of* and *part_of*.

A **resource** is a generalisation of two existing objects, representing physical and human assets of the extended enterprise. Therefore, a resource is always either a production unit or an actor.

A **process step** is an activity of the enterprise that represents part of process functionality needed to realise a basic task within the enterprise. Each process step comprehends attributes for identifier, name, description, documents and criticality. Each process step is assigned to a business unit of the extended enterprise, through the attribute *assigned_to*, providing information about its exact location. Process steps have two relationships defined among themselves: a hierarchy defines *parent_of* relation that represents a generalisation between two elements; and a decomposition relationship defines *consists_of* and *part_of*. Technologies enable process steps, in the sense that to produce an activity it is necessary to have some specific scientific knowledge. As a process step is an activity, it uses resources of the extended enterprise, i.e. it uses actors and production units.

A **product part** represents a complete product, a part of it, or even raw material used in the company, which connects in any way with other product parts and/or transformed to result in a whole product. Product parts include attributes for identifier, name, description, brand, serial number and completion degree. Each product part relates to a business unit, through the attribute *owned_by*, which provides exact information about where in the extended enterprise the product part is used. Additionally, business units within the extended enterprise also supply and sell product parts. Product parts have four relationships among themselves: a hierarchy defines *parent_of* relationship that represents a generalisation between two elements; a decomposition relationship defines *consists_of* and *part_of*; a relationship *connected_to* and *connected_with* defines product parts that are attached or united; and the relationship *replaced_by* and *replaces* defines possible substitutions of product parts to use in case of stock rupture. Product parts are the result of a process step, defined in the relationship *results_in*.

A **generic** is a generalisation of three existing objects, representing the three main elements of the extended enterprise: production units, process steps and product parts. Generics exist to ease several relationships among different elements and the three objects.

An **influence** represents power or constraints that one generic may have upon others. It is quite common, in an extended enterprise, that for example one machine affects how other machines work (e.g. a controller affects machines beneath it). Influences comprehend attributes for identifier, name, description and significance. Each influence is cause by one generic, defined in the attribute caused by generic, and can affect several generics, defined in the relationship *affects*.

A **state** represents a group of characteristics that can describe a generic, especially measurable information. A state includes attributes for identifier, name, description and documents. States have a relationship among themselves that defines a hierarchy, *parent_of*, which represents a generalisation between two elements. This hierarchy is extremely important for problem solving applications, since it implies inheritance of characteristics from parent to child. States relate to generics, through the relationship *attached_to*.

A **state item** represents a specific variable of a generic, i.e. a characteristic that can be measured at a certain instant of time. This information is especially useful to provide additional knowledge in the occurrence of a problem. State items are organised in categories defined by states, and divided into five types: Boolean, text, date, numeric and symbolic. State items include attributes for identifier, name, description, programmable logic controller (PLC) name, type, mandatory, accuracy, measurability and class. State items have additional attributes that are specific for each type. When the state item has the type text, then it is also necessary to define the attribute length, which defines the maximum number of characters allowed. When defining date or Boolean state items, there is no need for any additional attributes. In case of numeric state items, it is essential to define attributes for minimum, maximum, scale and precision. These identify the range allowed for the numeric state item, as well as number of decimal and total digits permitted. Finally, when defining symbolic state items, it is required to define a list of allowed symbols to choose from. State items have a relationship among themselves that defines a hierarchy, *parent_of*, which represents a generalisation between two elements.

A **parameter set** establishes a set of variables that connect process steps and technologies. Parameter sets have attributes for identifier, name and description. Parameter sets have a relationship to process steps, *enables*, and another relationship to technology, *belongs_to*.

A **nominal value** is a specific variable of the parameter set, which indicates the measures that are available for each technology and process step. A nominal value includes attributes for name and description. Variables that can be measured for the physical elements of the extended enterprise are already part of the model, defined as state items. Therefore, nominal values are actually a combination of three relationships of the type *valid_for*. Nominal values are valid for a specific technology, a parameter set and a state item.

A **problem type** provides classification of typical problems that occur in the extended enterprise. Problem types provide a first classification of a problem detected, and are defined according to the enterprise's know-how. Problem types comprehend attributes for identifier, name, description and documents.

A **cause** defines standard problem origins in the extended enterprise. While some problems can occur unexpectedly, others are predictable, and even described in troubleshoot sections of manuals. Therefore, it is possible to define a list of typical problems, which define problem types, and their origin, the causes. Causes include attributes for identifier, name, description, and documents.

An **action** defines an act carried out to eliminate a problem's cause. Similar to causes and problem types, this information exists in the extended enterprise expertise, often in manuals and employees' know-how. Actions include attributes for identifier, name, description, resources, and efforts. Each action relates to a cause with a sequence number, since several actions may be required to eliminate a cause.

Causes and actions have a semi-dynamic nature because the initial static set of instances defined grows more dynamically than any other construct in the static data. Although it is possible to define an initial set of instances for these two constructs, it increases substantially with the use of the problem-solving application.

2.3.2. DYNAMIC KNOWLEDGE

Once all the static data of the extended enterprise is collected and modelled, it is then possible to define the dynamic part of the model. Figure 2.3 represents the main constructs of the model's dynamic knowledge.

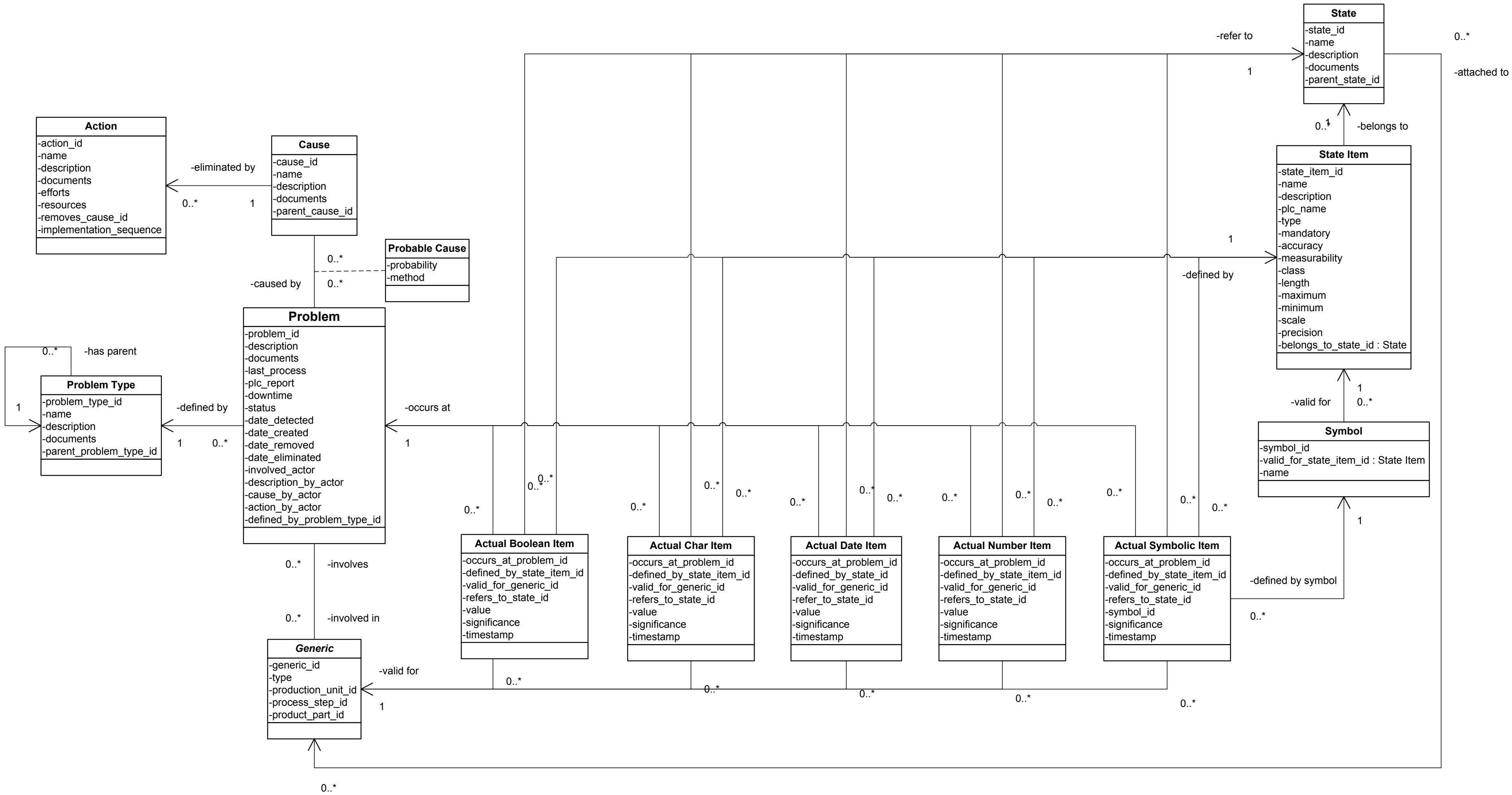


FIGURE 2.3. OVERVIEW OF MODEL'S DYNAMIC KNOWLEDGE.

A **problem** represents the occurrence of abnormal temporary situations. A problem is defined using a series of attributes including identifier, description, documents, last process executed, PLC report (if exists and is relevant), downtime, and status. In addition, there are four date attributes equally important to establish a diagnosis history in the extended enterprise: the date when the problem was detected, the date when the problem was created in the model, the date when the problem was removed, i.e. when the cause was identified, and the date when the problem was eliminated, i.e. when the actions to eliminate the cause were successfully carried out. Each problem is categorised with a relationship to problem type, using the attribute defined by problem type. Since industrial companies place a high value on responsibility and accountability, it is important to record information about actors that were somehow implicated in the process of diagnosing and solving problems. In order to accomplish this, problems include four attributes that establish relations to actors in the extended enterprise: *involved_actor* records who reported the problem in the first place, *description_by_actor* registers who finalised relating the problem with all its characteristics, *cause_by_actor* records who identified the problem's cause, and *actions_by_actor* registers who implemented the necessary actions to eliminate the problem.

A very important part of describing a problem is establishing relationships with elements of the extended enterprise, i.e. objects of the static part of the model. One of the most important relationships is establishing where exactly the problem occurred. This connection defines which physical elements of the extended enterprise, i.e. generics, were involved in the problem. This means that it is possible to identify the production units, process steps and product parts implicated in the problem.

Just identifying the generics does not provide a clear description of what may have happened. It is extremely advantageous to have a snapshot of the generics involved, i.e. register any possible measurable characteristics. These measurable characteristics of generics exist in the static part of the model, as state items. In the dynamic part of the model, it is possible to identify specific values for the state items, which are denominated **actual state items**. Each value can be one of five types: Boolean, date, number, text or symbol. An actual state item is defined by a state item, refers to a state, is valid for one generic and has occurred during one problem. An actual state item has additionally a timestamp to indicate when exactly the measure was registered.

A **probable cause** identifies a possible origin of the problem, and establishes a relation between problems (dynamic part of the model) and causes (static part of the model). As a problem can have more than one cause, each probable cause defines a relationship to a cause indicating its probability and diagnosis method (e.g. manual, diagnosis system, and reasoning).

2.4. MODELLING METHODOLOGY

Gathering, modelling, structuring and storing information are difficult tasks. Industrial companies usually search help for such processes, turning to experts in knowledge and information and communication technologies, frequently designated as knowledge engineers. Knowledge acquisition is the task of gathering information from any source, and knowledge elicitation is the sub-task of gathering knowledge from human experts (Shadbolt and Burton 1989). There are a number of tools to support knowledge acquisition and elicitation, but they require considerable experience to ensure an efficient process.

With the objective of supporting industrial companies in minimising the need for external support, the proposed model is not a stand-alone development. It is accompanied by a comprehensive methodology to help industrial companies in modelling their extending enterprises, with limited support from knowledge modelling experts. The objective of the methodology is to provide industrial actors with guidelines that allow them to identify the relevant information to be modelled within the extended enterprise, and also methods on how to efficiently acquire that information.

There have been several representations of steps or stages for a knowledge acquisition process. Buchanan et al. suggest five stages for knowledge acquisition: identification, conceptualisation, formalisation, implementation and testing (Buchanan, et al. 1983). Rook and Croghan further specify this knowledge acquisition process, by defining seven steps: knowledge framework specification, knowledge resource identification, macro-knowledge extraction, knowledge partitioning, micro-knowledge extraction, knowledge formalisation and knowledge encoding (Rook and Croghan 1989). Grover developed a simplified knowledge acquisition cycle comprehending three phases: domain definition, fundamental knowledge formulation and basal knowledge consolidation (Grover 1983).

All the knowledge acquisition processes start with a stage of defining the domain and objectives, which includes determining the type of information to be acquired and who is involved in the process. Afterwards there is the stage of knowledge acquisition and elicitation, where usually knowledge engineers try to collect the necessary information from all actors identified in the domain. The final stage is to validate the information collected and, if possible and desirable, extract additional knowledge based on the information collected, e.g. rules. These are the main stages of every knowledge acquisition process, which appear sometimes further detailed in more steps.

The current methodology proposes a process in four phases:

1. define the domain and actors;
2. collect static data;
3. collect dynamic data; and
4. extract rules.

The first phase is simpler than in many methodologies because of the model proposed, because companies do not need to formulate which type of information they need to model or acquire. The objective is to collect information to model all the classes defined in the enterprise model proposed. Therefore, the first phase aims at finding the most appropriate modelling team within the extended or virtual enterprise. To define the enterprise model, qualified staff must be involved. For this, it is necessary to build a project team with staff of all concerned areas, departments and even companies within the extended enterprise. This project team shall include staff from production, quality assurance, process development and information technology areas. As one of the objectives is to model information to be used in problem solving applications, it is essential to have staff experienced with current problems and the process connections. To ensure an efficient introduction, the project management shall be realised by an employee with experience on the implementation of information systems as well as on the application cases. The knowledge engineers support the management in identifying the actors involved in each phase of the process and relate to the appropriate data classes.

Because the proposed enterprise model is divided into a static and dynamic part, and the latter depends on the former's definition, the second phase focus on collecting instances of static data. The description of object instances in the enterprise model is a decisive procedure to get useful and efficient applications. If the instances defined are unsuitable, it might be possible that e.g. the numbers of relations between instances are unnecessarily increased. This decreases the efficiency of the model and limits its potential use.

Therefore, it is necessary to consider the following basic requirements for the definition of instances:

- minimum number of instances;
- clarity of instances (e.g. problems can only be assigned to one single problem type);
- simple extension of instances (the objects are defined in a way to be easily extended and the definition of new objects avoids the redefinition of existing objects).

The proposed model has many possible relationships among the objects. The full use of these relationships, especially hierarchies, supports the definition of a minimum number of instances for each object.

The modelling team shall provide the enterprise's static data in a specific order, to facilitate the process. Therefore, this second phase includes acquiring information on business units, actors, process steps, production units, product parts, technologies, states, and state items.

The company areas and business processes essentially describe the organisational construction of the extended enterprise and the activities are a functional description. For the collection of the information, respective reference models are a good basis (e.g. Supply-Chain Operations Reference Model, SCOR). Moreover, an extended enterprise normally has different process models. The modelling team has to consider these different models while collecting the process information.

The proposed methodology provides a checklist and a questionnaire for a structured interview aiming at eliciting the static data from the enterprise actors (see Annex B, Modelling Methodology Tools). The interviews are performed by knowledge engineers or by actors within the enterprise, following the guidelines provided. The purpose of the first set of interviews is to identify instances of the classes, including a detailed description. After the interviews, a second round of sessions uses teach-back tools where the team leader of the modelling process describes the information acquired so that experts can identify and correct errors and complete the information. After having identified the instances of each class, the team needs to define the relations among instances, which are an important part of the proposed enterprise model. The methodology proposes the use of laddering and card sorting techniques that allow actors to organise instances in hierarchies, using e.g. tree diagrams, and grouping instances by specific characteristics.

After having defined the enterprise information, it is possible to start collecting data about problem types, possible problem causes and actions. Usually the companies have a good categorisation of problem types, which appear listed in manuals and quality procedures. In addition to their own expertise, actors use existing information on causes to fill out the tables comprehended in the methodology. To support this work, the methodology includes tables with a pre-defined list of groups to structure the causes. The method to collect information on problem causes is based on the well-known Ishikawa or cause-and-effect diagrams (Ishikawa 1982). The methodology uses, as pre-defined groups, the 5 M's: Man, Machine, Material, Method and Mother Nature (or Environment). The objective of the team is then to decompose further each group into more specific causes. When the extended enterprise has no information available about problem causes, the methodology suggests performing a cause analysis for several concrete problems, using an Ishikawa diagram. The experts can identify the causes by attempting to answer a list of questions provided for each of the 5M's groups.

Apart from the problem causes information, it is also required to collect data over possible actions realised to eliminate the causes. Therefore, actors apply a similar procedure to the one used for problem causes. Actors collect enterprise available information on actions (e.g. from action forms according to DIN EN ISO 9000ff standards) and document it in the tables provided in the methodology. For a better survey, the methodology introduces groups, following the groups for problem causes, i.e. 5 M's. If the application targeted within the extended enterprise is very wide, the modelling team should consider introducing several hierarchy levels, which are supported by the proposed model and methodology. An example is to assign the 5 M's to each business process in the extended enterprise.

The team responsible for the enterprise model has to consider constantly the readability of the information defined and collected. For example, actors need to describe actions to eliminate problem causes as detailed as possible, enabling any actor to perform them afterwards. The methodology suggests the use of matrix-based techniques to map the possible causes to their usual actions.

Modelling the extended enterprise is a strongly iterative process. After defining a new instance, it is often necessary to adjust and complete the other instances or relations according to the new information and findings.

The third phase of the modelling process is to collect the dynamic data of the enterprise, i.e. occurrences of problems. In some situations, companies need to start using problem-solving tools immediately, such as case-based reasoning. These tools depend on instances defined in a knowledge base, which means that companies need to collect as many past instances of dynamic data, as possible. The phase of collecting dynamic data can therefore occur before starting to use any applications (because information is needed) or it runs during the standard use of an application system. Companies frequently document non-conformities following quality procedures. This information is extremely useful to document instances of problems occurred. The methodology proposes to complement this with interview and commentary techniques, where actors can explain what they usually do in specific situations. It is possible to observe the normal work of some actors, or ask them to comment and explain specific situations that are, for example, presented in videos.

Several authors identify knowledge acquisition and elicitation as the bottleneck for the successful implementation and adoption of knowledge-based systems. The objective of the proposed model and methodology is to contribute for companies to have an accessible mechanism to collect and re-use information for different applications. The approach was tested in several companies, in different domains, as described in chapter 5, Case studies.

All the applications presented relate to decision-making processes, and particularly problem solving. However, the model proposed includes a comprehensive set of static data capable of supporting other applications.

3. DECISION SUPPORT IN INDUSTRIAL ENVIRONMENTS

Many tasks in an industrial environment are somehow related to reaching a conclusion after considering several alternatives, i.e. making a decision. Companies face decisions everyday, involving several actors and situations (e.g. developing a new product, fixing a machine, hiring a new employee). With the market pressure and rapid changing environments, decisions are becoming more and more complex, and they involve more people, not necessarily from the same company. Quite often, decision-making processes involve different actors within the extended enterprise.

Improving individuals and groups abilities to solve problems and make decisions is an important issue in many sectors in a society such as education, industry, government and the military. Many researchers are turning to collaboration as a way to make such decisions (Grand 1999) (Klein 1999).

The evolution of telecommunications network technology has dramatically facilitated the sharing of information and the participation of individuals in the decision-making process (Karacapilidis, An Overview of Future Challenges of Decision Support Techniques 2006). Group decision-making becomes a necessity in the contemporary enterprise (Fjermestad and Hiltz 2000); the more different perspectives are taken into account, the smaller the chances of addressing the wrong problem and reaching an inadequate solution (Vennix 1996).

Decision making in a distributed environment through mutual collaboration of the participants has been termed as collaborative decision making (CDM). A definition of CDM, according to Karacapilidis (Karacapilidis, Dimitris and Costas, Computer-Mediated Collaborative Decision Making: Theoretical and Implementation Issues 1999), is the “process of decision making in a collaborative environment where the problems can be addressed through argumentative discourse and collaboration among the users involved.”

Collaborative decision making and the respective supporting systems address several research and development areas. Issues such as collecting, creating, eliciting, integrating, sharing and re-using data, information and knowledge are essential in a collaborative framework to make decisions. In addition, CDM has to comprehend a structured methodology to address decision-making analysis, argumentation among participants, negotiation and conflict resolution, and consensus management. Furthermore, a collaborative decision support system can only be efficient if it enables the integration of the several decision-making processes and tools, while stimulating human participation.

3.1. METHODS TO SUPPORT DECISION-MAKING

Decision-making is usually performed through debates and negotiations among a group of people (Boose, et al. 1993), and depends largely on the data and knowledge available. The decision making process involves the art of managing qualitative data and analysing it, i.e., integrating ideas developed in one area with ideas developing in another area, and then transferring it to those groups.

The knowledge necessary for decision-making is attained with different degrees of confidence at different stages of decision-making, and sometimes, incomplete knowledge is acquired. Collaboration is conducted under virtual dynamic team environment, and knowledge is shared with inadequate understanding. Decisions are made under the influence of many uncertain factors. Thus, the ability to handle different types of uncertainty in decision-making becomes extremely important (Qiu, Chui and Helander 2004).

However, despite the centrality of uncertainty in the decision-making, only few studies addressed this question (Lipshitz and Strauss 1997). In (Qiu, Chui and Helander 2004) it is proposed a model of knowledge-based collaborative decision-making, where three sources of uncertainties are identified: imprecise knowledge, dynamic team environment and conflict of system support. Decision-making usually involves knowledge from different sources that are vague, uncertain, default-based, or judgemental, and which have different degrees of reliability. Imprecise knowledge acquired by decision makers can be misleading in decision-making. There are inherent obstacles of virtual teams that come with uncertainties, such as the dynamic of trust. Dynamic team environment increases inadequate understanding of team objectives and update progress of project, and it also increases the difficulty in communication among teammates. The introduction of any tool into an environment has the potential to serve as a catalyst for change. The conflicts of system support exist in the following three categories: conflict with the natural flow of decision-making process, conflict in supporting the right team member and conflict in conveying the precise knowledge. The model presented in (Qiu, Chui and Helander 2004) comprehends methodologies on how to reduce uncertainties in knowledge-based collaborative decision-making.

One important issue in collaborative decision-making and collaborative decision support systems is the implementation of argumentation support systems for different types of groups and application areas. Such systems address the needs of a user to interpret and reason about knowledge during a discourse (Karacapilidis, Dimitris and Costas, Computer-Mediated

Collaborative Decision Making: Theoretical and Implementation Issues 1999). For instance, QuestMap (Conklin 1996) captures the key issues and ideas during meetings and creates shared understanding in a knowledge team, showing the history of an online conversation that led to key decisions and plans. Euclid (Smolensky, et al. 1987) is another system that provides a graphical representation language for generic argumentation. JANUS (Fischer, McCall and Morch 1989) is based on acts of analysing existing knowledge in order to foster the understanding of a design process. SEPIA (Streitz, Hannemann and Thuering 1989) is a knowledge-based authoring and idea processing tool for creating and revising hyper documents. Finally, Belvedere (Tan and Pearl 1994) uses a rich graphical language to represent different logical and rhetorical relations within a debate. Although these systems do not have decision-making capabilities, they provide a cognitive argumentation environment that stimulates discussion among participants (Karacapilidis, Dimitris and Costas, Computer-Mediated Collaborative Decision Making: Theoretical and Implementation Issues 1999) (Karacapilidis, Computer Supported Argumenation and Collaborative Decision Making: The HERMES System 2001).

Numerous web-based conferencing systems have also been deployed, such as AltaVista Forum Center, Open Meeting, NetForum and UK Web's Focus etc. They usually provide means for discussion structuring and user administration tools, while the more sophisticated ones allow for sharing of documents, online calendars, embedded e-mail and chat tool etc. However, there is a lack of consensus seeking abilities and decision-making methods (Hurwitz and Mallery 1995).

A prerequisite for computer-mediated CDM tools is the ability for the computer to "understand" (at least partially) the dialogue in a decision-related argument between people, and the discourse structure used in presenting supportive material in a document. This requires a computational model of the discourse acts, which are used in these cases. Although there has been work in artificial intelligence on dialogue and discourse in collaboration and negotiation (De Michelis and Grasso 1994) (Di Eugenio, et al. 1997) (Grosz and Sidner 1990) (Merin 1997), that work is not sufficient for modelling dialogues in the CDM context. More specifically, it is rather general and not explicitly oriented towards real-life CDM environments (Karacapilidis, Dimitris and Costas, Computer-Mediated Collaborative Decision Making: Theoretical and Implementation Issues 1999).

In (Sidner 1994), it is presented a model of collaborative negotiation based on the idea of establishing mutual beliefs, that is, beliefs that agents hold in common. This model rests upon the non-existence of deception, and appears fragile in the presence of mutual misunderstandings. The work of Cohen and Levesque (Cohen and Lavesque 1990) and of Smith and Cohen (Smith and Cohen 1996) is very similar to Sidner's work, but relies in addition on the primitive notion of joint goals. Core and Allen (Core and Allen 1997) introduce a scheme for annotating communication acts in dialogue, which ignores the formation of opinion by hearers about speakers.

An understanding of the implications in the CDM process requires a model of the mental attitudes of the agents involved (their beliefs, desires, intentions, goals etc.) as they pertain to the task at hand. Further, it requires a model for the particular form of discourse acts that agents use to communicate their knowledge and intentions, and affect the attitudes of others. In addition, it requires a model of the actions that relate to the argument process itself.

HERMES (Karacapilidis, Dimitris and Costas, Computer-Mediated Collaborative Decision Making: Theoretical and Implementation Issues 1999) is a web-based system that enhances group decision-making by providing an argumentation framework to the agents involved. Argumentation is performed through a set of discourse acts, especially designed for the CDM context following an artificial intelligence perspective. HERMES provides the appropriate machinery for automating processes such as discussion structure, consistency checking and reasoning for decision-making. Moreover, it includes further assistance modules with information retrieval, natural language processing and argument building features. However, this system focuses only on asynchronous collaboration.

CDM usually includes intricate debates and the need for negotiation among the individuals involved in the decision-making. Conflicts of interest are inevitable and support for achieving a consensus is a prominent part of the collaborative decision making process (Kim, et al. 2004).

Increased emphasis on collaborative decision-making processes has led to the development of consensus management techniques to develop a solution. The use of consensus monitoring tools has improved the likelihood of consensus attainment (Bhargava and Power 2001).

Conflicts generally arise during a collaborative process when individuals or groups hold different ideas about a specific issue or have divergent solutions to a particular problem and fail to arrive at a common goal. Conditions that promote effective conflict management focus on the problem or issue at hand, consideration of a wide range of alternative solutions, a cooperative climate, an organised and orderly process, and avoidance of artificial conflict-reducing devices such as voting or having the leader make the decision. Conflicts can often be successfully managed and resolved through collaboration and the effective support of the collaborative decision support system provided (Smari, et al. 2005).

Action Evaluation is a collaborative, goal-setting and evaluation process used for conflict management (Friedman, et al. 2003) (Rothman 1997). Action Evaluation is a value-driven process that has been successfully applied in dozens of large and small-scale projects to help groups and individuals forge agreements and develop strategies for success.

In (Smari, et al. 2005), Action Evaluation is used as a knowledge elicitation tool, to build a textual database of individuals and groups views and ideas that can be fused into their groups' shared purposes. Ultimately, these diverse purposes are integrated into one shared view and a shared action plan for all the groups and stakeholders of the collaboration.

Having participants in an organisation develop a shared view of a decision requires a collaborative process, simply defined as a mechanism by which people decide together. Developing a shared view for a decision differs from consensus in that it allows people in positions of authority (i.e. in a hierarchical enterprise such as a military organisation) to have final control over the decision reached (Smari, et al. 2005).

CDM presumes inevitable conflicts but supports reaching a shared view of a decision (Ngwenyama, Bryson and Mobolurin 1996). Deciding on the best solution requires the simultaneous consideration of a large amount of criteria, related to one another in intricately and often conflicting ways. Multi-Criteria Decision Making approaches (Triantaphyllou 2000) concentrate on problems with discrete decision spaces where the set of decision alternatives has been predetermined. Multi-Objective Decision Making applies when continuous decision-making revisions are used (Smari, et al. 2005).

Several methodologies support the decision process, i.e. methods that help actors making a choice. Although, some of these methodologies are not strictly related to CDM, they are relevant in supporting the choice process. The main methodologies were analysed in the scope of this state-of-the-art.

Analytical Hierarchy Process is especially suitable for complex decisions involving the comparison of decision elements which are difficult to quantify. It is based on the assumption that when faced with a complex decision, the natural human reaction is to cluster the decision elements according to their common characteristics. It involves building a hierarchy (ranking) of decision elements and then making comparisons between each possible pair in each cluster (as a matrix). This gives a weighting for each element within a cluster (or level of the hierarchy) and also a consistency ratio (useful for checking the consistency of the data) (T. Saaty 1980).

Criteria Rating Form and Weighted Ranking are suitable methodologies when it is necessary to select among several alternatives, to make a decision objectively or have a group agree on a decision. The criteria ranking form is an appropriate method to take into account the inputs and opinions of several participants, making it a suitable method to support CDM.

Gap analysis consists of defining the present state, the desired or 'target' state and hence the gap between them. In the later stages of problem solving, the aim is to look at ways to bridge the gap defined and this may often be accomplished by backward-chaining logical sequences of actions or intermediate states from the desired state to the present state. Gap analysis alone, however, is not adequate for all problem situations as goals may evolve and emerge during the course of problem solving. In addition, some problems have many alternative solutions, in which case backward-chaining search strategies will have little practical use.

A crucial stage in the formulation of operations strategy is the derivation of a ranked (or rated) list of competitive factors such as quality, flexibility, cost, etc. This list is used either to infer an appropriate set of strategic operations decisions or, in conjunction with an independently derived list of the organisation's performance, to prioritise each of the competitive factors. The method of Importance/Performance Matrix consists of building a matrix representing the importance scale in the x-axis and the performance in the y-axis. The list of competitive factors is then represented in the matrix. A $2x2$ matrix of importance/performance can be used but may be found too crude, while the most common uses the 9-point importance and performance scales.

Quantitative decision-making methods are suitable for situations where the objective is clearly stated, or where there are several alternative courses of action, or there is a calculable measure of the benefit or worth of the various alternatives. Uncertainties for which allowance must be made or probabilities calculated may include events beyond the control of the decision maker and uncertainty concerning which outcome (or external events) will actually happen. Given these conditions, standard statistical techniques using normal distribution data and probability calculation can be used to inform decision-making.

Strategic Assessment Model decomposes a strategic problem into clearly defined components in which all alternatives, factors, weights, and probabilities are depicted. Next, objective information and subjective judgements of experts are integrated by utilising several methods of problem structuring and information processing. This decomposition and evaluation is not intended to replace the decision-makers, rather, it provides a systematic approach to support, supplement, and ensure the internal consistency of their judgements through a series of logically sound techniques. Strategic Assessment Model divides the decision making environment into three parts: internal environment, the set of relevant factors that form the profile of the internal operations of the organisation; task environment, the set of relevant factors that have direct transactions with the organisation and the influence between these factors is reciprocal; and general environment, the set of relevant factors that can exert considerable influence on the organisation.

Strategic Assumptions Surfacing and Testing is a process which reveals the underlying assumptions of a policy or plan and helps create a map for exploring them. Strategic Assumptions Surfacing and Testing incorporates the following principles: adversarial – based on the premise that the best way to test an assumption is to oppose it; participative – based on the premise that the knowledge and resources necessary to solve and implement the solution to a complex problem is distributed among a group of individuals; integrative – based on the premise that a unified set of assumptions and action plan are needed to guide decision making, and that what comes out of the adversarial and participative elements can be unified; and managerial mind supporting – based on the premise that exposure to assumption deepens the manager's insight into an organisation and its policy, planning, and strategic problems.

The Strategic Choice Approach is used in face-to-face workshops of a decision making group. Strategic choice is viewed as an ongoing process in which the planned management of uncertainty plays a crucial role. The Strategic Choice Approach focuses on decisions to be made in a particular planning situation, whatever their timescale and whatever their substance. This method highlights the subtle judgements involved in agreeing how to handle the uncertainties which surround the decision to be addressed – whether these are technical, political or procedural. The approach is an incremental one, rather than one which looks towards an end product of a comprehensive strategy at some future point in time. This principle is expressed through a framework known as a 'commitment package'. In this, an explicit balance is agreed between decisions to be made now and those to be left open until specified time horizons in the future. The approach is interactive, in the sense that it is designed not for use by experts in a backroom setting, but as a framework for communication and collaboration between people with different backgrounds and skills.

There are many decision situations in which the information cannot be assessed precisely in a quantitative form but may be in a qualitative one, and thus, the use of a linguistic approach is necessary (Herrera and Herrera-Viedma, Linguistic decision analysis: steps for solving decision problems under linguistic information 2000). In CDM, criteria and preferences are often vaguely qualitative and cannot be estimated by exact numerical values. Therefore, a more realistic approach may be to use linguistic assessments instead of numerical values by means of linguistic variables (Delgado and Verdegay 1992) (Herrera e Verdegay, A linguistic decision process in group decision making 1996) (Herrera, Herrera-Viedma and Verdegay, A model of consensus in group decision making under linguistic assessments 1996) (Herrera, Herrera-Viedma and Verdegay, A rational consensus model in group decision making using linguistic assessments 1997) (Herrera and Verdegay, Linguistic assessments in group decision 1993), that is, variables whose values are not numbers but words or sentences in a natural or artificial language. Each linguistic value is characterised by a syntactic value or label and a semantic value or meaning. The label is a word or sentence belonging to a linguistic term set and the meaning is a fuzzy subset in a universe of discourse. The application of fuzzy set theory to decision-making problems, when only qualitative or uncertain information is available, has been the subject of much research over the last decades, e.g. (Chen and Hwang 1992) (Kacprzyk and Ferizzi 1990) (Tong and Bonissone 1984) (Yager 1981), and many others.

In (Huynh and Nakamori 2005), a new model is proposed, based on the probabilistic-based approach for the multi-expert decision-making problem under linguistic assessments. This approach is based on the ordered-structure-based semantics of linguistic term sets, which may be accepted universally, while fuzzy-set-based semantics of linguistic terms is often defined subjectively and context-dependently. Furthermore, by performing direct computation on linguistic terms, the burden of quantifying a qualitative concept is eliminated. It is also especially necessary and useful in situations where the fuzzy-set-based semantics is inapplicable due to the nature of linguistic information.

Computing facilities and information technologies enable the efficient transferring and sharing of knowledge across organisational boundaries, and allow collaborating individuals to benefit from experiences of other group members and experts. Information and communication technologies have been widely exploited in all areas of industry.

In the CDM domain, case-based reasoning and learning techniques have been particularly useful due to their resemblance to the way people evaluate a potential future action by using past experience, the scarcity (or even absence) of explicitly stated rules, and the ill-structured definitions of the associated problems (Aamodt and Plaza 1996) (Karacapilidis, Dimitris and Costas, Computer-Mediated Collaborative Decision Making: Theoretical and Implementation Issues 1999).

After a decision is made, it is vital to translate it into an implementation plan, i.e. elaborating a list of tasks with responsible to be carried out. If this step fails, the decision, however good it was, fails. Therefore, an important field of supporting decision-making is the decision implementation and follow-up. In this scope, there has been some work developed, relating decision meetings to the activities following them, and especially collecting automatic feedback about decision implementation (Valle, Prinz and Jarke 2006) (Borges, Pino and Valle 2005).

3.2. SYSTEMS TO SUPPORT DECISION

Over the past three, four decades, organisations have been using computers for a variety of tasks ranging from everyday secretarial work to more complex business processes and workflows. Many of these tasks involve certain level of decision-making ability on the part of the system. Quite a few tools, popularly called Decision Support Systems, have been developed in this regard (Eddy, et al. 2000). The aim of decision support systems is to produce a trusted and reasonable set of recommendations for helping the decision maker through the process.

The initial vision of decision support systems fostered the idea that the system should progressively replace the human judgement. This vision was supported, in the early 80s, by an explosion of research in topics such as artificial intelligence, information technologies and cognitive sciences. However, in the 90s, the focus of decision support systems changed from the system to the user. Because decision makers are not necessarily proficient in computer science and information technology, they need appropriate tools to easily follow the processes involved. Such tools should stimulate their participation giving them an active role, and enable human actors to use their instincts. In addition, industrial companies do not want to lose the accountability of a decision to a human actor. Therefore, this parallels the vision of the decision support systems community pioneers, that is, by supporting and not replacing human judgement, the system comes in second and the users first.

Decision support systems have significantly evolved during the last few decades (Ekbia 2006). The definition of decision support systems has changed from support technologies in semi-structured domains (Keen and Scott-Morton 1978) through interactive data models (Sprague and Carlson 1982) and group decision support systems (DeSanctis and Guadalupe 1987) to adaptable and domain-specific representational models (Turban 1992) and social decision support systems (Turoff, et al. 2002). More recently, Shim et al. (Shim, et al. 2002) have identified a trend towards the personalisation of decision support systems user interface, the use of Web-based technologies, and ubiquitous computing. These authors have also prescribed the development of active and intelligent systems as a promising path for the future.

In current literature, it is easy to find several notions and definitions of systems to support the process of decision-making. It is sometimes difficult to differentiate these systems, what is their focus and main functionality. This section presents a possible classification of the different systems to support decision-making, attempting to collect the several definitions found in the literature.

Decision support systems are interactive computer-based information systems designed to help human decision makers. These systems process data and models in order to identify, structure, and solve semi-structured or unstructured problems (R. Sprague 1980) (Zolghadri, Lecompte e Bourrieres s.d.). These systems were the first to appear in the field, and may still be used to embrace all the existing systems.

A more generic and tool-oriented definition, states that decision-making support systems encompass a collective set of computerised support tools, including decision support systems, executive information systems, expert systems, knowledge-based systems, and other standalone systems (Forgionne, et al. 2002).

Although the two definitions of decision-making and decision support systems slightly differ, they present the focus of such systems in collecting, analysing and presenting information in a structured form, to help a decision maker when realising a choice.

Companies are being pressured to excel in their capabilities. One form they have found to do this is to join efforts. This combination of resources in some activities has fostered group and teamwork in all types of companies in industrial environments. Nowadays, less and less tasks are executed by one individual alone. Even the new work trends, such as freelancers, is part of teams or networks, supported by information and communication technologies. This trend has also made its way in decision-support with the appearance of group and collaborative decision-making.

Group decision support systems have been defined as interactive computer-based systems that facilitate the solution of ill-structured problems by a set of decision makers that work together as a team (Kreamer and King 1988). The main objective of a group decision support system is to augment the effectiveness of decision groups through the interactive sharing of information between the group members and the computer (Huber 1984). This can be achieved by removing communication impediments, providing techniques for content of the discussion and systematically directing the pattern, timing, or content of the discussion (DeSanctis and Guadalupe 1987).

Technologies or systems that enable or enhance the ability of the participants involved in collaborative decision-making processes have been termed as collaborative decision support systems. These systems have been defined (Kreamer and King 1988) (Karacapilidis, Computer Supported Argumenation and Collaborative Decision Making: The HERMES System 2001) as “interactive computer-based systems which facilitate the solution of ill-structured or semi structured problems, by a group of decision makers working as a team”. These systems represent a step further in relation to group decision support systems, because they not only provide team support but they actually foster collaboration. Thus, the main objective of these systems is to augment the effectiveness of decision groups through the interactive sharing of information and knowledge among group members supported by computer facilities (Smari, et al. 2005). This can be achieved by (i) removing communication impediments, and (ii) providing techniques for structuring the decision analysis and systematically directing the pattern, timing, or content of the discussion (Karacapilidis, Dimitris and Costas, Computer-Mediated Collaborative Decision Making: Theoretical and Implementation Issues 1999).

More recently, there was a convergence among the research fields of decision support, artificial intelligence and knowledge management. From this, a number of information systems exist to generate knowledge for decision-making support. Collectively, these systems can be called intelligent decision support systems (Hans and Peter 1992). These systems integrate the functions of decision support systems and knowledge based systems to assist decision makers in building analytical models, offer advice on specific problem tasks, assist decision makers in performing decision analysis, and explain conclusions and recommendations (Hunsaker and Hunsaker 1981) (Tansley and Hayball 1993) (Sensiper 1998) (Silverman 1994).

Active decision-making support systems are a kind of intelligent decision-making support systems that take the initiative without getting specific orders. They respond to non-standard requests and commands when dealing with tasks in problem solving that are ambiguous and/or complex (Pistolesi 2006). Some of these systems remove the human actor from the loop, having the initiative and the decision made by the system.

Summarising, there is a wide variety of systems to support decision-making processes. However, most decision support programs can only calculate satisfaction levels. There is a need for adding unique analysis and reporting features, including: probability that a particular alternative is the best choice; assessment of the level of consensus for each alternative; guidance on what should be done next; and documentation of the entire decision-making process (Zha and Sririam, Knowledge-intensive Collaborative Decision Support for Design Process 2006). In addition, most of the systems do not address specific issues of industrial environments, such as company policy and hierarchy, the concept of extended enterprise, i.e. supporting all actors involved in the value and supply chain, issues of responsibility and tracking of actions and decisions, and fast response for changing demands. The approach presented in this thesis aims at contributing to decrease the state-of-the-art gap in supporting collaborative decision-making in industrial environments.

