UNIVERSITE DE TUNIS
INSTITUT SUPERIEUR DE GESTION

Thèse présentée en vue de l'obtention du
Titre Docteur en Informatique de Gestion

A New Process-Based Approach for Implementing an Integrated Management System (QSE): Algorithms and Tools

Elaborée par:

Ahmed Badreddine

Dirigée par:

Dr. Nahla Ben Amor

12 Octobre 2012

Acknowlegments

I would like to thank my advisor Mrs Nahla Ben Amor for her patience in supervising this work in a concerned way. I would like to address special thanks for you, for your support, your advise, your productive comments and for the many hours spent helping this work. Thank you for your endless patience in improving my writing, for your comments on chapter drafts and for your great efforts to explain things clearly and simply.

I am also thankful to Mr Taieb Ben Romdhane from Institut National des Sciences Appliquées et de Technologie de Tunis, for replying me each time I asked him questions regarding integrated management system. And for his valuable contribution in all the stages of this work.

Thanks to all the members of my laboratory LARODEC in Institut Supérieur de Gestion de Tunis and to my friends for all good and bad times we get together.

Finally, I want to express my thanks and love to all my family and to all persons who love me. This work would not have been possible without your support.

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General Introduction

The evolution of the current industrial context and the increasing of competition pressure led the companies to adopt new concepts of management. This evolution started in 1994 with focusing on control, customers requirements and continuous improvement, which leads organizations to be more oriented towards the standard ISO 9001 [8]. Later, in 1996 the companies felt the need to consider the environmental requirements for civil society, which led them to focus on the environmental management system ISO 14001 [2]. Soon after, in 1999 the safety of peoples and goods became a major concern as result of recurrent industrial accidents such as Chernobyl and AZF explosions. For this reason OHSAS 18001 [3] was proposed as the basis for certification of occupational health and safety management.

Generally, the implementation of these standards is done separately which leads to a parallel management systems without any coordination and with several redundant procedures since the three standards (i.e. Quality, Security, Environment) share close management techniques and principles [98]. Hence, proposing an integrated management system (IMS) including quality, security and environment management systems, also known as QSE management system, have drawn the attention of both academics and practitioners who studied the integration of the three systems from various viewpoints.

The major problems with these approaches is that they remain ad-hoc and that they only propose a partial integration of the three systems. In fact, according to Jorgensen et al. [57], the total integration of the three systems is only ensured via three levels namely *correspondence*, *coordination* and *integration* which are ignored by the existing researches.

Thus, our first aim in this thesis is to propose a global approach ensuring a total integration of the three systems and overcoming the weakness of existing ones by including a set of guidelines and factors for a successful integration. More precisely, *risk management*, *process approach* and *monitoring system* are used in order to satisfy the three levels of integration proposed by Jorgensen et al. [57]. Our approach will be implemented around three phases of the PDCA scheme namely Plan phase, Do phase and Check and Act phase. This scheme is a standard ensuring the continuous improvement in quality systems.

The second main contribution of this work concerns the proposition of an effective implementation of the main three phases of our process-based approach.

PLAN PHASE: At this stage, the challenge is to identify the factors contributing to the non-achievement of the QSE objectives and to define the appropriate treatments. To this end, the *risk management* is used as an integration factor. The major problem is that the existing risk management tools are not appropriate to deal with several management areas simultaneously. In fact, they are limited to a unique management area and they are restricted to a unique level of risk which does not respond to our requirements regarding the global QSE management system. Thus, first an extended Fuzzy FMEA method [49, 19, 91, 94] is proposed to identify the most critical risks relating to each QSE objective.

Then, once the critical risks are selected, their evaluation is proposed in order to assist the decision maker to define the appropriate decisions relative to each risk. Our idea consists in defining the whole scenario of each identified risk using *bow tie diagrams* which are popular and diffused probabilistic risk analysis tools [30].

In order to overcome the subjective and technical aspect of these tools, generally based on the expert knowledge, a new approach is proposed to construct bow tie diagrams which better reflects the real behavior of exiting systems. Our idea is to view bow ties as particular Bayesian networks [81] and to use standard learning algorithms to build them.

DO PHASE: At this stage, the challenge is to define the appropriate management plans composed of a set of procedures and treatments able to ensure the achievement of the already fixed objectives while taking into consideration the interaction between the three management areas, since some decisions can be beneficial for some of them and harmful for others.

To deal with, bow tie diagrams generated in the previous phase are transformed into a multi-objective influence diagram (MID) [74], which is one of the most commonly used graphical decision models for reasoning under uncertainty, and to evaluate it to generate the possible management plans.

CHECK and ACT PHASE: At this stage the challenge is to ensure the continuous improvement of the performance by selecting and implementing the most appropriate management plan within those generated in the previous phase. To this end, the effectiveness of each management plan towards the QSE objectives is measured using a performance measurement system (PMS).

To deal with, the implementation of a PMS structured is proposed around two main phases: the design phase which concerns the identification of the performance structure and the exploitation phase to express the performance relative to each QSE objective.

This thesis is organized as follows:

- Chapter 1 *A New Process-Based Approach for Implementing an Integrated Management System (QSE)*: presents our new process-based approach for implementing an integrated management system (QSE).

- Chapter 2 *New Approach to Identify and Analyze Multi-Leveled Risks*: proposes a new approach to identify and analyze multi-leveled risks. This approach is an extension of the fuzzy FMEA.

- Chapter 3 *A Bayesian Approach to Construct Bow tie Diagrams for Risk Evaluation*: presents a Bayesian approach to construct bow tie diagrams for risk evaluation.

- Chapter 4 *A Multi-objective Approach to Generate Optimal Management Plans*: proposes a multi-objective approach to generate the optimal management plans in an IMS-QSE.

- Chapter 5 *Proposition of a Performance Measurement System*: proposes a performance measurement system relative to an integrated Management System QSE.

- Chapter 6 *Global Implementation of the Process-Based Approach for IMS-QSE: Real Case of Study in the Petroleum Field*: presents a global implementation of our approach with an illustration on a real case of study in the petroleum field (TOTAL TUNISIA).