3.3. A GENERIC DECISION-MAKING PROCESS

There are several models on how the decision-making process should be. One of the most popular is Simon's Model of three phases (Simon, Administrative Behaviour 1997), which has been widely used by managers, researcher and decision-makers in general. Recent work extended this model to become a five-phase model (Mora, et al. 2003). This model is presented in Table 3.1 and is adopted here to support collaborative decision-making.

TABLE 3.1. DECISION-MAKING PHASES AND STEPS.

Phase	Step	Description
Intelligence	Data Gathering	Observation of reality and collecting of any relevant qualitative and quantitative data is done for the general situation of interest.
	Problem Recognition	Based on the interpretation of collected data, a well-focused problem statement and general objective is defined.
Design	Model Formulation	Using the well-focused problem, a predefined model is instanced with a set of courses of action, outcomes criteria, set of uncontrolled events and parameters, and the relationships between these variables. If a predefined model is unavailable, a new model must be developed.
	Model Analysis	Face validity and pilot test of the model is conducted to reduce any potential source of significant error.
Choice	Generation & Evaluation	With a validated model, all courses of action are evaluated (or dynamically generated) and what-if, sensitivity and goal-seeking analysis are conducted, in terms of the outcomes criteria.
	Selection	Best course of action is finally suggested, using an optimisation, satisfaction criteria, or other approach.
Implementation	Result Presentation	Selected course of action is reported to top management team for final organisation authorisation (a decision can be taken but not implemented).
	Task Planning	Decision authorised, is scheduled in a set of specific actions, where financial, human and material resources are estimated.
	Task Tracking	The set of specific actions are conducted and monitored until the planned end action is achieved.
Learning	Outcome-process Analysis	Process and outcome metrics are collected from decision-making team and organisation.
	Outcome-process Synthesis	Learned lessons on the top of decision-making process are identified and communicated to the top management and other team members.

3.4. TYPES OF DECISIONS AND THE PROCESS OF MAKING A DECISION

Besides the identified different systems to support decision-making, it is possible to distinct several types of decisions, and also methods to make them.

Generally speaking, a decision is a choice, which is to realise a certain goal by analysing subjective-objective conditions, generating alternatives, and choosing the most appropriate one among them (Zha and Sririam, Knowledge-intensive Collaborative Decision Support for Design Process 2006).

Simon divided decisions in two general categories: programmed and non-programmed (Simon, Administrative Behaviour 1997). Decisions are programmed to the extent that they are repetitive and routine, to the extent that a definite procedure has been worked out for handling them so they do not have to be treated from scratch each time they occur. On the other hand, decisions are non-programmed to the extent that they are novel, unstructured and unusually consequential.

It is possible to extend this categorisation considering the situation associated with the decision. The last reference suggests four types of situations requiring a decision.

Routine: The same circumstances repeat and when they appear, it is necessary to choose a proved course of action.

Emergency: Represent situations without precedent, which often require immediate decisions following course of events. These situations are usually very time-consuming because they imply considerable amount of hours dedicated in a short period of time.

Strategic: The most demanding type because it implies strategic choices such as deciding on purpose and objectives and converting them into specific plans for the company or sub-decisions.

Operational: Decisions related to the regular running of the company, including hiring and firing employees (human resources). These situations frequently require very sensitive handling.

People make decisions in different ways, which is also valid for companies. The capacity of decision-making has in fact been identified as a unique human capability. Several types of decision-making are presented by Shah (Shah and Shah, Types of Decision-Making n.d.).

Irreversible: These decisions, once made, cannot be unmade. Whatever is decided has its repercussions for a long time to come. It commits one irrevocably when there is no other satisfactory option to the chosen course. A manager should never use it as an all-or-nothing instant escape from general indecision.

Reversible: These are the decisions that can be changed completely, before, during or after the agreed action begins. Such type of decisions allows one to acknowledge a mistake early in the process rather than perpetuate it. This decision-making type is effective for situations with changing circumstances where reversal is necessary.

Experimental: This type of decisions is not final until the first results appear and prove to be satisfactory. It requires positive feedback before one can decide on a course of action. It is useful and effective when a correct move is unclear but there is a clarity regarding general direction of action.

Trial and Error: In this type of decisions, actors derive knowledge from past mistakes. The team selects a certain course of action and tries it out. If the results are positive, the action is carried further, if the results appear negative, another course is adopted and another trial is made. This iterative process continues until the actors achieve the right combination. It allows the manager to adopt and adjust plans continuously before the full and final commitment. It uses both, the positive and negative feedback before selecting one particular course of action.

Made in Stages: In this decision-making type, the team involved makes decisions in steps until they achieve the whole action. It allows close monitoring of risks as one accumulates the evidence of outcomes and obstacles at every stage. It permits feedback and further discussion before proceeding to the next stage of the decision.

Cautious: It allows time for contingencies and problems that may crop up later at the time of implementation. The decision-makers hedge their best efforts to adopt the right course. It helps to limit the risks inherent to decision-making, but may also limit the final gains. It allows one to scale down those projects that look too risky in the first instance.

Conditional: Decision-makers can alter these decisions if certain foreseen circumstances arise. It is an 'either/or' kind of decision with all options kept open. It prepares one to react if the competition makes a new move or if the game plan changes radically. It enables one to react quickly to the ever-changing circumstances of competitive markets.

Delayed: In this type of decisions, actors put the decision on hold until they feel the time is right. The team gives a go-ahead only when all required elements are in place. It prevents one from making a decision at the wrong time or before all the facts are known. At times, it may result into forgoing opportunities in a market that needs fast action.

These types of decision-making are not completely exclusive. In fact, quite often, a decision-making process is a combination of several of these types.

3.5. TEAM DECISION-MAKING PROCESS TYPE

The process of collaborative decision-making involves the work of a team in the process. However, this does not mean that all team members will in fact make the decision. It can happen that everyone is involved in the activities of collecting information, and even rating criteria, but only one person makes the decision in the end.

The method proposed aims at supporting different operation modes in teams, adjusting how each member contributes for the final decision. The approach presented supports the following team processes (Shah and Shah, Types of Decision-Making n.d.).

Majority Vote: Each person has a vote (expressed by hand or secret ballot) and the majority make the decision. This method is quick, efficient and offers a sense of finality, i.e. that the decision is made and final. However, it is possible to have a decision made with an opposition as large as 49% of the team. In addition, this method can rush the process to a vote without fully exploring all perspectives of the situation. This method is indicated when: there is a need for fast, participatory decisions; people already know the various issues and perspectives; the outcome will not have a significant adverse impact on the “losing” side; there is a need of obtaining a ‘sense of group’ prior to making a formal decision; or as a fallback strategy when consensus did not work out.

Unanimity: This method means that all team members agree in the same decision. This has the advantage of representing a string buy-in and requiring the participation of everyone. However, this is a very difficult process to achieve and one or two people have the capacity of holding the group hostage. This process is indicated when: the stakes are high and there is a great need for complete endorsement (solidarity); there is a desire to build community; or it is intended to send a message that “no one will be left out or left behind”.

Consensus: This process type indicates that everyone’s ideas have been heard and are included and people agree to support the decision and feel valuable. On the other hand, this process can be time consuming and can still result in post-meeting sabotage (derived from the feeling “That really was not my choice or preference!”). Consensus should be used when: decisions can be contemplated beforehand; people feel empowered to speak and express opinions at public meetings; organisational culture tolerates dissention and disagreement; the decision will have a high level of impact on each stakeholder; or the decision involves politically charged issues or the potential for “deep change”.

Committee: This process allows for delegation of tasks and frees others to do other things, and enables smaller groups to make decisions efficiently. These committees can also have a hierarchy defined following the company's structure or according to the situation at hand, for example building a hierarchy according to expertise or experience of the team members. This method has the disadvantages of possibly missing inputs from key people, or allowing people to feel left out from the decision-making, and requiring others to let go of control. Committees should be used when: particular competency or knowledge rests in a few people; there is a need for diverse viewpoints and/or skills; multiple decisions need to be made simultaneously; want to empower stakeholders selected for the committee; there is a great need to delegate responsibility; or want to stimulate creativity and want to build and foster relationships among participants.

Autonomous: This is an extremely efficient method where someone alones makes the decision, enabling also to protect privacy in sensitive matters. This method implies few checks or balances and brings no benefit of others' skills and insights. This process should be used when: there is only one person who is affected by the decision; there is a need to preserve confidence; the issues are of low-level importance; or in situations where the time to decide will not allow to setup a group decision process.

3.6. INDUSTRIAL CRITERIA

This work includes the elaboration of list of decision criteria to consider when making any decision in industry. The objective was to produce one general list of criteria, based on inputs gathered from industrial companies, covering all types of decisions. In each individual situation, actors rate the complete list, with the ability of ignoring any criteria on the list.

The list translates the need to maximise and/or minimise specific conditions, namely comprehending the following industrial decision criteria:

- **equipment costs** represent the expenses in acquiring tools or other devices;
- **operating costs** characterise the price of utilising the machines;
- **training costs** stand for the charge for instructing and preparing employees, e.g. to operate machines or realise new tasks;
- **personnel costs** symbolise the expense with the workforce;
- **expertise costs** represent the charge of hiring or sub-contracting temporary technical skills;
- **market share** characterises the percentage of total market segment that is serviced by the company;
- **strategic partners** symbolises the need to increase the number of alliances established with other companies (customers, suppliers or other business partners);

- **return on investment** is the ratio of money gained or lost on an investment relative to the amount of money invested;
- **profitability** represents how lucrative the company is,
- **growth potential** describes the prospective for a company to enlarge its business in terms of market capitalisation, production, sales, revenue, employment or management;
- **customer satisfaction** describes how the products and services supplied by a company meet or exceed the customers' expectations;
- **product/service quality** represents the ability of a product or service to perform its functions, measured in several factors that usually include reliability and ease of use;
- **process efficiency** symbolises the maximum amount of output (e.g. number of items assembled, number of products maintained) that can come out of a process without increasing resources;
- **employee productivity** defines the ratio of output per labour hours;
- **material/machine productivity** stands for the ratio of output produced per material used or per hours of machine operation;
- **efficient allocation of resources** symbolises that the maximum output is being achieved from the existing resources;
- **time to implement decision** defines the amount of hours needed to implement the selected alternative;
- **efforts to implement decision** characterises the materials, machines and employees necessary to implement the selected course of action;
- **company's image** defines how a business is perceived by the market and public in general, including its brand;
- **company's strategy** represents the objectives of the business in short, medium and long-term, including aspects such as markets to address, sustainability, contribution to society, among others; and
- **sustainability** defines the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

This list of criteria is general and can be applied to any decision in an industrial company. However, when making a decision it might be useful to group the criteria in categories, making its analysis easier. When examining a hierarchy of criteria, human actors can identify if any criteria is not applicable to a specific situation. In addition, actors can also add or refine existing criteria. The list of criteria is then organised in a hierarchy, as presented in Figure 3.1.

FIGURE 3.1. HIERARCHICAL REPRESENTATION OF DECISION CRITERIA.

In some decision situations, it is also useful to make a cost benefit analysis when choosing a specific alternative. In order to accomplish this, the criteria should be separated in costs and benefits, which are independently evaluated. The list of criteria proposed includes the costs represented in Figure 3.2.

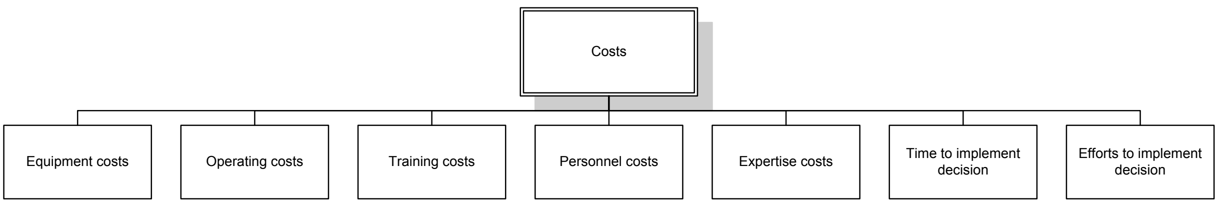


FIGURE 3.2. COSTS CRITERIA TO MAKE A DECISION.

The criteria proposed include also benefits, as presented in Figure 3.3.

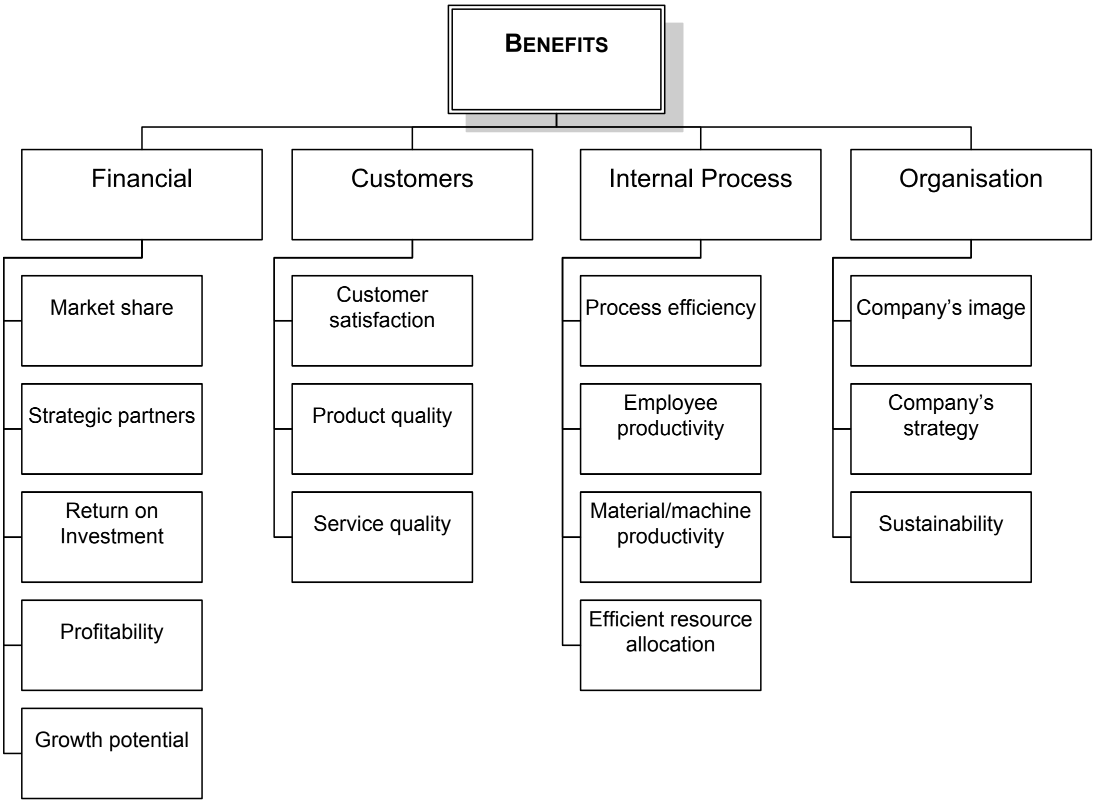


FIGURE 3.3. BENEFITS CRITERIA TO MAKE A DECISION.

In each decision-making situation, the human actors can choose the most appropriate representation of criteria, i.e. list, hierarchy or cost-benefit.

This list of criteria was included in a questionnaire distributed to industrial companies, as described in the next section. The criteria were refined according to the answers provided.

3.7. DECISION-MAKING IN INDUSTRY

The work developed includes the elaboration of a questionnaire with the objective of ascertaining what are the common current practices in industry, with respect to decision-making. The questionnaire uses the definitions and classifications presented in the previous sections. The resulting questionnaire, which is presented in Annex C, Decision-making questionnaire, was distributed among several industrial companies. However, the task of obtaining answers to such a document can be quite challenging. The results include twenty filled questionnaires, where some were not complete. Although the relatively small number makes the statistical analysis feeble, it is possible to identify trends in the common industrial practices, complemented by the author's experience in contacts with industrial partners, in the scope of several research projects.

The current section describes the tendencies presented by the questionnaires answered by industrial companies.

Most of the companies state that there are no systematic approaches established to support decision-making. This means that the process is highly influenced by the personal style of the people involved, but also by the organisational culture present.

Strategic and operational decisions are commonly made by small senior groups (including CEO or equivalent), business unit leaders and the CEO or equivalent. Frontline and shop floor employees usually make routine decisions, while emergency decisions seem to be quite wide spread through the company. However, the role of interdisciplinary teams is still quite reduced, and when present, it is limited to routine and emergency decisions.

Regarding the personal style of making decisions, there seems to be a balance between an emotional/intuitive and a logical/rational approach. With the exception of emotion or sensibility, which are rarely considered (or admitted), the companies seem to use hints and imagination, while using analysis, knowledge, ability, experience and logic to reach their conclusions.

When the culture, attitude, approach and policy of the companies' management towards the employees are considered, there is quite a conservative position. Companies focus primarily on the clients' needs, and the well-being of the company is always above any individual success. Moreover, employees said that it is quite difficult to change the organisation's thinking process. However, it is possible to see that the conservative trend is also changing, because issues such as acceptance of new ideas, personnel autonomy, motivation, innovation and exploitation of new opportunities are gaining relevance.

Considering types of decision-making, companies make use of the eight categories identified: irreversible, reversible, experimental, trial and error, made in stages, cautious, conditional and delayed. There is not a dominant style. Nevertheless, trial and error is often used for routine, strategic and operational decisions, while emergency decisions tend to use a cautious approach.

Whenever the decision-making process involves a team, its members are usually selected among the employees from the department most affected by the decision. Often, the team includes also employees from other departments that have valuable expertise for the decision-making. However, rarely or never is the CEO or other equivalent senior management representative involved, or any external consultants. Once the team is formed, the decision-making process often follows the company's hierarchy, or a special hierarchy created for the occasion, or consensus among all team members. A decision made by voting, where each team member has one vote is rarely or never used.

The industrial criteria listed in the questionnaire is extensively used in the four types of decisions, being very difficult to identify a predominance, especially considering the small amount of companies considered.

Regarding the sources used to collect information necessary to make a decision, there is a wide range considered in the answers analysed. The most searched sources are internal statistics, financial forecasts from the company, co-workers, researchers, external contacts, competitors, seminars and the Internet. On the other hand, sources such as company's library, academic experts, consultants and economic/market studies are rarely used. This classification is highly related to the types of decisions and the job description of the persons who answered the questionnaire. Most of the answers came from people in technical areas of the companies who are usually involved in making routine and emergency decisions. There were very few answers from people in higher ranks, who are usually occupied with strategic and operational decisions. This might explain the answers regarding the resources used, as the ones most selected are more suitable for routine and emergency situations, while the ones less identified are indicated for strategic and operational decisions.

Once the information is collected, decision-makers evaluate it based primarily on the expertise and experience of the person who provided the information. In addition, the hierarchical ranking of the information source, and the consistency and completeness of the information are also often considered.

4. PROBLEM SOLVING AND INNOVATION IN INDUSTRY

Innovation is a complex process, especially in companies, involving actors with different expertise and often geographically dispersed. Designing a new product, for example, follows an organisational procedure involving activities such as collecting requirements (from market or customers), designing the product, designing the manufacturing process, etc. Naturally, several problems arise during the process, which have to be handled by the team. Solving the problem means identifying any abnormal symptoms, describing the objective to be achieved, identifying options to consider, choosing the best alternative, and implementing the decision. This is an iterative and complex process when done by one individual, and can become an impossible task when it involves a multi-disciplinary team.

Two of the methods widely used in some of the mentioned areas are case-based reasoning (CBR) and the analytic hierarchy process (AHP). The two methods have been used, in this work, in the scope of problem solving and decision-making, respectively.

Case-based reasoning is a form of analogical reasoning, which consists in using examples to solve new problems, using a degree of similarity (Russell and Norvig 1995). Case-based reasoning keeps a memory of stored cases recording prior episodes, and generates a new solution by retrieving the most relevant cases from memory and adapting them to fit new situations (Leake 1996). However, when this memory is extensive, it can be difficult to select among the most relevant cases, i.e. to decide the course of action.

The Analytic Hierarchy Process is a theory of measurement concerned with deriving dominance priorities from paired comparisons of homogeneous elements with respect to a common criterion or attribute (T. Saaty 1991). This process uses a series of one-on-one comparisons to rate a series of alternatives to arrive at the best decision. The problem here is how to identify and formulate the alternatives to be considered.

This thesis presents an approach based on a combination of case-based reasoning and analytic hierarchy process to support innovation, particularly product design in industry involving several actors. The objective of the work is to overcome shortcomings of both methods in order to provide the most adequate support for multi-disciplinary teams when making decisions in innovation processes.

4.1. CASE-BASED REASONING

Case-based reasoning (CBR) uses what several studies have demonstrated to be a human capability, i.e. reasoning and making associations. Humans use prior examples when learning something new, or when trying to address a new situation. Humans are robust problem solvers; they routinely solve hard problems despite limited and uncertain knowledge, and their performance improves with experience (Leake 1996). The objective of CBR is to enhance and foster this capability. It is possible to divide CBR tasks into two classes, interpretive CBR and problem-solving CBR. Interpretive CBR uses prior cases as reference points for classifying or characterising new situations; problem-solving CBR uses prior cases to suggest solutions that might apply to new circumstances. There are several tools that support the development of CBR solutions, where jColibri (GAIA n.d.) is one of the most popular. There are also out-of-the-box integrated solutions with complete functionality packages to companies, e.g. eGain (eGain n.d.) or SpotLight (CaseBank n.d.). However, these tools are only appropriate for companies that want to start from scratch regarding to software, i.e. not using any existing system or repository. CBR has been used since the beginning of the 1990s in several domains such as medical, legal, accounting, finance, manufacturing, fault detection, diagnosis, etc. In industrial domains, especially in applications related with problem solving, there have been continuous development and applications (Gilboa and Schmeidler 2000) (Lian, Wang and Cheng 2010) (Ignat-Coman, et al. 2008) (Wu and Chen 2007) (Fan, et al. 2010) (Campos, Stokic and Neves-Silva 2004) (Campos and Neves-Silva 2010).

This section presents a CBR approach developed to support problem solving in industrial applications. The work developed uses and combines several methods found in literature and is based on the model presented in chapter 2 Enterprise model. Like other CBR applications, the proposed method stores cases in a repository or memory. When a new situation occurs, the method compares it to previous cases and finds the most similar ones.

Problems that occur in any process of the company are stored as cases in a repository, to be used by CBR. Each problem is described using the attributes described in the construct of Problem, defined in section 2.3.2 Dynamic knowledge. The most important characteristics for the CBR application are the following:

- **description** represents a textual explanation of what is observed as abnormal;
- **reporting actor** identifies the person who reported the problem;
- **involved generics** recognises within the company's catalogue the class(es) to which the product, process or machine involved in the problem belongs to; and

- **actual state items** describes a set of characteristics that can be measured for the generics involved in the problem (e.g. value of electrical current, level of oil in machine, colour code in PLC).

When a new problem occurs, designated current case, or CC, CBR computes the similarity between the attributes of the new problem and the ones stored in the repository, the stored cases, or SC, to identify a set of similar situations. CBR uses a weight-sum metric to calculate the similarity between a case CC and a target query SC, i.e.

$$\mathrm{sim}(\mathrm{SC}, \mathrm{CC}) = \frac{\sum_{i=1}^{n} w_i \mathrm{sim}(\mathrm{SC}_i, \mathrm{CC}_i)}{\sum_{i=1}^{n} w_i} \tag{4.1}$$

where SC_i and CC_i represent the attribute i in the stored and current cases and w_i represents the weight of attribute i in the similarity calculation. All the cases have n attributes and each of them contributes with a weight w_i for the similarity calculation. As described, problems have a set of attributes, but case-based reasoning does not use the textual description. As this work does not cover any language parsing or semantic interpretation, it would be useless to compare text. Therefore, the calculation of similarity uses reporting actor, involved generics and all available actual state items as attributes.

The similarity of reporting actor is a binary value: 1 if both problems were reported by the same actor and 0 if the problems were reported by different actors.

Companies need to define their enterprise model, especially the physical elements, using the constructs for Product Part, Production Unit and Process Step defined in section 2.3.1 Static knowledge. These three entities, collectively designated generics, include a hierarchical structure to group generics according to their inherited characteristics. Each type of generic (product parts, process steps or production units) uses the tree to represent all items of a company using a generalisation to specialisation approach. When reporting a problem, it is possible to identify only one involved generic, which is somewhere located in the tree catalogue, or several. It is actually quite common to have several generics involved in the same problem. For example, when a problem occurs in the shop floor of a manufacturing company, it might be possible to identify the product being handled, in which process and using which machine (three different generics). Calculating the similarity of the attribute involved generics means, therefore, determining the similarity of two sets of nodes in a tree structure.

For this, the use of the Generalised Vector-Space Model approach (Ganesan, Garcia-Molina and Widom 2003) is proposed. In the vector-space model, each element in the domain is a dimension in a vector space. A vector represents a collection, with components along exactly those dimensions corresponding to elements in the collection. The Cosine-Similarity

Measure defines the similarity between two vectors to be the cosine of the angle between them.

Let U be a rooted tree, with all nodes carrying a distinct label. Each node can have arbitrary fanout, and the leaves of U can be at different levels. Let $\mathrm{L_U}$ be the set of all labels in U. Let $\mathrm{LL_U}$ be the set of all labels on the leaves of U. $\mathrm{LL_U}$ is the element domain, on which there is a superimposed hierarchy described by U. Since there is a hierarchical structure imposed on $\mathrm{LL_U}$, a collection C induces a tree, a subgraph of U that consists of the ancestral paths of each leaf in C. The depth of a node in the hierarchy is the number of edges on the path from the root of U to that node. Given any two leaves l_1 and l_2 in U, the *Lowest Common Ancestor* $\mathrm{LCA}(l_1, l_2)$ is the node of greatest depth that is an ancestor of both l_1 and l_2. This LCA is always well defined, since the two leaves have at least one common ancestor – the root node – and no two common ancestors can have the same depth.

The unit vector corresponding to a leaf l is represented by $\vec{l}$. According to the traditional cosine-similarity measure, all leaf unit vectors are perpendicular to each other, which means that the dot product of any two of them is zero. The dot product of a unit vector with itself is equal to 1.

The similarity between two nodes, l_1 and l_2, of the product catalogue tree is calculated using equation (4.2).

$$\mathrm{sim}(l_1, l_2) = \vec{\mathrm{l}_1} \cdot \vec{\mathrm{l}_2} = \frac{2\mathrm{depth}\big(\mathrm{LCA}_U(l_1, l_2)\big)}{\mathrm{depth}(l_1) + \mathrm{depth}(l_2)} \tag{4.2}$$

This definition is consistent, since the right side of this equation always lies between 0 and 1. Note that the dot product is equal to 1 if and only if $l_1 = l_2$.

Let the set of leaf labels $\mathrm{LL_U}$ be $\{l_1, l_2, l_3, \dots, l_n\}$. Let $\mathrm{count_A}(l_i)$ be the number of times l_i occurs in collection A. Then, collection A is represented by the vector $\vec{\mathrm{A}} = \sum_{i=1}^{n} a_i \vec{l_i}$, where $a_i = W(l_i)\mathrm{count_A}(l_i)$ for $i = 1 \dots n$, and where $W(l_i)$ represents the weight of the leaf l_i. One problem can have several generics involved in it, defined by the collection of generics, A.

According to the generics' hierarchy, it is not possible to assume that the different "components" of a vector are perpendicular to each other. It is still possible to measure similarity by the cosine-similarity measure after dropping this assumption. If collection A is represented by the vector $\vec{\mathrm{A}} = \sum_i a_i \vec{l_i}$ and B by the vector $\vec{\mathrm{B}} = \sum_i b_i \vec{l_i}$, then

$$\vec{\mathrm{A}} \cdot \vec{\mathrm{B}} = \sum_{i=1}^{n} \sum_{j=1}^{n} a_i b_j \vec{l_i} \cdot \vec{l_j} \tag{4.3}$$

where $(\cdot)$ stands for the dot product between the two vectors.

This equation is identical to the standard Vector-Space Model, except that $\vec{l_i} \cdot \vec{l_j}$ is not equal to 0 whenever $i \neq j$. Finally, the cosine similarity between A and B is given by the traditional formula

$$\mathrm{sim}(\mathrm{A},\mathrm{B}) = \frac{\vec{\mathrm{A}} \cdot \vec{\mathrm{B}}}{\sqrt{\vec{\mathrm{A}} \cdot \vec{\mathrm{A}}}\sqrt{\vec{\mathrm{B}} \cdot \vec{\mathrm{B}}}} \tag{4.4}$$

Equation (4.4) defines the Generalised Cosine-Similarity Measure (Ganesan, Garcia-Molina and Widom 2003).

Each generic has a set of measurable characteristics, designated actual state items, such as dimensions, colour, and applications. These characteristics can have one of five different types: Boolean, text, discrete non-numerical variables, discrete numerical variables and continuous variables. This type range covers a very wide range of possibilities. The actual state items define characteristics verified in products, processes or machines when a problem occurred. This allows the actor to register a snapshot of the installation when the problem was detected. Analogous to the problem's field for description, CBR does not use the actual state items with type text. The similarity of the actual state items is the arithmetic mean of the several possible characteristics (Campos and Neves-Silva 2010).

Considering two Boolean variables x and y, the similarity $\mathrm{sim}(x,y)$ is defined as

$$\mathrm{sim}(x,y) = \begin{cases} 1 \Leftarrow x = y \\ 0 \Leftarrow x \neq y \end{cases} \qquad x, y \epsilon \{\mathrm{FALSE}, \mathrm{TRUE}\} \tag{4.5}$$

If one of the variables is defined as $unknown$, then the similarity $\mathrm{sim}(x,y)$ is defined as the probability of the two variables being equal, i.e.

$$\begin{aligned} \mathrm{sim}(x,y) &= P(x = y) \\ &= P(x = \mathrm{TRUE}|x)\, P(y = \mathrm{TRUE}|y) \\ &+ P(x = \mathrm{FALSE}|x)\, P(y = \mathrm{FALSE}|y) \end{aligned} \tag{4.6}$$

where $P(\mathrm{A}|\mathrm{B})$ is the conditional probability of A given B.

If the FALSE and TRUE results have the same probability for each unknown variable, the similarity is equal to 0.5.

Considering two discrete non-numerical, i.e. symbolic, variables, x and y, the similarity $\mathrm{sim}(x,y)$ is defined as

$$\mathrm{sim}(x,y) = \begin{cases} 1 \Leftarrow x = y \\ 0 \Leftarrow x \neq y \end{cases} \qquad x, y \epsilon \{\mathrm{C}_1, \mathrm{C}_2, \ldots, \mathrm{C}_m\} \tag{4.7}$$

If some of the variables are defined as $unknown$, then the similarity $\mathrm{sim}(x,y)$ is defined as the probability of the two variables being equal, i.e.

$$\mathrm{sim}(x,y) = P(x=y) = \sum_{i=1}^{m} P(x=\mathrm{C}_i|x)\, P(y=\mathrm{C}_i|y) \tag{4.8}$$

where m denotes the number of possible values. If the C_i results have the same probability for each unknown variable, then the similarity is given by

$$sim(x,y) = \begin{cases} 1 \Leftarrow x = y \cap x, y\epsilon\{\mathrm{C}_1, \mathrm{C}_2, \dots, \mathrm{C}_m\} \\ 0 \Leftarrow x \neq y \cap x, y\epsilon\{\mathrm{C}_1, \mathrm{C}_2, \dots, \mathrm{C}_m\} \\ 1/m \Leftarrow others \end{cases} \tag{4.9}$$

The Boolean variables are a special case of discrete non-numerical variables, with only two possible values. Therefore, when one of the values is $unknown$ the similarity between two Boolean variables is 0.5.

For numerical variables, it is useful to introduce the notion of distance between two variables D(x,y), and relate it with the similarity function through

$$\mathrm{sim}(x,y) = \mathrm{e}^{-\mathrm{D}(x,y)} \tag{4.10}$$

which means

$$\mathrm{D}(x,y) = -\ln\left(\mathrm{sim}(x,y)\right) \tag{4.11}$$

Considering two discrete numerical variables, x and y, the distance $\mathrm{D}(x,y)$ is defined as

$$\mathrm{D}(x,y) = \gamma \frac{|x-y|}{N_m - N_1} \qquad x, y\epsilon \left\{N_1, N_2, \dots, N_m : i > j \Rightarrow N_i > N_j\right\} \tag{4.12}$$

where γ is a scaling factor. In case of the variables is classified as $unknown$, the similarity $\mathrm{sim}(x,y)$ is the average similarity for all values in the set $\left\{N_1, N_2, \dots, N_m : i > j \Rightarrow N_i > N_j\right\}$

$$\mathrm{sim}(x,y) = \sum_{i=1}^{m} p_y(N_i) \mathrm{e}^{-\gamma \frac{|x-N_i|}{N_m - N_1}} \tag{4.13}$$

Considering two continuous variables, x and y, the distance $\mathrm{D}(x,y)$ is defined as

$$\mathrm{D}(x,y) = \gamma \frac{|x-y|}{b-a} \qquad x, y\epsilon[a,b] \tag{4.14}$$

where γ is a scaling factor. From (4.10), the similarity $\mathrm{sim}(x,y)$ is defined as

$$\mathrm{sim}(x,y) = \mathrm{e}^{-\gamma \frac{|x-y|}{b-a}} \qquad x, y\epsilon[a,b] \tag{4.15}$$

EXAMPLE 4.1: EFFECT OF FACTOR γ IN COMPUTING SIMILARITY VALUE

This example illustrates the effect of the factor γ in the computation of the similarity value. Consider two continuous variables (the same conclusion drawn for the discrete numerical case) x and y in the interval $[0, 10]$ and let $y = 2$. Figure 4.1 plots the value of similarity $\mathrm{sim}(x,y)$ using equation (4.15) for several values of the factor γ. The value of γ can be established from a more intuitive value such as the 50% similarity width $\Delta x_{50\%}$ using the formula

$$\gamma = -2\ln 0.5 \frac{b-a}{\Delta x_{50\%}} \approx \frac{10}{7}\frac{b-a}{\Delta x_{50\%}} \tag{4.16}$$

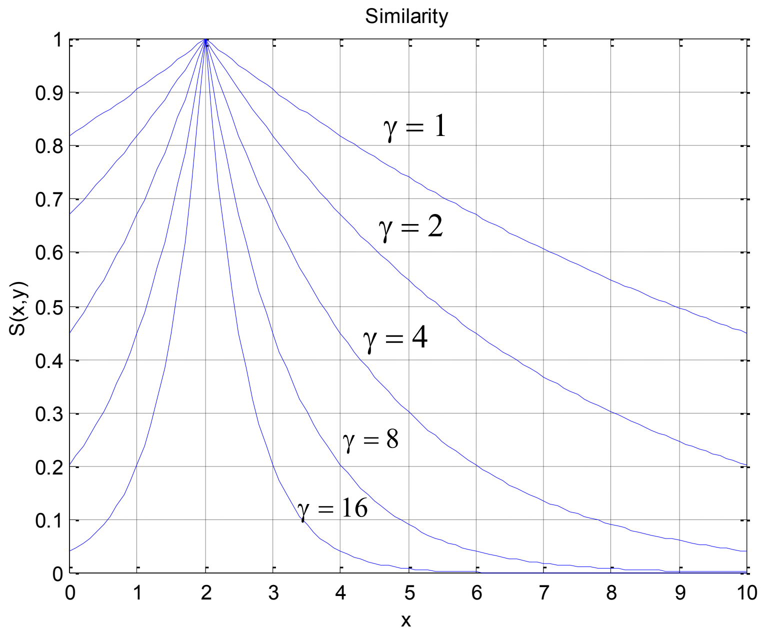


FIGURE 4.1. EFFECT OF PARAMETER γ IN THE COMPUTATION OF SIMILARITY VALUE.

If one of the variables is defined as $unknown$, with probability density function (p.d.f.) $p_y(y)$, then the similarity $\mathrm{sim}(x,y)$ is defined as the average similarity for the interval $[a,b]$

$$\mathrm{sim}(x,y) = \int_a^b p_y(y)\mathrm{e}^{-\gamma\frac{|x-y|}{b-a}}\,dy \tag{4.17}$$

EXAMPLE 4.2: COMPUTING SIMILARITY FOR A UNIFORM P.D.F. OF AN UNKNOWN VARIABLE

This example illustrates the computation of similarity for a uniform p.d.f. of an unknown variable. Consider two continuous variables, x and y, in the interval $[a,b]$ and let y be unknown. Let the p.d.f. of y be given by $p_y(y) = {}^1/_{(b-a)}$ (uniform distribution). Then, the similarity computed from (4.17) is given by

$$\mathrm{sim}(x,y) = \frac{2 - \mathrm{e}^{\left(-\gamma\frac{x-a}{b-a}\right)} - \mathrm{e}^{\left(-\gamma\frac{b-x}{b-a}\right)}}{\gamma} \tag{4.18}$$

Table 4.1 shows some values of similarity for several combinations of the known variable x and the factor γ. It is seen that for a uniform p.d.f., the maximum of similarity occurs when the known variable is in the midpoint of the interval and that the similarity decreases with the factor γ, since the similarity band is narrower.

TABLE 4.1. SIMILARITY VALUES FOR UNIFORM P.D.F. OF AN UNKNOWN VARIABLE.

$\frac{x-a}{b-a}$	$\gamma = 1$	$\gamma = 4$	$\gamma = 16$
0.0	0.63	0.24	0.06
0.3	0.76	0.41	0.12
0.5	0.79	0.43	0.13
0.7	0.76	0.41	0.12

The number of problems to be retrieved should be pre-determined and depends on the applications. The set of similar problems enables the appearance of situations that are different enough to have different causes. The human actor will then analyse the cause of the most similar problem and adapt it to the current problem, trying to implement the actions realised to eliminate the problem.

4.2. THE ANALYTIC HIERARCHY PROCESS

The Analytic Hierarchy Process (AHP) (T. Saaty 1991) is a powerful and flexible decision making process to help people set priorities and make the best decision when both qualitative and quantitative aspects of a decision need to be considered. By reducing complex decisions to a series of one-on-one comparisons, then synthesising the results, AHP not only helps decision makers arrive at the best decision, but also provides a clear rationale of what is the best.

The AHP is widely recognised as a useful tool to support multi-attribute decision-making. It is a compositional approach where a multi-attribute problem is first structured into a hierarchy of interrelated elements, and then a paired comparison of elements in terms of their dominance is elicited. Using AHP, an actor involved in the decision-making process is capable of choosing weights by comparing the importance of two criteria subjectively. Each human actor involved in the decision-making process owns a matrix of judgements, which is used to compute the individual weights given to each criterion by each user.

Researchers have been using AHP in various domains with successful results. Application fields include, as examples, supporting evaluating technologies (Sarkis and Sundarraj 2006), selecting business partners (Cao, et al. 2003) (Liu, Zhou and Tao 2006), analysing projects (Korpela and Tuominen 1997) (Meade and Presley 2002) or selecting location for a new plant (Yu and Li 2001). Additionally, researchers have combined AHP with other methods. The most found combination is of AHP and fuzzy, explored in different contexts (Cao, et al. 2003) (Mikhailov and Singh 2003) (Buyukozkan, Feyzioglu and D 2007). Other combinations include the Bayesian priorisation procedure (Altuzarra, Moreno-Jimenez and Salvador 2007) and neural networks (Matsuda, A Neural Network Model for the Decision-Making Process Based on AHP 2005) (Matsuda, A Neural Network Model for the Decision-Making Process Based on ANP 2006).

This thesis proposes an approach that applies AHP to support decision-making in the scope of solving problems in industrial environments, particularly problems that arise when designing new products or re-engineering existing ones.

The application of AHP to support decision-making involves the following steps:

1. Represent the decision problem in a hierarchical form, including all the criteria to be considered and the alternatives from which to choose.
2. Actors provide their individual judgements on criteria, comparing it in pairs.
3. Analyse the consistency of the judgements given by each actor.
4. Determine the criteria priority for each actor, from individual judgements.
5. Calculate group's criteria priority, from individual priorities.
6. Provide actors' individual judgements on alternatives, comparing them in pairs, and determine alternatives rating from individual judgements given by each actor.
7. Calculate group's alternatives rating, from individual ratings.
8. Calculate ranking of alternatives to make the decision.

The following sections describe each of these steps.

4.2.1. HIERARCHICAL REPRESENTATION OF A PROBLEM

The AHP reflects what appears to be an innate method of operation of the human mind. When presented with a multitude of elements, controllable or not, which comprise a complex situation, it aggregates them into groups, according to whether they share certain properties. The model of this brain function allows a repetition of this process, in that the groups are considered, or rather their identifying common properties, as the elements of a new level in the system. These elements may, in turn, be grouped according to another set of properties, generating the elements of yet another "higher", level, until a single "top" element is reached, which can often be identified as the goal of the decision-making process.

This description corresponds to what is commonly called a hierarchy, i.e. a system of stratified levels, each consisting of so many elements, or factors. The central question is, in terms of this hierarchy: how strongly do the individual factors of the lowest level influence its top factor, the overall goal?

When facing a decision-making scenario, it is always necessary to consider objectives and criteria, in order to select one of several possible outcome scenarios, or alternatives. This process is actually about building the hierarchy corresponding to the situation at hand, which can be complex and time-consuming. Therefore, one of the objectives of this method is to provide part of this hierarchy, which can be re-used and adapted for every situation.

In principle, a hierarchy representing a decision-making process can have any number of levels, according to the complexity of the situation. However, any hierarchy has to have at least three levels, as presented in Figure 4.2.

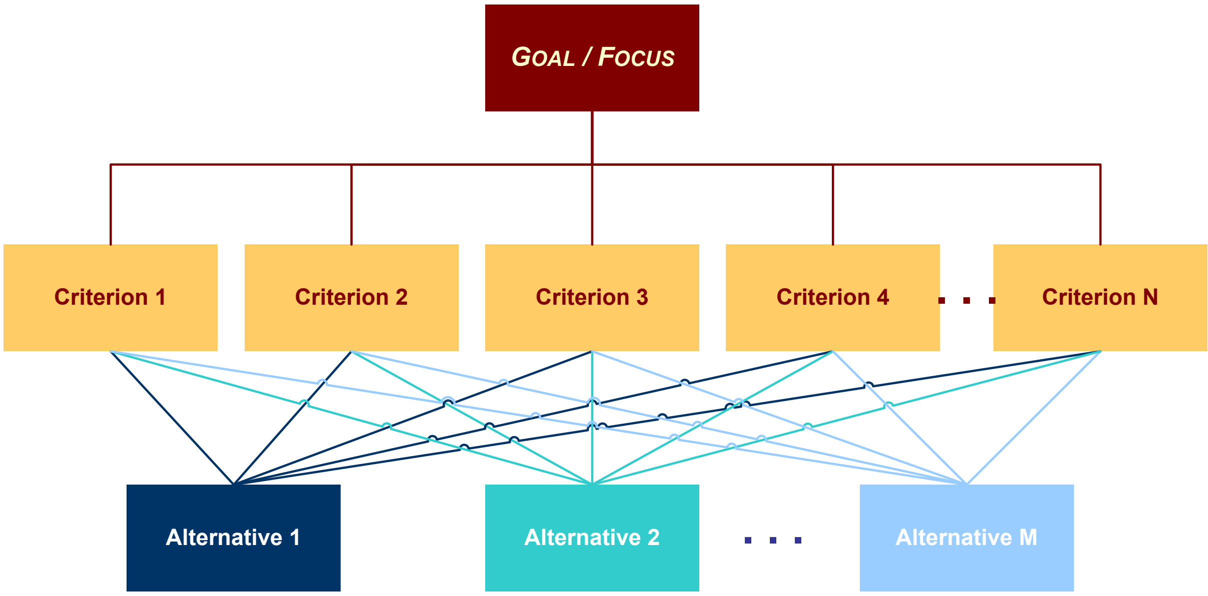


FIGURE 4.2. HIERARCHICAL REPRESENTATION OF A PROBLEM.

The top level of the hierarchy identifies the ultimate goal to be achieved, i.e. what is the objective of the decision. This objective can include issues as “hiring a new employee”, “designing a new product” or “fixing an oil leak in a machine”. The second or middle level represents the criteria to be considered when making the decision, i.e. the characteristics to be met when selecting an alternative. The third and last level identifies the several possible outcomes for the decision-making process. Deciding is choosing one of several alternatives, which implicates the previous definition of these alternatives. The several scenarios will be “measured” against the same criteria, of level two, as explained in the following sections.

This methodology provides a structure for the second level of the hierarchy adopted, while levels one and three will be specific to each situation. According to this, the second level comprehends the industrial criteria identified in section 3.6 Industrial criteria. There are several ways to structure a decision, and especially the criteria to be considered. It is possible to have a structure with all criteria, or to have separate structures for costs and benefits, or even to have a benefits, opportunities, costs and risks (BOCR) structure, which would have four hierarchies. The methodology proposed in this thesis addresses the first two options, i.e. usual hierarchy with all criteria and cost-benefit analysis. In order to use the BOCR analysis, actors must assign a weight to each of the strategic features (benefits, opportunities, costs and risks) and use it to weight the results obtained from each hierarchy individually. In any of the three cases indicated, AHP refers that the number of comparisons made at any time should be 7 ± 2. This is the main reason for representing a hierarchy, and is the reason for organising the list of criteria presented in 3.6 Industrial criteria in several levels.

In a situation where the users want to consider all criteria to select one of the alternatives, the hierarchy, using the industrial criteria defined, is the one represented in Figure 4.3. When comparing criteria, the actors first compare the criteria of level two of the hierarchy in pairs, e.g. compare *Financial* to *Customers*. Afterwards, actors compare pairs of the sub-criteria in level three of the hierarchy, following the groups represented. This means that actors will compare the sub-criteria in four groups, according to the colours represented. The actors then compare the alternatives in pairs with respect to each of the sub-criteria in level three.

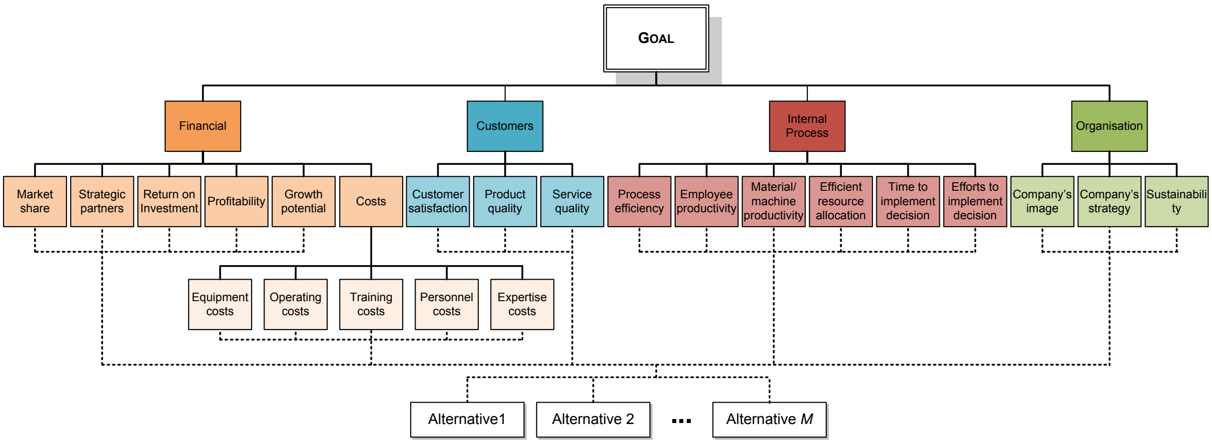


FIGURE 4.3. HIERARCHICAL REPRESENTATION OF A PROBLEM WITH DEFINED CRITERIA.

When the actors are in a situation that requires a cost-benefit analysis, the hierarchy of the problem is divided into two hierarchies. The actors use one hierarchy to analyse only the costs of the problem (see Figure 4.4) and a second hierarchy to analyse the benefits (see Figure 4.5). The actors use each hierarchy as in the previous method (with only one hierarchy) to achieve a ranking of alternatives. After analysing the two hierarchies, actors determine the cost-benefit ratio, by diving the ranking obtained from the costs hierarchy by the ranking obtained from the benefits hierarchy. Actors should select the alternative with the best cost-benefit ratio.

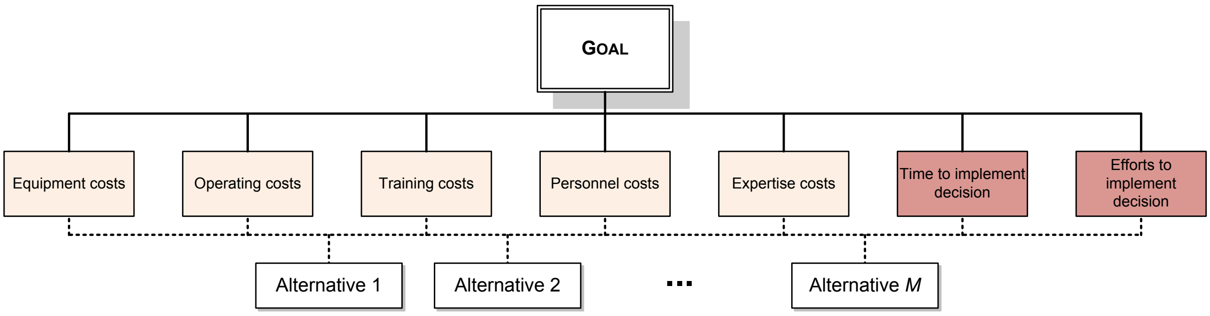


FIGURE 4.4. HIERARCHICAL REPRESENTATION OF PROBLEM'S COSTS.

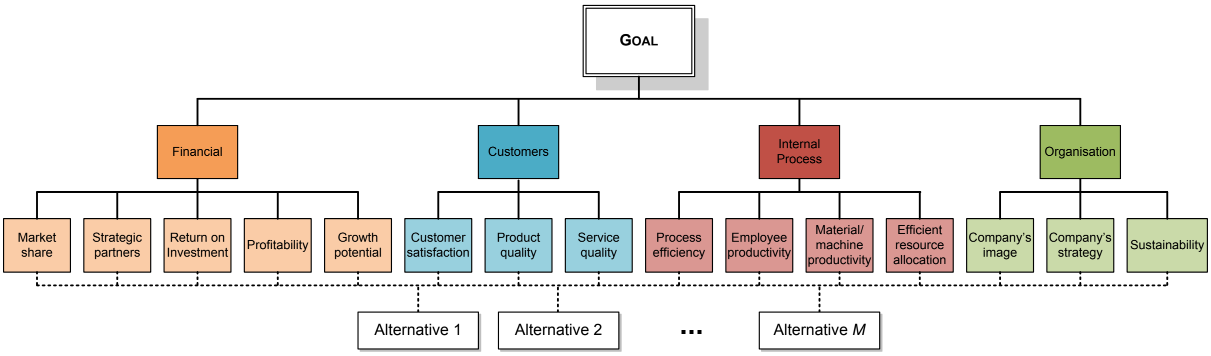


FIGURE 4.5. HIERARCHICAL REPRESENTATION OF PROBLEM'S BENEFITS.

In any decision, whatever the choice of consolidated hierarchy or cost-benefit analysis, the actors involved have the power to start by defining the hierarchy. This means that the hierarchies provided here are a guidance, but in any specific situation, actors can simply remove or add criteria, as they see fit.

4.2.2. COMPARING THE DECISION CRITERIA (INDIVIDUAL JUDGEMENTS)

Each actor has to define how important each criterion is, on his/her individual perspective. However, this can be a very difficult process, which can compromise the overall decision-making process. Instead of defining that one criterion is very important, it is quite often much easier to say that one specific criterion is more important than another one. Therefore, the AHP uses paired comparison of criteria, calling it collecting judgement from users.

The objective of this method is to derive, from the group's quantified judgement (i.e. from the relative values associated with pairs of criteria), a set of weights to be associated with individual criteria; in a sense, these weights should reflect the group's quantified judgements.

Considering the hierarchy presented, given the elements of one level, e.g. the second, and one element E of the next higher level, the elements of level two are compared in pairs in their strength of influence on E. This judgement produces a paired comparison matrix with N rows and N columns (because the hierarchy has N criteria). By convention, the comparison of strength is always done of an activity appearing in the column on the left against an activity appearing in the row on top, filling in a table as the one presented in Table 4.2. The table is filled in by answering questions as e.g. "How much more important is Criterion 1 than Criterion 2?". The answer to this question fills in the element marked with (*) in Table 4.2.

TABLE 4.2. CRITERIA PAIRWISE COMPARISON TABLE.

Decision	Criterion 1	Criterion 2	Criterion 3	...	Criterion *N*
Criterion 1		(*)			
Criterion 2					
Criterion 3					
...					
Criterion *N*					

Let $C_1, C_2, \ldots, C_N$ be the set of criteria. The quantified judgements on pairs of criterion C_i, C_j are represented by an NxN matrix

$$\mathbf{B} = (b_{ij}) \qquad (i,j = 1,2,\ldots,N) \tag{4.19}$$

The entries b_{ij} are defined by the following entry rules:

Rule 1. If $b_{ij} = \alpha$, then $b_{ji} = {}^{1}\!/_{\alpha}$, $\alpha \neq 0$.

Rule 2. If C_i is judged to be equal relative importance as C_j, then $b_{ij} = 1$, $b_{ji} = 1$; in particular, $b_{ii} = 1$, for all i.

Thus, the matrix $\mathbf{B}$ is reciprocal and has the form

$$\mathbf{B} = \begin{bmatrix} 1 & b_{12} & \ldots & b_{1N} \\ {}^{1}\!/_{b_{12}} & 1 & \ldots & b_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ {}^{1}\!/_{b_{1N}} & {}^{1}\!/_{b_{2N}} & \ldots & 1 \end{bmatrix} \tag{4.20}$$

The provision of these judgements requires a scale to be defined and used by all actors involved. One possibility would be to consider a scale of paired comparison from 0 to ∞. However, such a scale assumes that somehow human judgement is capable of comparing the relative dominance of any two objects, which is not the case. The human ability to discriminate is highly limited in range and when there is considerable disparity between the objects or activities being compared, human guesses tend to be arbitrary and usually far from the actual. This suggests that it might be more appropriate to consider a scale with a finite range. In fact, the bounds should be rather close in a region which reflects the human real capability at making ratio comparisons.

Human actors' ability to make qualitative distinctions is well represented by five attributes: equal, weak, strong, very strong, and absolute. However, it is often quite difficult to represent a judgement, and a scale should allow compromise between adjacent attributes when greater precision is needed. Therefore, the scale adopted comprehends nine consecutive values, as described in Table 4.3 (T. Saaty 1991).

TABLE 4.3. SCALE TO REPRESENT CRITERIA JUDGEMENT.

Intensity of importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Weak importance of one over another	Experience and judgement slightly favour one criterion over the other
5	Essential or strong importance	Experience and judgement strongly favour one criterion over another
7	Very strong or demonstrated importance	A criterion is favoured very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one criterion over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between adjacent scale values	When compromise is needed
Reciprocals of above nonzero	If criterion i has one of the above nonzero numbers assigned to it when compared with criterion j, then j has the reciprocal value when compared with i	A reasonable assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

After defining judgements for all criteria, and before using this information to calculate weights, it is possible to analyse the consistency of the information provided.

4.2.3. ANALYSING JUDGEMENT CONSISTENCY

In general, what is meant by consistency is that when there is a basic amount of raw data, all other data can be logically deduced from it. In doing paired comparison to relate N criteria so that each one is represented in the data at least once, it is necessary $N-1$ pairwise comparison judgements. From these, all other judgements can be deduced simply by using the following kind of relation: if criterion C_1 is 3 times more dominant than criterion C_2 and criterion C_1 is 6 times more dominant than criterion C_3. It should follow that C_2 should be twice as dominant as C_3 and C_3 should have half of the dominance of C_2. If the numerical value of the judgement in the (2, 3) position is different from 2 then the matrix is inconsistent. This can actually happen quite frequently. Even if one has the whole real numbers to use for judgements, unless the person occupies full attention methodically to build up the judgements from $N-1$ basic ones, the numbers provided are not likely to be fully consistent. In addition, for most problems it is very difficult to identify $N-1$ judgements which relate all criteria and of which one is absolutely certain.

As explained before, b_{ij} denotes the number indicating the strength of C_i when compared with C_j. The matrix of these numbers b_{ij} is denoted $\mathbf{B}$, or

$$\mathbf{B} = (b_{ij}) \tag{4.21}$$

As noted before, $b_{ji} = {}^{1}/_{b_{ij}}$, that is, the matrix $\mathbf{B}$ is reciprocal.

Considering a perfect judgement in all comparisons made, then $b_{ik} = b_{ij}b_{jk}$ for all i, j, k and the matrix $\mathbf{B}$ is called consistent.

The consistency of a positive reciprocal matrix is equivalent to the requirements that its maximum eigenvalue λ_{max} should be equal to N. It is also possible to estimate the departure from consistency, or Consistency Index (C.I.) by

$$\text{C. I.} = \frac{\lambda_{max} - N}{N - 1} \tag{4.22}$$

It is noted that $\lambda_{max} \geq N$ is always true. It is possible to estimate how bad the consistency is in a given problem by comparing its value of the consistency index with the value from randomly chosen judgements and corresponding reciprocals in the reverse positions in a matrix of the same size. The consistency index of a randomly generated reciprocal matrix from the scale 1 to 9, with reciprocals forced, is called the random index (R.I.). The average values of random index for matrices of order 1 to 15 have been calculated by researchers, using the scale 1 to 9, with sample size of 500 (until order 11) and 100 (upwards). Table 4.4 indicates these calculated values.

TABLE 4.4. CALCULATED VALUES OF RANDOM INDEX.

Matrix order	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Average R.I.	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

The consistency ratio (C.R.) is the ratio of C.I. to the average R.I. for the same order matrix. An acceptable matrix should have a consistency ratio of 0.10 or less. When the consistency ratio is higher than 0.10, the actors should revise their judgements before continuing. However, the team should have rules on how to realise this iteration of judgements. This methodology provides some ideas, but each team should have rules pre-defined before starting the decision process. It is necessary to consider that inconsistency is not related to consensus. The objective of minimising inconsistency is not related to harmonising dissident opinions in the group. Actors will still maintain different opinions among them, but each actor will have consistent opinions. If there is the objective of avoiding any inconsistency altogether, than actors should only provide $N-1$ judgements for N criteria. This is the minimum number of comparisons needed. The other values can be calculated from the judgements provided. However, in most situations, the team leader should not block inconsistency, as it brings opinions that are more diverse. In any case, the actors have to provide $\frac{N(N-1)}{2}$ judgements to compare N criteria. There are two options to revise judgements, according to the following text.

Option 1: Revise individual judgments

Each actor provides a matrix, $\mathbf{B}$, with their individual judgements, and for which there is a consistency index and ratio. The team leader identifies the actors that have a consistency ration higher than 0.10 for their respective judgement matrix, $\mathbf{B}$. The team leader asks the most inconsistent actors to revise their individual judgements. The team leader should not ask modifications outside a range of 10%. The objective of this is to avoid having actors believe they have to change their minds. The aim is to make small modifications in the matrix of judgements to make it more consistent.

After the actors have revised their judgements, the new matrixes are built and new consistency indexes and ratios calculated. If necessary, the process should be performed again. If there was no improvement at all in consistency, the team leader should analyse if the actors did revise their opinions. In cases where an impasse comes up, the team leader has to intervene and modify the criteria or the team.

Option 2: Revise individual judgments based on individual priorities

This second options is used to revise judgements after the individual priorities are determined from each matrix of judgements. The team leader does the following:

1. Identifies any judgements in all the matrixes that do not match the requirement of $b_{ij} = {}^{1}/_{b_{ji}}$. Most of the times, this situation is prevented by the system used by the actors to provide the judgements. This means that usually actors only provide half of

the judgements, to fill in the matrix from the main diagonal up, while the rest is automatically filled in.

2. The team leader identifies the most inconsistent judgements, independent of the actors who provided them. A consistent judgement always verifies $b_{ij} = {}^{w_i}/_{w_j}$, where w_i and w_j are the weights of influence. Therefore, it is necessary to calculate the deviation for all judgments of all actors, according to $\varepsilon_{ij} = b_{ij} w_j / w_i$, where $\varepsilon_{ij} = 1$ for consistent judgements. The team leader should identify actors who provided judgements with $\varepsilon_{ij} > 1.1$, to use the same 10% rule again. The team leader asks the actors to revise the identified judgements only in order to improve inconsistency.

The matrixes are adjusted with the new judgements and new consistency indexes and ratios calculated. If necessary, the process is performed again. If there was no improvement at all in consistency, the team leader should analyse if the actors did revise their opinions. In cases where an impasse comes up, the team leader has to intervene and modify the criteria or the team.

4.2.4. DEFINING INDIVIDUAL CRITERIA WEIGHT

Having recorded the quantified judgements on pairs $(\mathrm{C}_i, \mathrm{C}_j)$ as numerical entries b_{ij} in the matrix $\mathbf{B}$, the problem now is to assign to the N contingencies $\mathrm{C}_1, \mathrm{C}_2, \dots, \mathrm{C}_N$ a set of numerical weights $w_1, w_2, \dots, w_N$ that would "reflect the recorded judgements".

Considering the elements $\mathrm{C}_1, \mathrm{C}_2, \dots, \mathrm{C}_N$ of the second level of our hierarchy, the objective is to find weights of influence $w_1, w_2, \dots, w_N$ on the element "Goal" of the highest level, based on the matrix of numbers, representing the judgement of paired comparisons, which is the basic tool.

As stated before, the matrix $\mathbf{B}$ is reciprocal, i.e. $b_{ji} = {}^{1}/_{b_{ij}}$. In addition, it was also stated that matrix $\mathbf{B}$ would be consistent if $b_{ik} = b_{ij} b_{jk}$ for all i, j and k.

An obvious case of a consistent matrix is one in which comparisons are based on exact measurements; that is, the weights $w_1, w_2, \dots, w_N$ are already known. Then,

$$b_{ij} = \frac{w_i}{w_j} \qquad i, j = 1, \dots, N \tag{4.23}$$

and thus

$$b_{ij} b_{jk} = \frac{w_i}{w_j} \frac{w_j}{w_k} = \frac{w_i}{w_k} = b_{ik} \tag{4.24}$$

Also, of course,

$$b_{ji} = \frac{w_j}{w_i} = \frac{1}{w_i/w_j} = \frac{1}{b_{ij}} \qquad (4.25)$$

The matrix equation

$$\mathbf{Bx} = \mathbf{y} \qquad (4.26)$$

where $\mathbf{x} = [x_1, \dots, x_N]^{\mathrm{T}}$ and $\mathbf{y} = [y_1, \dots, y_N]$, is a shorthand notation for the set of equations

$$\sum_{j=1}^{N} b_{ij} x_i = y_i \qquad i = 1, \dots, N \qquad (4.27)$$

It is possible to observe that from $b_{ij} = w_i/w_j$, we obtain

$$b_{ij} \frac{w_j}{w_i} = 1 \qquad i, j = 1, \dots, N \qquad (4.28)$$

and consequently

$$\sum_{j=1}^{N} b_{ij} w_j \frac{1}{w_i} = N \qquad i = 1, \dots, N \qquad (4.29)$$

or

$$\sum_{j=1}^{N} b_{ij} w_j = N w_i \qquad i = 1, \dots, N \qquad (4.30)$$

which is equivalent to

$$\mathbf{Bw} = N\mathbf{w} \qquad (4.31)$$

In matrix theory, this formula expresses the fact that $\mathbf{w}$ is an eigenvector of $\mathbf{B}$ with eigenvalue N. When written out fully this equation look as follows

$$\mathbf{B} = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_N} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_N} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_N}{w_1} & \frac{w_N}{w_2} & \cdots & \frac{w_N}{w_N} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_N \end{bmatrix} = N \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_N \end{bmatrix} \qquad (4.32)$$

This holds for the "ideal" case where the weights are already known. Considering the practical case, in which b_{ij} are not based on exact measurements, but on subjective judgements, b_{ij} deviate from the "ideal" ratios $w_i \,/\, w_j$, and therefore the equation $\mathbf{Bw} = N\mathbf{w}$ will no longer hold. However, two facts of matrix theory apply to this practical scenario.

The first one is that if $\lambda_1, \dots, \lambda_N$ are the numbers satisfying the equation

$$\mathbf{Bx} = \lambda\mathbf{x} \qquad (4.33)$$

i.e., are the eigenvalues of $\mathbf{B}$, and if $b_{ii} = 1$ for all i, then

$$\sum_{i=1}^{N} \lambda_i = N \tag{4.34}$$

Therefore, if $\mathbf{Bw} = N\mathbf{w}$ holds, then all eigenvalues are zero, except one, which is N. Clearly, then, in the consistent case, N is the largest eigenvalue of $\mathbf{B}$.

The second fact is that if one changes the entries b_{ij} of a positive reciprocal matrix $\mathbf{B}$ by small amounts, then the eigenvalues change by small amounts.

Combining these results, it is possible to conclude that if the diagonal of a matrix $\mathbf{B}$ consists of ones ($b_{ii} = 1$), and if $\mathbf{B}$ is consistent, then small variations of the b_{ij} keep the largest eigenvalue, λ_{max}, close to N, and the remaining eigenvalues close to zero.

Therefore, the problem is this: if $\mathbf{B}$ is the matrix of paired comparison values, in order to find the priority vector, it is necessary to find the vector $\mathbf{w}$ that satisfies

$$\mathbf{Bw} = \lambda_{max}\mathbf{w} \tag{4.35}$$

Since (4.35) does not provide a unique solution but a direction for $\mathbf{w}$, it is necessary to select the normalised solution that guarantees $\sum_{i=1}^{N} w_i = 1$.

The result of this methodology step is a vector containing the weight of each criterion considered, given by the normalised eigenvector correspondent to the maximum eigenvalue of $\mathbf{B}$. Therefore, considering the criteria $\mathrm{C}_1, \dots, \mathrm{C}_N$, each user has registered judgements that led to the definition of the vector

$$\mathbf{w} = \begin{bmatrix} w_1 \\ \vdots \\ w_N \end{bmatrix} \tag{4.36}$$

If the decision-making process involves a team with L members, then the result comprehends L vectors like the one presented in (4.36). The next step consists on how to combine the individual opinions, to define the group's definition of weight for each criterion.

4.2.5. CALCULATING GROUP CRITERIA WEIGHT

Considering the decision-making process includes a team with L actors, and each of them has provided individual judgements, leading to the definition of L different vectors $\mathbf{w}$ representing the individual criteria weights. The opinion of each team member is expressed in a vector

$$\mathbf{w}^{(k)} = \begin{bmatrix} w_1^{(k)} \\ \vdots \\ w_N^{(k)} \end{bmatrix} \qquad i = 1, \dots, N \text{ and } k = 1, \dots, L \tag{4.37}$$

where k indicates the index of the actor in the team.

Each person represents a “piece” of the team, which can be distributed in different ways. This means that each team member has an individual weight, identifying his/her “position” in the team. This weight can be the same for all team members, in cases of equal voting, but it can happen that some members have a more relevant position than others (e.g. in cases of committees).

There are two possibilities to aggregate the individual opinions of different actors: aggregate individual judgements (provided by matrixes $\mathbf{B}$), or aggregate individual priorities (provided by vectors $\mathbf{w}$). Teams use the first method when the group acts together as a unit, i.e. when individuals are willing to, or must, renounce to their own preferences for the sake of the group. In these situations, the group becomes a new individual. On the other hand, teams use the second method when the group represents a collection of separate individuals. In industrial environments, there is always a major concern with accountability and responsibility of actors in any situation. Therefore, companies do not want to lose the individual identities in group decision-making. Consequently, the methodology presented in this thesis uses aggregation of individual priorities to support collaborative decision-making that still represents individuals as well. In order to aggregate individual priorities, it is possible to use either an arithmetic or geometric mean (Forman and Peniwati 1998). Regarding this aspect, the methodology here proposed has chosen to use the arithmetic mean, also because of industrial requirements. Actors in industrial environments tend to be suspicious of methods and particularly systems they do not know, and especially that they do not understand. The arithmetic average is identified with an arithmetic progression, which is considered linear, simpler and easier to understand. Even if actors do not all have the some weight in the team, they understand that their role is directly weighted by a simple constant.

Supposing that each expert in the team has a weight, p_k, with $\sum_{k=1}^{L} p_k = 1$, then the total weight of the group for one specific criterion, i, is given by

$$w_i = \sum_{k=1}^{L} w_i^{(k)} p_k \tag{4.38}$$

Therefore, the vector representing the total criteria weight, i.e. considering all the individual judgements provided is represented by:

$$\mathbf{w} = \begin{bmatrix} \sum_{k=1}^{L} w_1^{(k)} p_k \\ \vdots \\ \sum_{k=1}^{L} w_N^{(k)} p_k \end{bmatrix} \tag{4.39}$$

4.2.6. INDIVIDUAL CLASSIFICATION OF ALTERNATIVES

Since the possible outcome alternatives of the situation under analysis are identified and represented in the hierarchy, it is necessary to find some method to classify them. According to AHP, the method is to compare pairs of the elements of the last hierarchical level, i.e. the alternatives, in their strength of influence on each element of the immediately upper hierarchical level, i.e. the criteria, or in the proposed hierarchy, the sub-criteria.

Therefore, the process is similar to the first paired comparison performed (see section 4.2.2 Comparing the decision criteria (individual judgements)). However, this judgement produces one paired comparison matrix with M rows and M columns (because the hierarchy has M alternatives), for each criterion. Each user will produce N matrices of M rows and M columns. The alternatives will be compared in pairs concerning each criterion individually.

By convention, the comparison of strength is always done of an alternative appearing in the column on the left against an alternative appearing in the row on top, filling in a table as the one presented in Table 4.5. The table is filled in by answering questions as e.g. “How much more important is Alternative 1 than Alternative 2, with respect to Criteria *N*?”.

TABLE 4.5. ALTERNATIVES PAIRWISE COMPARISON TABLE.

Criterion N	Alternative 1	Alternative 2	...	Alternative M
Alternative 1				
Alternative 2				
...				
Alternative M				

Let $C_1, C_2, \dots, C_N$ be the set of criteria and $A_1, A_2, \dots, A_M$ the different alternatives. For each different criteria, the quantified judgements on pairs of alternatives A_m, A_n are represented by an MxM matrix

$$\mathbf{F}_i = (f_{mn}), \qquad (m, n = 1,2, \dots, M) \; and \; (i = 1,2, \dots, N) \tag{4.40}$$

Similarly to matrix $\mathbf{B}$ previously defined, the entries f_{mn} are defined by the following entry rules:

Rule 1. If $f_{mn} = \alpha$, then $f_{mn} = 1/\alpha$, $\alpha \neq 0$.

Rule 2. If A_m is judged to be equal relative importance as A_n, then $f_{mn} = 1$, $f_{nm} = 1$; in particular, $f_{mm} = 1$ for all m.

This, the matrix $\mathbf{F}_i$ has the form

$$\mathbf{F}_i = \begin{bmatrix} 1 & f_{12} & \cdots & f_{1M} \\ 1/f_{12} & 1 & \cdots & f_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ 1/f_{1M} & 1/f_{2M} & \cdots & 1 \end{bmatrix} \qquad i = 1, \dots, N. \tag{4.41}$$

Therefore, the problem is this: if $\boldsymbol{F}$ is the matrix of paired comparison values, in order to find the priority vector, it is necessary to find the vector $\mathbf{s}$ that satisfies

$$\mathbf{Fs} = \lambda_{max}\mathbf{s} \tag{4.42}$$

Since (4.35) does not provide a unique solution but a direction for $\mathbf{s}$, it is necessary to select the normalised solution that guarantees $\sum_{i=1}^{M} s_i = 1$.

For each criteria $\mathrm{C}_1, \dots, \mathrm{C}_N$, each user compares the alternatives considered. As a result, each user *k* defines a group of *N* vectors of the type

$$\mathbf{s}_i^{(k)} = \begin{bmatrix} s_1^{(i,k)} \\ \vdots \\ s_M^{(i,k)} \end{bmatrix} \qquad i = 1, \dots, N \text{ and } k = 1, \dots, L \tag{4.43}$$

There are decision problems in which the main concern is to choose the best alternative independently of what other alternatives may come to light after the initial rating. In other problems, the best alternative may depend on what other alternatives are added. When there is dependence among alternatives, it is necessary to use the paired comparisons of alternatives together with the normalisation. This is the distributive mode in AHP, and results in $\mathbf{s}_i^{(k)}$ defined by (4.43). On the other hand, when the alternatives are independent, it is necessary to preserve the initial rating from changing if irrelevant alternatives are added. In these cases, the elements of vector $\mathbf{s}_i^{(k)}$ are divided by its maximum element. This is the ideal mode in AHP.

The N vectors $\mathbf{s}_i^{(k)}$ can be combined in one matrix $\mathbf{S}^{(k)}$, expressing the weights defined by the user k to the M alternatives, regarding the N criteria considered. The matrix is composed with the terms s_{ji}, where j is the alternative (in the rows) and i indicates the criteria (represented in columns):

$$\mathbf{S}^{(k)} = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1N} \\ s_{21} & s_{22} & \cdots & s_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ s_{M1} & s_{M2} & \cdots & s_{MN} \end{bmatrix}, \qquad k = 1, \dots, L \tag{4.44}$$

4.2.7. CALCULATING GROUP CLASSIFICATION OF ALTERNATIVES

As defined previously, each expert has a role in the team. This role may be different in the distinct phases of the decision process. Therefore, the methodology proposed in this thesis allows the possibility of one actor having one role when defining criteria's weights and a different role when rating the alternatives. According to this, each actor has, in this step, a weight q_k, with $\sum_{k=1}^{L} q_k = 1$, representing the respective role in the group. This weight is necessary to compute the total view of the group about the several alternatives individually judged. The matrices $\mathbf{S}^{(k)}$ defined are combined, taking into account the user's role, resulting that the rating of one alternative *j* regarding one criteria i is given by

$$s_{ji} = \sum_{k=1}^{L} s_{ji}^{(k)} q_k \tag{4.45}$$

Therefore, the matrix representing the total alternatives ratings, i.e. considering all the individual judgements provided is represented by:

$$\mathbf{S} = \begin{bmatrix} \sum_{k=1}^{L} s_{11}^{(k)} q_k & \sum_{k=1}^{L} s_{12}^{(k)} q_k & \cdots & \sum_{k=1}^{L} s_{1N}^{(k)} q_k \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{k=1}^{L} s_{M1}^{(k)} q_k & \sum_{k=1}^{L} s_{M2}^{(k)} q_k & \cdots & \sum_{k=1}^{L} s_{MN}^{(k)} q_k \end{bmatrix} \tag{4.46}$$

The matrix $\mathbf{S}$ provides the total ratings of all alternatives regarding the criteria, i.e. how each alternative satisfy each criterion.

4.2.8. ORDERING ALTERNATIVES

After providing judgements on the importance of the criteria, resulting in criteria weights, and judgements on the satisfaction of each alternative, it is possible to finally order the M alternatives to find out the most satisfactory one.

The final ranking of the alternatives $\mathrm{A}_1, \dots, \mathrm{A}_M$ is given by

$$\mathbf{y} = \mathbf{S}\mathbf{w} \tag{4.47}$$

which is equivalent to

$$\mathbf{y} = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1N} \\ \vdots & \vdots & \ddots & \vdots \\ s_{M1} & s_{M2} & \cdots & s_{MN} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_N \end{bmatrix} \tag{4.48}$$

resulting in

$$\mathbf{y} = \begin{bmatrix} \sum_{i=1}^{N} s_{1i} w_i \\ \vdots \\ \sum_{i=1}^{N} s_{Mi} w_i \end{bmatrix} \tag{4.49}$$

The element with the higher value in vector $\mathbf{y}$, i.e. the element y_j, corresponds to the alternative A_j that better satisfies the criteria considered.

When the team chooses to perform a cost-benefit analysis, these steps are performed twice: once for the hierarchy of costs, and the second time for the hierarchy of benefits. In the end, the actors have two vectors of rankings of alternatives, where each was obtained from one hierarchy. The actors divide the ranking obtained through the costs hierarchy by the ranking obtained through the benefits hierarchy. This gives a cost-benefit ration for each alternative. The team should select the alternative with the lowest ratio, i.e. lower costs and higher benefits.

EXAMPLE 4.3 USING AHP TO SATISFY A CUSTOMER REQUEST

This example is based on information collected in a real situation occurred in a company that designs and assemblies acclimatisation units. Further details about the company and other tests realised are described in 5.2 Assembling Companies.

Consider that a company receives a request from a customer regarding an acclimatisation solution for a large shopping mall. As the company has considerable experience in the field, it has to consider if any existing solution meet the requirements or not. After analysing the request and the product catalogue, the company identifies three possible solutions:

1. Sell to the customer an existing solution A that meets the minimum requirements only;
2. Re-engineer an existing solution B to comply to all the requirements from the customer; or
3. Develop a new solution C completely tailored to the customer.

In order to address the problem, the company starts by forming a team who will be responsible for making the decision. The company selects a team with three actors:

1. Actor 1, from the department of design and engineering, is responsible for developing the best solution for each situation.
2. Actor 2, from the department of production, handles the internal processes of the company, controlling its resources and scheduling.
3. Actor 3, from the department of marketing and sales, deals with activities related to customer relationship management and promotion of products.

Now, the team needs to consider all the relevant criteria in order to select the best alternative. The first step is to structure the problem in a hierarchy, as presented in Figure 4.6. The team used the criteria proposed in this thesis as starting point, but eventually removed some criteria they thought irrelevant for the current situation.

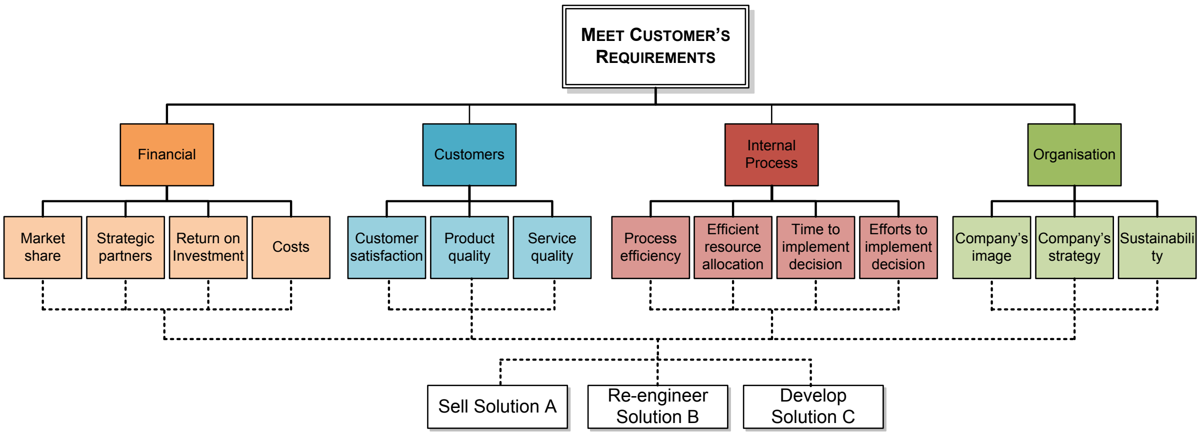


FIGURE 4.6. HIERARCHICAL REPRESENTATION OF EXAMPLE OF PROBLEM TO MEET CUSTOMER'S REQUIREMENTS.

After defining the hierarchy, including the criteria and alternatives, the actors start providing their individual judgements about the criteria in the decision situation. Each actor will compare the criteria in pairs, according to the following:

- Compare criteria in the second level of the hierarchy, i.e. FINANCIAL, CUSTOMERS, INTERNAL PROCESS and ORGANISATION.
- Compare sub-criteria in the third level of the hierarchy according to the respective criteria:
  - Compare sub-criteria in the criteria group FINANCIAL, i.e. market share, strategic partners, return on investment, and costs;
  - Compare sub-criteria in the criteria group CUSTOMERS, i.e. customer satisfaction, product quality and service quality;
  - Compare sub-criteria in the criteria group INTERNAL PROCESS, i.e. process efficiency, efficient resource allocation, time to implement decision and efforts to implement decision;
  - Compare sub-criteria in the criteria group ORGANISATION, i.e. company's image, company's strategy and sustainability.

According to this description, each actor has to fill in five comparison tables: one for the criteria and four for the sub-criteria groups. For each matrix with N elements (some have three elements and others have four), each actor was asked to provide $\frac{N(N-1)}{2}$ judgements. The tables given to the users were half-filled with the reciprocals for the judgements. Therefore, each actor provided b_{ij} while the immediate relation $b_{ji} = {}^{1}/_{b_{ij}}$ was automatically filled in. This number of judgements allows for inconsistency from the actors, which is handled later.

Table 4.6 represents the individual judgements provided by actor 1, from the department of design and engineering. The several tables refer to the criteria and sub-criteria, as explained previously. Each matrix is filled in with the judgements provided by the actor and the consistency index and ratios are indicated below the matrix.

TABLE 4.6. INDIVIDUAL JUDGEMEMENTS OF CRITERIA BY ACTOR 1.