Chapter 1

A New Process-Based Approach for Implementing an Integrated Management System (QSE)

1.1 Introduction

The past decade has seen the emergence of a three standards namely *ISO 9001* to meet the requirements of quality management system [8], *ISO 14001* to meet the requirements of environmental management system [2] and *OHSAS 18001* to meet the health and safety management [3]. The main tasks of these standards is to sets the goals and objectives, outlines the strategies and tactics, and develops the plans necessary controls relative to each management area.

The major problem with these three management systems is that they were proposed separately and thus their combination in the same organization is not an obvious task since they have common and confused procedures. Generally, parallel management systems are used, leading to separate and independent implementations of each system suffering from several weaknesses since they require many duplicate management tasks. In fact, the three standards share similar management techniques and principles such as formulating policies, defining roles and responsibilities, assigning management representatives and train personnel [98]. In practice, it has been proven to be difficult to deal with separate management systems covering quality, environment, and occupational health and safety and to ensure their alignment with the organization's strategy [48, 100].

Hence, proposing an integrated management system (IMS) including quality, environment and safety management systems also known as QSE management system has drawn the attention of both academics and practitioners. Existing researches studied the integration of the three systems from various viewpoints, including examining the possibility of integrating, analyzing the potential of it and exploring possible ways and criteria for its success. Nevertheless, a few studies have developed methodologies and approaches to implement an IMS.

This chapter proposes a new process-based approach of implementing an integrated management system (IMS), on the basis of three aspects used as integrated factors namely, risk management, process approach and a global monitoring system and satisfying the three integration levels defined by Jorgensen et al. [57], namely, correspondence, coordination and integration. The different steps of the proposed approach cover the whole PDCA (Plan, Do, Check, Act) scheme.

The remainder of this chapter is organized as follows: Section 2 gives a brief recall on the three management systems quality, security and environment. Section 3 presents the existing integrating management systems QSE. Section 4 presents the integrating factors used in our approach. Finally, section 5 presents our new process-based approach for implementing an integrated management system.

Main results presented in this chapter are published in [14, 16].

1.2 A brief recall on the three management systems Quality,Security, Environment(QSE)

This section gives a brief presentation of the three standards ISO 9001(resp. ISO 14001, OHSAS 18001) relative to the quality(resp. environment, security) management systems.

1.2.1 Quality management system (ISO 9001)

The ISO 9001 [8] is by far the world's most established quality framework, currently being used by around 897,000 organizations in 170 countries worldwide. The Quality management system, (QMS) may be defined as a formal set of policies and procedures that define how an organization will manage their production realization, in order to maximize the customers satisfaction and the efficiency of the organization.

The first two editions of the standard series ISO 9001, relative to the quality system, were published in 1987 and have been revised several times. The most important revision was done in 2000 and the most recent one in 2008 [8]. With these versions, the standard has moved from quality assurance (i.e. a set of procedures that check whether a product or service is being developed according to a specified requirements) to the quality management.

The quality management system (QMS) is based on eight principles namely *customer focusing*, *system approach*, *leadership*, *people*, *process approach*, *continual improvement*, *factual approach*, *supplier relationship* [8].

Figure 1.1 shows the continual improvement of the QMS which is a process-based approach based on four processes detailed as follows:

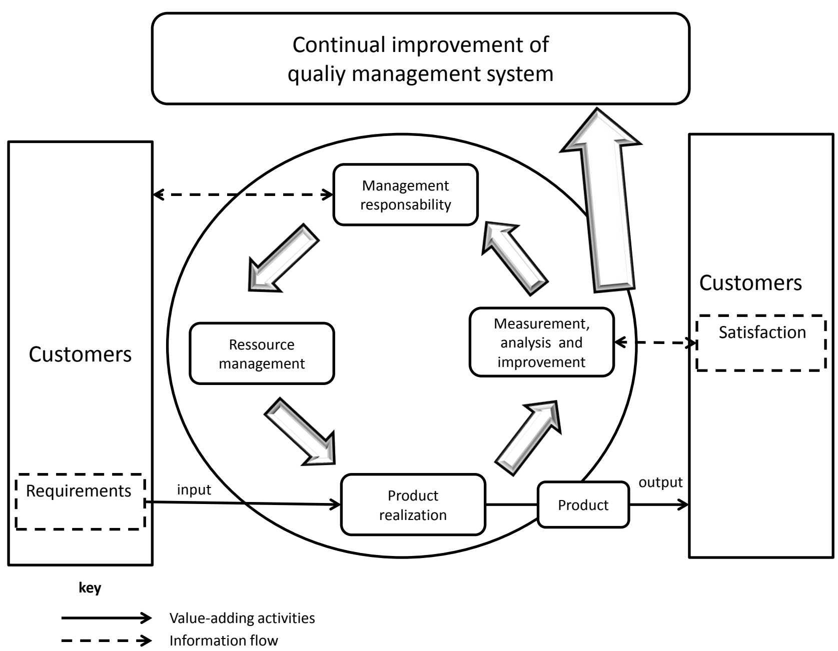

Figure 1.1: Model of process-based quality management system [8]

- *Management responsibility process* ensured via six main steps:

1. **Management commitment**: In this step, the standard requires that top management provides evidence for their commitment through communications within the organization by communicating the importance of requirements, establishing quality policy, establishing quality objectives, conducting management reviews, ensuring the availability of necessary resources and appropriate training.
2. **Determining customer requirements**: In this step, the direction ensures that stakeholder's needs and expectations are determined, converted into requirements by achieving stakeholder's satisfaction.
3. **Quality Policy**: Here, the direction should ensure that quality policy is appropriate to the purpose of the organization, communicated, understood within the organization, and reviewed for continuing suitability. In addition, they should provide a framework to establish and review quality objectives.
4. **Quality objectives**: In this step, the direction should ensure that the quality objectives are established. This latter should be measurable and consistent with the quality policy including the commitment to continual improvement. In addition, the top management has to ensure that the planning of the quality management system is performed to meet the quality objectives.
5. **Responsibility and authority**: In this step, first, the responsibility and the authority are defined and communicated as part of resource planning in order to facilitate an effective quality management. Then, the direction should ensure that appropriate communication processes are established between their various levels and functions and that communication takes place regarding the processes of the quality management system and their effectiveness.
6. **Management review**: In this step, the quality management system should be reviewed in planned intervals to ensure its continuing suitability, adequacy and effectiveness. The review shall evaluate the need to change the quality management system, including quality policy and quality objectives. Records from management reviews shall be

maintained.