Actor 1	Financial	Customers	Internal Process	Organisation	Priority
Financial	1.000	0.333	0.200	1.000	0.099
Customers	3.000	1.000	0.333	3.000	0.263
Internal Process	5.000	3.000	1.000	3.000	0.523
Organisation	1.000	0.333	0.333	1.000	0.116
C.I.	0.039				1.000
C.R.	0.043				

Actor 1	Market share	Strategic partners	Return on investment	Costs	Local Priority	Global Priority
Market share	1.000	1.000	1.000	0.333	0.167	0.016
Strategic partners	1.000	1.000	1.000	0.333	0.167	0.016
Return on investment	1.000	1.000	1.000	0.333	0.167	0.016
Costs	3.000	3.000	3.000	1.000	0.500	0.049
C.I.	0.000				1.000	0.099
C.R.	0.000					

Actor 1	Customer satisfaction	Product quality	Service quality	Priority	Global Priority
Customer satisfaction	1.000	1.000	3.000	0.429	0.113
Product quality	1.000	1.000	3.000	0.429	0.113
Service quality	0.333	0.333	1.000	0.143	0.038
C.I.	0.000			1.000	0.263
C.R.	0.000				

Actor 1	Process efficiency	Efficient resource allocation	Time to make a decision	Efforts to make a decision	Local Priority	Global Priority
Process efficiency	1.000	1.000	1.000	0.333	0.175	0.092
Efficient resource allocation	1.000	1.000	1.000	1.000	0.241	0.126
Time to implement decision	1.000	1.000	1.000	0.333	0.175	0.092
Efforts to implement decision	3.000	1.000	3.000	1.000	0.409	0.214
C.I.	0.052				1.000	0.523
C.R.	0.057					

Actor 1	Company's image	Company's strategy	Sustainability	Priority	Global Priority
Company's image	1.000	5.000	3.000	0.651	0.075
Company's strategy	0.200	1.000	3.000	0.223	0.026
Sustainability	0.333	0.333	1.000	0.127	0.015
C.I.	0.147			1.000	0.116
C.R.	0.254				

As stated in section 4.2.3 Analysing judgement consistency, it is desirable to have all judgements matrixes with a consistency ratio below than 0.10. However, it is possible to see that actor 1 has provided some inconsistent judgements when comparing the sub-criteria of the criteria group organisation. The last matrix indicated by actor 1 has a consistency ratio of 0.254. This methodology proposes the calculation of $\varepsilon_{ij} = b_{ij}w_j/w_i$ for all elements in the inconsistent matrix. The result of this calculation is represented in the left part of Table 4.7. It is possible to see that the comparison between sustainability and company's image has $\varepsilon_{31} = 1.71$, which means that the judgement provided by the actor is too small. On the other hand, the comparisons between company's strategy and company's image, and between sustainability and company's strategy have $\varepsilon_{21} = 0.585$ and $\varepsilon_{32} = 0.585$, which means these two judgements have values that are too high. The actor was then asked to re-consider revising these three judgements, changing the values provided by one step (from 1/3 to 1/5) or even half-a-step (from 1/3 to 1/4). The actor accepted, and the new judgements are represented in the right part of Table 4.7, with a consistent ratio of 0.033.

TABLE 4.7. REVISION OF SOME INDIVIDUAL JUDGEMEMENTS OF CRITERIA BY ACTOR 1.

Actor 1	Company's image	Company's strategy	Sustainability
Company's image	1.000	1.710	0.585
Company's strategy	0.585	1.000	1.710
Sustainability	1.710	0.585	1.000

Actor 1	Company's image	Company's strategy	Sustainability	Priority	Global Priority
Company's image	1.000	3.000	5.000	0.637	0.074
Company's strategy	0.333	1.000	3.000	0.258	0.030
Sustainability	0.200	0.333	1.000	0.105	0.012
C.I.	0.019			1.000	0.116
C.R.	0.033				

Table 4.8 and Table 4.9 represent the individual judgements provided by actors 2 and 3 for the criteria and sub-criteria. It is possible to see that all matrixes have consistency ratios below 0.10.

TABLE 4.8. INDIVIDUAL JUDGEMEMENTS OF CRITERIA BY ACTOR 2.

Actor 2	Financial	Customers	Internal Process	Organisation	Priority
Financial	1.000	0.200	0.143	0.200	0.051
Customers	5.000	1.000	0.200	0.333	0.145
Internal Process	7.000	5.000	1.000	1.000	0.449
Organisation	5.000	3.000	1.000	1.000	0.355
C.I.	0.068				1.000
C.R.	0.076				

Actor 2	Market share	Strategic partners	Return on investment	Costs	Local Priority	Global Priority
Market share	1.000	1.000	1.000	1.000	0.250	0.013
Strategic partners	1.000	1.000	1.000	1.000	0.250	0.013
Return on investment	1.000	1.000	1.000	1.000	0.250	0.013
Costs	1.000	1.000	1.000	1.000	0.250	0.013
C.I.	0.000				1.000	0.051
C.R.	0.000					

Actor 2	Customer satisfaction	Product quality	Service quality	Priority	Global Priority
Customer satisfaction	1.000	0.143	0.200	0.072	0.010
Product quality	7.000	1.000	3.000	0.649	0.094
Service quality	5.000	0.333	1.000	0.279	0.040
C.I.	0.032			1.000	0.145
C.R.	0.056				

Actor 2	Process efficiency	Efficient resource allocation	Time to make a decision	Efforts to make a decision	Local Priority	Global Priority
Process efficiency	1.000	1.000	7.000	5.000	0.441	0.198
Efficient resource allocation	1.000	1.000	5.000	5.000	0.404	0.181
Time to implement decision	0.143	0.200	1.000	1.000	0.075	0.033
Efforts to implement decision	0.200	0.200	1.000	1.000	0.081	0.036
C.I.	0.005				1.000	0.449
C.R.	0.005					

Actor 2	Company's image	Company's strategy	Sustainability	Priority	Global Priority
Company's image	1.000	1.000	1.000	0.333	0.118
Company's strategy	1.000	1.000	1.000	0.333	0.118
Sustainability	1.000	1.000	1.000	0.333	0.118
C.I.	0.000			1.000	0.355
C.R.	0.000				

TABLE 4.9. INDIVIDUAL JUDGEMEMENTS OF CRITERIA BY ACTOR 3.

Actor 3	Financial	Customers	Internal Process	Organisation	Priority
Financial	1.000	1.000	7.000	5.000	0.417
Customers	1.000	1.000	7.000	5.000	0.417
Internal Process	0.143	0.143	1.000	0.200	0.045
Organisation	0.200	0.200	5.000	1.000	0.122
C.I.	0.070				1.000
C.R.	0.077				

Actor 3	Market share	Strategic partners	Return on investment	Costs	Local Priority	Global Priority
Market share	1.000	5.000	3.000	1.000	0.419	0.175
Strategic partners	0.200	1.000	0.200	0.333	0.070	0.029
Return on investment	0.333	5.000	1.000	1.000	0.239	0.100
Costs	1.000	3.000	1.000	1.000	0.272	0.113
C.I.	0.062	C.R.	0.069		1.000	0.417

Actor 3	Customer satisfaction	Product quality	Service quality	Priority	Global Priority
Customer satisfaction	1.000	3.000	3.000	0.600	0.250
Product quality	0.333	1.000	1.000	0.200	0.083
Service quality	0.333	1.000	1.000	0.200	0.083
C.I.	0.000			1.000	0.417
C.R.	0.000				

Actor 3	Process efficiency	Efficient resource allocation	Time to make a decision	Efforts to make a decision	Local Priority	Global Priority
Process efficiency	1.000	1.000	0.200	0.200	0.083	0.004
Efficient resource allocation	1.000	1.000	0.200	0.200	0.083	0.004
Time to implement decision	5.000	5.000	1.000	1.000	0.417	0.019
Efforts to implement decision	5.000	5.000	1.000	1.000	0.417	0.019
C.I.	0.000				1.000	0.045
C.R.	0.000					

Actor 3	Company's image	Company's strategy	Sustainability	Priority	Global Priority
Company's image	1.000	5.000	5.000	0.714	0.087
Company's strategy	0.200	1.000	1.000	0.143	0.017
Sustainability	0.200	1.000	1.000	0.143	0.017
C.I.	0.000			1.000	0.122

Figure 4.7 presents the priorities assigned to each criteria, which are extracted from the judgements provided by each actor. It is possible to identify the different views given by the three actors, mainly polarised by their department. Actor 1 is from the department of design and engineering, actor 2 is from the production department, and actor 3 is from the department of marketing and sales.

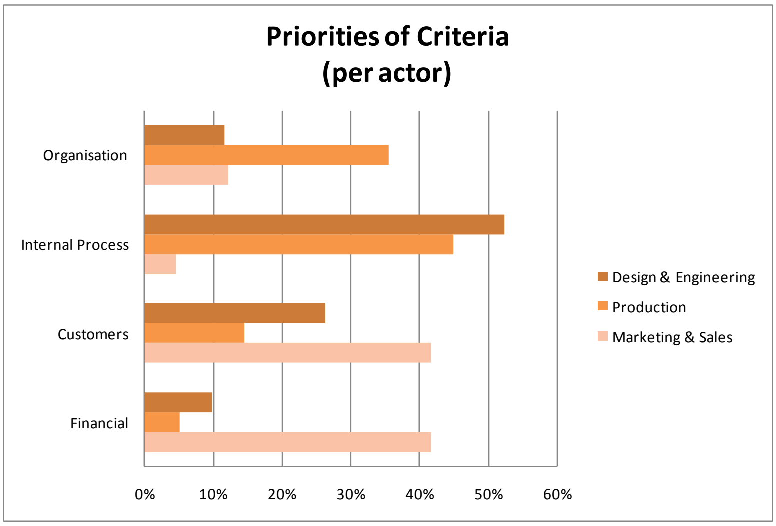


FIGURE 4.7. CRITERIA PRIORITIES ASSIGNED BY EACH ACTOR.

Figure 4.8 displays the priorities given by each actor to each of the sub-criteria represented in the decision situation hierarchy.

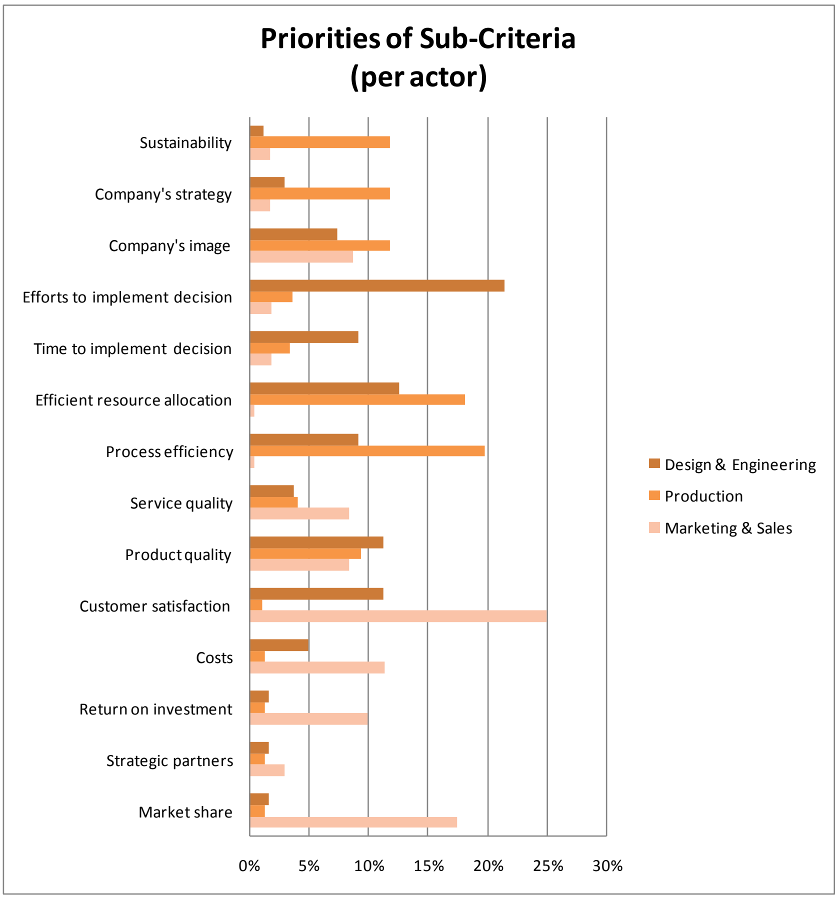


FIGURE 4.8. SUB-CRITERIA PRIORITIES ASSIGNED BY EACH ACTOR.

From the individual criteria priorities, the calculation of the group's criteria weights is straightforward. In order to aggregate the individual priorities for the criteria, each team member is assigned a role, or weight. For this purpose, the team has the following role distribution: actors 1 and 2 have weights of 40% each, and actor 3 has a weight of 20%. The total weight of each criterion is the weighted arithmetic mean of the individual priorities. The result of the group's criteria priorities is presented in Figure 4.9.

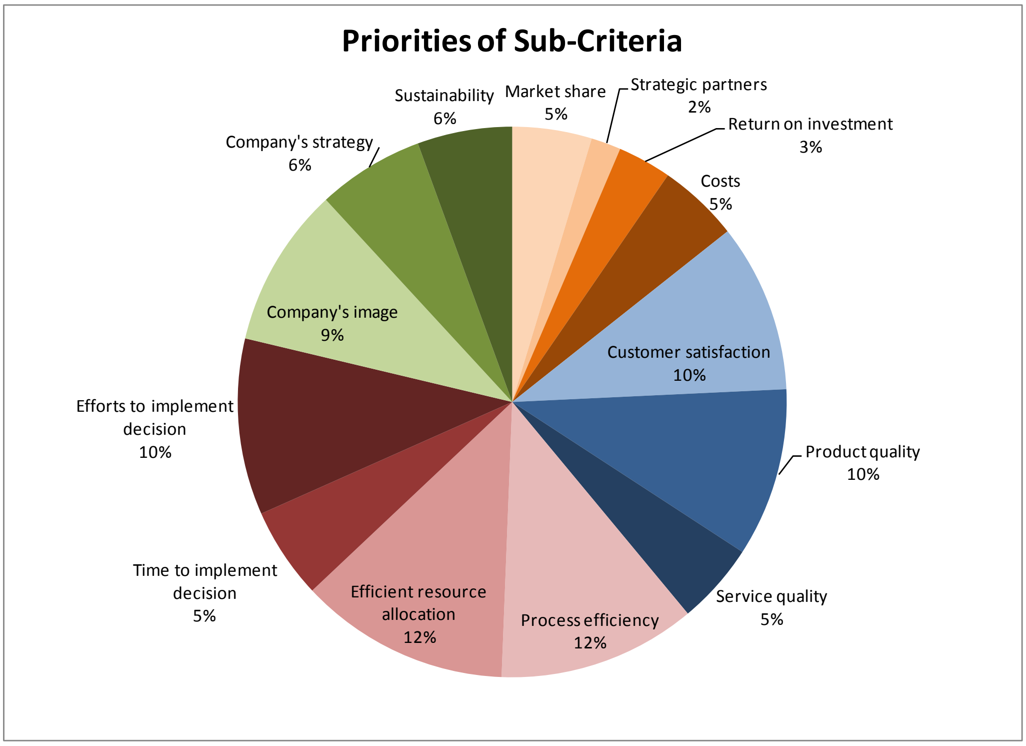


FIGURE 4.9. CRITERIA WEIGHTS DEFINED BY THE TEAM.

After having the weights for the criteria, the teams need to compare the three alternatives regarding each sub-criteria. This means that each actor will fill in 14 matrixes with dimension $3x3$. In order to define these judgements, the actors had to provide three values, while the reciprocals were automatically determined. The process is actually quite similar to the one where actors provided judgements on criteria.

Table 4.10, Table 4.11 and Table 4.12 provide an overview of the individual judgements provided by the three actors, when comparing the possible alternatives to the sub-criteria identified in the hierarchy. Each of the fourteen matrixes provided by the three actors was analysed with respect to the consistency index and ration, as indicated in the tables. All the judgements provided by the actors in this phase were in the range of consistency accepted, i.e. with a consistency ration lower than 0.10.

TABLE 4.10. INDIVIDUAL JUDGEMEMENTS OF ALTERNATIVES BY ACTOR 1.

Market share	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	0.200	0.156
Re-engineer Solution B	1.000	1.000	0.333	0.185
Develop Solution C	5.000	3.000	1.000	0.659
C.I.	0.015			1.000
C.R.	0.025			

Strategic partners	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	0.333	0.333	0.143
Re-engineer Solution B	3.000	1.000	1.000	0.429
Develop Solution C	3.000	1.000	1.000	0.429
C.I.	0.000			1.000
C.R.	0.000			

Return on investment	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

Costs	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	3.000	3.000	0.600
Re-engineer Solution B	0.333	1.000	1.000	0.200
Develop Solution C	0.333	1.000	1.000	0.200
C.I.	0.000			1.000
C.R.	0.000			

Customer satisfaction	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	0.200	0.143	0.072
Re-engineer Solution B	5.000	1.000	0.333	0.279
Develop Solution C	7.000	3.000	1.000	0.649
C.I.	0.032			1.000
C.R.	0.056			

Product quality	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

Service quality	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

Process efficiency	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

Efficient resource allocation	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	0.333	0.200
Re-engineer Solution B	1.000	1.000	0.333	0.200
Develop Solution C	3.000	3.000	1.000	0.600
C.I.	0.000			1.000
C.R.	0.000			

Time to implement decision	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	5.000	9.000	0.751
Re-engineer Solution B	0.200	1.000	3.000	0.178
Develop Solution C	0.111	0.333	1.000	0.070
C.I.	0.015			1.000
C.R.	0.025			

Efforts to implement decision	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	5.000	9.000	0.751
Re-engineer Solution B	0.200	1.000	3.000	0.178
Develop Solution C	0.111	0.333	1.000	0.070
C.I.	0.015			1.000
C.R.	0.251			

Company's image	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

Company's strategy	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	0.200	0.143
Re-engineer Solution B	1.000	1.000	0.200	0.143
Develop Solution C	5.000	5.000	1.000	0.714
C.I.	0.000			1.000
C.R.	0.000			

Sustainability	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	0.200	0.143
Re-engineer Solution B	1.000	1.000	0.200	0.143
Develop Solution C	5.000	5.000	1.000	0.714
C.I.	0.000			1.000
C.R.	0.000			

TABLE 4.11. INDIVIDUAL JUDGEMEMENTS OF ALTERNATIVES BY ACTOR 2.

Market share	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

Strategic partners	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	0.333	0.200	0.105
Re-engineer Solution B	3.000	1.000	0.333	0.258
Develop Solution C	5.000	3.000	1.000	0.637
C.I.	0.019			1.000
C.R.	0.033			

Return on investment	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	3.000	0.429
Re-engineer Solution B	1.000	1.000	3.000	0.429
Develop Solution C	0.333	0.333	1.000	0.143
C.I.	0.000			1.000
C.R.	0.000			

Costs	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	3.000	5.000	0.637
Re-engineer Solution B	0.333	1.000	3.000	0.258
Develop Solution C	0.200	0.333	1.000	0.105
C.I.	0.019			1.000
C.R.	0.033			

Customer satisfaction	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	0.333	0.333	0.143
Re-engineer Solution B	3.000	1.000	1.000	0.429
Develop Solution C	3.000	1.000	1.000	0.429
C.I.	0.000			1.000
C.R.	0.000			

Product quality	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

Service quality	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

Process efficiency	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	3.000	0.333	0.258
Re-engineer Solution B	0.333	1.000	0.200	0.105
Develop Solution C	3.000	5.000	1.000	0.637
C.I.	0.019			1.000
C.R.	0.033			

Efficient resource allocation	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	3.000	0.333	0.258
Re-engineer Solution B	0.333	1.000	0.200	0.105
Develop Solution C	3.000	5.000	1.000	0.637
C.I.	0.019			1.000
C.R.	0.033			

Time to implement decision	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	5.000	9.000	0.751
Re-engineer Solution B	0.200	1.000	3.000	0.178
Develop Solution C	0.111	0.333	1.000	0.070
C.I.	0.015			1.000
C.R.	0.025			

Efforts to implement decision	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	5.000	9.000	0.751
Re-engineer Solution B	0.200	1.000	3.000	0.178
Develop Solution C	0.111	0.333	1.000	0.070
C.I.	0.015			1.000
C.R.	0.025			

Company's image	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

Company's strategy	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	0.333	0.200
Re-engineer Solution B	1.000	1.000	0.333	0.200
Develop Solution C	3.000	3.000	1.000	0.600
C.I.	0.000			1.000
C.R.	0.000			

Sustainability	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

TABLE 4.12. INDIVIDUAL JUDGEMEMENTS OF ALTERNATIVES BY ACTOR 3.

Market share	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	0.333	0.143	0.088
Re-engineer Solution B	3.000	1.000	0.333	0.243
Develop Solution C	7.000	3.000	1.000	0.669
C.I.	0.004			1.000
C.R.	0.006			

Strategic partners	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	0.333	0.143	0.088
Re-engineer Solution B	3.000	1.000	0.333	0.243
Develop Solution C	7.000	3.000	1.000	0.669
C.I.	0.004			1.000
C.R.	0.006			

Return on investment	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

Costs	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	3.000	3.000	0.600
Re-engineer Solution B	0.333	1.000	1.000	0.200
Develop Solution C	0.333	1.000	1.000	0.200
C.I.	0.000			1.000
C.R.	0.000			

Customer satisfaction	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	0.200	0.111	0.058
Re-engineer Solution B	5.000	1.000	0.200	0.207
Develop Solution C	9.000	5.000	1.000	0.735
C.I.	0.059			1.000
C.R.	0.101			

Product quality	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	3.000	3.000	0.600
Re-engineer Solution B	0.333	1.000	1.000	0.200
Develop Solution C	0.333	1.000	1.000	0.200
C.I.	0.000			1.000
C.R.	0.000			

Service quality	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	3.000	3.000	0.600
Re-engineer Solution B	0.333	1.000	1.000	0.200
Develop Solution C	0.333	1.000	1.000	0.200
C.I.	0.000			1.000
C.R.	0.000			

Process efficiency	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

Efficient resource allocation	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

Time to implement decision	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	3.000	0.429
Re-engineer Solution B	1.000	1.000	3.000	0.429
Develop Solution C	0.333	0.333	1.000	0.143
C.I.	0.000			1.000
C.R.	0.000			

Efforts to implement decision	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	3.000	0.429
Re-engineer Solution B	1.000	1.000	3.000	0.429
Develop Solution C	0.333	0.333	1.000	0.143
C.I.	0.000			1.000
C.R.	0.000			

Company's image	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	0.200	0.111	0.058
Re-engineer Solution B	5.000	1.000	0.200	0.207
Develop Solution C	9.000	5.000	1.000	0.735
C.I.	0.059			1.000
C.R.	0.101			

Company's strategy	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	0.333	0.143	0.088
Re-engineer Solution B	3.000	1.000	0.333	0.243
Develop Solution C	7.000	3.000	1.000	0.669
C.I.	0.004			1.000
C.R.	0.006			

Sustainability	Sell Solution A	Re-engineer Solution B	Develop Solution C	Priority
Sell Solution A	1.000	1.000	1.000	0.333
Re-engineer Solution B	1.000	1.000	1.000	0.333
Develop Solution C	1.000	1.000	1.000	0.333
C.I.	0.000			1.000
C.R.	0.000			

The judgements given by each actor are used to determine the ratings of the alternatives against the sub-criteria defined. The individual ratings are aggregated into a team rating using again a weighted arithmetic mean. However, in this step of the decision process, the actors have slightly different roles. Actor 1, from engineering and design, and actor 2, from production, have both a weight of 35%, while actor 3, from marketing and sales, has a weight of 30%. Figure 4.10 presents the aggregated rating provided by the team, according to each sub-criteria.

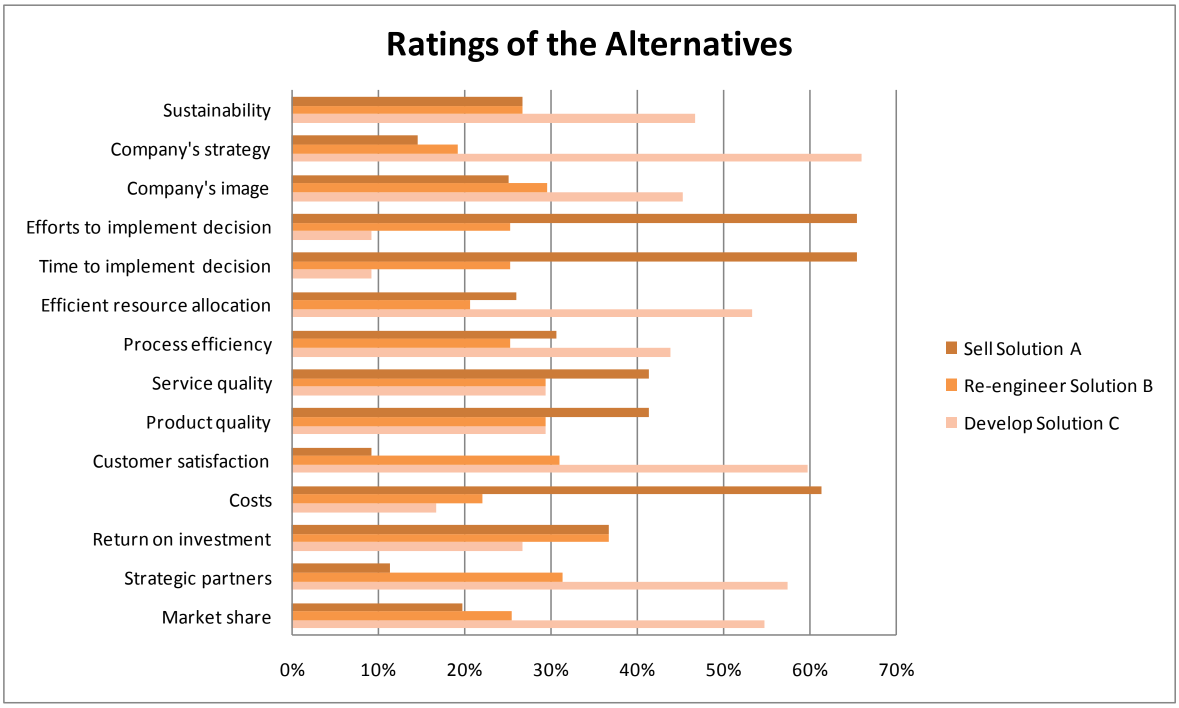


FIGURE 4.10. RATING OF ALTERNATIVES BY THE TEAM.

With the weights defined for the sub-criteria and the ratings of the alternatives for each sub-criteria, the ranking of the alternatives is immediate. It is a matter of weighting each rating to the weight defined for the respective sub-criteria. Figure 4.11 presents the resulting ranking of alternatives.

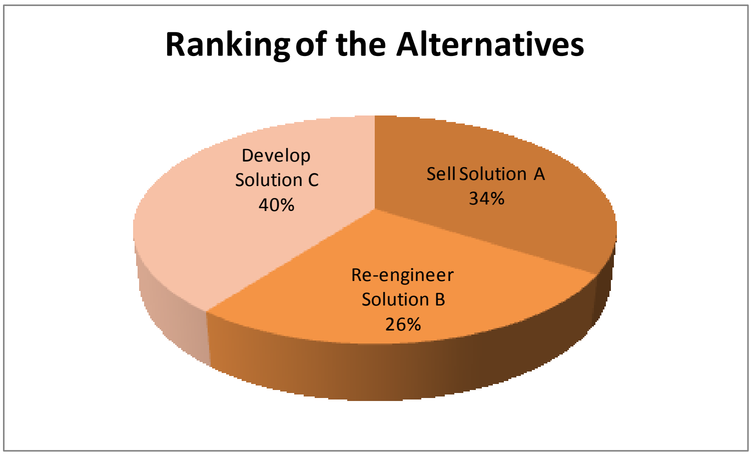


FIGURE 4.11. RANKING OF THE ALTERNATIVES.

The team concluded that developing a new solution is the best of action to take to meet this customer's requirements and fulfil the company's criteria.

4.3. COMBINING AHP AND CBR

This proposed approach combines case-based reasoning and the analytic hierarchy process, in order to support a team in solving problems that come up in an innovative process, such as designing a new product. These problems are usually more complex than the ones related to maintenance in the shop-floor and are also less specific in terms of variables defined, and therefore require a more elaborated approach. The two methods described in the previous sections of this chapter, CBR and AHP, will be used to support decision-making processes.

This thesis proposes CBR to support decision-making in the scope of problem solving, where the user has access to previous similar situations and tries to adapt one to the current problem. CBR is highly recommended for well-structured problems and the similarity results depend highly on the information provided in the cases. For example, a company that has a repository with problems very well documented with specific variable values (i.e. actual state items) will obtain better results from CBR than a company that only registers e.g. the product involved in the problem. The diversity of information is directly related to the detail of the similarity measure. When the first company obtains a similarity of 100%, it means that the two problems are exactly the same, i.e. same products with the same measured variables, and the same involved actor. However, when the second company obtains a similarity of 100% it may just mean that both problems had the same actor and product involved. This is often not enough to select an appropriate solution and adapt it to the current situation. Usually, the problems registered in the scope of an innovation process have fewer details because they relate to products under development that have less possible measures. When using CBR in an innovation process, the similar problems may just be too general to enable a selection by the actors involved.

The AHP approach proposed in this thesis is appropriate for complex decision-making processes that require the analysis of multiple alternatives regarding multiple criteria, and involving several actors. This is usually the situation of innovation processes in industrial companies. However, in order to use the AHP approach, actors must start by structuring the problem in a hierarchy. For this, actors must identify the criteria and all the alternatives. The methodology presented in this thesis proposes a hierarchy of criteria that actors can use or adapt. However, in most situations, it might not be easy to identify and describe the alternatives, from which the choice will be made.

CBR has the bottleneck of providing results that may be too general to be adapted immediately by the actors, without any additional processing. AHP has the disadvantage of having to specify the alternatives in the beginning of the process.

In order to try to overcome the bottlenecks of each of the methods when dealing with innovation in industrial environments, this thesis proposes a combination of CBR and AHP, as presented in Figure 4.12 (Campos and Neves-Silva 2010).

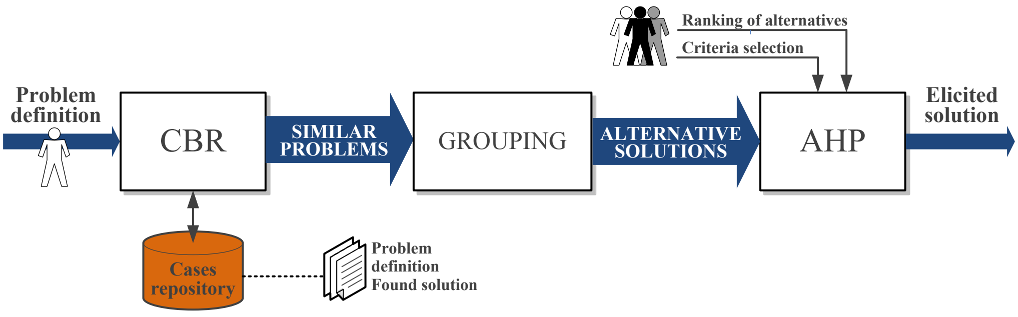


FIGURE 4.12. APPROACH COMBINING CBR AND AHP.

If a problem comes up when designing a new product, the team describes the problem, including identifying the product in the company's catalogue and the requirements (actual state items) to be met. This problem is then compared with previous situations, which are stored as cases in a repository. The CBR computes similarity between the new problem and stored cases, producing a list of most similar cases (Campos, Stokic and Neves-Silva 2004). CBR will only use solved cases for comparison with the current problem. This means that all the problems identified as similar have one single cause identified as the reason for the problem. According to the model proposed (see chapter 2 Enterprise model), each cause is removed by one or a set of actions, pre-defined in the model. Therefore, each similar problem has one identified cause and a list of actions implemented to eliminate the problem.

The objective of AHP is to support the team of actors in selecting the most appropriate choice to follow. Therefore, the objective is to identify possible groups of actions as alternatives to feed to the AHP.

This list of similar problems is processed to identify a set of distinct causes among all the similar problems. According to the model proposed, each cause has its own list of actions, i.e. the same action is not applied to two different causes. Identifying distinct causes is equivalent to identifying distinct set of actions implemented. Each list of actions is an alternative, including the documentation of the problems where it was used.

The alternatives, i.e. lists of actions, are fed into the AHP. The team of actors selects criteria to make the decision and judge the alternatives according to the selected criteria. The result of this process is an ordered ranking of alternatives, considering the opinion of all team members. The first alternative is considered the best solution for the problem.

4.4. ACTOR'S WEIGHTS ADAPTATION BY MARKET RANKING FEEDBACK

The work presented in the previous section of this thesis assumes that the success of a decision results from a deterministic evaluation of the merits of an alternative over a set of criteria. Based on this, would it be possible to analyse the success of a decision made by a group of human actors and use it to adapt the weight each actor should represent in future decisions? This section deals with this research problem. If companies can learn from the implementation of decisions, they can adapt their decision making process to reinforce the most successful decisions. More specifically, if a company can identify the actors in a team that contributed the most for a successful decision, these specific actors could have a more relevant role in future decisions.

This work proposes a Cartesian approach to the problem where each criterion represents an orthogonal direction. The orthogonality is not a fundamental condition, but derives from the assumption that the overall ranking of an alternative A_i, y_i, available for decision results from the weighted average of the merits in the several different criteria $\{\mathrm{C}_1, \mathrm{C}_2, \ldots, \mathrm{C}_N\}$, i.e.

$$y_i = \sum_{j=1}^{N} w_j s_{ij} \tag{4.50}$$

where the weights w_i sum 1. This equation derives directly for each element in the vector defined in equation (4.49).

4.4.1. THE MARKET

Let us use the term **market** to represent the final evaluator of the decision's merit once implemented and define

$$\mathbf{w}^{(\mathrm{E})} = \left[\mathrm{w}_1^{(\mathrm{E})} \quad \ldots \quad \mathrm{w}_\mathrm{N}^{(\mathrm{E})}\right]^\mathrm{T} \tag{4.51}$$

as the vector of weights that the market will use to evaluate the selected decision. In normal conditions, these values are unknown to the decision makers.

Additionally, consider a set of available and pre-identified alternatives $\{\mathrm{A}_1, \mathrm{A}_2, \ldots, \mathrm{A}_M\}$ for decision and let the matrix

$$\mathbf{U} = \begin{bmatrix} u_{11} & \ldots & u_{1N} \\ \vdots & \ddots & \vdots \\ u_{M1} & \ldots & u_{MN} \end{bmatrix} \tag{4.52}$$

represent the values (i.e. measured merits) of the alternatives in the criteria, where u_{ij} is the value of alternative A_i in criterion C_j. Thus,

$$\mathbf{v}^{(\mathrm{E})} = [v_1 \quad \cdots \quad v_M]^\mathsf{T} = \mathbf{U}\mathbf{w}^{(\mathrm{E})} \tag{4.53}$$

represents the column-vector where v_i is the market value of alternative A_i. Without any additional criteria, the best decision would be to select for implementation the alternative with the maximum value, i.e.

$$\mathrm{A}_i \,:\, i = \arg\left\{\max_i v_i\right\} \tag{4.54}$$

Again, it is underlined that the decision makers, usually, are not aware of the values of these quantities. If this reality is known there is no need for any decision making process.

4.4.2. THE DECISION MAKING GROUP

In the scenario of group decision making, several (human) actors $\{\mathrm{H}_1, \mathrm{H}_2, \dots, \mathrm{H}_L\}$ are involved in establishing the importance (i.e. weight) of the criteria and rating the alternatives. According to their beliefs about the market's behaviour, as well as other factors considered relevant for the success of the decision, each actor indicates their individual weights for the criteria. A weighting matrix combines all the weights defined by all the actors

$$\mathbf{W} = \begin{bmatrix} w_1^{(1)} & \cdots & w_1^{(L)} \\ \vdots & \ddots & \vdots \\ w_N^{(1)} & \cdots & w_N^{(L)} \end{bmatrix} \tag{4.55}$$

where each column of the matrix represents the weights of each actor for all criteria N. In any decision process, it is natural to have deviations among actors regarding the importance of criteria. These deviations are not only due to misperceptions on market's behaviour. The expertise, background and position of the person in the company affect the opinion of what is more relevant. In addition, while the CEO of a company always has the "big picture" in mind, some employees in areas that are more technical or in positions of middle management, tend to prioritise their departments. For example a person can legitimately try to optimise a local long-term cost functional not entirely aligned with the global short-term success of the decision.

Additionally, analogously to what the true market has been modelled to do, the actors evaluate the merits of each alternative individually for each criterion resulting in a compiled matrix

$$\mathbf{S} = \begin{bmatrix} s_{11} & \cdots & s_{1N} \\ \vdots & \ddots & \vdots \\ s_{M1} & \cdots & s_{MN} \end{bmatrix} \tag{4.56}$$

where $s_{ij} = v_{ij} + \eta_{ij}$ is the best estimation of the true rating of alternative A_i in criterion C_j, polluted with some measuring deviation η_{ij}. Using (4.55) and (4.56), it is possible to derive the expected value of each alternative by each actor, given by

$$\mathbf{Y} = \begin{bmatrix} y_1^{(1)} & \cdots & y_1^{(L)} \\ \vdots & \ddots & \vdots \\ y_M^{(1)} & \cdots & y_M^{(L)} \end{bmatrix} = \mathbf{SW} \tag{4.57}$$

where each line represents the expected value of one alternative for the several actors. The index of the maximum element of each column represents the index of the alternative that each actor, individually, would select as best. However, the objective is to make a unique decision and the weighted arithmetic mean is a common approach (Forman and Peniwati 1998). This means that it is possible to compute the group's expectation of the alternatives market value from

$$\mathbf{y} = \mathbf{Yp} \tag{4.58}$$

where $\mathbf{p} = [p_1 \quad \cdots \quad p_L]^{\mathrm{T}}$ is the weight of each actor for aggregating $\mathbf{y}$, where each element represents the voting weight of an actor. Alternatively, it is possible to compute the expected market value $\mathbf{v}^{(\mathrm{E})}$ from

$$\mathbf{y} = \mathbf{Sw} \tag{4.59}$$

where

$$\mathbf{w} = \mathbf{Wp} \tag{4.60}$$

is the group criteria vector. The vector $\mathbf{y}$ is a column-vector with as many inputs as alternatives under consideration. Without any additional restriction, the group will select as best for implementation the alternative with the maximum value, i.e.

$$\mathrm{A}_i : \ i = \arg\left\{\max_i y_i\right\} \tag{4.61}$$

which could be different from the market's best defined by (4.54).

EXAMPLE 4.4: DECISION PROBLEM WITH TWO CRITERIA AND THREE ACTORS

Consider the following decision problem with $N = 2$ criteria, $\{\mathrm{C}_1, \mathrm{C}_2\}$, where the market's best criteria weights are given by $\mathbf{w}^{(\mathrm{E})} = [0.4 \quad 0.6]^{\mathrm{T}}$.

Additionally, consider $M = 3$ alternatives, $\{\mathrm{A}_1, \mathrm{A}_2, \mathrm{A}_3\}$, such that their perfect rating on the criteria is given by

$$\mathbf{U} = \begin{bmatrix} 4.0 & 8.0 \\ 6.0 & 6.0 \\ 9.0 & 3.0 \end{bmatrix},$$

where each line represents the rating of each alternative in the two criteria. Thus, from (4.53) the true market's values of the alternatives are

$$\mathbf{v}^{(\mathrm{E})} = \mathbf{U}\mathbf{w}^{(\mathrm{E})} = \begin{bmatrix} 6.4 \\ 6.0 \\ 5.4 \end{bmatrix}$$

i.e., alternative A_1 has the maximum value in the market with a value of 6.4 and the best decision would be to select it for implementation.

Consider now, $L = 3$ (human) actors $\{\mathrm{H}_1, \mathrm{H}_2, \mathrm{H}_3\}$ involved in the group decision scenario. Their individual selection for the weights are given by

$$\mathbf{W} = \begin{bmatrix} 0.3 & 0.7 & 0.9 \\ 0.7 & 0.3 & 0.1 \end{bmatrix}$$

where each column vector of the matrix represents the weights of each actor.

In a first approach, consider that the actors are capable of perfect rating of the alternatives, i.e.

$$\mathbf{U} = \mathbf{S}$$

and thus, from (4.57) the expected value of the alternatives is

$$\mathbf{Y} = \mathbf{U}\mathbf{W} = \begin{bmatrix} 6.8 & 5.2 & 4.4 \\ 6.0 & 6.0 & 6.0 \\ 4.8 & 7.2 & 8.4 \end{bmatrix}$$

where each column vector corresponds to each actor. This means that, individually, actor H_1 would select A_1 with an expected value of 6.8 and actors H_2 and H_3 would select A_3 with expected values of 7.2 and 8.4, respectively.

Without any a priori information, the group decision-making process initialises with equal decision weights for the actors, i.e.

$$\mathbf{p} = \begin{bmatrix} \frac{1}{L} & \frac{1}{L} & \frac{1}{L} \end{bmatrix}^{\mathrm{T}}$$

the group aggregated criteria is

$$\mathbf{w} = \mathbf{W}\mathbf{p} = \begin{bmatrix} 0.63 & 0.37 \end{bmatrix}^{\mathrm{T}}$$

and the group's expected value is

$$\mathbf{y} = \mathbf{Y}\mathbf{p} = \mathbf{U}\mathbf{w} = \begin{bmatrix} 5.5 \\ 6.0 \\ 6.8 \end{bmatrix}$$

i.e., alternative A_3, different from A_1, has the maximum expected value with a value of 6.8 and the group's decision is to select it for implementation.