- *Resource management process* ensured via three main steps:

  1. **Provision of resources**: In this step, the direction should determine and provide, in a temporary manner, the resources needed to be implemented in order to improve the processes of the quality management system and to address stakeholder's satisfaction.
  2. **Training, awareness and competence**: In this step, the direction ensure that the personnel, who are assigned responsibilities, defined in the quality management system are competent on the basis of appropriate education, training, skills and experience.
  3. **Improving work environment**: In this step, the direction shall identify and manage the human and physical factors of the work environment needed to achieve conformity of service, and participate in developing and implementing policies and procedures related to the work environment, including workplace hazards and transportation to and from work sites.

- *Product realization process* ensured via five steps:

  1. **Planning production realization**: This step shall identify and implement the sequence of activities required to prepare and deliver its products or services to stakeholders. Such planning shall be consistent with the requirements of quality management system and documented in a form suitable manner. This planning shall determine services and products quality objectives, documents, processes and resources to the each service or product and records to confirm that service or product delivery meets requirements.
  2. **Considering stakeholder's expectation**: Here, the direction should provide the required resources those for availability, delivery and post delivery process, in order to consider the stakeholder's expectation. These requirements should be ensured prior the commitment that they are defined.

3. **Design and development planning**: This step shall determine first the design and the development stages, then it assures the reviewing, the verification and the validation of the different activities appropriate to each stage, and finally it affects responsibility to each activity

4. **Manage purchasing activities**: Here, the direction should evaluate and select the appropriate suppliers according to the requirements contained in the purchasing documents.

5. **Manage delivery activities**: In this step, the direction should control the delivery activities to all stakeholders. To deal with, the direction shall provide staff training and required tools (e.g. appropriate information, work instructions, equipment) and implementing monitoring and control activities.

- *Measurement, analysis and improvement process* ensured via three steps:

1. **Stakeholder satisfaction measurement**: Here, the direction shall monitor information relating to stakeholder's perception as measurements of performance of the quality management system.

2. **Internal audit**: In this step, the direction shall conduct internal audits to determine whether the quality management system conforms to the requirements of the ISO 9001:2008 standard. Also, the direction shall develop an audit program which takes into consideration the status and the importance of the processes and areas to be audited, as well as the results of previous audits. Finally, audit criteria, scope, frequency and methods shall be defined.

3. **Monitoring and measurement of processes**: Here, the direction shall apply suitable methods for monitoring, and measurement of the different processes. Monitoring and measurement shall be carried out at appropriate stages of each process based on program planning.

   For the continual improvement, the direction should continually improve the effectiveness of the quality management system by the use of the quality policy, quality objectives, audit results, analysis of data, corrective and preventive action and management review.

1.2.2 Environmental management system (ISO 14001)

The standard relative to the Environmental Management System (EMS), known as ISO 14001 [2], was first published in 1996 and revised in 2004. This system may be defined as a formal set of policies and procedures that is used to develop and implement the environmental policy and to manage its aspects by providing tools to enable the organizations to control the impact of their activities, products and services on the natural environment aspect. Figure 1.2 shows different steps of the EMS which can be seen as continuous improvement system.

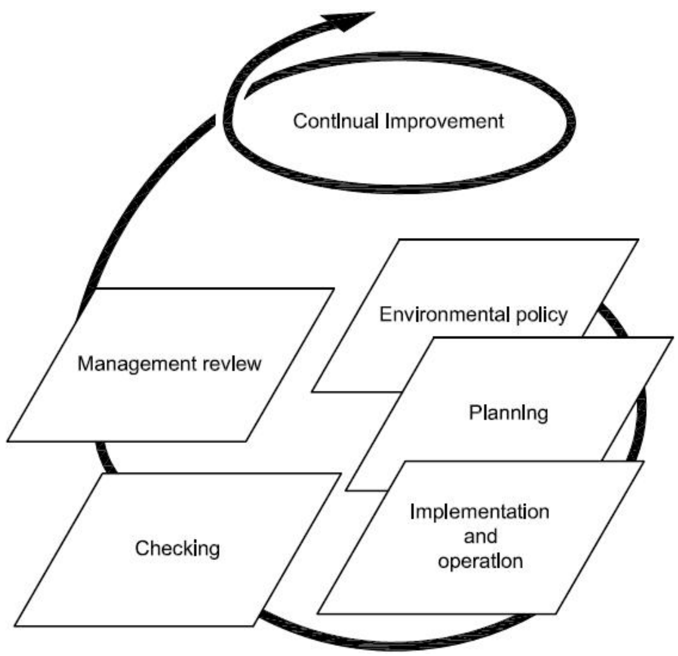

Figure 1.2: The environmental management system according to ISO 14001 [2]

The different phases of environmental management system are detailed as follows:

- *Environmental policy*: One of the requirements for a company is to establish an environmental policy document that is appropriate to the nature, scale and impacts of the company. This latter includes a commitment to continual improvement and prevention of pollution, and provides the framework for setting and reviewing environmental objectives and targets. The policy normally points out the key priority areas for environmental efforts and indicates the direction of environmental work.

- *Planning phase* ensured via three steps:

  1. **Environmental aspects identification**: A company using an EMS shall establish, implement and maintain procedures to identify the environmental aspects of its activities, products and services within the defined scope of the environmental management system, then determining those aspects that have or can have significant impact on the environment.

  2. **Identifying legal and other requirements**: The organization shall establish, implement and maintain procedures for identifying and accessing the legal and other environmental requirements that are applicable to it. The organization shall ensure that these applicable legal requirements and other requirements to which the organization subscribes are taken into account in establishing, implementing and maintaining its environmental management system. One intention with standardized EMSs is to make sure that companies comply with the identified requirements.

  3. **Setting objectives, targets and programs**: The organization shall establish, implement and maintain objectives and targets, in order to achieve environmental performance improvements, these goals shall be measurable and consistent with environmental policy, including the commitments to the prevention of pollution, and established based on the results of the environmental review, which means that at least some of them should affect the significant environmental aspects. Furthermore, the company should consider the wording in the environmental policy, business requirements and the views of targeted parts.