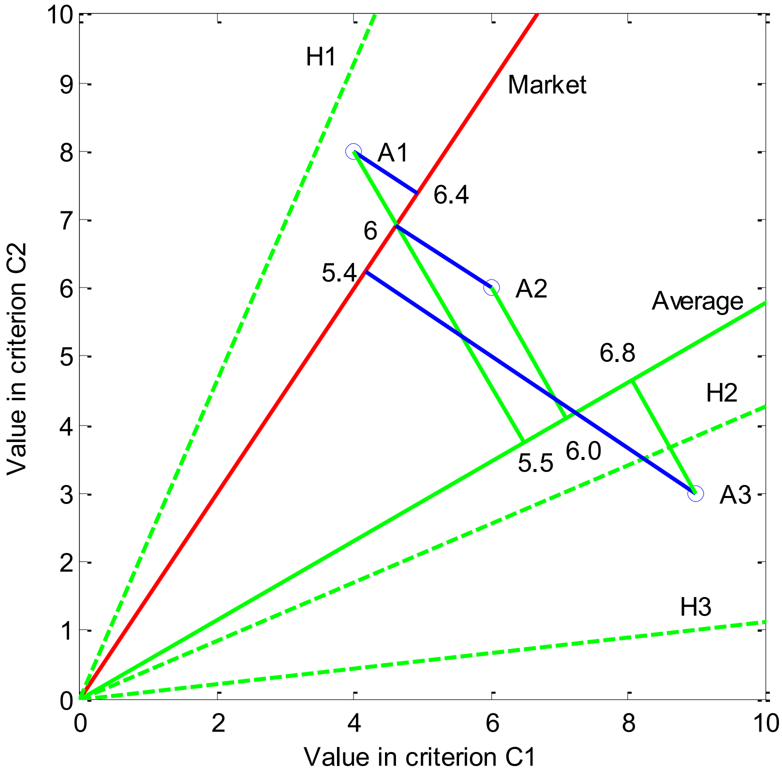


FIGURE 4.13. VALUES AND CRITERIA FOR ALTERNATIVES IN **EXAMPLE 4.4**.

Figure 4.13 depicts a geometric interpretation for this example. The solid line identified as "Market" represents the vector direction of market's criteria $\mathbf{w}^{(\mathrm{E})}$; the three dotted lines identified by "H1","H2","H3" represent the three vector directions for the criteria weights of the three actors involved taken from $\mathbf{W}$ and the solid line identified as "Average" represents the vector direction of group's criteria $\mathbf{w}$. The alternatives $\{A_1, A_2, A_3\}$ are marked directly on the plot with their respective ratings in each criterion. The value of each alternative A_i is proportional to the size of the vector obtained from the orthogonal projection of the points A_i over the vector directions of the criteria. The lack of alignment between the true market criteria and the average of actor's criteria results on an opposite sorting of the alternatives.

4.4.3. FEEDBACK INFORMATION FROM MARKET

As initially formulated, the objective of this development is to incorporate some feedback from the market to modify the weights each actor should have in the decision making process.

Assuming that it is possible to measure the success of an implemented decision in the same referential framework used to support the decision-making process, the problem of adapting actors' weights has to answer the following:

Is there a set of actor's weights in the team, such that, in the presence of perfect ranking capability and noiseless measuring of the true value of the implemented alternative, the expected value matches exactly the measured one?

The answer to this question can be divided in two parts:

- Find the market criteria weights from the provided feedback; and
- From the best estimative on the market criteria weights $\hat{\mathbf{w}}^{(\mathrm{E})}$ find the adequate actors' weights, $\mathbf{p}$.

The first part is equivalent to asking if there is a valid solution $\hat{\mathbf{w}}^{(\mathrm{E})}$ for

$$\mathbf{e}_i \mathbf{U} \hat{\mathbf{w}}^{(\mathrm{E})} = v_{\mathrm{A}i} \tag{4.62}$$

Where the alternative A_i, is the implemented one and thus the only source for feedback and $\mathbf{e}_i$ is the unit vector that has unity in its i^{th} position and zeros elsewhere. Adding the restriction that the elements of $\hat{\mathbf{w}}^{(\mathrm{E})}$ must sum 1, when the number of criteria is larger than two, (4.62) has infinite solutions. This means that, to estimate a market with *N* criteria, it is necessary to have at least $N-1$ independent decision-making processes, i.e. with $N-1$ different implemented alternatives.

The following example illustrates the determination of $\hat{\mathbf{w}}^{(\mathrm{E})}$ for the special case when $N=2$, including a geometric interpretation of the solution.

EXAMPLE 4.5: PROCESSING FEEDBACK FROM MARKET IN DECISION PROBLEM WITH 2 CRITERIA AND 3 ACTORS

Consider again the scenario described in **Example 4.4**. After the implementation of the decision with the maximum expected value, i.e. A_3 with expected value of 6.8, it was measured the true value of this alternative, $v_{A_3} = 5.4$. Then, the estimated market's criteria weights are given by the solution of

$$[0 \quad 0 \quad 1] \mathbf{U} \hat{\mathbf{w}}^{(\mathrm{E})} = v_{A_3}$$

where the first two terms represent the ratings of alternative A_3 taken from $\mathbf{U}$ matrix. Additionally, the solution is restricted by $[1 \quad 1]\hat{\mathbf{w}}^{(E)} = 1$, i.e. the weights sum 1. Thus, for this example, the estimated market's criteria weights is the solution of

$$\begin{bmatrix} 9.0 & 3.0 \\ 1 & 1 \end{bmatrix} \hat{\mathbf{w}}^{(E)} = \begin{bmatrix} 5.4 \\ 1 \end{bmatrix}$$

which is

$$\hat{\mathbf{w}}^{(E)} = [0.4 \quad 0.6]^T$$

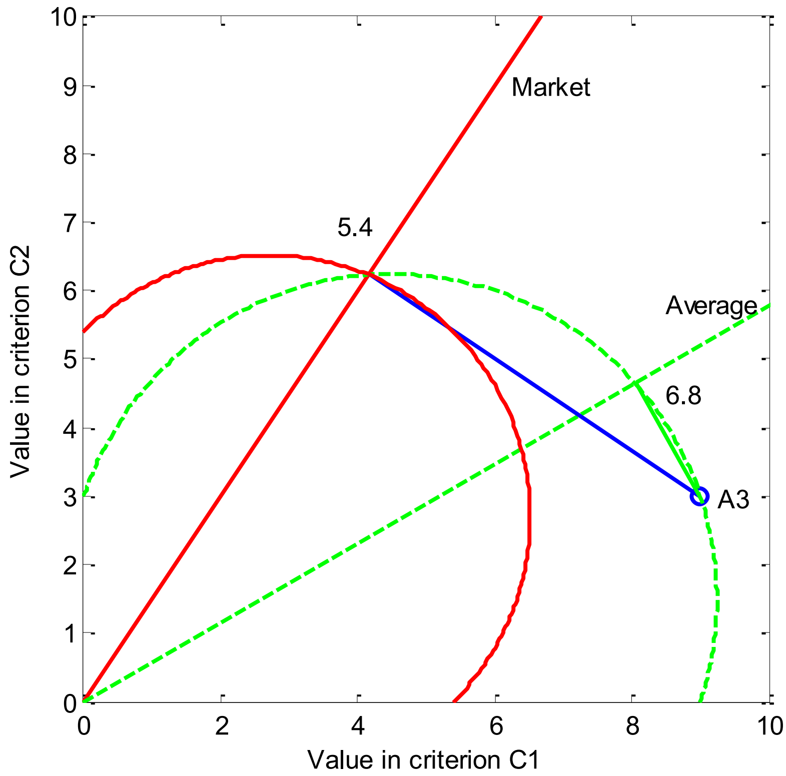


FIGURE 4.14. VALUES AND CRITERIA FOR ALTERNATIVES IN **EXAMPLE 4.5**.

Figure 4.14 depicts a geometric interpretation of this solution. The dotted curve (in green) represents the projection of alternative A_3 over all possible values for weights given by the group of actors. In particular, this curve passes in the individual criteria values (rankings 3.0 and 9.0) on the point A_3 itself and on the selected decision. The solid curve (in red) represents the geometric place of all alternatives that are valued 5.4 over all possible values for weights given by the group of actors. In particular, this curve passes in the pairs $(0, 5.4)$ and $(5.4, 0)$; and in the projection of A_3 over the market's direction. These two curves intercept in the direction given by the markets, i.e. providing the solution for the best criteria weights.

The second part of determining the actors' weights is about the capability of the actors' directions, as vectors, to compose the market direction (i.e. market's criteria weights). In normal conditions, this would result simply in a requirement for orthogonality, such that a minimum set of actors be a basis, in the mathematical sense. However, it is necessary to introduce the additional restriction that none of the actors have negative weights, which directly implies that none of the actors will have a weight larger than 1.

The determination of the actors' weights is equivalent to ask if there is a valid solution $\mathbf{p}^*$ for

$$\mathbf{W}\mathbf{p}^* = \hat{\mathbf{w}}^{(\mathrm{E})} \tag{4.63}$$

under the restriction that all elements of $\mathbf{p}^* = [p_1^* \quad \cdots \quad p_L^*]^\mathrm{T}$ respect

$$p_i^* \in [0; 1] \tag{4.64}$$

where $\hat{\mathbf{w}}^{(\mathrm{E})}$ is the estimative obtained, if possible, from (4.62). The solution of (4.63)-(4.64) depends on the relation between the number of actors and the number of criteria.

Case 1: the number of actors L equals the number of criteria N, i.e. $L = N$.

This case is straightforward and the solution of (4.63) exists if $\mathbf{W}$ is non-singular. In that case, the solution is given by

$$\mathbf{p}^* = (\mathbf{W})^{-1}\hat{\mathbf{w}}^{(\mathrm{E})} \tag{4.65}$$

If the solution verifies (4.64), it is taken as valid; if not, no solution exists. The singularity condition means that all actors' opinions are relevant regarding the criteria's weights.

Case 2: the number of actors L is larger than the number of criteria N, i.e. $L > N$.

Now, the number of unknown variables – the actors' weights – is larger than the number of equations. Then, the solution set has infinite elements. In fact, for this case there are $L - N$ actors that can be stated as irrelevant if the remaining N are enough to build up a Case 1 scenario with a valid solution.

However, it is interesting, at this point, to introduce some additional limitations to narrow the infinite set of solutions without discarding the participation of some of the actors. This will be of particular interest in the presence of ranking and measuring uncertainty. For selection strategy, it is important to consider the participation of all actors to be as large as possible. Then the problem is an optimisation problem finding

$$\max_{\mathbf{p}^*}\left\{\min_i\{p_i^*\}\right\} \tag{4.66}$$

under the restrictions given by (4.63)-(4.64).

The following example illustrates the characterisation of this solution.

EXAMPLE 4.6: DETERMINING BEST WEIGHTS FOR THREE ACTORS FROM MARKET FEEDBACK IN DECISION PROBLEM WITH TWO CRITERIA

Using the scenario extended in **Example 4.5**, consider now – under the assumption of deterministic ranking and market's value measure – the determination of the best weights for the actors using the knowledge of $\hat{\mathbf{w}}^{(\mathrm{E})}$. The problem is rather straightforward as one intends that the weighted average of the actors' criteria result in the market's criteria. This is

$$\mathbf{W}\mathbf{p}^* = \hat{\mathbf{w}}^{(\mathrm{E})}$$

i.e. for this example

$$\begin{bmatrix} 0.3 & 0.7 & 0.9 \\ 0.7 & 0.3 & 0.1 \end{bmatrix} \mathbf{p}^* = \begin{bmatrix} 0.4 \\ 0.6 \end{bmatrix}$$

which does not have a unique solution due to the existence of more actors than criteria. A possible solution can be selected as

$$\mathbf{p}^* = [0.83 \quad 0.00 \quad 0.17]^{\mathrm{T}}$$

ignoring the contribution of actor H_2.

Alternatively, using the proposed strategy of maximising the minimum contribution of all actors described by (4.66), it is possible to obtain the solution by numerical methods, yielding

$$\mathbf{p}^* = [0.80 \quad 0.10 \quad 0.10]^{\mathrm{T}}$$

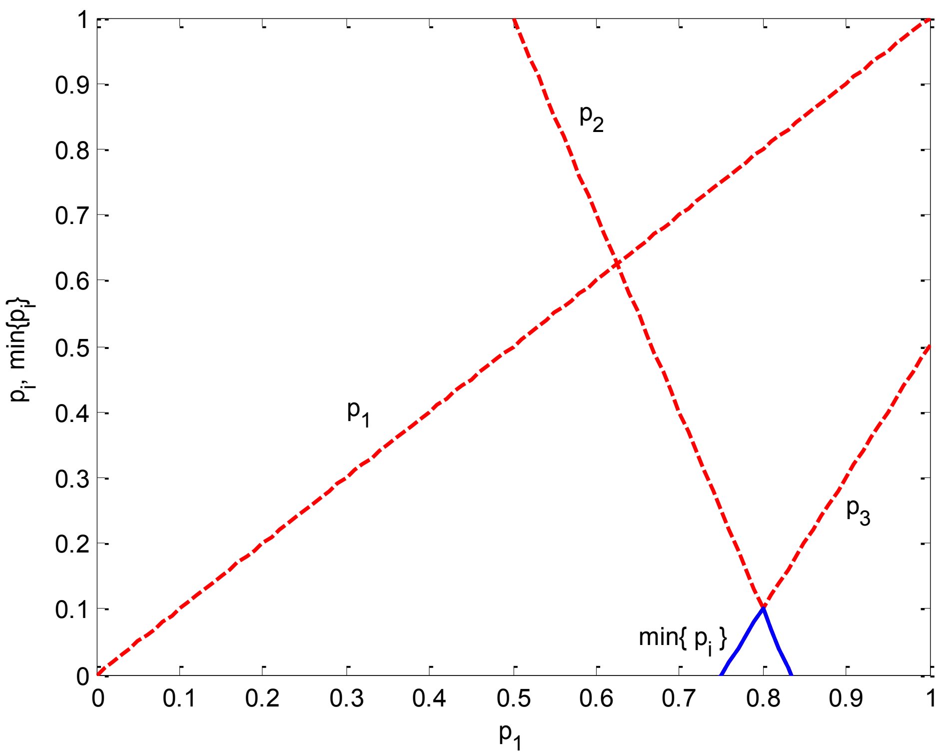


FIGURE 4.15. ACTORS' WEIGHTS IN **EXAMPLE 4.6**.

Figure 4.15 depicts the solution space for this example and presents the solution of the maximisation problem.

At this point, one question arises. If it is possible to estimate directly the market's criteria, what is the point in representing these as actors' weights? The ultimate goal is to find out the criteria to use in the decision process and the market's criteria would work perfectly if it is known. The answer, according with the strategy here proposed, is that the actors as intelligent entities, with different levels and directions of polarisation, have a cognitive perception of the market's behaviour, including perception on the trends under varying conditions. The goal of the proposed algorithm is to take advantage of that perception capability and filter out the polarisations by weighted averaging of the opinions expressed.

Case 3: the number of actors L is less than the number of criteria N, i.e. $L < N$.

In a real case complex scenario, this case should be the most common one, having several aspects under evaluation (i.e. criteria) and a group of experts from the several departments involved in the decision-making problem.

Now, (4.63) has more equations that unknown variables and, unless some of the equations are not independent, there will be no direct solution. Let H be the subspace generated by the span of $\mathbf{W}$ columns. In vector space terms, this means that the space generated by the individual criteria (i.e. the column-vectors of $\mathbf{W}$) of the L actors is not sufficient to cover all possible market criteria $\mathbf{w}^{(\mathrm{E})}$, which ultimately could be $\mathbb{R}_{+}^{N}$. The best it can be done is to look for the vector in H that most approximates $\widehat{\mathbf{w}}^{(\mathrm{E})}$, which is the same as the orthogonal projection of $\widehat{\mathbf{w}}^{(\mathrm{E})}$ in H. In line with this proposal, a least square approach to (4.63) yields the solution

$$\mathbf{p}^{*} = \left(\mathbf{W}^{\mathrm{T}}\mathbf{W}\right)^{-1}\mathbf{W}^{\mathrm{T}}\widehat{\mathbf{w}}^{(\mathrm{E})} \tag{4.67}$$

if the columns of $\mathbf{W}$ are linearly independent. The last independency condition just means that the actors have to think differently about the criteria weights, which is a basic assumption for the approach.

The following example illustrates the characterisation of this solution.

EXAMPLE 4.7: DECISION PROBLEM WITH THREE CRITERIA AND TWO ACTORS

Consider the following decision problem with $N = 3$ criteria, $\{\mathrm{C}_1, \mathrm{C}_2, \mathrm{C}_3\}$, where the market's best criteria weights are given by

$$\mathbf{w}^{(\mathrm{E})} = [0.55 \quad 0.30 \quad 0.15]^{\mathrm{T}}$$

Additionally, consider $M = 2$ alternatives, $\{\mathrm{A}_1, \mathrm{A}_2\}$, such that their perfect rating on the criteria is given by

$$\mathbf{U} = \begin{bmatrix} 5.00 & 7.00 & 1.00 \\ 4.00 & 1.50 & 8.00 \end{bmatrix}$$

where each line represents the ratings of each alternative in the 3 criteria. Thus, from (4.53), the true market's values of the alternatives are

$$\mathbf{v}^{(\mathrm{E})} = \mathbf{U}\mathbf{w}^{(\mathrm{E})} = \begin{bmatrix} 5.00 \\ 3.85 \end{bmatrix}$$

i.e., alternative A_1 has the maximum value in the market with a value of 5.0 and the best decision would be to select it for implementation.

Consider now, $L = 2$ (human) actors, $\{\mathrm{H}_1, \mathrm{H}_2\}$, involved in the group decision scenario. Their individual selection for the weights are given by

$$\mathbf{W} = \begin{bmatrix} 0.70 & 0.10 \\ 0.20 & 0.20 \\ 0.10 & 0.70 \end{bmatrix}$$

where each column vector of the matrix represents the weights of each actor summing 1.

Again, consider that the actors are capable of perfect rating of the alternatives, i.e.

$$\mathbf{S} = \mathbf{U}$$

and thus, from (4.57) the expected value of the alternatives is

$$\mathbf{Y} = \mathbf{U}\mathbf{W} = \begin{bmatrix} 5.0 & 2.6 \\ 3.9 & 6.3 \end{bmatrix}$$

where each column vector corresponds to each actor. This means that, individually, actor H_1 would select A_1 with an expected value of 5.0 and actor H_2 would select A_2 with an expected value of 6.3.

Without any *a priori* information, the group decision-making process initialises with equal decision weights for the actors, i.e.

$$\mathbf{p} = \begin{bmatrix} \frac{1}{L} & \frac{1}{L} \end{bmatrix}^{\mathrm{T}}$$

the group aggregated criteria is

$$\mathbf{w} = \mathbf{W}\mathbf{p} = \begin{bmatrix} 0.4 & 0.2 & 0.4 \end{bmatrix}^{\mathrm{T}}$$

and the group's expected value is

$$\mathbf{y} = \mathbf{Y}\mathbf{p} = \mathbf{U}\mathbf{w} = \begin{bmatrix} 3.80 \\ 5.10 \end{bmatrix}$$

i.e., alternative A_2, different from A_1, has the maximum expected value with a value of 5.10 and the group's decision is to select it for implementation.

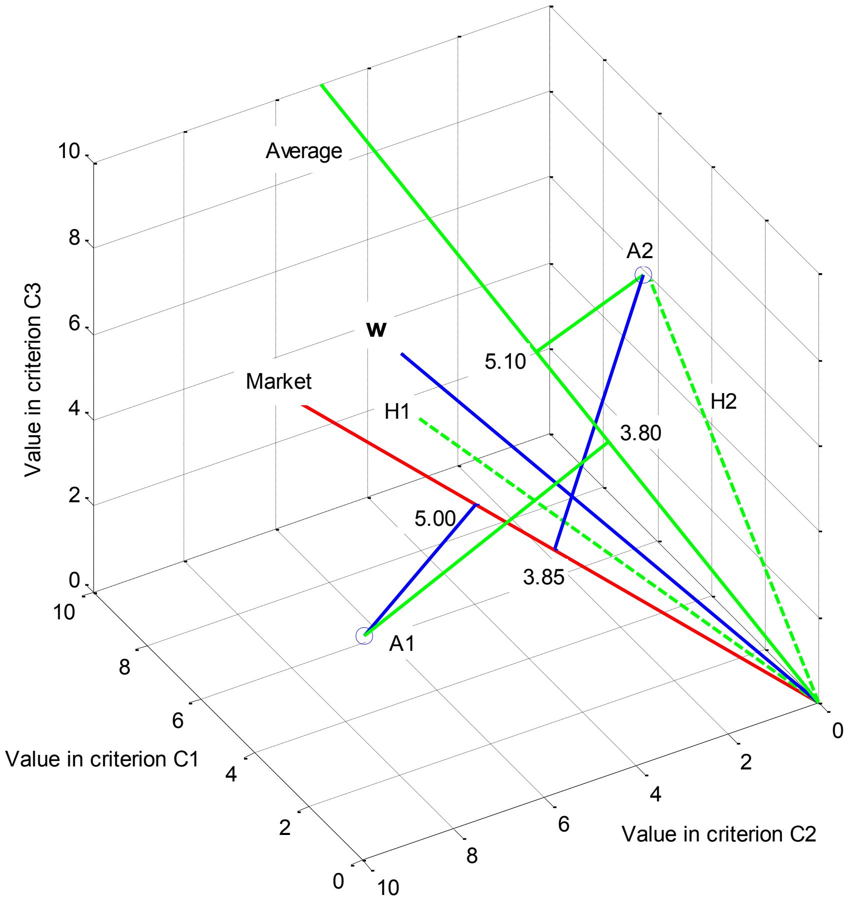


FIGURE 4.16. VALUES AND CRITERIA FOR ALTERNATIVES IN **EXAMPLE 4.7**.

Figure 4.16 depicts a geometric interpretation for this example. The solid (red) line identified as "Market" represents the vector direction of market's criteria $\mathbf{w}^{(\mathrm{E})}$; the two dotted lines identified by "H1","H2" represent the two vector directions for the criteria weights of the two actors involved taken from $\mathbf{W}$ and the solid (green) line identified as "Average" represents the vector direction of group's criteria $\mathbf{w}$. The alternatives $\{\mathrm{A}_1, \mathrm{A}_2\}$ are marked directly on the plot with their respective ratings in each criterion. The value of each Alternative A_i is proportional to the size of the vector obtained from the orthogonal projection of the points A_i over the vector directions of the criteria. The lack of alignment between the true market criteria and the average of actor's criteria results on an opposite sorting of the alternatives.

Additionally, after estimating the market criteria using (4.62), the solution (4.67) yields

$$\mathbf{p}^* = [0.85 \quad 0.15]^{\mathrm{T}}$$

The group criteria weights are now given by

$$\mathbf{w} = \mathbf{W}\mathbf{p}^* = [0.58 \quad 0.19 \quad 0.18]^{\mathrm{T}}$$

which is the orthogonal projection of the market criteria vector in the linear span of the column-vectors of $\mathbf{W}$ and represented in Figure 4.16 with a solid (blue) line marked "$\mathbf{w}$".

To finish the example, it is important to verify which alternative would be selected using these actors' weights. Now, the group's expected value is

$$\mathbf{y} = \mathbf{Y}\mathbf{p}^* = \mathbf{U}\mathbf{w} = \begin{bmatrix} 4.39 \\ 4.02 \end{bmatrix}$$

and alternative A_1 has the maximum expected value with a value of 4.39 and the group's decision would be to select it for implementation. This final part is not represented in Figure 4.16 for the sake of simplicity.

4.4.4. EXAMPLES WITH RANKING UNCERTAINTY

The proposed approach presented in this chapter considers the complete decision-making process under noisy rating by human actors. However, despite this, the four examples presented in the previous sections were built with the assumption

$$\mathbf{S} = \mathbf{U}$$

The following examples repeat **Example 4.4** to **Example 4.7** in the presence of ranking uncertainty.

EXAMPLE 4.8: DECISION PROBLEM WITH TWO CRITERIA AND THREE ACTORS, UNDER UNCERTAINTY

Consider again the scenario described in **Example 4.4** where the market's best criteria weights were given by

$$\mathbf{w}^{(\mathrm{E})} = [0.4 \quad 0.6]^{\mathrm{T}}$$

and the alternatives $\{\mathrm{A}_1, \mathrm{A}_2, \mathrm{A}_3\}$, with true market's ranking on the criteria given by

$$\mathbf{U} = \begin{bmatrix} 4.0 & 8.0 \\ 6.0 & 6.0 \\ 9.0 & 3.0 \end{bmatrix}$$

Consider the (human) actors $\{\mathrm{H}_1, \mathrm{H}_2, \mathrm{H}_3\}$ involved in the group decision scenario with the same individual weights

$$\mathbf{W} = \begin{bmatrix} 0.3 & 0.7 \\ 0.7 & 0.3 \\ 0.9 & 0.1 \end{bmatrix}^{\mathrm{T}}$$

Now, the actors are rating the alternatives with an error, in the example

$$\mathbf{S} = \begin{bmatrix} 4.30 & 8.05 \\ 6.52 & 5.92 \\ 8.77 & 2.13 \end{bmatrix}$$

and thus the expected value of the alternatives is

$$\mathbf{Y} = \mathbf{SW} = \begin{bmatrix} 6.93 & 5.43 & 4.67 \\ 6.10 & 6.34 & 6.46 \\ 4.12 & 6.78 & 8.11 \end{bmatrix}$$

again, where each column vector corresponds to each actor. This means that, individually, actor H_1 would select A_1 with an expected value of 6.93 and actors H_2 and H_3 would select A_3 with expected values of 6.78 and 8.11, respectively.

As in **Example 4.4**, without any a priori information, the group decision making process initialises with equal decision weights for the actors, the group aggregated criteria is (again)

$$\mathbf{w} = \mathbf{Wp} = \begin{bmatrix} 0.63 & 0.37 \end{bmatrix}^{\mathrm{T}}$$

and the group's expected value is

$$\mathbf{y} = \mathbf{Yp} = \mathbf{Sw} = \begin{bmatrix} 5.68 \\ 6.30 \\ 6.34 \end{bmatrix}$$

i.e., alternative A_3 has the maximum expected value with a value of 6.34 and the group's decision is to select it for implementation.

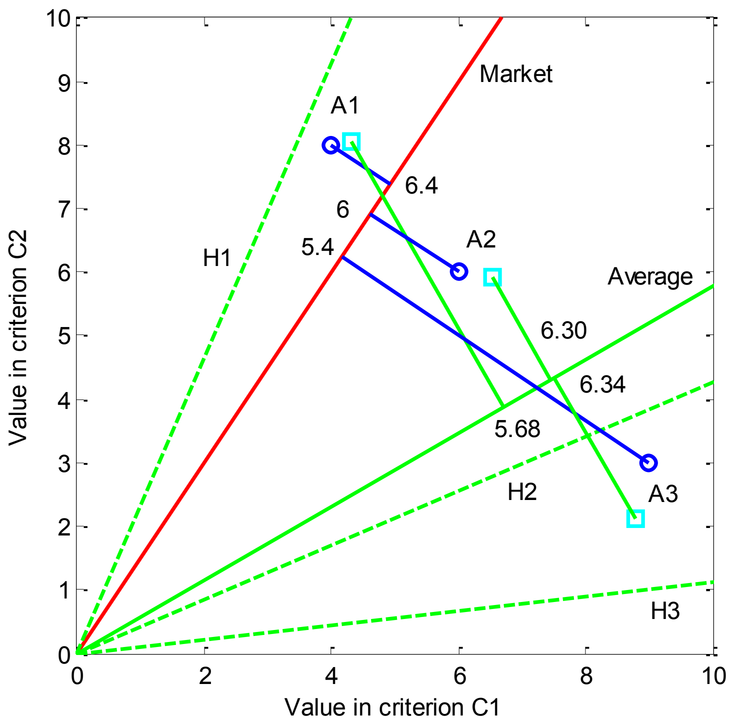


FIGURE 4.17. VALUES AND CRITERIA FOR ALTERNATIVES IN **EXAMPLE 4.8**.

Figure 4.17 depicts the geometric interpretation for this example and it is directly compared with Figure 4.13. The alternatives $\{A_1, A_2, A_3\}$ are marked directly on the plot with their respective true ratings in each criterion – marked with circles – and their ranking evaluated by the group of actors – marked with squares.

EXAMPLE 4.9: PROCESSING FEEDBACK FROM MARKET IN DECISION PROBLEM WITH TWO CRITERIA AND THREE ACTORS, UNDER UNCERTAINTY

Following the previous example, after the implementation of the decision with the maximum expected value, i.e. A_3 with expected value of 6.34, the estimated market's criteria weights are given by the solution of

$$[0 \quad 0 \quad 1]\mathbf{S}\widehat{\mathbf{w}}^{(E)} = v_{A_3}$$

where the true value of this alternative is still $v_{A_3} = 5.4$. Thus, for this example, the estimated market's criteria weights is the solution of

$$\begin{bmatrix} 8.77 & 2.13 \\ 1 & 1 \end{bmatrix} \widehat{\mathbf{w}}^{(E)} = \begin{bmatrix} 5.4 \\ 1 \end{bmatrix}$$

which is

$$\widehat{\mathbf{w}}^{(E)} = [0.49 \quad 0.51]^T$$

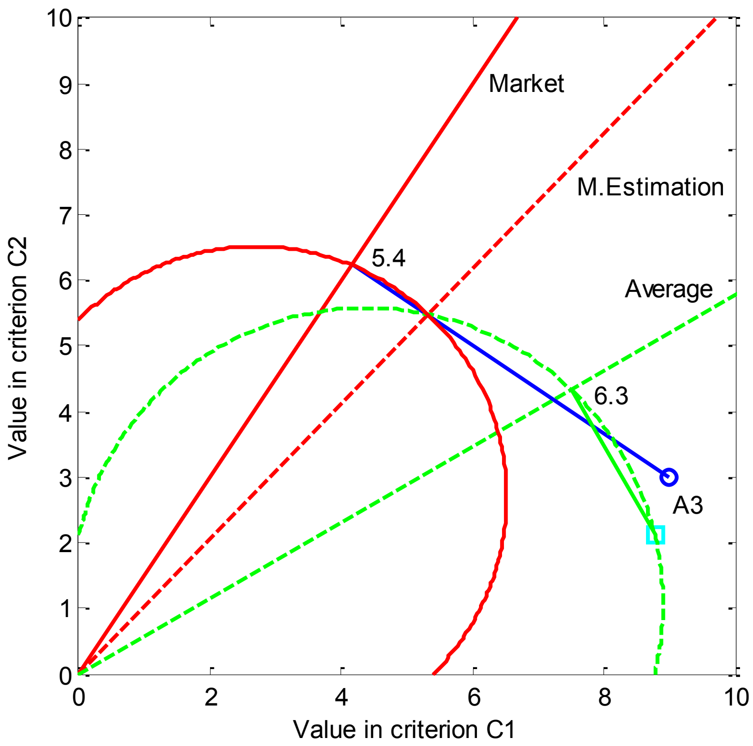


FIGURE 4.18. VALUES AND CRITERIA FOR ALTERNATIVES IN **EXAMPLE 4.9**.

Figure 4.18 depicts a geometric interpretation of this new solution, directly comparable with Figure 4.14 from **Example 4.5**. The two curves intercept now in the estimated direction deviated from the true market's direction. This deviation is only due to the ranking error on alternative A_3, the only one that was really implemented and measured. It is somehow direct to understand that a measuring error in v_{A_3} would, as well, introduce additional error on the estimation of market's criteria weight. This deviation is propagated to the calculation of the best weights for the actors. Following the same strategy presented in **Example 4.6**, results in (see Figure 4.15)

$$\mathrm{p}^* = [0.62 \quad 0.19 \quad 0.19]^{\mathrm{T}}$$

EXAMPLE 4.10: DETERMINING BEST WEIGHTS FOR 3 ACTORS FROM MARKET FEEDBACK IN DECISION PROBLEM WITH 2 CRITERIA, UNDER UNCERTAINTY

Using the scenario extended in **Example 4.9**, consider now the determination of the best weights for the actors using the knowledge of $\hat{\mathbf{w}}^{(\mathrm{E})}$. The problem is rather straight forward as one intends that the weighted average of the actors' criteria result in the market's criteria. This is

$$\mathbf{W}\mathbf{p}^* = \hat{\mathbf{w}}^{(\mathrm{E})}$$

i.e. for this example

$$\begin{bmatrix} 0.3 & 0.7 & 0.9 \\ 0.7 & 0.3 & 0.1 \end{bmatrix} \mathbf{p}^* = \begin{bmatrix} 0.49 \\ 0.51 \end{bmatrix}$$

Using the proposed strategy of maximising the minimum contribution of all actors, described by (4.66) the solution can be obtained by numerical methods, yielding

$$\mathbf{p}^* = [0.62 \quad 0.19 \quad 0.19]^{\mathrm{T}}$$

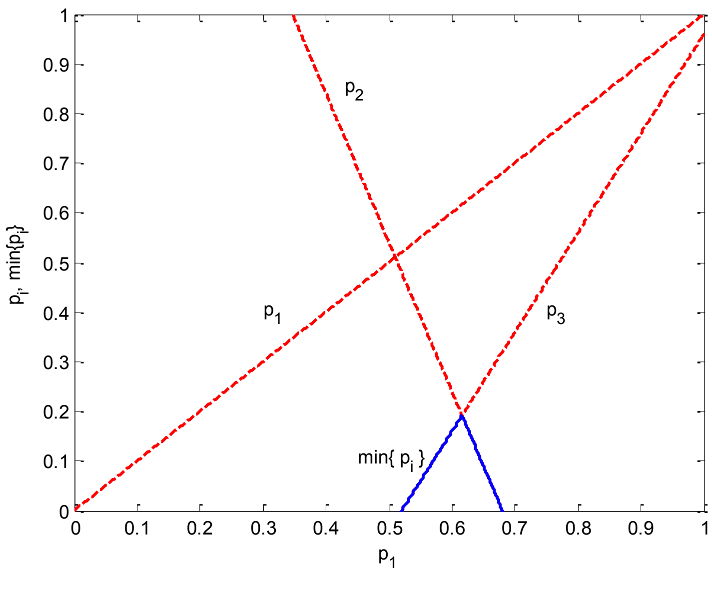


FIGURE 4.19. ACTORS' WEIGHTS IN **EXAMPLE 4.10**.

Figure 4.19 depicts the solution space for this example and presents the solution of the maximisation problem.

EXAMPLE 4.11: DECISION PROBLEM WITH THREE CRITERIA AND TWO ACTORS, UNDER UNCERTAINTY

Following **Example 4.7**, consider again the decision problem with $N = 3$ criteria $\{\mathrm{C}_1, \mathrm{C}_2, \mathrm{C}_3\}$ where the market's best criteria weights are given by

$$\mathbf{w}^{(\mathrm{E})} = [0.55 \quad 0.30 \quad 0.15]^{\mathrm{T}}$$

Additionally, consider $M = 2$ alternatives $\{\mathrm{A}_1, \mathrm{A}_2\}$, such that their perfect rating on the criteria is given by

$$\mathbf{U} = \begin{bmatrix} 5.00 & 7.00 & 1.00 \\ 4.00 & 1.50 & 8.00 \end{bmatrix}$$

where each line represents the rating of each alternative in the 3 criteria. Thus, from (4.53), the true market's values of the alternatives are

$$\mathbf{v}^{(\mathrm{E})} = \mathbf{U}\mathbf{w}^{(\mathrm{E})} = \begin{bmatrix} 5.00 \\ 3.85 \end{bmatrix}$$

i.e., alternative A_1 has the maximum value in the market with a value of 5.0 and the best decision would be to select it for implementation.

Consider now, $L = 2$ (human) actors $\{\mathrm{H}_1, \mathrm{H}_2\}$ involved in the group decision scenario. Their individual selection for the weights are given by

$$\mathbf{W} = \begin{bmatrix} 0.70 & 0.10 \\ 0.20 & 0.20 \\ 0.10 & 0.70 \end{bmatrix}$$

where each column vector of the matrix represents the weights of each actor summing 1.

Now, the actors are ranking the alternatives with an error, in the example

$$\mathbf{S} = \begin{bmatrix} 5.37 & 6.81 & 1.81 \\ 3.94 & 1.15 & 7.89 \end{bmatrix}$$

and thus the expected value of the alternatives is

$$\mathbf{Y} = \mathbf{S}\mathbf{W} = \begin{bmatrix} 5.30 & 3.16 \\ 3.77 & 6.15 \end{bmatrix}$$

where each column vector corresponds to each actor. This means that, individually, actor H_1 would select A_1 with an expected value of 5.30 and actor H_2 would select A_2 with an expected value of 6.15.

Without any a priori information, the group decision-making process initialises with equal decision weights for the actors, i.e.

$$\mathbf{p} = \begin{bmatrix} \frac{1}{L} & \frac{1}{L} \end{bmatrix}^{\mathrm{T}}$$

the group aggregated criteria is

$$\mathbf{w} = \mathbf{W}\mathbf{p} = \begin{bmatrix} 0.4 & 0.2 & 0.4 \end{bmatrix}^{\mathrm{T}}$$

and the group's expected value is

$$\mathbf{y} = \mathbf{Y}\mathbf{p} = \mathbf{U}\mathbf{w} = \begin{bmatrix} 4.22 \\ 4.96 \end{bmatrix}$$

i.e., alternative A_2, different from A_1, has the maximum expected value with a value of 4.96 and the group's decision is to select it for implementation.

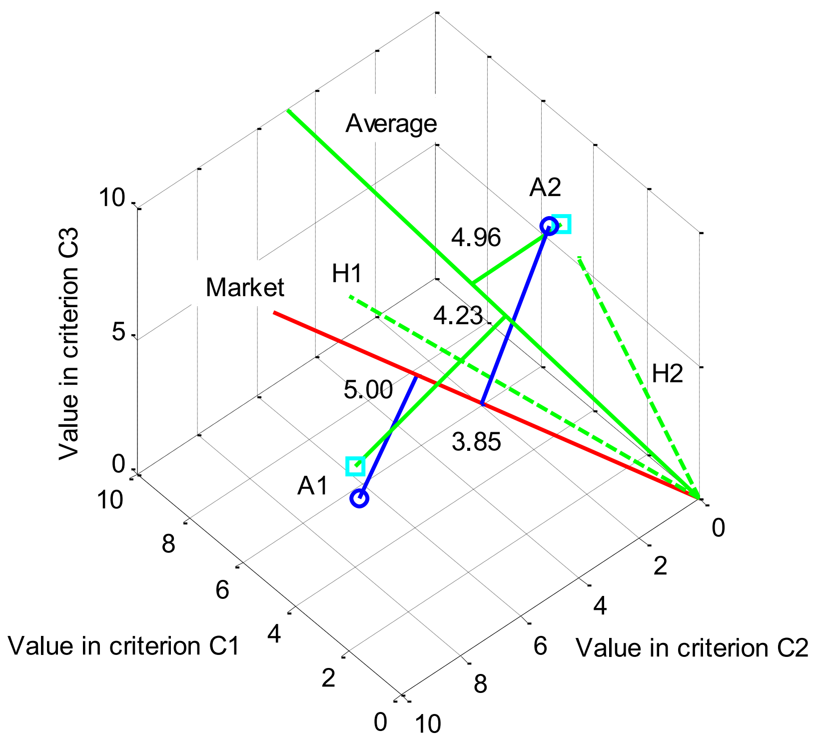


FIGURE 4.20. VALUES AND CRITERIA FOR ALTERNATIVES IN **EXAMPLE 4.11**.

Figure 4.20 depicts a geometric interpretation for this example. The solid (red) line identified as "Market" represents the vector direction of market's criteria $\mathbf{w}^{(\mathrm{E})}$; the two dotted lines identified by "H1", "H2, represent the two vector directions for the criteria weights of the two actors involved taken from $\mathbf{W}$ and the solid (green) line identified as "Average" represents the vector direction of group's criteria $\mathbf{w}$. The alternatives $\{\mathrm{A}_1, \mathrm{A}_2\}$ are marked directly on the plot with their respective ratings in each criterion. The value of each Alternative A_i is proportional to the size of the vector obtained from the orthogonal projection of the points A_i over the vector directions of the criteria.

4.4.5. ADAPTIVE ACTORS' WEIGHTS FROM MARKET FEEDBACK

The final purpose of this methodology is to use all information available from past decisions to select the best weights for the actors in the group decision-making process. The previous sections have demonstrated that, in the presence of uncertainty, the estimations for market criteria become deviated from the true value. It is proposed to use a learning mechanism based on recursive least squares (RLS) to continuously refine the weights of the actors.

Thus, consider again the model (4.53)

$$\mathbf{v}^{(\mathrm{E})} = \mathbf{U}\mathbf{w}^{(\mathrm{E})}$$

This gives the estimation model

$$z(j) = \boldsymbol{\phi}^{\mathsf{T}}(j)\hat{\mathbf{w}}^{(\mathrm{E})}(j)$$

where

$$z(j) = v_i^{(\mathrm{E})}(j)$$

is the output with the measured market value of the implemented decision i and

$$\boldsymbol{\phi}(j) = \mathbf{e}_{\mathrm{i}}\mathbf{S}(j)$$

is the data vector with the ranking of that alternative in the several criteria, both at decision process j. The vector $\hat{\mathbf{w}}^{(\mathrm{E})}(j)$ is the best estimation of the true market criteria at the decision process j.

The adaptation algorithm iterates at each decision process as follows.