- *Implementation and operation phase* ensured via five steps:

  1. **Assigning responsibility and authority**: In order to fulfill the standards requirements, roles, responsibilities and authorities shall be

defined, documented and communicated. This is in order to create an effective management system, and implies that essential resources are provided for.

2. **Management of human resources**: To become certified, the direction shall ensure that personnel who are assigned responsibilities defined in the environmental management are competent on the basis of appropriate education, training, skills and experience. In addition, the direction shall identify the competency needs for personnel performing activities affecting environmental management system.
3. **Communication and documentation**: Each organization using an environmental management system shall establish procedures for internal and external communication. Furthermore, well organized documentation is required, which means that core elements of the systems shall be described, as well as their interaction, and that documents must be legible, dated, readily identifiable, maintained in an orderly manner etc.
4. **Setting operational control**: The organization shall determine those operations and activities that are associated to significant environmental aspects and consistent with its environmental policy, objectives and targets like waste management, water consumption, hazardous materials, odor and emissions.
5. **Provisions emergency preparedness**: The organization shall establish, implement and maintain procedures to identify potential emergency situations and potential accidents that can have an impacts on the environment. Thus, provisions for emergency preparedness and response are necessary.

- *Checking phase* ensured via five steps:

1. **Monitoring and measurement**: The organization shall establish, implement and maintain procedures to monitor and operations that can have a significant environmental impact. Procedures shall be established for monitoring and measuring key characteristics of opera-

tions and activities that can have a significant impact on the environment. The monitoring and measurement activities must be carried out on a regular basis. It is specified that procedures are needed for a periodical evaluation of compliance with environmental legislation and regulations.

2. **Evaluation of compliance**: The organization shall establish, implement and maintain procedures for periodically evaluating compliance with applicable legal and other requirements.

3. **Setting corrective and preventive action**: A certified organization must have procedures to define responsibilities and authorities for handling and investigating non-conformance, taking to mitigate possible impacts and for initiating and completing corrective and preventive action.

4. **Control of records**: The organization shall establish and maintain records as necessary to demonstrate conformity to the requirements of its environmental management system and of this International Standard, and the results achieved.

5. **Internal audit**: An internal audits of the environmental management system are conducted at planned intervals to determine whether the EMS has been properly maintained, and conforms to the the planned arrangements. In fact, the purpose of environmental auditing procedure is to ascertain whether an organization fulfills the requirements of a standard and other fundamental commitments. After auditing, the results are communicated to top management.

- *Management review phase*: In order to ensure the effectiveness and the adequacy of the implemented EMS, the top management shall reviews it at planned intervals in order to verify the assessing opportunities for the improvement and the need for changes. Records of the management reviews shall be retained. The output of management reviews shall include decisions and action related to possible changes to environmental objectives, policy and targets, consistent with the commitment to continual improvement.

1.2.3 Occupational health and safety management system (OHSAS 18001)

The standard relative to the Occupational Health and Safety Management System (OHSAS), was first proposed in 1999 [3] and revised in 2007 in order to create and maintain a safe working environment. This standard is applicable to any organization in order to establish an OHS management system, to enable an organization to control its OHSAS risks and improve its OHS performance, which will help it to minimize risks regarding its employees and customers. This standard has the same structure (see Figure 1.2) and follows the same steps as the standard ISO 14001 (see section 1.2.2).

1.3 Survey of existing integrated management systems

One of the major concerns of the companies is to implement the three management systems simultaneously, but although they are designed to be compatible, there still exist some differences between them. Firstly, the stakeholders for ISO 9001 and OHSAS 18001 are different, for the QMS, the stakeholders are the users i.e. buyers of products or services and for OHSAS they are the workers and the staff who produce or manufacture the products/services. The stakeholders for the EMS can both be within the organization (e.g. employees) as well as outside the organization (e.g. members of the public) because adverse environmental issues can materialize during the building process and upon completion. As for interests, the QMS involves the product or service quality, the EMS focuses on improving a company's environmental performance through the prevention of pollution created by the operations and activities of the company whereas the OHSAS addresses safety in the process of manufacturing the products/services. In addition, the three standards require many duplicate management tasks, such as training, awareness and competence, communication, document control, monitoring and measurement, setting corrective and preventive action and internal audit.

Also it has been shown that it is not easy to deal with many objectives and policy at the same time, leading to confusing and contradictory procedures.

Clearly, the parallel implementation of the three management systems can lead to confusing and contradictory procedures. For these reasons proposing an integrated management system (IMS) including quality, environment and safety management systems also known as QSE management system have drawn the attention of both academics and practitioners.

Research concerning integrated management systems, started at the same time with the publication of EMS in 1996 by Puri [84] where a set of guidelines were proposed in order to integrate the EMS and QMS. Once the OHSAS was formulated, the need to consider the three systems was resented and many researches have been carried out in order to build more sustainable integrated management systems. Theses researches can be classified into three categories:

1. The first discusses the relations among the three management systems as *similarities* which define the points, features and details in which the three standards are similar [18, 32, 60, 84, 87, 100]. *Compatibilities* which define the points features and details in which the three standards are harmonious [33, 37, 55]. And *differences* which define the points features and details in which the three standards are in conflict [55, 59].

2. On the basis of these three characteristics the second one proposes a set of guidelines including ideas and factors for a successful integration of the three systems. In this context, Karapetrovic [58] discusses various ideas for the development of an integrated management system, together with the supporting audit methodologies. In fact, two ideas have been proposed, the first consists in creating a generic management system standard to support integration and the second prong relates to auditing in order to generate a generic audit system standard. Fresner et al. [43] propose through the experience of two small companies in Austria an immediate and visible improvement in OH&S, service quality and EMS. Tranmer [95] proposes a multi-level integration, aligning the QMS and EMS with the business objectives. Moreover, Jorgensen et al. [56, 57], propose three ambitious levels to ensure the total integration of the three systems namely *correspondence*, *coordination* and *integration*. Zeng et al. [104] define the internal and ex-

ternal factors affecting the implementation of IMS through a structured questioner survey conducted in china.

3. Using results and ideas from the second category, the third one proposes models and approaches to implement an IMS. In this context, Wilkinon et al. [99] propose two approaches, the first consists in achieving integration including the emergence of documentation through aligned approach and similarities in the three standards and the second implements the integrated system through a total quality management approach. Another important work is the one of Labodova [66] who proposes two ways of integration, the first consists of the introduction of individual systems followed by the integration of originally separate ones and the second is an integrating management system based on the risk analysis. Finally, Zeng et al. [104], propose a different approach based on the definition of specific integration factors extracted from the questionnaires then they propose a synergetic multi-level model for implementing an IMS.

We can also mention the case of several countries which have developed their own integrated management standard such as Australia [6] and France [101]. However, these local standards can not be intended for certification since they just represent guidelines and recommendations for the integration.

In this review, it seems clear that the proposed approaches only propose a partial integration of the three systems since they are not coherent with the three levels of integration proposed by Jorgensen et al. [57]. Indeed the approach proposed by Labodova [66] involves only the correspondence level, by introducing the risk management, which is insufficient to deal with all management systems since it allows a separate evaluation of risks levels relative to each system and ignoring the interaction between them. Also the approach proposed by Zeng et al. [104] is only based on the internal and external factors affecting the implementation and does not take into account the three levels of integration. Thus, our idea is to overcome the weaknesses of the existing systems by proposing a new process-based approach for implementing a total integrating management system.

Our basic idea consists in implementing the three management systems according the so called PDCA scheme (Plan, Do, Check , Act). This means that the implementation of the three management systems will be divided into four steps :

- **Plan**: Review the current situation, define general requirements, policy and planning.
- **Do** : Develop strategies and carry out the task to achieve the policies, objectives and targets.
- **Check**: Monitor and measure the different implemented activities, and audit their performance against policies, objectives, targets, and report the results.
- **Act**: Implement action to continually improve performance.

Consequently, the three management systems are designed in a cyclic way, based on information from monitoring and regular audits, top management has the task to review the system as a strategy to meet up with the requirements of continual improvement. After review, if the policy can be adjusted, new policy and targets can be established, training can be complemented etc. The correspondence of the three standards according to the PDCA cycle is shown in Table 1.1.

1.4 Integration factors

In order to implement a robust integrated management system, the three integration levels recently defined by Jorgensen et al. [57] are used and detailed as follows:

1. *Correspondence*: This level is important since it increases the compatibility between the three systems in order to reduce add-problems issued from parallel systems as bureaucracy and duplication of work tasks. In addition, this level minimizes duplication of paper work and confusion between standards. It also, simplifies the internal and external audits. From an administrative point of view the following benefits could be obtained:

Table 1.1: Correspondence between the three standards regarding the PDCA cycle

Standards	ISO 9001:2008	OHSAS 18001:2007	ISO 14001 :2004
Plan	General requirements Management responsibility commitment and policy Planning	General requirements Environmental policy Planning	General requirements OH&S Policy Planning
Do	Resource management Product realization	Implementation and operation	Implementation and operation
Check	Measurement analysis and improvement	Checking and corrective action	Checking and corrective action
Act	Review included in Management responsibility	Management review	Management review

- Minimization of documentation and records.
- Less bureaucracy and reduction of paperwork.
- Cost savings by optimization of time and resources assigned to the system.
- Simplification of internal and external audits.

2. *Coordination*: This level is based on a common understanding of generic process and tasks management cycles (Plan-Do-Check-Act) and it essentially ensures synergies and tradeoffs between the three systems by aligning their policies and coordinating their objectives and targets. And the potential benefits of such integration are:

    - More focus on interrelations synergies as well as tradeoffs between quality, environment, occupational health and safety, and social accountability.
    - Objectives and targets are set up, coordinated and balanced.
    - Organization and responsibilities are defined in one place.

3. *Integration*: This level leads to the interaction with stakeholders, continuous improvement of the performance, a better understanding of internal and external challenges and also to a responsibility culture.

To satisfy these three levels, our idea is to use three integration factors, the first one is *the risk management* to guarantee, the correspondence between the three management systems, the second is *the process approach* to coordinate between the activities and to reach more efficiently the objectives, and the third is a *monitoring system* to ensure the integration as continuous improvement of the performance around the same structure i.e. (Plan-Do-Check-Act). Before detailing our approach, we will just give some basic concepts concerning these three integration factors.

1.4.1 Risk management

The risk management is defined as a set of principles and practices aimed at identifying, analyzing, evaluating and treating each eventual existing risk factor [24, 51]. The risk factors are seen as events hindering an organization to reach their objectives. In literature, many approaches related to risk management have been defined, such as checklists, analytical frameworks, risk response strategies and process models. But the most common and used approaches are the process model which specify stepwise tasks for managing risks. Typically, they specify the individual activities believed to be necessary to manage risk and how these activities should be sequenced to effectively manage risk. In practice, many management process models exist, the most popular onces are PMI 2001 [82], Standards Australia [5], and Risk Diagnosing Methodology [61], moreover the International Organization for Standardization (ISO) has recently defined an international standard ISO 31000 [4] as a set of principles and guidelines in order to implement a risk management process in an effective manner. The different activities of this standard shown in Figure 1.3 [4] are detailed as follows:

1. **Establishing the context**: In this phase, the objectives related to each activity are defined in order to develop the criteria that are used to evaluate the risks. Moreover, all the required resources needed to identify each

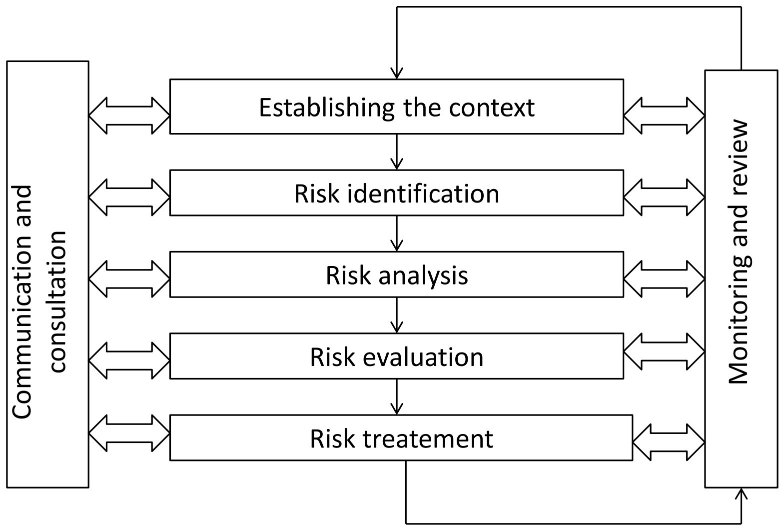

Figure 1.3: Risk management process

potential risk should be defined in this phase such as qualified personnel, material, and documentation.