Algorithm for adaptation of actor's weights based on market feedback

1. Initialise vector $\hat{\mathbf{w}}^{(\mathrm{E})}(0)$ with the best estimation for criteria. This can be directly derived from (4.60) and equal weights for all L actors, i.e.

   $$\hat{\mathbf{w}}^{(\mathrm{E})}(0) = \mathbf{W}\begin{bmatrix}\frac{1}{L} & \cdots & \frac{1}{L}\end{bmatrix}^{\mathsf{T}}$$

   Additionally, initialise the covariance matrix $\mathbf{P}(0)$ with

   $$\mathbf{P}(0) = \beta\mathbf{I}_N$$

   where β is a constant with a high value.
2. At each implemented decision process iterate the following equations:

$$\mathbf{K}(j) = \frac{\mathbf{P}(j-1)\boldsymbol{\phi}(j)}{\lambda + \boldsymbol{\phi}^{\mathsf{T}}(j)\mathbf{P}(j-1)\boldsymbol{\phi}(j)}$$

$$\hat{\mathbf{w}}^{(\mathrm{E})}(j) = \hat{\mathbf{w}}^{(\mathrm{E})}(j-1) + \mathbf{K}(j)\left(z(j) - \boldsymbol{\Phi}^{\mathsf{T}}(j)\hat{\mathbf{w}}^{(\mathrm{E})}(j-1)\right)$$

$$\mathbf{P}(j) = \lambda^{-1}\mathbf{P}(j-1) - \lambda^{-1}\mathbf{K}(j)\boldsymbol{\Phi}^{\mathsf{T}}(j)\mathbf{P}(j-1)$$

where $\lambda \approx 1$ is the forgetting factor.

3. Perform normalisation on $\hat{\mathbf{w}}^{(\mathrm{E})}(j)$ such that its elements sum up 1.
4. Use the current estimation of the market criteria $\hat{\mathbf{w}}^{(\mathrm{E})}(j)$ to update the actors' weights according to the feedback methods (4.65)-(4.67) for the specific situation.

As long as the observations and estimation noise are uncorrelated, the estimative will converge to the optimal weights. In fact, the error in estimation of the value of the alternatives is independent of the measuring error on the true value of the implemented decision.

The following example illustrate the convergence properties of the proposed algorithm.

EXAMPLE 4.12: ADAPTING ACTORS' WEIGHTS FROM MARKET FEEDBACK

Consider again the decision problem of **Example 4.11** with $N = 3$ criteria $\{\mathrm{C}_1, \mathrm{C}_2, \mathrm{C}_3\}$ where the market's best criteria weights are given by

$$\mathbf{w}^{(\mathrm{E})} = [0.55 \quad 0.30 \quad 0.15]^{\mathsf{T}}$$

Additionally, consider sets of $M = 2$ alternatives $\{\mathrm{A}_1, \mathrm{A}_2\}$, such that their perfect rating on the criteria is given by a random $\mathbf{U}(j)$ with inputs in the interval $[0; 10]$. Thus, from (4.53), the true market's values of the alternatives are $\mathbf{v}^{(\mathrm{E})}(j) = \mathbf{U}(j)\mathbf{w}^{(\mathrm{E})}$ and different for each decision process.

As in the previous example, consider $L = 2$ (human) actors $\{\mathrm{H}_1, \mathrm{H}_2\}$ involved in the group decision scenario. Their individual selection for the criteria weights are given by

$$\mathbf{W} = \begin{bmatrix} 0.70 & 0.10 \\ 0.20 & 0.20 \\ 0.10 & 0.70 \end{bmatrix}$$

where each column vector of the matrix represents the weights of each actor summing 1.

The actors are rating the alternatives with an error $\mathbf{S}(j) = \mathbf{U}(j) + \mathbf{N}(j)$, where $\mathbf{N}(j)$ is the Gaussian matrix where each element has zero mean and 0.25 variance. Thus, the expected value of the alternatives is $\mathbf{Y}(j) = \mathbf{S}(j)\mathbf{W}$.

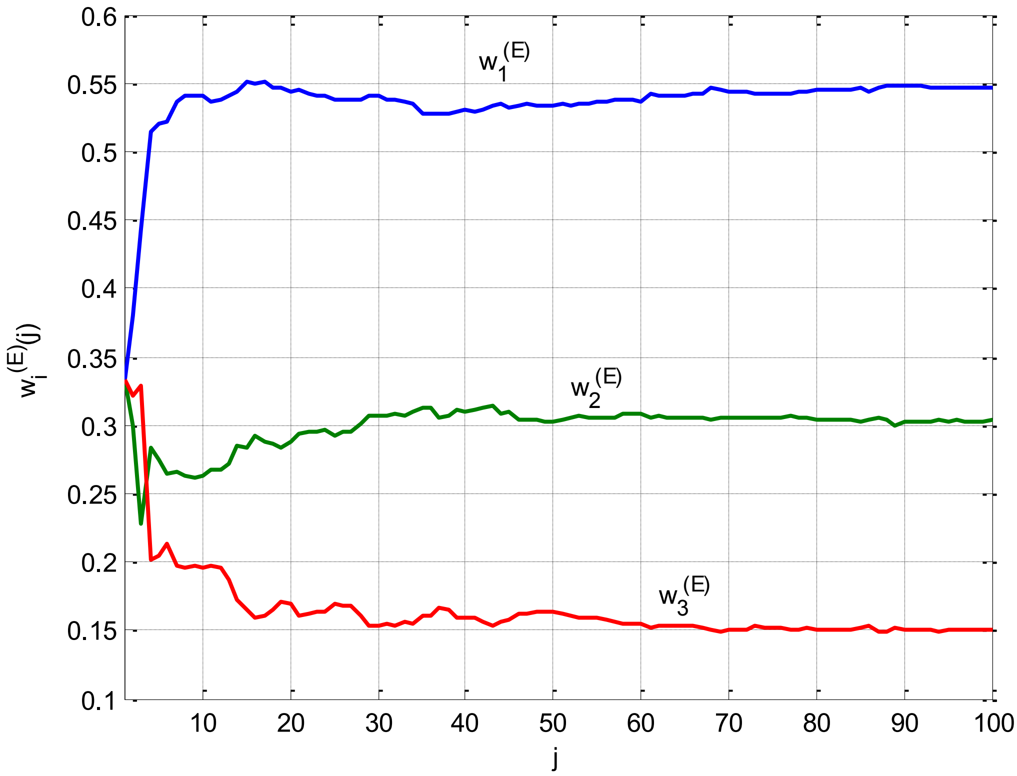


Figure 4.21. Market's weights estimation in **Example 4.12**.

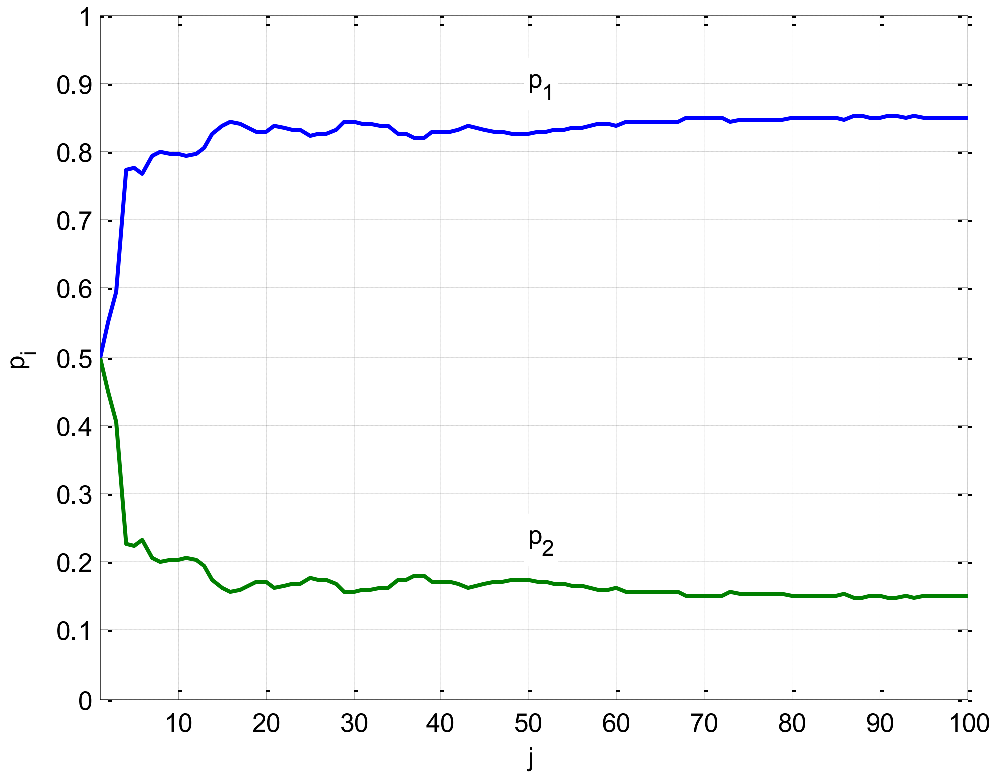


Figure 4.22. Actors' weights estimation in **Example 4.12**.

Figure 4.21 and Figure 4.22 depict the evolution of the inputs of vectors $\widehat{\mathbf{w}}^{(\mathrm{E})}(j)$ and $\mathbf{p}^{*}(j)$ with iteration time j, respectively. The final values of this simulation match the market weights of 0.55, 0.30 and 0.15. Additionally, the majority of the convergence happens in the first 10 iterations. The final values of the actors' weights of 0.85 and 0.15 in $\mathbf{p}^{*}$ are in accordance with equation (4.67). For this simulation, the introduction of the feedback and adaptive adjustment of the weights lowered the rate of wrong decisions from 20% to 10%.

4.5. REMARKS

This chapter presented three approaches to support decision-making situations in industrial environments. These approaches use two well-known methods, CBR and AHP, and their respective combination. The chapter highlights that while CBR is suitable for problem solving applications, especially of routine problems, AHP and the combination of CBR and AHP are especially suited to support decisions in the scope of innovation processes. The decisions made in these situations tend do be more complex and involve larger and more diverse teams.

This chapter also proposes an algorithm to adjust the weights of each actor in the decision team based on information about the decision implementation. The objective is to use decision follow-up information to adjust the role of actors in decision-making situations.

5. CASE STUDIES

In the scope of several research projects, it was possible to implement and test some of the work presented in the previous chapters of this thesis. The work related to the enterprise model, presented in chapter 2 Enterprise model, started in the scope of manufacturing companies, and has expanded to other industrial areas. Therefore, this section presents seven test cases where the proposed model has been successfully applied, always with the purpose of supporting decisions, particularly problem solving applications. In addition, the decision support methods proposed in this work, namely case-based reasoning, analytic hierarchy process and the combination of the two, were applied in some of the test cases. According to this, the results have been validated in two manufacturing companies, two assembling companies, two engineering services companies and one software company. The objective of this section is to highlight the wide application of the proposed model, describing possible interpretations of the classes introduced and the successful use of the decision support approach in industrial companies.

5.1. MANUFACTURING COMPANIES

Two large manufacturing companies were modelled following the approach proposed, with the objective of supporting a problem-solving scenario.

The first company is a well-known manufacturer of high-quality vehicles that uses advanced manufacturing technology to maintain their market position. The company wanted to improve its problem solving approach in the shop floor, by reducing the time needed to diagnose and eliminate a problem. In addition, the manufacturer was also interested in improving the exchange of knowledge, by improving the methods for knowledge acquisition and storage. This last objective would be valuable for training employees, particularly newcomers.

This company tested the proposed enterprise model and the case-based reasoning approach. As the company has many manufacturing plants, with considerable dimensions, it was necessary to define a limited scope to enable the success of the testing procedure. The company chose to validate the approach in a part of one of its manufacturing plants, dedicated to the production of rear axles for cars. This area was selected because of its high complexity and high level of automation, which allowed some automatic collection of dynamic information and a high impact in problem solving (if successful). The rear axle of a car is composed of many small parts and it takes 38 welding cells, 62 welding robots and 14 handling robots to manufacture it (Fischer and Stokic 2002). Each welding cell contains fixture devices that develop the axle progressively. All the cells, robots and fixture devices are controlled by a Programmable Logic Controller (PLC), as represented in Figure 5.1.

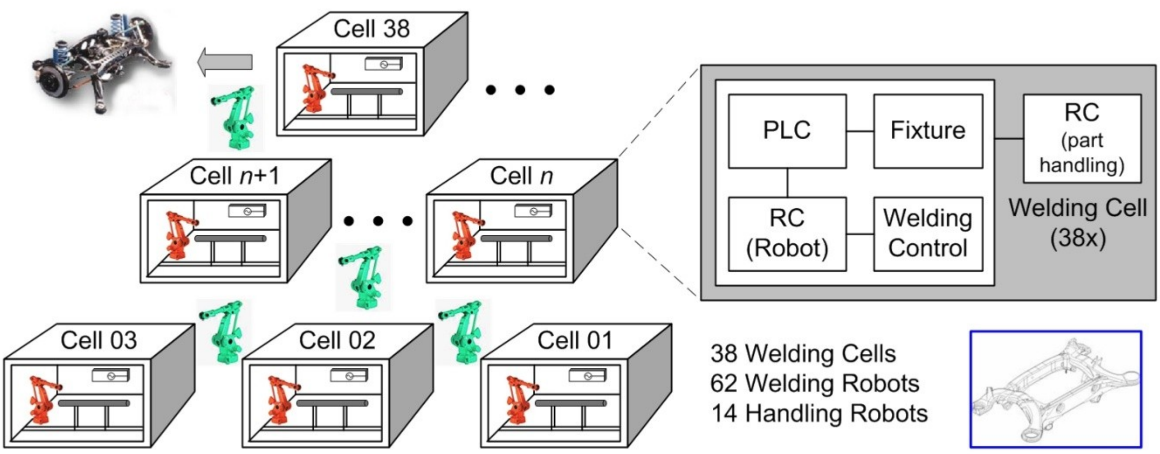


FIGURE 5.1. MANUFACTURING PLANT OF A REAR AXLE.

Prior to these tests, the company stored the outputs from the PLC, without any thorough analysis. These reports were only used by employees, who examined them and mainly talked to each other to try to solve any problem in the shop-floor. The company wanted to store any occurred problems, comprehending a description of what happened, what was measured, what was the cause diagnosed, and what was done to remove it. This approach would allow any employee to quickly see a past problem that could support in solving a current situation.

The model developed includes a detailed description of the manufacturing processes, the tools and machines used and all the parts produced until the final product, in this case the rear axle, was complete. In addition, the model included the actors involved in each of the processes, and their respective expertise in terms of technologies used in the processes. Each physical element (process, part and machine) was described in detail, including a list of all variables that can be measured, where most of them could be obtained from the PLC. Moreover, the company identified a set of typical problems that could be used as categories, to list as problem types. Finally, the model included the causes of the typical problems, and also the actions implemented to remove those causes. The modelling process was led by the process engineering department of the company, which is responsible, among other tasks, for continuous improvement in the company.

Figure 5.2 and Figure 5.3 show some examples of production units and states defined in the model of this manufacturing company.

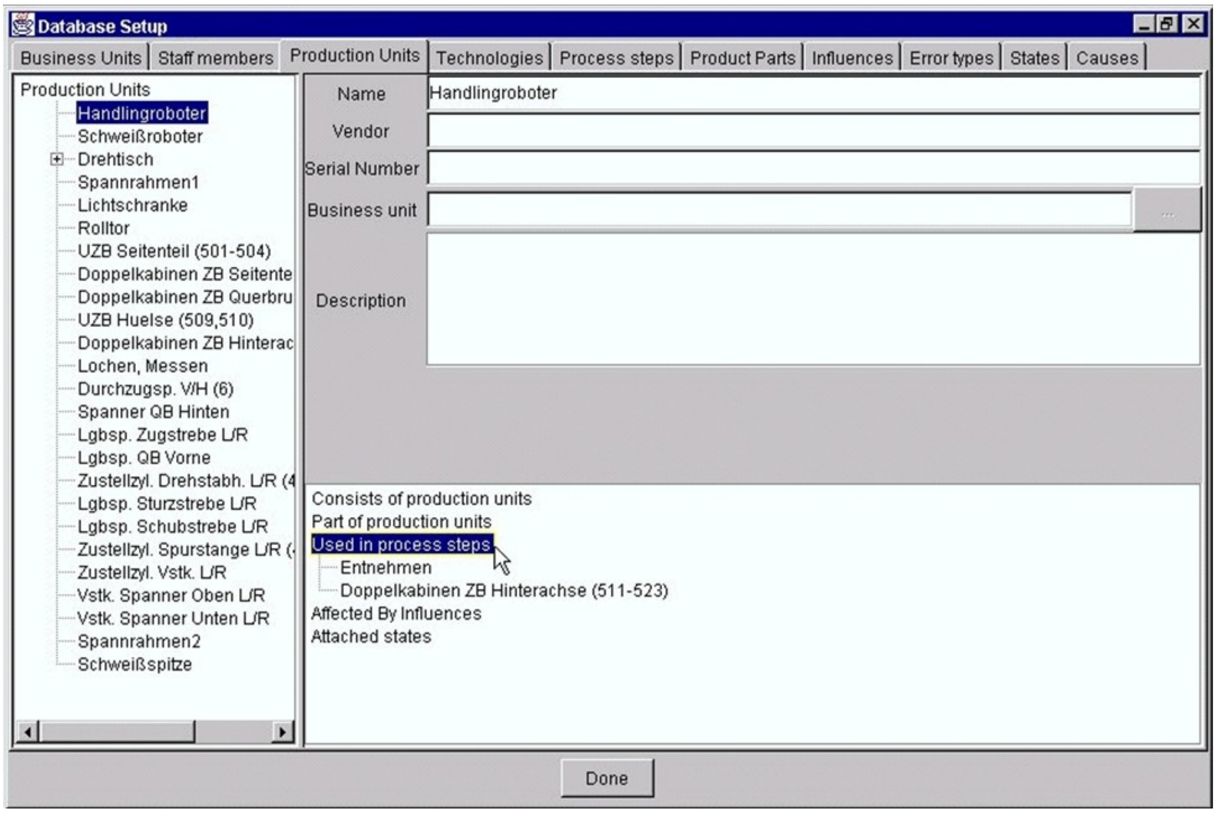


FIGURE 5.2. PRODUCTION UNITS OF MANUFACTURING COMPANY 1.

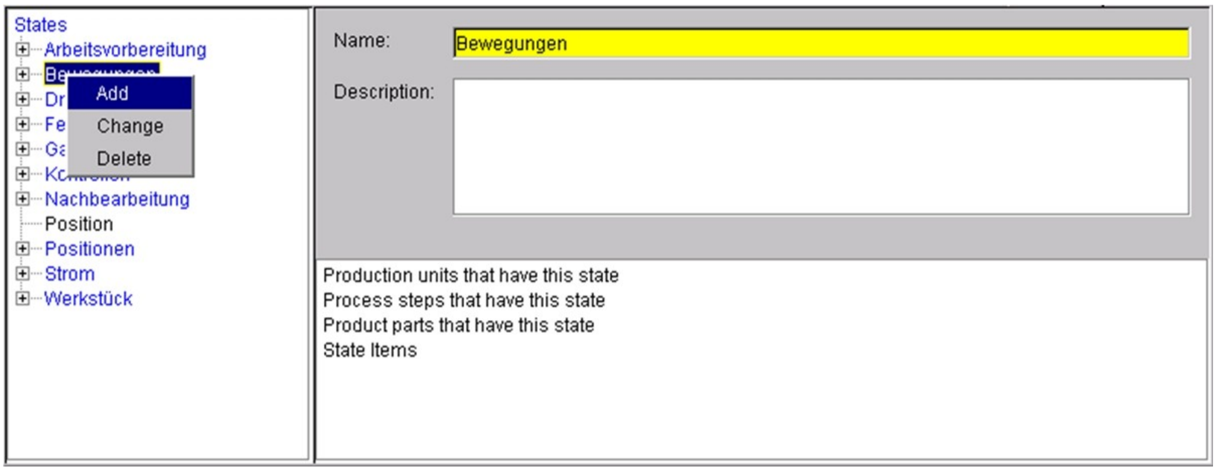


FIGURE 5.3. STATES OF MANUFACTURING COMPANY 1.

The resulting model was quite complex in amount of instances and especially interactions among them, but provided a straightforward application of the enterprise model proposed. After the described definition of the static model, the company was ready to start registering problems.

The person responsible for the modelling process in this company identified the model to be a significant result. Having only one knowledge base with a detailed description of all processes, machines, products, people and problems of a part of the manufacturing plant was something non-existent. Before this implementation, information was widespread throughout different systems, according to its application: logistics, production planning, invoicing, acquisition, sales etc.

A case-based reasoning (CBR) module, following the approach proposed in the previous chapter, was developed and applied in this company, tightly connected to the enterprise model implemented. The CBR was fully based on the enterprise model, to take complete advantage of the static data of the company, and therefore, provide accurate information. The model and the CBR module were tested in the scope of a European project, in several tasks completing approximately 22 months. Therefore, the module was improved and several tests were done. In addition, the results obtained also improved with the amount of problems recorded.

In the final tests, the company was able to correctly identify the causes for 95 to 98% of the problems occurred. There are a couple of reasons that explain the results. The first is related to the model. The structure of the problems, and their relation to exact physical elements in the company (specific process, machines etc.) was essential to provide a clear and high re-usability of information. The second reason is related to the level of detail achieved in describing the problems, which is connected to the high level of automation present in the manufacturing plant. The PLC was connected to the problem description, and all the values measured for a specific machine could be imported into a problem description. As the CBR approach is based on calculating the similarity between a new problem and stored problems, these detailed descriptions were quite useful in providing differentiated results. The company also registered some measures regarding business aspects of these tests. The results obtained in this test case are highlighted in Table 5.1.

TABLE 5.1. RESULTS FROM TESTS IN MANUFACTURING COMPANY 1.

Metric description	Result achieved
Problems correctly diagnosed (cause identified)	ca. 95 – ca. 98%
Reduction of costs in searching causes of problems	ca. 30%
Reduction of average time spent to identify problem's cause	ca. 45%
Reduction in costs for training new employees	ca. 10%
Reduction of downtime in machines	ca. 6%

The second company is one of the biggest manufacturers of beverage cans, with over 60 plants in 20 countries. Beverage cans are mainly composed of two parts: the can and the end. The end is actually the cover of the can, with the respective opening, which is only attached to the can after both are manufactured. These two parts are usually manufactured in different plants and connected just before packaging and delivering. This company is characterised by high automation manufacturing processes and an extremely high production volume. In Germany alone, four plants produce 4 billion cans per year, and an additional plant produces 6 billion ends per year. The company wanted to provide the highest production availability and continuously improve its manufacturing processes. The company has several ICT systems, which are not integrated, and produce results that have to be analysed by managers in time-consuming meetings. In addition, prior to these tests, the company had some paper-based records of problems, which were not related to any machine data. There was also an identified issue of problems arising in the beginning of a shift, due to lack of communication between shifts.

The company chose a specific part of the can manufacturing process to test the proposed approach. The production of a can starts with cutting tin plate to form small cups, which are then stretched and ironed until they form a cylinder with the height of the desired can. These cylinders are washed, coated and dried. However, a can is not a perfect cylinder. Therefore, the top part of the cylinder needs to be adjusted to its final form, before adding the end, or top. The process of reducing the upper section of the can, called necking, is performed in fifteen consecutive stations, where each reduces the diameter of the can by one millimetre. One the desired diameter is reached, it is necessary to create a flange to seal the filled can securely to its end. The fifteen stations of necking and the flanging are all done in one very complex machine called the Necker, which processes 2400 cans per minute. After the Necker, there is a compartment with a camera to test the cans and provide information about each piece (see Figure 5.4). The Necker was the main focus of the tests performed, because it is responsible for 25% of the scrap of the whole production.

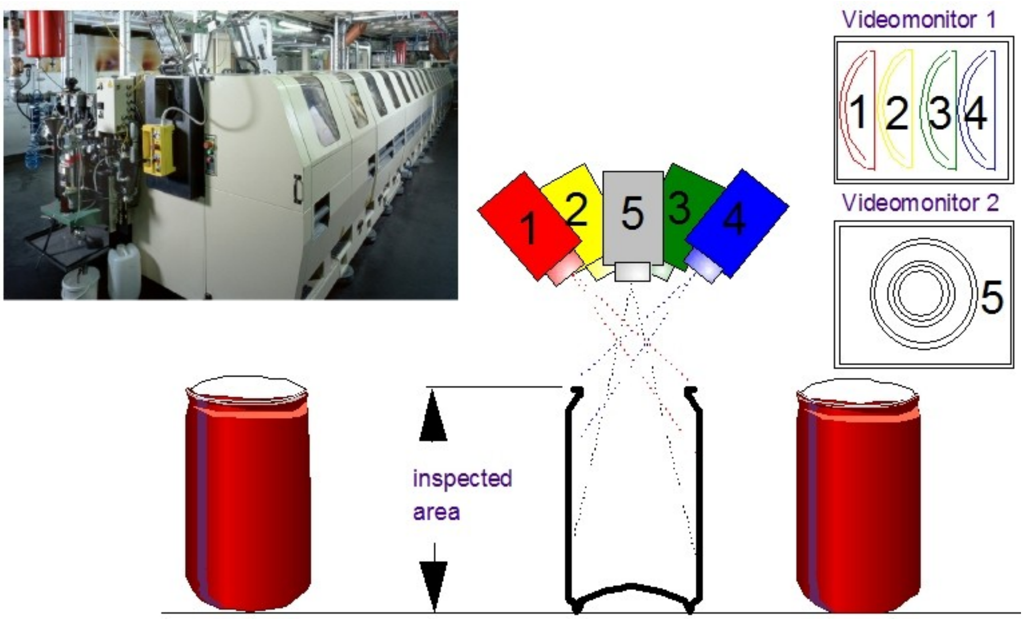
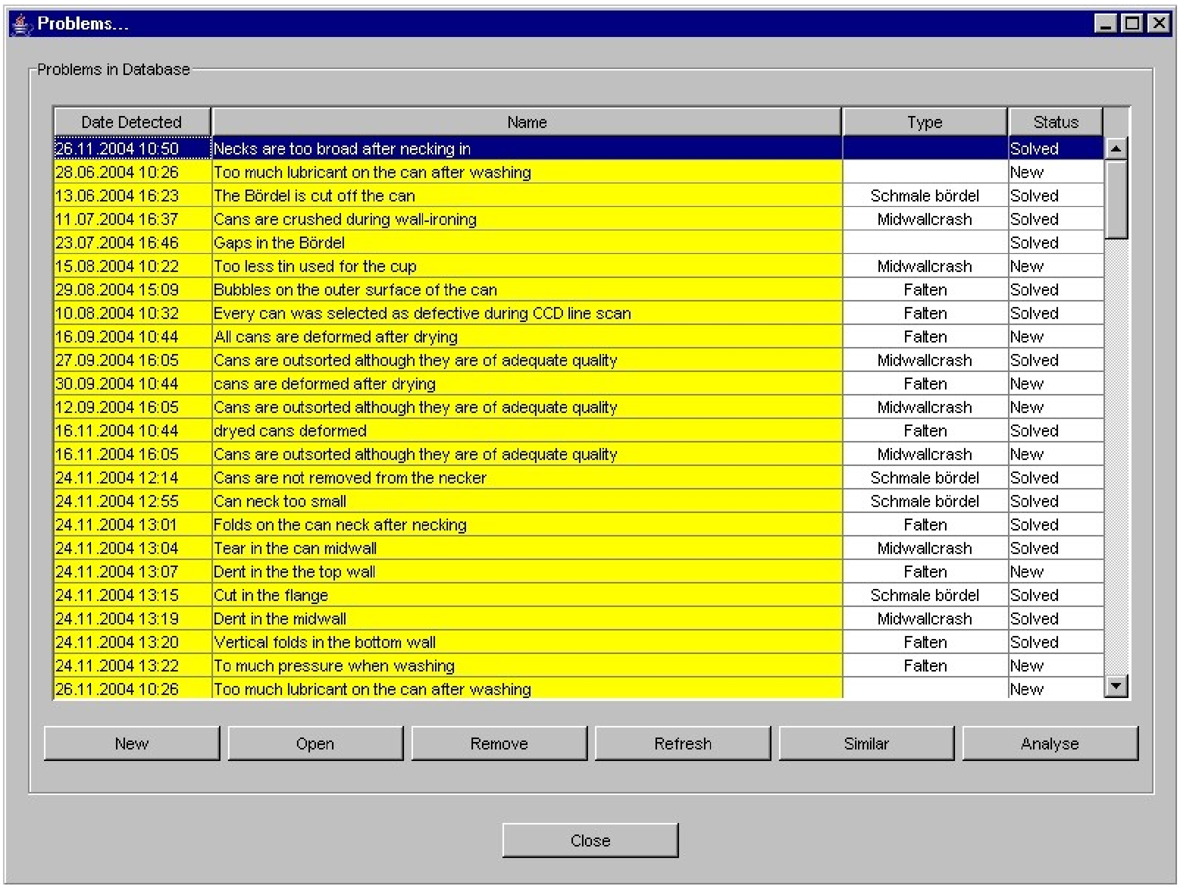


FIGURE 5.4. PROCESS OF NECKING AND TESTING CANS.

The enterprise model developed includes the complete manufacturing plant for cans, with the process steps, production units and product parts. The production units are the most important element of the model, and represented with more detail. The manufacturing plant modelled has two lines to produce cans, and all its machines were modelled. The product parts were represented in a generalised form, e.g. cup or necked can, without specific instances. With the objective of applying a CBR approach to problem solving, based on comparison with past problems, the company did not emphasise modelling the human actors. Employees are users of the supporting system but not a key element in the model. The information provided by the testing system following the Necker provides important measures about the cans, modelled as state items.

After defining all the static part of the model, the company invested some time in registering problems occurred, which existed in paper-form. This registration of problems allowed starting using the system with a collection of problem cases, enabling from the beginning appropriate results from the CBR. The test of the system over a period of 21 months allowed improving the knowledge base, increasing the number of cases, and therefore advancing the results obtained.

Figure 5.5 shows a list of examples of the problems diagnosed with the approach tested and Figure 5.6 details the registration of one problem occurred in the manufacturing shop floor.



Date Detected	Name	Type	Status
26.11.2004 10:50	Necks are too broad after necking in		Solved
28.06.2004 10:26	Too much lubricant on the can after washing		New
13.06.2004 16:23	The Bördel is cut off the can	Schmale bördel	Solved
11.07.2004 16:37	Cans are crushed during wall-ironing	Midwallcrash	Solved
23.07.2004 16:46	Gaps in the Bördel		Solved
15.08.2004 10:22	Too less tin used for the cup	Midwallcrash	New
29.08.2004 15:09	Bubbles on the outer surface of the can	Falten	Solved
10.08.2004 10:32	Every can was selected as defective during CCD line scan	Falten	Solved
16.09.2004 10:44	All cans are deformed after drying	Falten	New
27.09.2004 16:05	Cans are outsorted although they are of adequate quality	Midwallcrash	Solved
30.09.2004 10:44	cans are deformed after drying	Falten	New
12.09.2004 16:05	Cans are outsorted although they are of adequate quality	Midwallcrash	New
16.11.2004 10:44	dryed cans deformed	Falten	Solved
16.11.2004 16:05	Cans are outsorted although they are of adequate quality	Midwallcrash	New
24.11.2004 12:14	Cans are not removed from the necker	Schmale bördel	Solved
24.11.2004 12:55	Can neck too small	Schmale bördel	Solved
24.11.2004 13:01	Folds on the can neck after necking	Falten	Solved
24.11.2004 13:04	Tear in the can midwall	Midwallcrash	Solved
24.11.2004 13:07	Dent in the the top wall	Falten	New
24.11.2004 13:15	Cut in the flange	Schmale bördel	Solved
24.11.2004 13:19	Dent in the midwall	Midwallcrash	Solved
24.11.2004 13:20	Vertical folds in the bottom wall	Falten	Solved
24.11.2004 13:22	To much pressure when washing	Falten	New
26.11.2004 10:26	Too much lubricant on the can after washing		New

FIGURE 5.5. EXAMPLES OF PROBLEMS IN MANUFACTURING COMPANY 2.

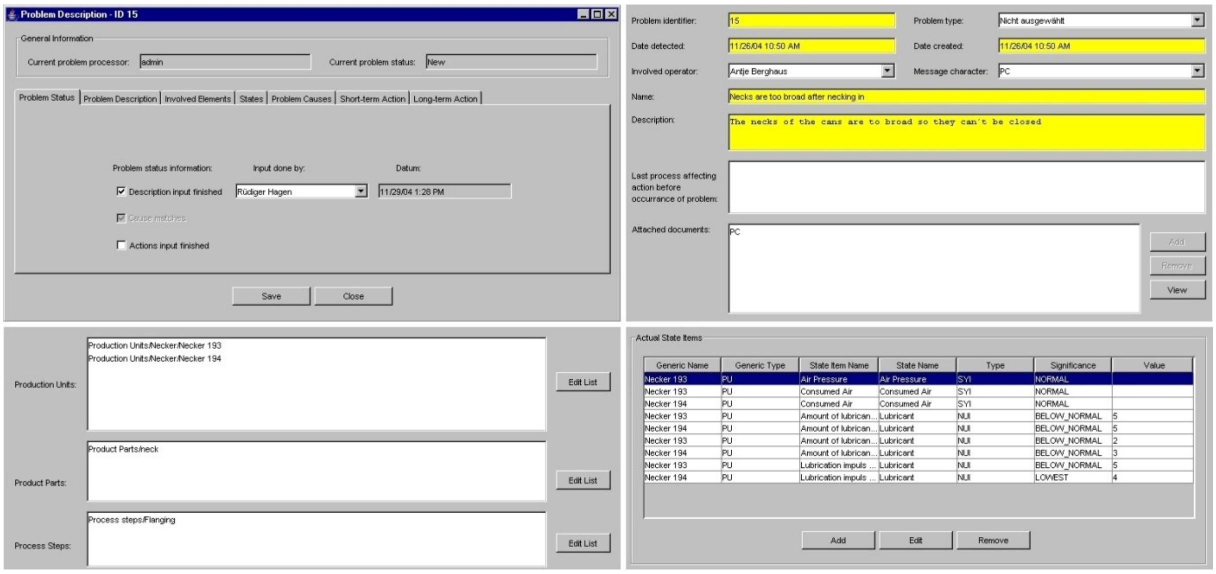


FIGURE 5.6. DETAILS OF A PROBLEM'S DESCRIPTION.

The enterprise model of this company is, similarly to the first manufacturing company, a direct application of the model proposed in chapter 2 Enterprise model. The results achieved in this test case are summarised in Table 5.2.

TABLE 5.2. RESULTS FROM TESTS IN MANUFACTURING COMPANY 2.

Metric description	Result achieved
Problems correctly diagnosed (cause identified)	ca. 90 – ca. 95%
Reduction of costs in searching causes of problems	ca. 25%
Reduction of average time spent to identify problem's cause	ca. 35%
Reduction of waste associated with problems	ca. 10%

5.2. ASSEMBLING COMPANIES

Two assembling companies were also involved in testing the proposed approach. These two applications have similarities with the manufacturing companies, but also some differences, caused by the low-level of automation in the companies.

The first assembling company develops, produces and supports military aircrafts. The company has more than fifty years of experience in assembling aircraft structures and systems. This experience has developed in the company expertise in dealing with a large numbers of components and the associated tolerance problems it brings. The company was producing a multi-role fighter aircraft which uses state-of-the-art technology. This single-seat fighter is capable of performing an extensive range of Air-to-Air, Air-to-Surface and reconnaissance missions employing the most modern range of weapons. The company aimed at meeting the demands of current and future warfare threats, while at the same time meeting strict requirements for flight safety, reliability, training efficiency and low operating costs. Although the product in question is of undeniable complexity, the production process was mainly manual, i.e. assembling, performed by highly specialised and skilled workers, as presented in Figure 5.7.

FIGURE 5.7. ASSEMBLING PLANT OF A FIGTHER AIRCRAFT.

The department involved in modelling this enterprise is directly responsible for process improvements and quality in the plant. Especially in the area of fuselage assembly, there are needs to establish a system that enables integrating knowledge from different departments in order to efficiently perform changes in the products and processes and increase productivity and quality within the transition phase (after product changes). This company wanted to decrease the problems occurred in the assembling processes and whenever possible access problems occurred in similar processes, even if already discontinued.

This test case involved mainly the assembly company, with little use of the extended enterprise. As most of the processes are based on assembling, the company does not use complex machines in its plant. Therefore, the model focused much more on process steps, i.e. the assembling activities, and on the product parts used as input and output. The object production unit received very little attention in this test case, due to its low relevance in the problems occurred. On the other hand, the employees and their respective expertise were of key importance in this company. The human actors are the ones fully reporting and solving problems.

This test case used the enterprise model combined with a case-based reasoning module to support problem solving. The main objective was to increasingly acquire and register some of the implicit knowledge used daily by the employees to solve problems.

This company had an approach to register, in paper, problems occurred. These problems were described by one employee, diagnosed and solve by the same person or a colleague, and checked by someone in the quality department. The paper forms included some textual description of the problem, cause and actions, but especially timestamps of each phase and the person responsible for each step. Accountability is a key issue for companies, especially when dealing with very sensitive products, as is this case. It was possible to translate these paper records in problem descriptions, ready to be used by the CBR module. This process required a joint effort with the company's quality staff. Table 5.3 lists some examples of the problems registered using the software tested and solved with the approach proposed.

TABLE 5.3. EXAMPLES OF PROBLEMS IN ASSEMBLING COMPANY 1.

Problem description	Problem type	Product Part	Process Step	Cause
Part cannot be mounted	Operator	Wing	Assembly	Lack of a part
Collision between parts/tools	Operator	Cockpit	Assembly	Distance between parts incorrect
Part cannot be mounted	Operator	Cockpit	Assembly	Part damaged
Part cannot be mounted	Operator	Wing	Assembly	Part produced faulty
Fuel leak	Test & function	Fuel system	Final inspection	Fuel system faulty
Electrical problem	Cleaning	Cockpit	Final inspection	Dirt and debris found

The CBR module, combined with the enterprise model, enabled the correct diagnosis of around 50% of the problems occurred. This number is considerable lower than the one registered in the manufacturing companies. The main reason for this is the lack of automation in the shop-floor of this assembling company, while in the manufacturing companies the detailed definition of almost all variables is enabled by all machines involved in any problem. In this test case, any measurements are based on what employees can register, which happens usually running some diagnosis software after the problem has occurred. Sometimes, it is difficult to identify if the measures belong to the current problem or a previous one. The CBR approach does not take full advantage of the implicit expertise of human actors, which was extremely important in this test case. Therefore, the diagnostics tool was complemented with a rule-based reasoning (RBR) module (Campos, Stokic and Neves-Silva 2004). The company's employees have invaluable years of experience and know that when something happens it is usually because of a finite number of options. The use of both reasoning methods raised the number of problems diagnosed to 90%. The tests performed involved several incremental versions of the modules, and occurred during a period of 22 months. The results achieved in this test case (using CBR and RBR) are presented in Table 5.4.

TABLE 5.4. RESULTS FROM TESTS IN ASSEMBLING COMPANY 1.

Metric description	Result achieved
Problems correctly diagnosed (cause identified)	ca. 90%
Amount of problems diagnosed with the approach tested	ca. 85%
Reduction of costs in searching causes of problems	ca. 27%
Reduction of average time spent to identify problem’s cause	ca. 40%
Reduction of downtime of workers	ca. 10%

The second assembling company designs, produces and trades air conditioning equipment for residential, commercial and industrial use (see Figure 5.8). The company has its own brand name but it is also an original equipment manufacturer for other brands. The production process of the company comprehends the manufacturing of all metallic components, copper kits (refrigeration) and electrical boards as well as the subsequent assembly of those half-finished products and other components.

FIGURE 5.8. ASSEMBLING OF LARGE-SCALE AIR CONDITIONING UNITS.

In addition, the company also invests in designing and developing customised solutions for specific applications, such as hospital or military infrastructures. As a part of the company's strategy to establish itself in a very competitive market, there was a strong investment in providing not only products but also services. Maintenance and after-sales services have a strong impact on the brand image, and consequently on sales and costs, while the price must remain attractive.

This company was looking for support in two different areas: provide an effective maintenance service for its commercial and industrial customers, which have large-scale acclimatisation units; and design customised solutions meeting the specifications of large customers.

In addition, this test case has a twofold objective: remote maintenance and design. This test case brought a major focus to the extended enterprise. The business units modelled include the several departments of the company, the customers and some third-party companies that are sometimes sub-contracted for maintenance services. The process steps are not relevant in this test case, as both applications (problem solving and design) are more directly related to people. Some generic process steps were modelled for the air conditioning company. The air conditioning units could either be modelled as production units, seen as tools used in a process of the customer, or product parts, seen as items assembled and sold by the assembling company. All the air conditioning units were modelled as production units, in a very detailed way. Production units include, in this model, a well structured hierarchy representing the company's catalogue. The modelled production units include specific instances, with the relation to which company they belong. This information was very important for the problem solving application. Moreover, actors play an important role in this test case. Customers usually have contact persons, and the assembly company assigns specific employees to each customer. The model includes the actors of the extended enterprise, from the several companies involved, identifying their expertise and their responsibilities regarding business units and production units.

Problems also have a dual approach in this test case, as they are used for both applications, i.e. remote maintenance and design. The two classes of problems are differentiated in the system through a flag.

In problem solving, problems are registered, including any measures recorded by the air conditioning unit that is malfunctioning. The problem record can be analysed both at customer's site and at the assembling company. The CBR approach allows actors to search previous similar problems and obtain some diagnosis on what could be the cause and what to do to eliminate it.