2. **Risk identification**: Means the recognition of any source of risk, their causes and their potential consequences. The main objective of the identification phase is to generate a comprehensive list of potential risks. To deal with, organization should apply risks identification tools and techniques which are suited to its objectives. The most commonly used method to identify potential risks is the brainstorming.

3. **Risk analysis**: Provides data in order to assist in the evaluation and treatment of risks. It involves consideration of the sources of risk, their consequences and the likelihood that those consequences may occur. The risk is analyzed by combining estimations of consequences and likelihood in the context of existing control measures.

4. **Risk evaluation**: The purpose of the risk evaluation is to assist the decision maker to define the appropriate treatments. Usually, it involves comparing the level of risk found during the analysis process with risk criteria

established in the context analysis phase. This comparison leads to define a list of potential treatments and decisions (e.g preventive and corrective action) if the level of risk does not satisfy the risk criteria.

5. **Risk treatment**: Risk treatment involves selecting one or more decisions and treatments to reduce the level of risks already identified. It is based on a cyclical process, until the level of risk complies with the organization's risk criteria.

6. **Monitoring and review**: After implementing the appropriate treatments, it is necessary to monitor the level of risks and to check the effectiveness of the risk management plans. In this phase, the initial management plan can be changed or modified until the desired level of risks are reached.

7. **Communication and consulting**: Communication and consultation with internal and external stakeholders should take place at each stage of the risk management process. Therefore, a plan to communicate and consult with both internal and external stakeholders should be developed.

Clearly the use of risk management as an integrating factor, increases the compatibility and the correspondence between the three systems. In fact, it reduces add-problems issued from parallel implementations since the same source of hazard can cause several risks relative to the three management systems (QSE). For instance, an explosion in a plant (as the AZF one) can cause:

- a *security problem* since employees can be injured,
- an *environmental problem* since it can blow out the windows of nearby residents and pollute the air,
- and a *quality problem* since it can generate a supply disruption for customers.

The risk management is the common factor between each management system to identify each risk source and possible target system relating to quality, security and environment leading to a possible failure to reach up different objectives. Once, the sources of risks are identified, each risk is evaluated by the combination of the probability of occurrence and the consequences of it. This evaluation allows us to define the appropriate preventive, corrective and improvement plans to reduce the levels of risks. Finally, the direction should provide the personnel, technical and financial resources required for each program.

1.4.2 Process-based approach

To deal with coordination as integration level, all the activities of a company and their interactions are considered in the same model. To satisfy this requirement, the process-based approach seems to be an adequate tool. This approach is only a normative requirement of the standard ISO 9001:2008, and our idea is to adopt it for the three standards to have a global process-based approach integrating the requirements of stakeholders and taking into account quality, security and environment aspects. A process is defined by ISO 9001:2008 [8] as a set of inter-related or interacting activities which transforms inputs into outputs and goes on to state that processes in an organization are generally planned and carried out under controlled conditions to add value. Therefore, the process-based approach allows us to model all the activities of a company and their interaction in the same model namely process cartography.

In order to manage each process four characteristics should be considered:

- **Process purpose**: Each process needs a purpose for it to add values. it describes the main role of the process and identify what is going to be converted.
- **Process objectives**: Process objectives provide a means to measure the effectiveness with which the process fulfills its purpose.
- **Process inputs**: The inputs of a process are considered to be those things that are transformed by the process into outputs.
- **Process outputs**: the outputs of a process are the result transformation from input and by considering the process objectives.

Thus, we can conclude that the process cartography allows us on one hand to identify the inputs and the outputs of each process, which leads us to a common understanding of the generic process and the examination of synergies and trade-offs, and on the other hand to the alignment of policy, objectives and targets. In addition, the process analysis allows the identification of sources of hazard. Usually, this identification is performed using fishbone diagram (The cause and effect diagram), as shown in Figure 1.4, by grouping them into five main categories:

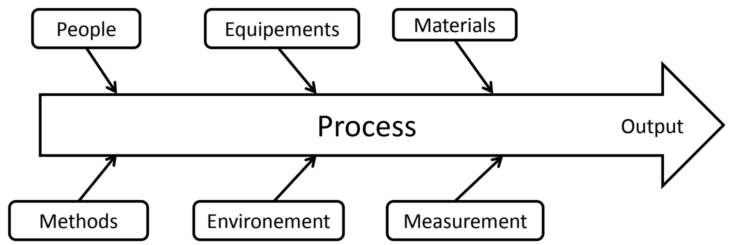

Figure 1.4: Fishbone diagram

- *People*: Anyone involved with the process
- *Methods*: How the process is performed and the specific requirements for doing it, such as policies, procedures, rules, regulations and laws.
- *Equipment*: Any equipment, computers, tools etc. required to accomplish the job
- *Materials*: Raw materials, parts, pens, paper, etc. used to produce the final product.
- *Measurement*: Data generated from the process that are used to evaluate its quality.
- *Environment*: The conditions, such as location, time, temperature, and culture in which the process operates.

This identification is the starting point to control the process and to define the requirements such as personnel, technical, and financial resources to reach up different objectives. Also, the process approach provides an adequate framework to analyze the potential causes of risks and help decision makers to adopt the appropriate decisions for the three systems.

1.4.3 Monitoring System

To ensure the monitoring of the global system and the integration as a continuous improvement of the performance evaluating the states of processes have to be ensured. To ensure this requirement the following phases are proposed:

- **Process measurement**: An adequate tool to ensure this task is the use of performance indicators which are variables indicating the effectiveness and/or efficiency of a part or whole of any process or system in order to evaluate its state with regard to pre-set objectives. Typically, a model of performance indicators is composed of three main parameters i.e. objectives, measures and evaluations [20]

- **Process monitoring**: This phase is implemented in order to control the whole process and to look for unusual occurrences or indicators of potential change in performance, usually a wide range of sensors can be used such as vibration detectors, infrared devices to detect body heat, infrared beams etc.