In supporting the design process, this company tested the AHP approach and also the combination of AHP with CBR. For this purpose, problems are used to model customer requirements on what they need as customised solution. The description includes a set of variables to be met by the air conditioning unit to be designed, which are considered future state items (using the constructs for actual state items). When receiving a new customer's request, the company fills in the problem description and can use CBR to identify if any similar products, meaning products with similar requirements, have been previously designed. The previous designs are then considered as alternatives by the design team, which includes employees from design, production, maintenance and sales. Some preliminary tests have been made using AHP to rate the criteria to be considered in the decision and rate the possible alternatives, in order to choose the most suitable design for each situation. These tests have inspired Example 4.3, in section 4.2 The Analytic Hierarchy Process.

Figure 5.9 presents some of the production units defined for the model of this assembling company. Figure 5.10 and Figure 5.11 display, respectively, a list of examples of problems and a list of similar problems provided by CBR.

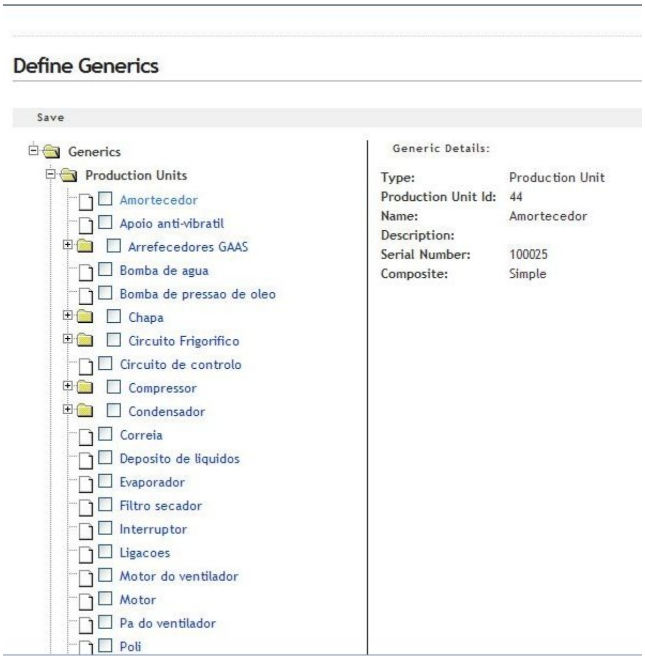


FIGURE 5.9. PRODUCTION UNITS DEFINED FOR ASSEMBLING COMPANY 2.

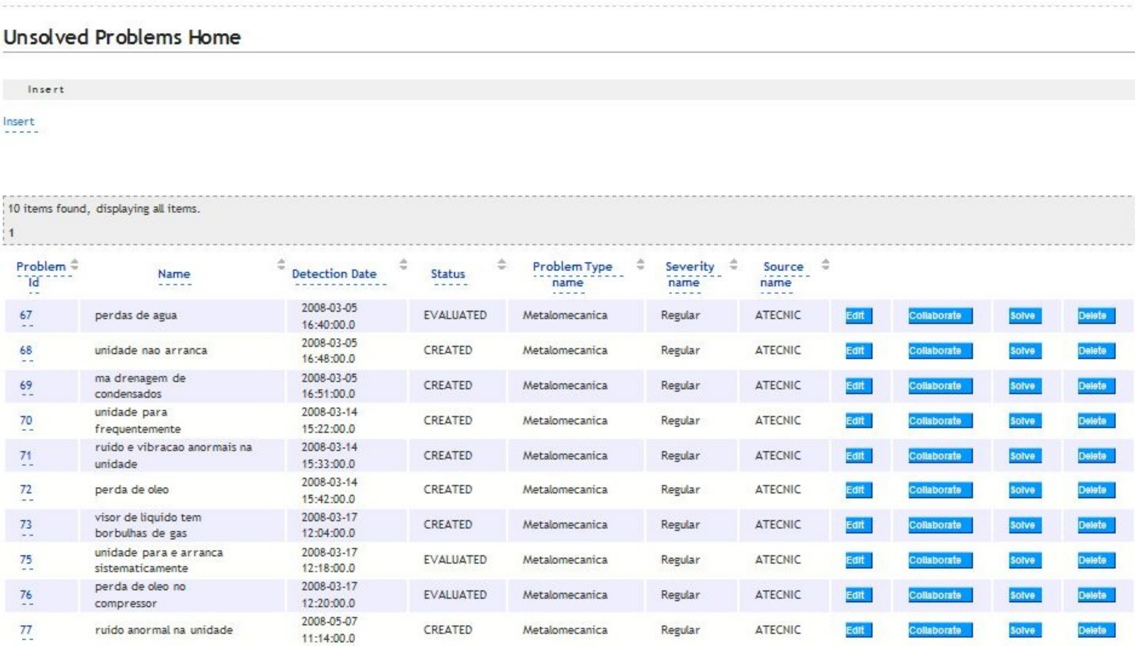


FIGURE 5.10. EXAMPLES OF PROBLEMS DEFINED FOR ASSEMBLING COMPANY 2.

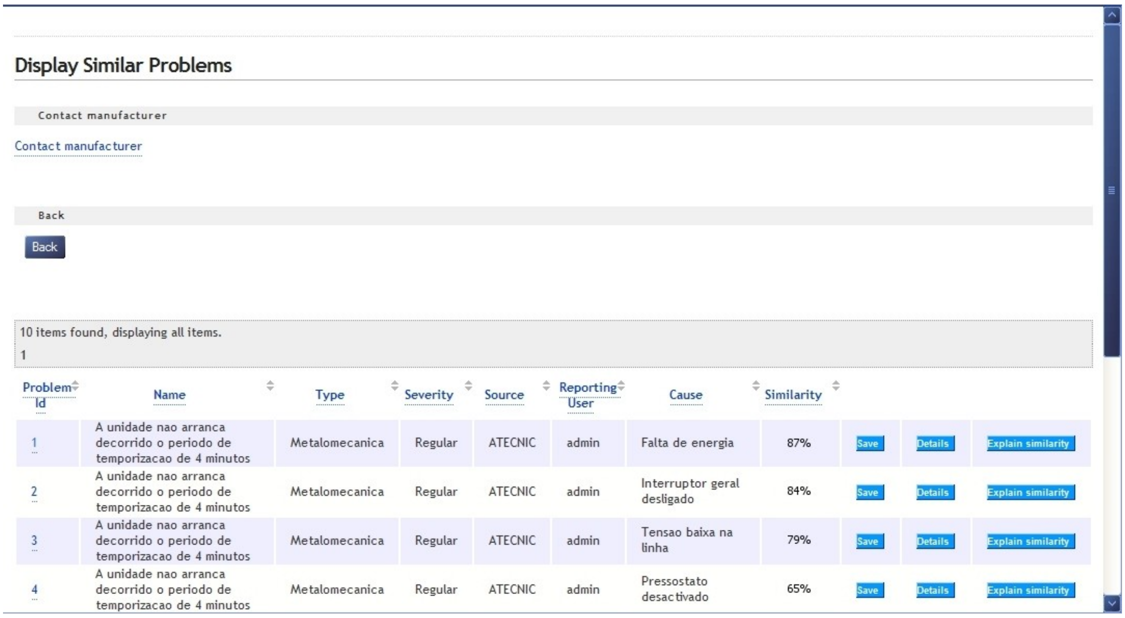


FIGURE 5.11. SIMILAR PROBLEMS IDENTIFIED BY CBR IN ASSEMBLING COMPANY 2.

The model, CBR and AHP modules were progressively tested in the company through a period of 19 months. The company has identified that one of the main benefits achieved from this test case was the structuring of information. The company has now a model that allows several applications, a detailed record of problems occurred in units installed at customers, and a detailed record of customer requirements and the subsequent designed products. These are intangible benefits, which have improved the company's operation and impact on the brand image. Other benefits registered by the company are summarised in Table 5.5.

TABLE 5.5. RESULTS FROM TESTS IN ASSEMBLING COMPANY 2.

Metric description	Result achieved
Reduction in average time to solve a problem	ca. 91 – ca. 97%
Reduction of problems that require diagnostics travel	ca. 70%
Reduction of customer complaints due to maintenance	ca. 100%
Reduction of problems that require involvement of highly specialised staff	ca. 75%
Reduction of time needed to gather information to prepare a reconfiguration report	ca. 90%
Reduction of time needed to design a new product	ca. 50%

5.3. ENGINEERING SERVICES COMPANIES

Some of the work described in this thesis was also validated in two companies that develop engineering solutions in two different areas. These two companies develop solutions according to customers' requirements and install them at the customers. The development process consists in designing the engineering solution and then implementing it using products and machines available on the market.

The first company develops precision cutting tools for cutting shapes out of all kinds of flexible materials. These tools are then used to perform precision cutting tasks for a whole range of industries from aerospace, automotive, medical, and pharmaceutical, to shoe and packaging industries. The company produces a wide range of cutting fixtures and provides a range of cutting services. The cutting fixtures are based on rotary (cylindrical) cutting forms and also flat press forms (see Figure 5.12). These fixtures are used to cut different shapes and materials. Examples include car gaskets, floor tiles, greeting cards, paint pads, packaging material and car carpets.

The company is very innovative and is constantly striving to produce novel cutting techniques and products. The company has several patents for innovative cutting products, such as the rotary cutting and creasing process, plus the novel skin cutting processes. The development process of an innovative solution is a complex procedure that is highly based on human expertise. Therefore, the ability of sharing and re-using knowledge can play a major role. The company wants to be able to solve problems that occur while developing a new product, by accessing information on problems that occurred in the development of similar products.

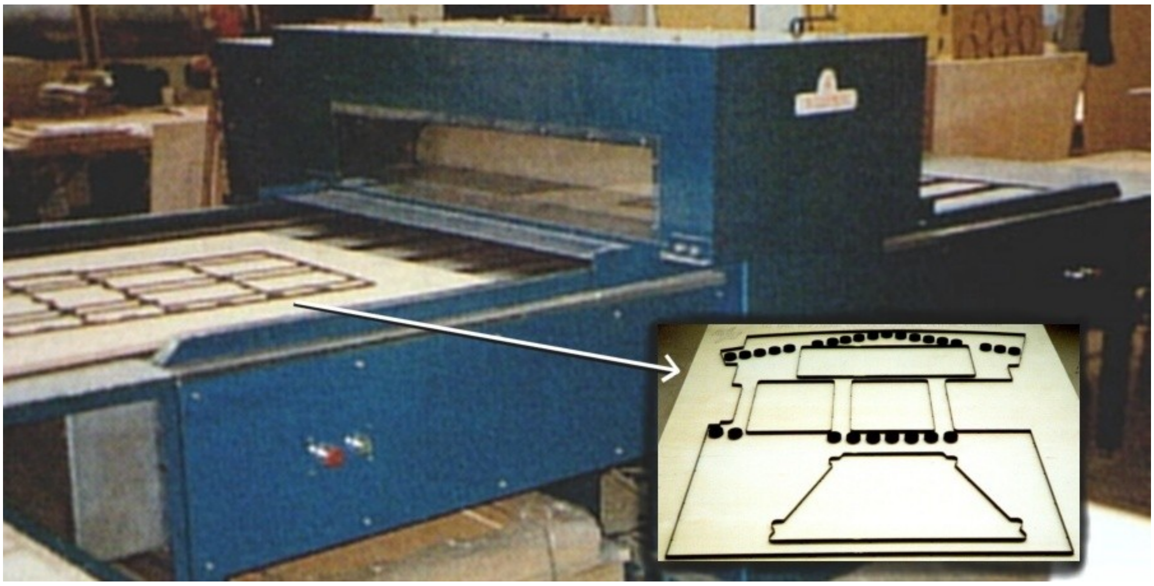


FIGURE 5.12. CUTTING FORM AND FIXTURE.

This company has a strong relation to its customers, who require custom designed solutions, and to its long-term suppliers, who provide the cutting blades and are often involved in the design of new solutions. The process of creating a new cutting solution is a collaborative practice involving actors from the extended enterprise: the customer who specifies the requirements to be met, the company who design the solution, and the supplier who provides some of the parts and suggestions on how to use them.

The process of creating a new cutting solution starts with a customer's request with some specifications, which are forwarded to the product development. The design department works on devising a solution in collaboration with the customer and the suppliers. The solution is produced and assembled. This production step is the development of the form, which is the base on which the cutting blades, rubbers, punches etc. are placed. The forms can be cylindrical (rotary cutting) or flat (flatbed cutting). Once the solution is fully implemented, it is tested and refined and finally delivered.

The enterprise was modelled focusing on the product parts, which represent the products used (e.g. cutting blades) and assembled to produce the final cutting solution. The processes of this model are not very detailed and almost match the company's departments (design, testing etc.). The extended enterprise is very important in this test case, since the model includes companies that supply the cutting blades and the companies that buy the cutting solutions. Therefore, the actors of the extended enterprise and their respective expertise are very important in this model. The production units of this model are almost nonexistent and represent tools such as CAD system, or screwdriver. These production units were modelled mainly as a company's exercise of achieving a complete extended enterprise model, but they were not really used in this application.

This company wanted to reduce the time needed to design a new cutting solution, by re-using information from similar previous projects. To achieve this, problems were interpreted as requirements from the customers, specifying the solution needed. The description of the requirement included specifications to be met (e.g. number of items to be cut per hour, dimensions etc.) were modelled as state items and attached to the requirements as future state items (using the constructs for actual state items specified in the enterprise model). During the process of designing the new solution, i.e. solving the requirement, the group of actors involved could contribute with ideas for the design process. The employees could use CBR to identify similar previous design processes (of similar cutting solutions) to re-use ideas and solutions.

The company used the model and the CBR approach to support the design of new products. The approach allowed the company to better structure customer requirements, allowing for an efficient re-use of information. The time needed to develop a new solution was reduced together with the amount of iterations needed between the company, the customer and the suppliers. In addition, the approach tested fostered an improved involvement of the employees in the design process, increasing their participation and motivation in the company's processes and strategy.

Figure 5.13, Figure 5.14 and Figure 5.15 display some examples of entities modelled for this engineering services company, namely, product parts, problem types and actions.

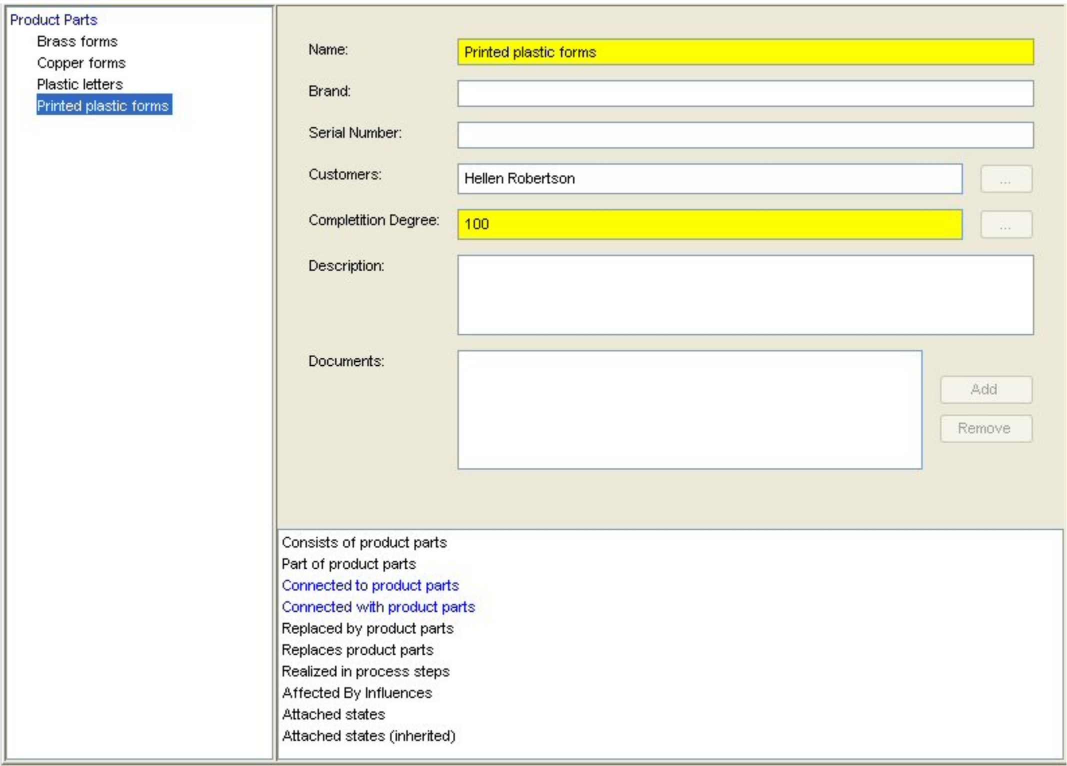


FIGURE 5.13. PRODUCT PARTS MODELLED IN ENGINNERING SERVICES COMPANY 1.

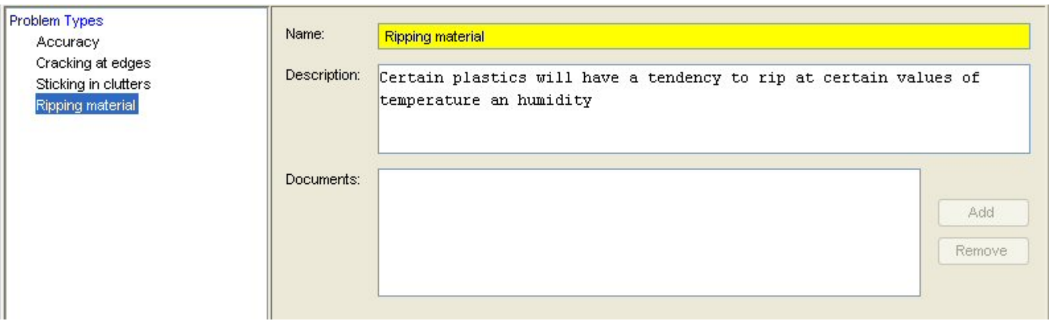


FIGURE 5.14. PROBLEM TYPES DEFINED FOR ENGINEERING SERVICES COMPANY 1.

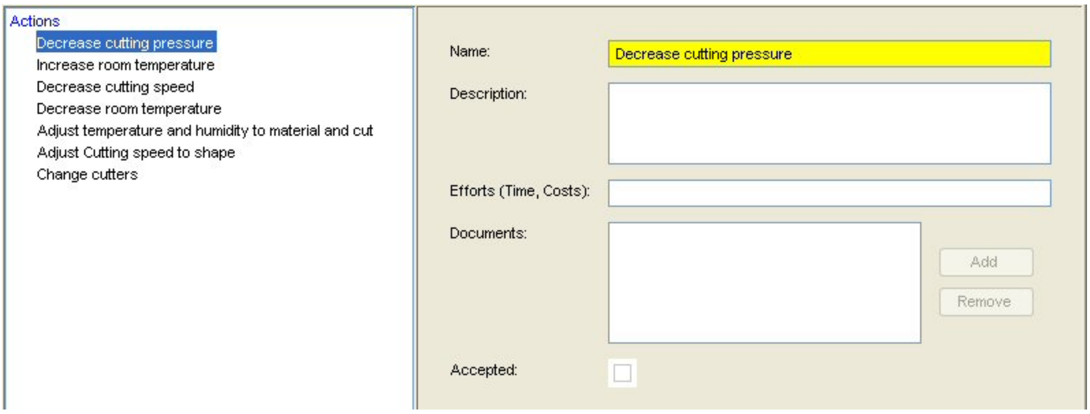


FIGURE 5.15. ACTIONS DEFINED FOR ENGINEERING SERVICES COMPANY 1.

This company tested the approach proposed for a period of 17 months. Table 5.6 summarises the test results obtained in this test case, registering both technical and business metrics.

TABLE 5.6. RESULTS FROM TESTS IN ENGINEERING SERVICES COMPANY 1.

Metric description	Result achieved
Increase the number of ideas generated by the company for new products	ca. 100%
Reduction of average time spent to design new solution	ca. 45%
Increase the number of times information is re-used	ca. 75%
Reduction of time spent in iterating information with customer and/or supplier	ca. 50%

The second company provides engineering services and equipment to industry, particularly using compressed air technology. The company specialises in the field of compressed air, material handling, power tools, pneumatic and product finishing systems. The service and technical teams of the company provide customised maintenance solutions to meet clients' needs. This also includes energy conservation programmes designed to achieve better equipment efficiency with optimum systems distribution and production needs evaluations.

The service provided includes consultation, design, proposal, supply, installation, commissioning, maintenance and aftercare. This company focus on innovative solutions that meet the customer requirements but also save resources.

The company receives a scenario from a customer, e.g. regarding a compressed air system for spray painting, detailing objectives to be met (i.e. in measurable terms, such as parts to be painted per minute or hour). The company studies the scenario, reviews commercial products and develops a solution. This process involves working with the suppliers to put together an engineering solution with a compressed air system for spray painting, for example (see Figure 5.16). Such system uses an air compressor, spray guns, nozzles, all of which are bought to suppliers. The company develops the specifications and assembles all parts together. Afterwards, if the solution is accepted by the customer, the company buys the necessary products, builds the system and installs it at the customers' site.

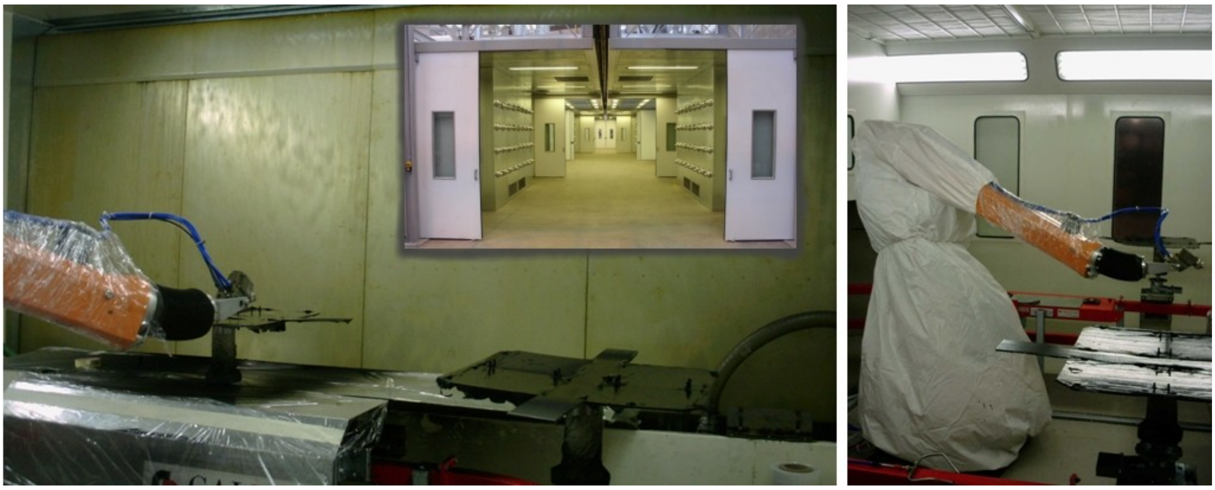
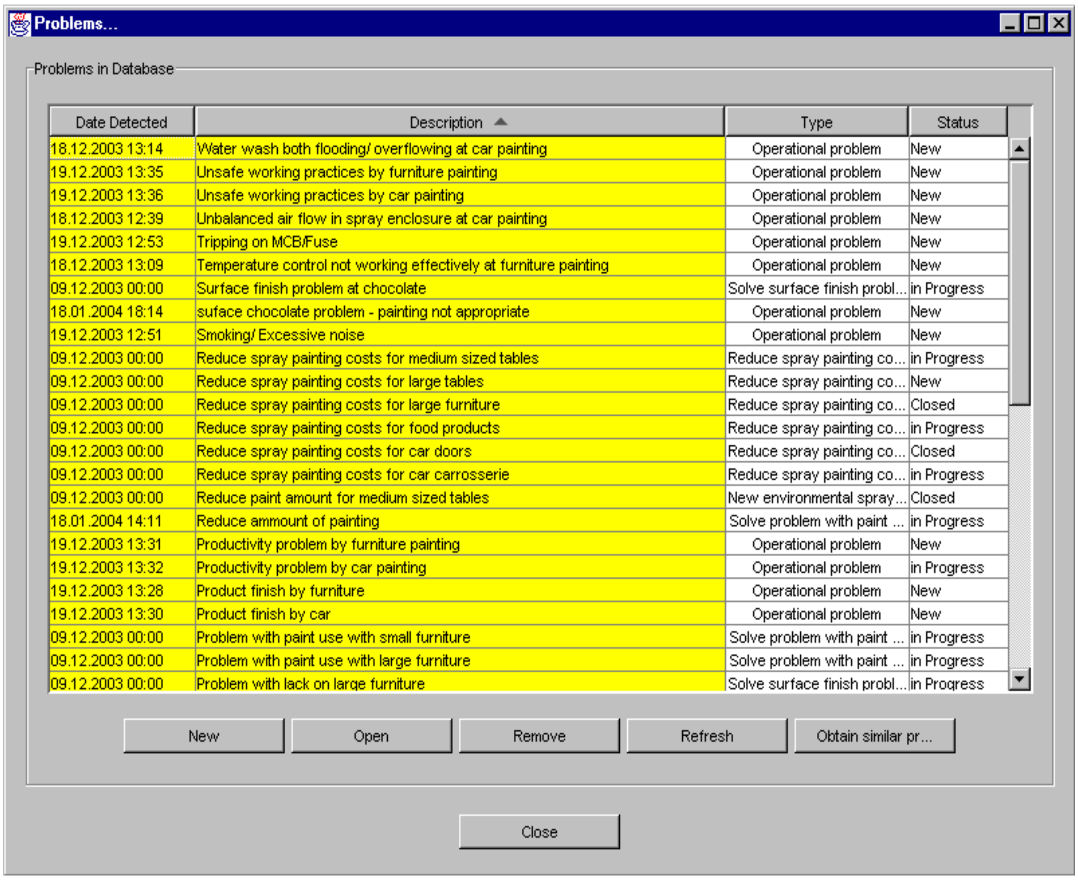


FIGURE 5.16. EXAMPLE OF A CUSTOMISED SPRAY PAINTING SOLUTION.

This test case also focuses on product parts, which are bought and assembled to provide the engineering solution. These product parts are modelled in detail, using fully the hierarchy provided in the enterprise model. Another important aspect is modelling the other companies in the extended enterprise, i.e. the customers who request the solutions and the suppliers who provide parts. The connection between parts and suppliers is very important, to enable collaboration among the different actors of the extended enterprise. Process steps and production units are not relevant and very simple, such as design, test, screw driver, etc. Similar to the previous test case, the objective of this company is to collect information and knowledge that can be re-used in future situations, especially when they involve similar products or solutions. In this model, the solution requests, specified by customer, are an interpretation of problems, which include measures to be achieved, modelled as state items. Each new customer request is modelled as a new "problem" with products involved and goals to be achieved. The company can then use CBR to search for previous similar situations and try to re-use or adapt previous solutions.

One of the main objectives of this company was to achieve an appropriate way to register problems and customer requests in a structure that allowed efficient re-use. This goal was considered successfully met by the approach tested. The approach also enabled to strengthen and tighten relations with customers and suppliers, allowing them to have a more active role in designing the engineering solutions. The company managed to achieve products with higher quality, but whose design consumed less time. Overall, the company feels that these benefits contributed to improve its brand image.

Figure 5.17 represents a list of examples of problems registered in this company, and Figure 5.18 displays the analysis performed by the CBR approach to diagnose the cause of one problem.



Date Detected	Description	Type	Status
18.12.2003 13:14	Water wash both flooding/ overflowing at car painting	Operational problem	New
19.12.2003 13:35	Unsafe working practices by furniture painting	Operational problem	New
19.12.2003 13:36	Unsafe working practices by car painting	Operational problem	New
18.12.2003 12:39	Unbalanced air flow in spray enclosure at car painting	Operational problem	New
19.12.2003 12:53	Tripping on MCB/Fuse	Operational problem	New
18.12.2003 13:09	Temperature control not working effectively at furniture painting	Operational problem	New
09.12.2003 00:00	Surface finish problem at chocolate	Solve surface finish probl...	in Progress
18.01.2004 18:14	suface chocolate problem - painting not appropriate	Operational problem	New
19.12.2003 12:51	Smoking/ Excessive noise	Operational problem	New
09.12.2003 00:00	Reduce spray painting costs for medium sized tables	Reduce spray painting co...	in Progress
09.12.2003 00:00	Reduce spray painting costs for large tables	Reduce spray painting co...	New
09.12.2003 00:00	Reduce spray painting costs for large furniture	Reduce spray painting co...	Closed
09.12.2003 00:00	Reduce spray painting costs for food products	Reduce spray painting co...	in Progress
09.12.2003 00:00	Reduce spray painting costs for car doors	Reduce spray painting co...	Closed
09.12.2003 00:00	Reduce spray painting costs for car carrosserie	Reduce spray painting co...	in Progress
09.12.2003 00:00	Reduce paint amount for medium sized tables	New environmental spray...	Closed
18.01.2004 14:11	Reduce ammount of painting	Solve problem with paint ...	in Progress
19.12.2003 13:31	Productivity problem by furniture painting	Operational problem	New
19.12.2003 13:32	Productivity problem by car painting	Operational problem	in Progress
19.12.2003 13:28	Product finish by furniture	Operational problem	New
19.12.2003 13:30	Product finish by car	Operational problem	New
09.12.2003 00:00	Problem with paint use with small furniture	Solve problem with paint ...	in Progress
09.12.2003 00:00	Problem with paint use with large furniture	Solve problem with paint ...	in Progress
09.12.2003 00:00	Problem with lack on large furniture	Solve surface finish probl...	in Progress

FIGURE 5.17. LIST OF PROBLEMS FROM ENGINEERING SERVICES COMPANY 2.

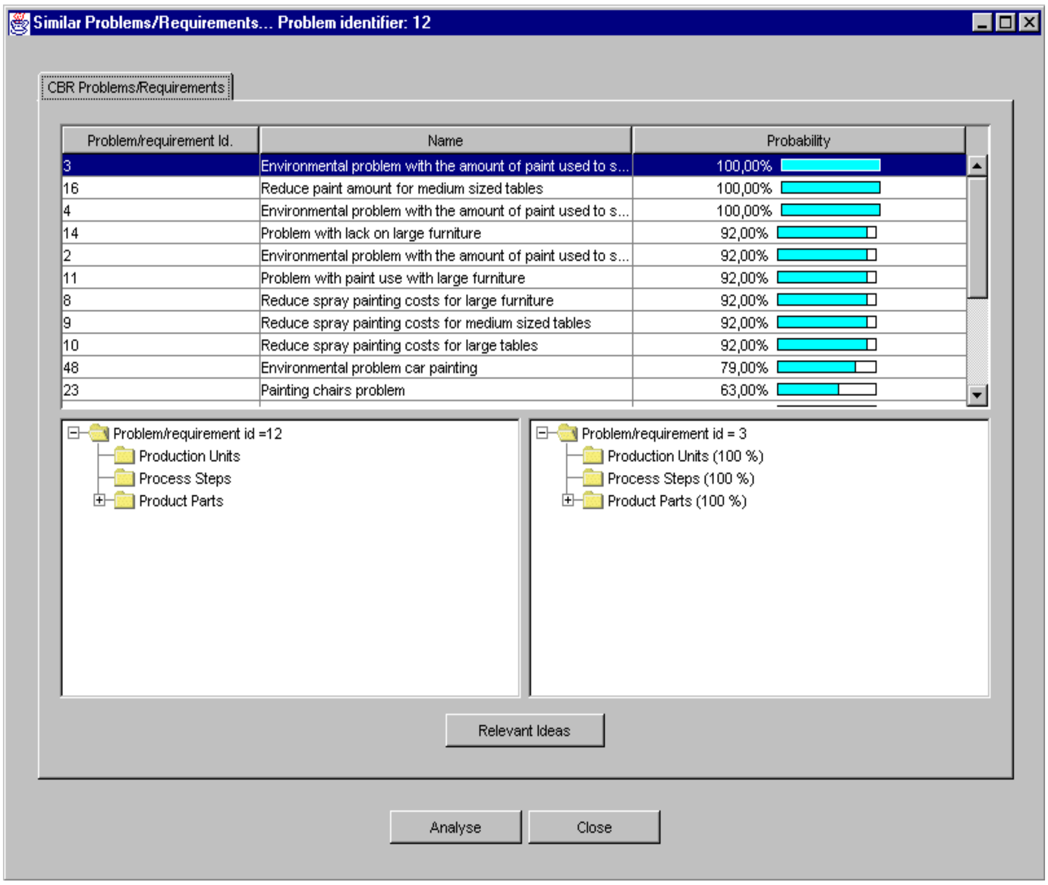


FIGURE 5.18. CBR ANALYSIS OF PROBLEMS FROM ENGINEERING SERVICES COMPANY 2.

This company tested the proposed approach during 17 months. The results achieved in the tests performed in this company are summarised in Table 5.7.

TABLE 5.7. RESULTS FROM TESTS IN ENGINEERING SERVICES COMPANY 2.

Metric description	Result achieved
Increase the number of ideas generated by the company for new products	ca. 100%
Increase number of ideas provided by customers and/or suppliers	ca. 50%
Reduction of average time spent to design new solution	ca. 35%
Reduction of time and efforts to solve a problem when designing a new product	ca. 40%

The two engineering solution companies provide custom-made solutions to their customers, based on specifications and requirements provided. Both companies were looking for support in making their design processes more structured and efficient, especially by re-using past information. The two companies were modelled with a strong focus on product parts, representing both components bought and the final products developed. In addition, these two engineering companies have models with the spotlight on the extended enterprise components. For both companies, the relations with customers and suppliers are very important, as well as the relations between the physical elements of the engineering company (the product parts) and the other companies of the extended enterprise.

Both companies were modelled following the extended enterprise model proposed in chapter 2 Enterprise model. The same constructs were used to model these companies and all the previous ones. However, these engineering companies have a stronger focus on the other companies of the extended enterprise, when compared with the manufacturing companies. In addition, these companies required a “re-interpretation” of problems defined in the enterprise model. In the manufacturing and assembling companies, problems are malfunctions or anomalies that occur in processes or products of the extended enterprise. Here, problems are faced as requirements to be met by some product that has yet to be designed or developed.

5.4. SOFTWARE COMPANY

Some of the work presented in the previous chapters of this thesis was also applied in an information technology system and service provider, which delivers complete information and communication technology (ICT) systems to its customers. This company specifies and develops the software solutions, but also overtakes the complete installation and maintenance. The solutions provided include network infrastructure, specific hardware, customised market available software systems, customer specific software, and all related training and on-line support. This company also overtakes the systems installation at the customers’ sites and their complete maintenance. One of the company’s objectives is to provide a high quality after sales service, contributing to long term customers. Therefore, reaction time to solve a problem and minimisation of problems occurred are important aspects of the company’s operation.

The objective of this company is to improve customer support, by providing the best maintenance service possible. In order to achieve this, it is essential for the company to have an efficient problem solving process. The company chose one of its most important products to test the approach proposed in this thesis: an ICT system for reservation, booking and selling of tickets for passenger ships (see Figure 5.19). This ICT system is used in several customers, and its booking activities occur mainly 1 or 2 hours before the ship’s departure. System failures or any performance degradation during this time are critical and require immediate reaction by the company maintaining the ICT system.

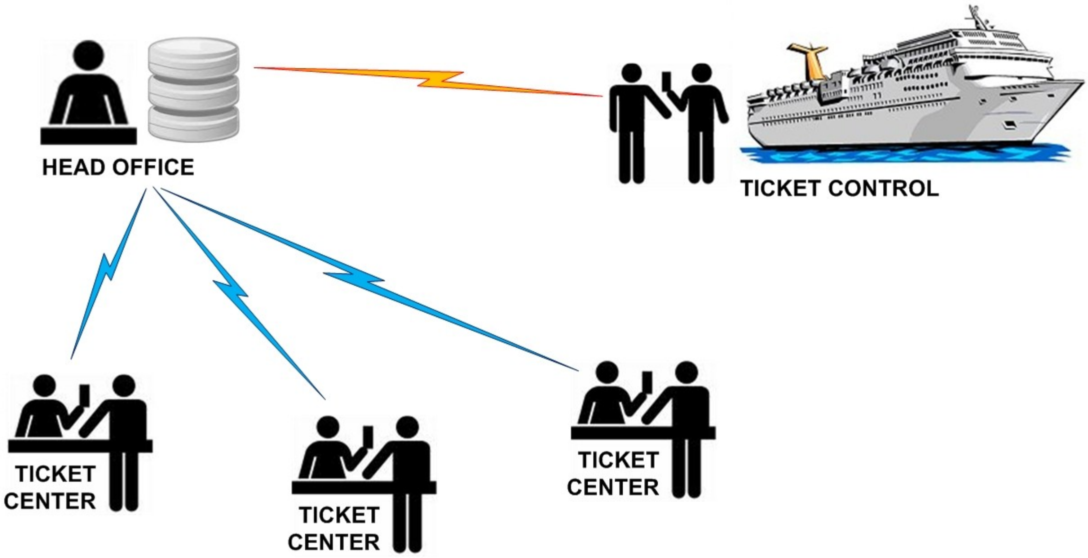


FIGURE 5.19. OVERVIEW OF RESERVATIONS ICT SYSTEM.

The company wanted to record problems that occur at their customer, the shipping company, where their product is installed. This approach is different from the manufacturing companies, for example, who were recording problems occurring in-house. According to this, this test case has a significant component on the extended enterprise, with the need to model this company and its customers, as business units. The problems occur at the customer companies, when they are operating their daily processes. In the model developed, the product parts, production units and process steps are spread throughout the extended enterprise, and do not belong to the same company. With the objective of modelling what happens in the customer's operation, the process steps of the ICT company are actually not important. The focus is on maintenance provided by the ICT company, and all its other process steps are not involved. Therefore, the model has to include instead the process steps of the customer, which are in this case, reserving, booking, selling, printing ticket etc. The model allows each process step to belong to one business unit, which defines the relation between the process step and the company operating it. These process steps use a production unit, i.e. a tool, which is the software system provided by the ICT company. While this software system is a product of the ICT company, it is a production unit of the customer. The software may not be a typical tool, but it is a utensil needed for the customer to fulfil a process step. The product parts of this model are the tickets issued and printed by the shipping company.

This approach allows modelling how different instances of the same software system (production unit) are used in different process steps, of different customers (business units). The software company uses the model to centralise all the information about problems occurred with their software product, independent of the customer where they are installed. This allows the company to re-use knowledge among customers and even prevent the occurrence of problems in some customers, based on problems that occurred in other customers. In addition, the ICT company can use information about problems to continuously improve their products.

The company tested the CBR approach to support problem solving during a period of 17 months. The CBR was actually used by the customers also, trying to identify causes for problems and solving the situations themselves. One of the objectives of the ICT company was to try to increase the customers' autonomy and reduce the need for one of their employees to personally diagnose and solve all problems. The approach tested allowed customers to obtain quick suggestion on what could be the cause for a problem and what to do to fix it. The cases used by CBR were all the problems collected in all the customers, but the information displayed was filtered to ensure privacy of each customer. Table 5.8 lists some examples of problems registered and diagnosed with the proposed approach.

TABLE 5.8. EXAMPLES OF PROBLEMS IN SOFTWARE COMPANY.

Problem description	Problem type	Production Unit	Cause
Printing failure, no ticket printed	No printing produced	Booking system Printer	Cartridge empty
Printing failure, ticket faulty	No printing produced	Booking system Printer	Inappropriate paper
Printing failure, no ticket printed	No printing produced	Booking system Printer	Network connection off
Printing failure, ticket faulty	No printing produced	Booking system Printer	Inappropriate paper
Printing failure, no ticket printed	No printing produced	Booking system Printer	Wrong printing configurations
Not possible to reserve seats	No booking	Booking system PC client	Boat configuration missing
Boarding not possible	No boarding	Booking system Infrared reader	Infrared reader not working
Boarding not possible	No boarding	Booking system Infrared reader	Boarding list is missing

The results achieved in this test case are summarised in Table 5.9.

TABLE 5.9. RESULTS FROM TESTS IN SOFTWARE COMPANY.

Metric description	Result achieved
Reduction of resources to support a product	ca. 25%
Reduction of customer complaints about products	ca. 50%
Increase problem solving actions performed by the customer	ca. 35%
Reduction of number of re-occurrences of a problem	ca. 40%

5.5. REMARKS

This chapter described the application of some of the work presented in the previous chapters of this thesis in seven industrial companies. The objective was to illustrate the applicability of the approaches from this thesis and demonstrate its versatility in real industrial environments. This section summarises the results achieved, highlighting commonalities and differences among the test cases.

The seven companies had the objective of having an appropriate framework to support their problem solving processes, in the scope of maintenance and design of new products. The two manufacturing companies and the first assembling company focused on problems occurring during their production processes, trying to minimise downtime of machines and increasing efficiency of production. The second assembling and the software companies focused on remote maintenance, i.e. in solving problems that occurred in products they had installed at their customers' sites. The two engineering services and the second assembling companies focused on supporting problem solving during the design process, i.e. while creating new solutions or products.