- **Process analysis**: This phase is performed on the basis of the data generated by the different sensors, and includes several activities as collect the data from monitoring activities, update the different measures etc.

1.5 New process-based approach for IMS

We propose in this section, a new approach for a total integration of the three management systems i.e. Quality, Security and Environment by considering the three integration factors i.e. the risk management, the process-based approach and the monitoring system. Our approach is illustrated by Figure 1.5, where the different steps cover the whole PDCA (Plan, Do, Check, Act) scheme. The idea here is to gather these steps into three phases so that the first one concerns the Plan step, the second the Do step and the third the Check and the Act steps. These three phases can be detailed as follows:

- **Plan phase**: This phase leads us to a better understanding of the current situation in order to carry out the objectives and to define for each process

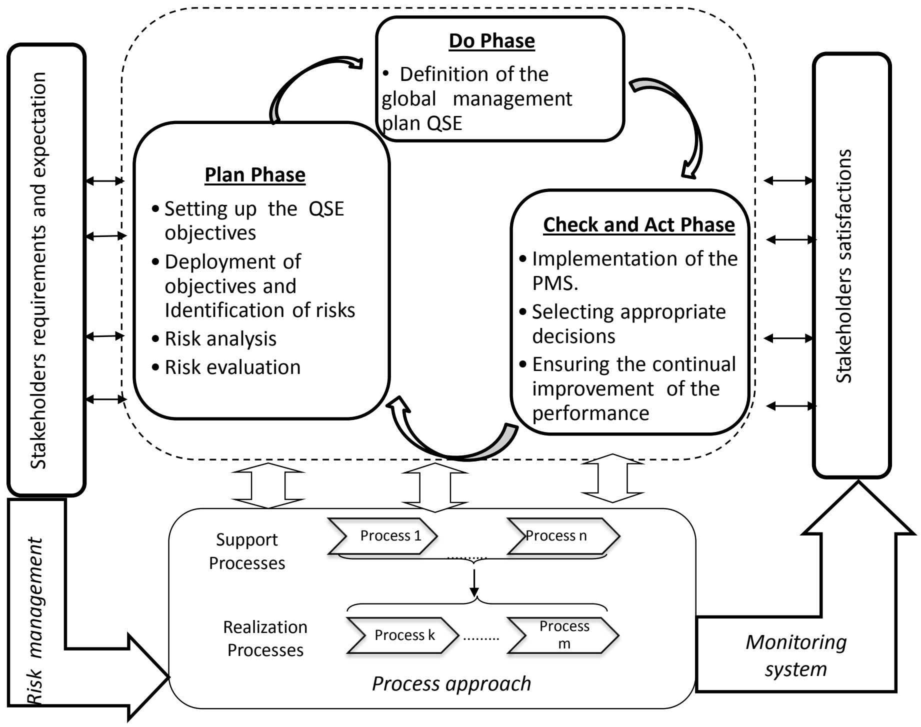

Figure 1.5: Proposed process-based approach for IMS

the requirements, tools, methods, responsibilities and the resources. To this end, four steps are proposed, the first consists in setting up all quality, security and environment objectives issued from the requirements and the expectations of stakeholders (i.e. customers, employees, population, environment, etc.). As shown in Figure 1.6, in the second phase, the deployment of these objectives in each process is ensured on the basis of the support and the realization process to coordinate and balance them, from this step all the existing risks in relation with the QSE objectives are identified.

The third step consists in the analysis of each existing risk in order to select the most critical ones leading to a possible failure to reach up the objectives. Thus as shown in Figure 1.7,the levels of risk according to each objective are calculated. And finally, on the basis of these values the most critical and important ones are selected.

In the fourth step, an evaluation of each selected risk is proposed in order to

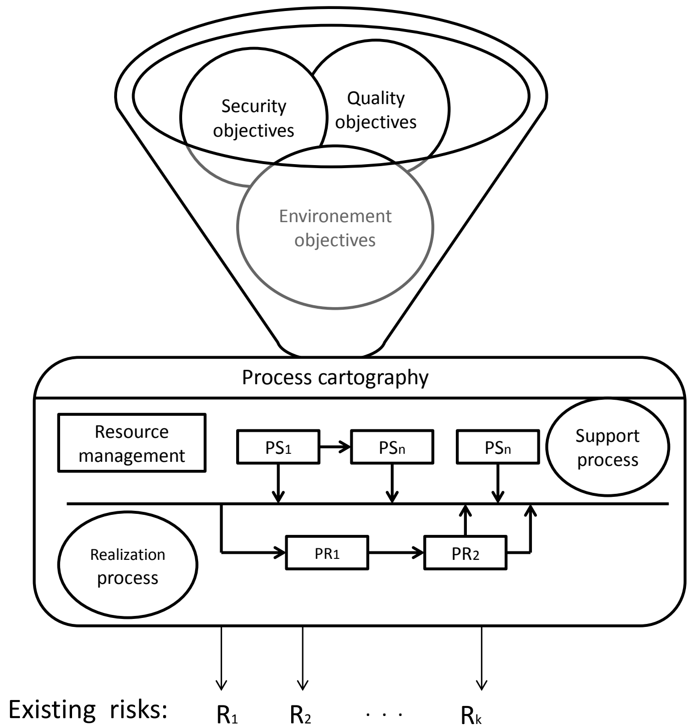

Figure 1.6: Objectives deployment

assist the decision maker to define the appropriate treatments. To this end, the whole scenario of each identified risk is identified, which allows us to select in more effective manner the appropriate preventive action to reduce the occurrence of the risk and the protective action to reduce its severity.

- **Do phase**: On the basis of the deployed QSE objectives and their most critical risks, their relative treatments are identified in this phase. To this end, the management plans QSE are defined which composed of a set of procedures and treatments able to ensure the achievement of the already fixed objectives while taking into consideration the interaction between the three QSE management areas.