The enterprise model proposed in chapter 2 Enterprise model was used in the seven test cases, without modifying any construct. Some test cases required a slightly different interpretation of some constructs, but their structure, attributes and relations were still valid. For example, to support design, problems were interpreted as requirements, but the construct was exactly the same used in problem solving. The main focus of the models defined in the seven test cases is different. The two manufacturing companies, aiming at solving in-house problems in their manufacturing plants, focused on production units and process steps. The first assembling company, also seeking to solve in-house problems in their production sites, focused on processes and product parts, while production units were almost irrelevant due to the lower level of automation in the production. The two engineering services companies, wanting to support problem solving in developing new engineering solutions, focused on customers, requirements and product parts. The second assembling and the software companies, aiming at solving customers' problems, focused on product parts.

These seven industrial test cases focused on two different business applications: maintenance and design. These two applications validate that the decision approach presented in this thesis is valid for different situations. The proposed approach uses two methods, CBR and AHP, and the combination of both, to support industrial decision-making processes. The choice of the most appropriate method to support a decision process is tightly connected to the type of decision. The two applications mentioned in the test cases, maintenance and design, represent, quite often, very different situations. Maintenance decisions are usually routine situations that involve one actor, or a very small team, and demand an urgent answer. If a machine suddenly stops a manufacturing or assembly process, it has to be re-started as soon as possible, to avoid prohibitive penalties in the companies. A design process is generally a process that involves a larger and more diverse team, combining several departments and expertise within an extended enterprise, and lasts several days, weeks, months or even years, according to the complexity of the product. However long the design process may be, companies prefer it to be thoughtful and strategic, rather than urgent and rushed. Therefore, the two applications showcased in this chapter, represent different teams and especially different time operations and urgency levels. These considerations have to impact on the most appropriate approach to support the respective decisions.

The CBR approach is used to support maintenance applications, where problems are often a re-occurrence of past situations that demand an urgent answer. One actor or a small team can rapidly access a similar previous situation and adapt the solution implemented before, trying to solve and eliminate the problem as soon as possible. The AHP approach is used to support decisions in the scope of design processes, because they involve multi-disciplinary teams that have to combine their different perspectives taking the necessary time to do it. Design processes are usually integrated in the company's strategy, which makes their documentation highly important.

In the test cases presented in this chapter, CBR was used as support for maintenance problem solving in five test cases and as support for design problem solving in two cases. The two services engineering companies develop solutions in very specific areas of expertise, which allows them to highly re-use partial and sometimes complete solutions. Therefore, these two test cases were able to use CBR as support for problem solving in design. However, the proposed approach grew to include AHP and its combination with CBR, which provides a better support for design situations. The second assembling company has used the combination of CBR and AHP to support design, overcoming the bottlenecks of the two methods individually.

In all test cases, the companies selected the parts of their extended enterprises to model, in order to showcase potential benefits that could be presented to the management or business partners.

Most of these companies operate several information and communication technology systems, with different purposes, such as resource planning, invoicing etc. The information needed for the model existed in the companies, dispersed in these systems and in the form of manuals (e.g. problem causes) and employees' expertise.

The seven companies appreciated the result of having a systematic approach to support decision processes that enables a high level of accountability among the actors and enables repeatability. This approach gives companies the tools to repeat successful situations and analyse unsuccessful ones to learn how not to repeat them. Moreover, the seven companies also highlighted the importance of centralising a model of their enterprises in one single "place". The model describes all the main objects in the enterprises, and particularly their connections. This model enables not only the tested approach for decision support, but also the possibility of building any other applications on top of the same model.

6. CONCLUSIONS AND FUTURE WORK

The objective of this thesis is to contribute to support decision-making process in industrial environments, particularly the ones that involve several actors, which are designated by collaborative decision-making. Industrial companies need a systematic approach to support decision-making, allowing them to replicate successful decisions and avoid unsuccessful ones. In addition, industrial companies always impose requirements on accountability and responsibility of any action within their extended enterprises. These requirements are the reason for the emphasis of this thesis on human aspects. The decision support approach proposed in this work is strongly human-centric and does not aim at replacing the decision-maker. The methods proposed have the objective of supporting the human actor in collecting, gathering, comparing and analysing information, to enable the actor to make the best-informed decision.

One of the most problematic issues in industrial companies relates to how to represent and store information and knowledge, which is needed for daily activities. It is quite often to find references, in literature, to knowledge acquisition as the bottleneck for the full application of knowledge management and expert systems in industrial and business environments. Actually, the problem starts with the lack of a model that companies can use to represent their business. This thesis includes a survey of existing modelling methodologies, which are conceptual modelling techniques for describing the structure and business processes of an enterprise. Additionally, it includes a review of existing modelling standards currently used to try to unify approaches in enterprise engineering and integration. It proposes a new enterprise model to represent extended or virtual enterprises and enable several applications, particularly problem solving and decision support. The proposed model includes a set of constructs that companies should model to achieve an appropriate representation of their operations, resources and business. A modelling methodology to help industrial companies in modelling their extended enterprises with limited support from knowledge modelling experts can, as well, be found. The information represented in the enterprise model relates to the companies, so their actors should be in charge of the modelling process, instead of external persons. The proposed modelling methodology includes a set of steps to help users in gathering the necessary information to model their enterprise and includes supporting tools, such as a checklist or questionnaire for interviews.

Companies face decisions every day, with increasingly complex situations and increasingly larger and more distributed teams involved. Research laboratories, consultants and software companies use a wide range of designations for tools and/or methods that aim at supporting decision-making. This work includes a study of existing methods to support decision-making, trying to highlight research work developed. Additionally, it comprises a survey of systems to support decision-making, clarifying the several terms used in literature, their commonalities and differences. Additionally, there is a summary of industrial practices on decision-making processes, trying to identify trends regarding methods and approaches used. This work used questionnaires and interviews with industrial companies performed by the author. From these contacts and additional experience, it was possible to elaborate a list of general criteria that can be applied in a wide range of decision situations. These criteria were represented in a hierarchical form to enable a better analysis and divided into costs and benefits.

Problem solving is a relevant application field of decision-making in industrial environments. Companies need to register problems occurred internally in their processes and have a structured way to solve them. This thesis proposes a case-based reasoning (CBR) approach, which is based on the enterprise model previously presented. The CBR method uses the constructs of the enterprise model to register the cases used in the reasoning process. CBR compares two problems through the attributes of reporting actor, involved generics and actual state items. The proposed CBR approach uses a weight-sum metric to calculate the similarity between two cases, and a cosine similarity to calculate the similarity of involved generics and actual state items, because these attributes are defined by vectors in a tree hierarchy.

The Analytic Hierarchy Process (AHP) is a useful tool to support multi-attribute decision-making. In the scope of this work, the AHP is proposed to support solving problems that occur in the scope of innovation processes in industry. The main characteristic of this proposed AHP approach is the inclusion of a pre-defined hierarchy that can be applied in very diverse decision situations in industry. The hierarchy uses the criteria previously proposed, arranged in several levels. The decision-makers only need to revise the criteria suggested, adding or removing any necessary elements. Additionally, the team defines the alternatives and follows the approach proposed to select the best alternative.

Although both CBR and AHP have been successfully used in several applications, they have limitations. On one hand, when the repository of cases grows significantly, and contains many similar cases, the results from CBR becoming increasingly difficult to analyse. The human actor using the approach can receive a result of 20 similar problems that are very similar, or the human actor cannot properly analyse to select which one to adapt to the current situation. On the other hand, the AHP approach requires the definition of a hierarchy that represents the decision situation. This means that actors need to identify all the criteria to consider and the alternatives, from which the choice will be made. The current work proposes a list of criteria to be adapted to any decision situation, but it can be very difficult to identify all the alternatives to consider. When performing this analysis, it is possible to think that actors are not sure what to do with the similar cases provided by CBR and also do not know how to define the possible alternatives in AHP. Therefore, this thesis proposes a combination of these two methods, CBR and AHP, where the aggregated similar cases given by CBR are used as alternatives in the AHP. The main objective of this work is to overcome the shortcomings of both these methods and support decision-making in innovation situations in the most appropriate form. Using this approach, a human actor can document a problem occurred in the course of an innovation process, use CBR to obtain previous similar situations, and use AHP to select which of the similar cases is the best to follow on the current situation.

In collaborative decision-making, the focus is on the human actors that compose the decision team. It is possible that all actors have the same role in the company, or not. The role of the actor in a team is defined by a weight, having the weight of all actors in the team summing 1. How can companies establish such weights and, especially, how can they know they have defined the most appropriate weight for each actor? This thesis proposes an algorithm to adapt the weight of actors in a decision team, by using information from the implementation of the decision. This means that actors systematically involved in successful situations aligned with the company's strategy should probably have an increased role in the team.

The work presented in this document includes seven case studies that represent tests of some of the methods presented throughout the thesis. The seven test cases represent two manufacturing companies, two assembling companies, two services engineering companies and one software company. The enterprise model proposed was adapted and applied in the seven test cases, highlighting its adaptability and applicability. The model was used to support different applications, such as problem solving, innovation, remote maintenance etc., but always involving different steps of collaboration within the extended enterprises. The seven test cases also implemented and tested the CBR approach, in tight collaboration to the enterprise model, enabling an evolution of the method proposed throughout the testing period. One of the test cases also served to demonstrate a preliminary study of the applicability of AHP.

This thesis summarises an approach to support collaborative decision making in industrial environments. It is necessary to highlight that the proposed approaches are used to support the human actor and not replace it. As stated before, industrial companies are very keen on accountability and therefore they have problems accepting that a software system may be responsible for a decision in a company. The work developed has a theoretical component, of developing methods that may be applicable to industrial environments. However, it also comprehends a strong practical and empirical component, supported by the experience in several projects funded by the European Union, where the author had the change of developing knowledge management and expert systems for industrial environments. In this scope, it is necessary to emphasise that the introduction of any new system into a company is a very disruptive process. Researcher cannot forget this. There is usually a huge gap between research and its applicability in industrial environments. For example, while fields such as artificial intelligence are now developing very innovative methods and technologies (e.g. augmented reality), many companies still consider innovative to have one single enterprise model used by all its ICT applications. There is a lot of work to do to enable the full application of information systems in industry, especially in topics of knowledge acquisition and representation, considered very challenging.

The author is continuing its work in the topic of industrial information systems and decision support in industrial environments. Some of the topics in future work related to industrial information systems include the collection of data in non-intrusive ways, and semantic-based processing of collected data. Regarding decision support in industrial environments, the author is developing a method to represent a decision team in a hierarchical form and have a systematic approach to define the role of each actor in the team. Moreover, the approach based on the analytic hierarchy process will be adapted to support decision-making in the domain of energy efficiency.

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ANNEX A. MODEL SPECIFICATION

Construct template for Business Unit

	HEADER
Construct label	BU
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of Business unit, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
	BODY
Descriptives	
Description	short textual description of the Business Unit
Relationships	
Parent_Of	[<identifier> "/" <name>]● of Business Units that are children of this Business Unit instance
Child_Of	[<identifier> "/" <name>] of Business Unit that is the parent of this Business Unit instance
Part_Of	[<identifier> "/" <name>]● of Business Units that are part of this Business Unit instance
Consists_of	[<identifier> "/" <name>]● of Business Units that decompose this Business Unit instance
Responsible	[<identifier> "/" <name>] of Actor that is responsible or heads this Business Unit instance
Includes	[<identifier> "/" <name>]● of Actors that belong to this Business Unit instance
Controls	[<identifier> "/" <name>]● of Production Units that are controlled by this Business Unit instance
Assigns	[<identifier> "/" <name>]● of Process Steps that are allocated to this Business Unit instance
Owns	[<identifier> "/" <name>]● of Product Parts that are property of this Business Unit instance
Supplies	[<identifier> "/" <name>]● of Product Parts that are supplied by this Business Unit instance

Buys	[<identifier> "/" <name>]● of Product Parts that are sold to this Business Unit instance

Construct template for Actor

HEADER	
Construct label	AC
Identifier	<model-unique-string>
Name	[<noun>], the name of Actor, where <noun> indicates the surname
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
BODY	
Descriptives	
First name	[<noun>], the name of Actor, where <noun> indicates the first name of the person
Description	short textual description of the Actor
Username	the string to be used as username for this Actor
Password	the string to be used as password for this Actor
Relationships	
Belongs_to	[<identifier> "/" <name>] of Business Unit to which this Actor instance is allocated
Knows	[<identifier> "/" <name>]● of Technologies that define the expertise for this Actor instance
Responsible_for	[<identifier> "/" <name>]● of Business Units that are headed by this Actor instance

Construct template for Technology

HEADER	
Construct label	TE
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of Technology, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
BODY	
Descriptives	

Description	short textual description of the Technology
Documents	string with path for documents relevant to describe this Technology instance
Relationships	
Parent_Of	[<identifier> "/" <name>]● of Technologies that are children of this Technology instance
Child_Of	[<identifier> "/" <name>] of Technology that is the parent of this Technology instance
Known_by	[<identifier> "/" <name>]● of Actors that have knowledge about this Technology instance
Constrained_by	[<identifier> "/" <name>]● of State Items that restrain this Technology instance
Validated_by	[<identifier> "/" <name>]● of Nominal Values that are valid for this Technology instance
Includes	[<identifier> "/" <name>]● of Parameter Sets that belong to this Technology instance

Construct template for Production Unit

	HEADER
Construct label	PU
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of Production Unit, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
	BODY
Descriptives	
Description	short textual description of the Production Unit
Documents	string with path for documents relevant to describe this Production Unit instance
Serial number	textual information about the serial number of this Production Unit instance when it represents a specific machine
Relationships	
Parent_Of	[<identifier> "/" <name>]● of Production Units that are children of this Production Unit instance
Child_Of	[<identifier> "/" <name>] of Production Unit that is the parent of this Production Unit instance
Controlled_by	[<identifier> "/" <name>] of Business Unit that holds the responsibility for this Production Unit instance

Supplied_by	[<identifier> "/" <name>] of Business Unit that sold this Production Unit instance
Part_of	[<identifier> "/" <name>]● of Production Units that include this Production Unit instance, defining a decomposition
Consists_of	[<identifier> "/" <name>]● of Production Units that define the decomposition of this Production Unit instance

Construct template for Resource

	HEADER
Construct label	RE
Identifier	<model-unique-string>
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
	BODY
Descriptives	
Type	PU | AC
Relationships	
Is_PU	[<identifier> "/" <name>] of Production Unit that defines this Resource instance
Is_AC	[<identifier> "/" <name>] of Actor that defines this Resource instance

Construct template for Process Step

	HEADER
Construct label	PS
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of Process Step, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
	BODY
Descriptives	
Description	short textual description of the Process Step
Documents	string with path for documents relevant to describe this Process Step instance
Criticality	percentage of how critical this Process Step is for the whole production
Relationships	

Parent_Of	[<identifier> "/" <name>]● of Process Steps that are children of this Process Step instance
Child_Of	[<identifier> "/" <name>] of Process Step that is the parent of this Process Step instance
Assigned_to	[<identifier> "/" <name>] of Business Unit that holds the responsibility for this Process Step instance
Part_of	[<identifier> "/" <name>]● of Process Steps that include this Process Step instance, defining a decomposition
Consists_of	[<identifier> "/" <name>]● of Process Steps that define the decomposition of this Process Step instance
Enabled_by	[<identifier> "/" <name>]● of Parameter Sets that enable this Process Step instance
Uses	[<identifier> "/" <name>]● of Resources used in this Process Step instance
Realises	[<identifier> "/" <name>]● of Product Parts that result from this Process Step instance

Construct template for Product Part

HEADER	
Construct label	PP
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of Product Part, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
BODY	
Descriptives	
Description	short textual description of the Product Part
Documents	string with path for documents relevant to describe this Product Part instance
Brand	name of the brand of this product
Serial number	description of the serial number of this Product Part instance if it represents a specific physical product
Completion degree	percentage indicating the contribution to the end product
Relationships	
Parent_Of	[<identifier> "/" <name>]● of Product Parts that are children of this Product Part instance

Child_Of	[<identifier> “/” <name>] of Product Part that is the parent of this Product Part instance
Owned_by	[<identifier> “/” <name>] of Business Unit that holds the responsibility for this Product Part instance
Supplied_by	[<identifier> “/” <name>] of Business Unit that supplied this Product Part instance
Sold_to	[<identifier> “/” <name>] of Business Unit to which this Product Part instance is sold
Part_of	[<identifier> “/” <name>]● of Product Parts that include this Product Part instance, defining a decomposition
Consists_of	[<identifier> “/” <name>]● of Product Parts that define the decomposition of this Product Part instance
Connected_to	[<identifier> “/” <name>]● of Product Parts to which this Product Part instance is connected (backwards) to form an end product
Connected_with	[<identifier> “/” <name>]● of Product Parts to which this Product Part instance is connected (forwards) to form an end product
Replaces	[<identifier> “/” <name>]● of Product Parts that this Product Part instance can replace in case of stock rupture
Replaced_by	[<identifier> “/” <name>]● of Product Parts that can replace this Product Part instance in case of stock rupture
Realised_by	[<identifier> “/” <name>]● of Process Steps from which this Product Part instance results

Construct template for Generic

	HEADER
Construct label	GN
Identifier	<model-unique-string>
Authority	[[NIL | “:” <identifier> “/” <name>] [NIL | “:” <identifier> “/” <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
	BODY
Descriptives	
Type	PU | PS | PP
Relationships	
Is_PU	[<identifier> “/” <name>] of Production Unit that defines this Generic instance
Is_PS	[<identifier> “/” <name>] of Process Step that defines this Generic instance
Is_PP	[<identifier> “/” <name>] of Product Part that defines this Generic instance
Affected_by	[<identifier> “/” <name>]● of Influences that affect this Generic instance

Causes	[<identifier> "/" <name>]● of Influences that are caused by this Generic instance
Attached	[<identifier> "/" <name>]● of States that are attached to this Generic instance
Involved_in	[<identifier> "/" <name>]● of Problems in which this Generic instance is involved

Construct template for Influence

	HEADER
Construct label	IF
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of Influence, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
	BODY
Descriptives	
Description	short textual description of the influence
Significance	percentage indicating how much this influence can affect the generics
Relationships	
Caused_by	[<identifier> "/" <name>] of Generic that causes this Influence instance
Affects	[<identifier> "/" <name>]● of Generics that are affected by this Influence instance

Construct template for State

	HEADER
Construct label	ST
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of State, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
	BODY
Descriptives	
Description	short textual description of the State

Documents	string with path for documents relevant to describe this State instance
Relationships	
Parent_Of	[<identifier> “/” <name>]● of States that are children of this State instance
Child_Of	[<identifier> “/” <name>] of State that is the parent of this State instance
Attached_to	[<identifier> “/” <name>]● of Generic for which this State instance is valid
Includes	[<identifier> “/” <name>]● of State Items that are defined for this State instance

Construct template for State Item

	Header
Construct label	SI
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of State Item, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | “:” <identifier> “/” <name>] [NIL | “:” <identifier> “/” <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
	Body
Descriptives	
Description	short textual description of the State Item
Type	BOI | NUI | DAI | SYI | CHI
PLC name	identification of the controller that might provide this value
Mandatory	indication if this value is mandatory for a specific generic
Accuracy	percentage indicating the accuracy of the value, usually related to the measuring method
Measurability	percentage indicating the possibility of measuring this variable
Class	NORMAL | ERROR
Length	number of characters (only available for text state items)
Maximum	maximum value allowed (only available for numeric state items)
Minimum	minimum value allowed (only available for numeric state items)
Scale	number of total digits (only available for numeric state items)
Precision	number of decimal digits (only available for numeric state items)
Relationships	
Parent_Of	[<identifier> “/” <name>]● of State Items that are children of this State Item instance
Child_Of	[<identifier> “/” <name>] of State Item that is the parent of this State Item instance
Belongs_to	[<identifier> “/” <name>] of State to which this State Item instance belongs to

Constraints	[<identifier> "/" <name>]● of Technologies that are limited by this State Item instance
Defined_by	[<identifier> "/" <name>]● of Symbols that are valid for this State Item instance (only available for symbolic state items)

Construct template for Symbol

HEADER	
Construct label	SY
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of Symbol, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
BODY	
Relationships	
Valid_for	[<identifier> "/" <name>] of State Item for which this Symbol instance is valid for

Construct template for Nominal Value

HEADER	
Construct label	NV
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of Nominal Value, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
BODY	
Descriptives	
Description	short textual description of the Nominal Value
Relationships	
Valid_for_PM	[<identifier> "/" <name>] of Parameter Set for which this Nominal Value instance is valid
Valid_for_SI	[<identifier> "/" <name>] of State Item for which this Nominal Value instance is valid

Construct template for Parameter Set

<table>
<tr><th colspan="2">HEADER</th></tr>
<tr><td>Construct label</td><td>PM</td></tr>
<tr><td>Identifier</td><td><model-unique-string></td></tr>
<tr><td>Name</td><td>[<adjective> <noun> | <noun>], the name of Parameter Set, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope</td></tr>
<tr><td>Authority</td><td>[[NIL | “:” <identifier> “/” <name>] [NIL | “:” <identifier> “/” <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]</td></tr>
<tr><th colspan="2">BODY</th></tr>
<tr><td>Descriptives</td><td></td></tr>
<tr><td>Description</td><td>short textual description of the Parameter Set</td></tr>
<tr><td>Relationships</td><td></td></tr>
<tr><td>Belongs_to</td><td>[<identifier> “/” <name>] of Technology to which this Parameter Set instance belongs to</td></tr>
<tr><td>Enables</td><td>[<identifier> “/” <name>]● of Process Steps that are enabled by this Parameter Set instance</td></tr>
<tr><td>Includes</td><td>[<identifier> “/” <name>]● of Nominal Values for which this Parameter Set instance is valid</td></tr>
</table>

Construct template for Problem Type

<table>
<tr><th colspan="2">HEADER</th></tr>
<tr><td>Construct label</td><td>PT</td></tr>
<tr><td>Identifier</td><td><model-unique-string></td></tr>
<tr><td>Name</td><td>[<adjective> <noun> | <noun>], the name of Problem Type, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope</td></tr>
<tr><td>Authority</td><td>[[NIL | “:” <identifier> “/” <name>] [NIL | “:” <identifier> “/” <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]</td></tr>
<tr><th colspan="2">BODY</th></tr>
<tr><td>Descriptives</td><td></td></tr>
<tr><td>Description</td><td>short textual description of the Problem Type</td></tr>
<tr><td>Documents</td><td>string with path for documents relevant to describe this Problem Type instance</td></tr>
<tr><td>Relationships</td><td></td></tr>
<tr><td>Parent_Of</td><td>[<identifier> “/” <name>]● of Problem Types that are children of this Problem Type instance</td></tr>
</table>

Child_Of	[<identifier> "/" <name>] of Problem Type that is the parent of this State Item instance
Defines	[<identifier> "/" <name>]● of Problems that are defined by this Problem Type instance

Construct template for Cause

HEADER	
Construct label	CS
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of Cause, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
BODY	
Descriptives	
Description	short textual description of the Cause
Documents	string with path for documents relevant to describe this Cause instance
Relationships	
Parent_Of	[<identifier> "/" <name>]● of Causes that are children of this Cause instance
Child_Of	[<identifier> "/" <name>] of Cause that is the parent of this Cause instance
Causes	[<identifier> "/" <name>]● of Problems that are caused by this Cause instance
Eliminated_by	[<identifier> "/" <name>]● of Actions that have to be realised to eliminate this Cause instance

Construct template for Action

HEADER	
Construct label	AN
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of Action, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
BODY	
Descriptives	
Description	short textual description of the Action

Documents	string with path for documents relevant to describe this Action instance
Efforts	description of human efforts necessary to implement this Action instance
Resources	description of physical resources necessary to implement this Action instance
Sequence	indication of the implementation sequence of the Action, when several actions are needed
Relationships	
Parent_Of	[<identifier> "/" <name>]● of Causes that are children of this Cause instance
Child_Of	[<identifier> "/" <name>] of Cause that is the parent of this Cause instance
Defines	[<identifier> "/" <name>]● of Probable Causes that are defined by this Cause instance
Eliminated_by	[<identifier> "/" <name>]● of Actions that have to be realised to eliminate this Cause instance

Construct template for Problem

	HEADER
Construct label	PR
Identifier	<model-unique-string>
Name	[<adjective> <noun> | <noun>], the name of Problem, where <noun> indicates the functionality or purpose, and <adjective> optionally indicates the scope
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
	BODY
Descriptives	
Description	short textual description of the Problem
Documents	string with path for documents relevant to describe this Problem instance
Last process	description of the last thing done before the problem occurred
PLC report	XML file with a report from a PLC relevant for the problem
Downtime	numeric indication of any downtime caused by this problem
Status	CREATED | DESCRIBED | SOLVED | ELIMINATED
Date detected	date when the problem report was created in the knowledge base
Date created	date when the problem was detected in the installation
Date removed	date when the problem's cause was identified
Date eliminated	date when the actions to eliminate the problem were successfully implemented
Relationships	
Defined_by	[<identifier> "/" <name>] of Problem Type that defines this Problem instance
Caused_by	[<identifier> "/" <name>]● of Probable Causes that caused the occurrence of this Problem instance

Involves	[<identifier> “/” <name>]● of Generics that are involved in this Problem instance
Occurred_ABI	[<identifier> “/” <name>]● of Actual Boolean Items that were measured and registered during or shortly after the occurrence of the Problem instance in Generics involved in the Problem instance
Occurred_ACI	[<identifier> “/” <name>]● of Actual Char Items that were measured and registered during or shortly after the occurrence of the Problem instance in Generics involved in the Problem instance
Occurred_ADI	[<identifier> “/” <name>]● of Actual Date Items that were measured and registered during or shortly after the occurrence of the Problem instance in Generics involved in the Problem instance
Occurred_ANI	[<identifier> “/” <name>]● of Actual Numeric Items that were measured and registered during or shortly after the occurrence of the Problem instance in Generics involved in the Problem instance
Occurred_ASI	[<identifier> “/” <name>]● of Actual Symbolic Items that were measured and registered during or shortly after the occurrence of the Problem instance in Generics involved in the Problem instance

Construct template for Actual Boolean Item

HEADER	
Construct label	ABI
Identifier	<model-unique-string>
Authority	[[NIL | “:” <identifier> “/” <name>] [NIL | “:” <identifier> “/” <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
BODY	
Descriptives	
Value	TRUE | FALSE
Significance	significance of this value for the problem description
Timestamp	timestamp when the value was measured or read
Relationships	
Occurs_at	[<identifier> “/” <name>] of Problem when this Actual Boolean Item instance has occurred
Defined_by	[<identifier> “/” <name>] of State Item that defines this Actual Boolean Item instance (the State Item has to have type BOI)
Refers_to	[<identifier> “/” <name>] of State to which this Actual Boolean Item instance refers
Valid_for	[<identifier> “/” <name>] of Generic involved in the problem for which this Actual Boolean Item instance is valid

Construct template for Actual Char Item

	HEADER
Construct label	ACI
Identifier	<model-unique-string>
Authority	[[NIL | “:” <identifier> “/” <name>] [NIL | “:” <identifier> “/” <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
	BODY
Descriptives	
Value	text with the value for this Actual Char Item
Significance	significance of this value for the problem description
Timestamp	timestamp when the value was measured or read
Relationships	
Occurs_at	[<identifier> “/” <name>] of Problem when this Actual Char Item instance has occurred
Defined_by	[<identifier> “/” <name>] of State Item that defines this Actual Char Item instance (the State Item has to have type CHI)
Refers_to	[<identifier> “/” <name>] of State to which this Actual Char Item instance refers
Valid_for	[<identifier> “/” <name>] of Generic involved in the problem for which this Actual Char Item instance is valid

Construct template for Actual Date Item

	HEADER
Construct label	ADI
Identifier	<model-unique-string>
Authority	[[NIL | “:” <identifier> “/” <name>] [NIL | “:” <identifier> “/” <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
	BODY
Descriptives	
Value	timestamp with the value for this Actual Date Item
Significance	significance of this value for the problem description
Timestamp	timestamp when the value was measured or read
Relationships	
Occurs_at	[<identifier> “/” <name>] of Problem when this Actual Date Item instance has occurred

Defined_by	[<identifier> "/" <name>] of State Item that defines this Actual Date Item instance (the State Item has to have type DAI)
Refers_to	[<identifier> "/" <name>] of State to which this Actual Date Item instance refers
Valid_for	[<identifier> "/" <name>] of Generic involved in the problem for which this Actual Date Item instance is valid

Construct template for Actual Number Item

HEADER	
Construct label	ANI
Identifier	<model-unique-string>
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
BODY	
Descriptives	
Value	number with the value for this Actual Number Item
Significance	significance of this value for the problem description
Timestamp	timestamp when the value was measured or read
Relationships	
Occurs_at	[<identifier> "/" <name>] of Problem when this Actual Number Item instance has occurred
Defined_by	[<identifier> "/" <name>] of State Item that defines this Actual Number Item instance (the State Item has to have type NUI)
Refers_to	[<identifier> "/" <name>] of State to which this Actual Number Item instance refers
Valid_for	[<identifier> "/" <name>] of Generic involved in the problem for which this Actual Number Item instance is valid

Construct template for Actual Symbol Item

HEADER	
Construct label	ASI
Identifier	<model-unique-string>
Authority	[[NIL | ":" <identifier> "/" <name>] [NIL | ":" <identifier> "/" <name>]] of Actor or Business Unit respectively, having authority to design or maintain this particular instance]]
BODY	
Descriptives	

Significance	significance of this value for the problem description
Timestamp	timestamp when the value was measured or read
Relationships	
Defined_by	[<identifier> “/” <name>] of Symbol that defines the value for this Actual Symbol Item instance
Occurs_at	[<identifier> “/” <name>] of Problem when this Actual Symbol Item instance has occurred
Defined_by	[<identifier> “/” <name>] of State Item that defines this Actual Symbol Item instance
Refers_to	[<identifier> “/” <name>] of State to which this Actual Symbol Item instance refers
Valid_for	[<identifier> “/” <name>] of Generic involved in the problem for which this Actual Symbol Item instance is valid

ANNEX B. MODELLING METHODOLOGY TOOLS

Checklist to collect static data

- ✓ Business Units: companies and respective departments.
- ✓ Technologies: scientific topics that reflect expertise spread in the extended enterprise.
- ✓ Actors: people in the several companies and/or departments and their respective expertise.
- ✓ Production Units: tools used in the extended enterprise to support activities.
- ✓ Process Steps: activities of the extended enterprise, which transform an input to realise a product.
- ✓ Product Parts: products realised or used in the activities of the extended enterprise, which can represent anything from raw material to an end product.
- ✓ States: groups of characteristics valid for production units, process steps and/or product parts.
- ✓ State Items: individual variables that can be measured for a specific production unit, process step and/or product part.
- ✓ Influences: limitations that one physical element may have on others.
- ✓ Problem Types: list of typical problems that occur in the extended enterprise and can be used for classification of problems.
- ✓ Causes: List of causes that are identified for typical problems.
- ✓ Actions: List of actions to be implemented to remove a specific typical cause.

Questionnaire for semi-structured interview to employees

NOTE TO THE INTERVIEWER: The employees of industrial companies in extended enterprises are usually sceptic towards explicitly providing their knowledge and are generally busy people. During the interview, be cordial, direct and as succinct as possible. It is not mandatory to obtain all information in one single interview. The information obtained will be crossed with other sources and other exercises will follow to validate and complete the extended enterprise model. The questions in this interview are targeted at employees that have explicit and implicit knowledge about the processes of the extended enterprise. The objective is to acquire knowledge about their “environment” and not the whole extended enterprise.

1. Identify yourself and your job position.
2. Identify your department within the company.
3. With which other departments do you contact in the scope of your job?
4. Identify the people with whom you work and name their respective departments.
5. Can you describe the expertise needed for your job?
6. List the tools/machines you use in your daily job, and explain how and for what you use each of them.
7. Describe the measures that are possible to obtain for any machine or product in your department. Describe any controlling and/or automation infrastructure available in your department that can provide any of these measures.
8. List a list of typical problems that occur frequently in the processes where you work.
9. For each “typical problem”, describe the usual cause and what is done to fix it.

Questionnaire for semi-structured interview to managers

NOTE TO THE INTERVIEWER: Managers of industrial companies in extended enterprises are usually very busy people but have the ultimate responsibility to ensure the successful introduction of knowledge-based systems. Therefore, it is of their interest to collaborate to achieve the best enterprise model available. During the interview, be cordial, direct and as succinct as possible. It is not mandatory to obtain all information in one single interview. The information obtained will be crossed with other sources and other exercises will follow to validate and complete the extended enterprise model. This interview is targeted to managers of the extended enterprise, who have access to the “big picture”. This means that the questions are now directed to the whole enterprise and not to a specific department (in opposition to the previous interview).

1. Identify yourself and your job position.
2. Identify all departments within your company.
3. Identify the main customers, suppliers and other business partners of your company.
4. Name the person responsible for each company and department.
5. Describe the overall technical expertise available in the company.
6. (Show the list of all actors already identified in other interviews) Identify the department where each of these employees belongs.
7. Describe roughly the overall production/manufacturing/assembly processes in the company. Try to identify the output of each step, but mainly the finished products.
8. Identify which products are sold to which customers.
9. Identify which machines/tools are bought to each supplier.

DECISION-MAKING QUESTIONNAIRE

Please fill in the following information

Job title: ______________________________

Age: ☐ < 30 ☐ 31 – 45 ☐ > 46

Gender: ☐ Female ☐ Male

Department: ______________________________

Company Name: ______________________________

Company Type: (please select from below)

Non Manufacturing Companies

☐ Agriculture, hunting and forestry	☐ Fishing	☐ Mining and quarrying
☐ Electricity, gas and water supply	☐ Construction	☐ Wholesale and retail trade; repair of motor vehicles, motorcycles and personal and household goods
☐ Hotels and restaurants	☐ Transport, storage and communication	☐ Financial intermediation
☐ Real estate, renting and business activities	☐ Public administration and defence; compulsory social security	☐ Education
☐ Health and social work	☐ Other community, social and personal service activities	☐ Activities of households
☐ Extra-territorial organizations and bodies		

Manufacturing Companies

☐ Manufacture of food products, beverages and tobacco	☐ Manufacture of textiles and textile products	☐ Manufacture of leather and leather products
☐ Manufacture of wood and wood products	☐ Manufacture of pulp, paper and paper products, publishing and printing	☐ Manufacture of coke, refined petroleum products and nuclear fuels
☐ Manufacture of chemicals, chemical products and man-made fibres	☐ Manufacture of rubber and plastic products	☐ Manufacture of other non-metallic mineral products
☐ Manufacture of basic metals and fabricated metal products	☐ Manufacture of machinery and equipment n.e.c.	☐ Manufacture of electrical and optical equipment
☐ Manufacture of transport equipment	☐ Manufacturing n.e.c.	

1. Who makes decisions in your company? For each type of decision (indicated in the columns) select the actors involved in the decision-making processes (check all that apply for each type).

	Routine[1]	Emergency[2]	Strategic[3]	Operational[4]
Small senior group, including CEO or equivalent	☐	☐	☐	☐
Business unit leaders	☐	☐	☐	☐
CEO or equivalent	☐	☐	☐	☐
Frontline employees (e.g. shift leader)	☐	☐	☐	☐
Shop floor employees	☐	☐	☐	☐
Interdisciplinary teams	☐	☐	☐	☐
Other please specify: ______________________ ______________________ ______________________ ______________________	☐	☐	☐	☐

2. Is there a formal systematic approach in your company (e.g. a methodology) to be followed by everyone when making any decision? (If yes please indicate name)

☐ No ☐ Yes

Please specify: ________________________________

3. Each person has its own style of making decisions. Please rate the following issues taking into account the most dominant style in your department, or, if possible, company.

	Always	Often	Rarely	Never
Make conclusions based on hunches/hints	☐	☐	☐	☐
Analyse all individual issues to understand the global picture	☐	☐	☐	☐
Use imagination to create and foster new ideas	☐	☐	☐	☐
Use knowledge, ability and experience	☐	☐	☐	☐
Being driven by emotion or sensibility	☐	☐	☐	☐
Apply logic to reach conclusions	☐	☐	☐	☐

[1] The same circumstances repeat and when they appear, it is necessary to choose a proved course of action.
[2] Situations without precedent, often requiring immediate decisions following course of events; very time consuming.
[3] The most demanding type; implies strategic choices such as deciding on purpose and objectives and converting them into specific plans for the company or sub-decisions.
[4] Decisions are related to the regular running of the company, including hiring and firing employees (human resources); requires very sensitive handling.

4. Consider the culture, attitude, approach, and policy of your management's company towards employees. Classify as true or false the following sentences, describing your company's culture.

	True	False
New ideas are, quite often, refused or set aside.	☐	☐
All personnel is entitled to its autonomy and is able to show initiative.	☐	☐
The focus of the organisation is in facing and solving problems.	☐	☐
Stability and experience are the most valued attributes in the company.	☐	☐
The opinions and policies change frequently, according to the circumstances.	☐	☐
The command and control are the dominant process.	☐	☐
It is almost impossible to change the organisation's thinking process.	☐	☐
New and creative ideas are very welcome.	☐	☐
The organisation focus primarily on the clients needs.	☐	☐
The emphasis of the company resides in exploiting new opportunities.	☐	☐
Motivation and innovation are among the most important characteristics.	☐	☐
The objectives of the company and the individuals are tightly associated.	☐	☐
The organisation is not always driven by external needs.	☐	☐
The well-being of the company is above any individual success.	☐	☐

5. Indicate which of the following types of decision-making are used in your company. Please write numbers from 1 to 4 in each space, where 1 is *vital* and 4 is *irrelevant*.

	Routine	Emergency	Strategic	Operational
IRREVERSIBLE After the decision is made, it cannot be annulled.				
REVERSIBLE The decision can be completely modified, either before, during or after it is made.				
EXPERIMENTAL The decision is not final until the first test results are available and considered satisfactory.				
TRIAL AND ERROR Decisions are made, tried and adopted according to the course of actions.				
MADE IN STAGES Decisions are made in steps until the whole action is completed.				
CAUTIOUS The decision takes into account contingencies or problems which may occur later.				
CONDITIONAL The decisions can be modified if foreseen circumstances arise.				
DELAYED The decision is put on hold until the right moment; a				

go-ahead is given only when required elements are in place.				

6. When the decision-making process involves a team, please indicate how the team is formed by selecting all the actors usually part of the team.

	Always	Often	Rarely	Never
Employees from the department most affected by the decision.	☐	☐	☐	☐
Employees from other departments that have valuable expertise for the decision-making.	☐	☐	☐	☐
CEO or other equivalent senior management representative.	☐	☐	☐	☐
External consultants.	☐	☐	☐	☐
Other please specify: ______________________ ______________________ ______________________ ______________________	☐	☐	☐	☐

7. When the decision-making process involves a team, please indicate how the decision is made to consider inputs from all team members.

	Always	Often	Rarely	Never
Following the company's hierarchy. The most senior member makes the final decision.	☐	☐	☐	☐
The decision is made by voting, where each member has one vote.	☐	☐	☐	☐
The team has a special hierarchy created for the occasion. The team leader (not necessarily the most senior member of the company) makes the final decision.	☐	☐	☐	☐
The decision is made by consensus of all team members.	☐	☐	☐	☐
Other please specify: ______________________ ______________________ ______________________ ______________________	☐	☐	☐	☐

8. For the several types of decisions previously considered, indicate the criteria used when making the decision. Please write numbers from 1 to 4 in each space, where 1 is *vital* and 4 is *irrelevant*.

	Routine	Emergency	Strategic	Operational
Operational costs				
Short-term benefits				
Long-term benefits				
Return on investment				
Physical resources used				

	Routine	Emergency	Strategic	Operational
Human resources used				
Product/ service quality				
Manufacturing/assembly process efficiency				
Risk assessment				
Suppliers constraints				
Efforts to implement the decision				
Time necessary to make the decision				
Others (please fill in the rows)				

9. To make the decision, it is necessary to collect information and knowledge. Please rate the sources of information used by you and your company in decision-making processes.

	Always	Often	Rarely	Never
Company's library	☐	☐	☐	☐
Internal statistics	☐	☐	☐	☐
Financial forecasts from the company	☐	☐	☐	☐
Co-workers	☐	☐	☐	☐
Researchers in the company	☐	☐	☐	☐
Friends	☐	☐	☐	☐
External contacts	☐	☐	☐	☐
Competitors	☐	☐	☐	☐
Newspapers and journals	☐	☐	☐	☐
Seminars and workshops	☐	☐	☐	☐
Internet	☐	☐	☐	☐
Management	☐	☐	☐	☐
Academic experts	☐	☐	☐	☐
Consultants	☐	☐	☐	☐
Economic/ market studies	☐	☐	☐	☐
Other please specify: ____________________ ____________________ ____________________ ____________________	☐	☐	☐	☐

10. Once the information is collected, how is it used? Please specify how decision-makers base their evaluation and use the information available.

	Always	Often	Rarely	Never
Hierarchical ranking of the information source	☐	☐	☐	☐
Expertise of the person who provided the information	☐	☐	☐	☐
Experience of the person who provided the information	☐	☐	☐	☐
Consistency	☐	☐	☐	☐
Completeness	☐	☐	☐	☐
Uncertainty	☐	☐	☐	☐
Presentation	☐	☐	☐	☐
Other please specify: ____________________ ____________________ ____________________ ____________________	☐	☐	☐	☐