- **Check and Act phase**: Once the do phase achieved, the most appropriate management plan should be selected and implemented to reach the QSE

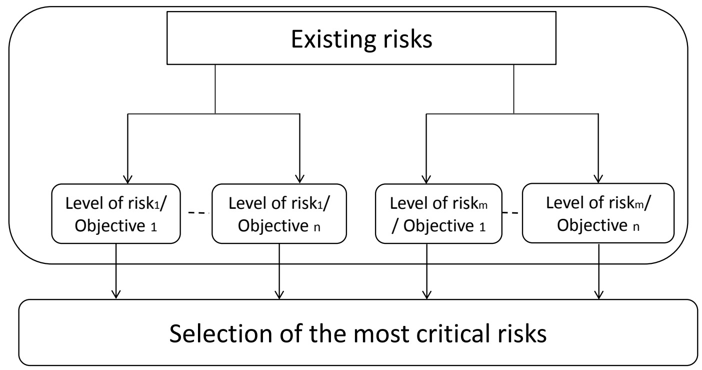

Figure 1.7: Risk analysis and selection phase

objectives and to ensure the continuous improvement of the performance. To this end, the effectiveness of different management plans defined in the previous step are measured and the most appropriate one are selected. To deal with, a performance measurement system (PMS) is implemented to evaluate the effectiveness of selected treatments and to estimate the degree of objectives achievement.

1.6 Conclusion

This chapter proposes a new process-based approach for implementing an integrated management system respecting Quality, Security and Environment standards. Our approach covers the whole PDCA (Plan, Do, Check, Act) scheme and ensures from its initialization a coherent and complementary design. This is visible from the definition of different objectives where a predictive step supported by adequate tools is introduced in order to ensure their coherence so that they can control the three systems simultaneously. Using these objectives, a global management program is designed through a controlled deployment. This is realizable on the basis of the process-based approach and the risk management. This program will integrate an optimized planning of all resources and methods needed for an effective management. Moreover, it will be consolidated by an adapted global monitoring system respecting the three standards. Once the most critical risks, their relative scenario and their relative treatments are defined in the Plan phase, a Do phase ensures the definition of the appropriate management plans leading to reach the QSE objectives. Finally, the most appropriate management plan is selected in a Check and Act phase, by adopting the principles of the factual approach of decision-making. One of the main advantages of our approach consists in its adequacy with the eight fundamental principles of quality management. In addition, we remain in coherence with the three integration levels recently defined by Jorgensen et al. [57], namely the correspondence, coordination and the integration which will be taken into account in the various phases of our approach. Finally, the concretization of our approach depends on its enrichment by adequate tools in order to ensure the effective and operational integration by objectives. Thus, in the next chapter the implementation of the most important part of the plan phase is proposed which consists in *the deployment of the objectives, the identification of risks*, and *their analysis.*

Chapter 2

New Approach to Identify and Analyze Multi-Leveled Risks

2.1 Introduction

As detailed in the previous chapter, our proposed IMS approach is based on three main phases (i.e. Plan phase, Do phase, Check and Act phase). In this chapter, the implementation the most important part of the plan phase is proposed consisting in *the deployment of the objectives, the identification of the risks*, and *their analysis*. The main objective in this part is to carry out the most critical risks using as inputs the process cartography and the QSE objectives. To this end, the use of the risk management is proposed to ensure the correspondence between the three management areas and their related objectives.

The risk management is defined as a set of principles and practices whose purpose is to identify, analyze, evaluate and treat eventual risks. Existing approaches for risk management can be divided into two categories:

- *Qualitative risk analysis*: The qualitative risk analysis aims to identify, analyze and treat each identified risk. Several methods have been proposed in this direction. Within the most important ones we can mention preliminary risk analysis (PRA) [44], the hazard and operability study (HAZOP) [63], and the failure mode and effects analysis (FMEA)[79], the common factor between these methods is that they use a set of guide words (i.e. low, moderate, high etc.) to evaluate the level of risks. Except the FMEA, remaining methods can not be used in any context. In fact, the PRA is mainly used as a prior conceptual phase, and the HAZOP is especially performed in the chemical field.

- *Tree-based risk analysis*: These techniques are mainly used to represent the whole scenario of a given risk in a graphical way. Within the most common ones, we mention bow tie diagrams [30], Markov modeling [73], dynamic event logic analytical methodology [29] and event tree analysis method [73].

Within these methods, the *Failure Mode and Effects Analysis* (FMEA) [79] appears as one of the most popular and diffused risk management methods. Moreover, several researches have been carried out to enhance its performance by introducing fuzzy logic concepts to evaluate the risk level in a more flexible way. Such a new version, called fuzzy FMEA [19, 49, 91, 94]. The fuzzy FMEA was initially designed to assign to each risk a unique *Risk Priority Number* (RPN) which is not adapted to our case since each risk will have an impact on the three management areas.

Thus, our idea is to extend the fuzzy FMEA by defining for each risk a multi-leveled *Risk Priority Number* relative to different QSE objectives. Then, to ensure the selection phase of the most critical risks, a multi-criteria approach is used which is the *Analytic Hierarchical Process* (AHP) [88].

The remainder of this chapter is organized as follows: Section 2 recalls the Fuzzy Failure Mode and Effects Analysis (FMEA) method. Section 3 presents the Multi-leveled Fuzzy FMEA (MLF-FMEA) to analyze and select the most critical ones in the context of an integrated management system.

Main results presented in this chapter are published in [15, 19].

2.2 Fuzzy Failure Mode and Effects Analysis (FMEA)

Initially proposed by the US military in 1962 as a process tool, the *Failure Mode and Effects Analysis* (FMEA) has became one of the most popular risk management tools to identify and analyze risks in many industrials fields such as manufacturing, assembly processes, products and equipment. In 1980s, the FMEA was widely used by the quality community as a total quality management tool and in 1990s as a six sigma tool.

The FMEA is based on a ranking of different risks on the basis of their *Risk Priority Number* (RPN). In fact, for each risk R_k it associates a *Risk Priority Number* RPN_k based on three parameters such that:

- *Occurrence* OC_k expressing the rate at which R_k will occur before any additional process controls are applied. This can be done by looking at similar products or processes and the failure modes that have been documented for them.
- *Severity* S_k evaluating the seriousness of an effect of R_k. Since there is several possible effects of R_k, only the most important is considered.
- *Detection* D_k expressing the likelihood that the detection methods will detect R_k (A high detection number indicates that the chances of detection are low).

To evaluate these three parameters, linguistic scales should be defined in order to convert their qualitative descriptions given by the expert to a quantitative one. Table 2.1 shows an example of a linguistic scale with four levels describing the occurrence (OC), severity (S) and detectability (D). For example if the expert evaluates the occurrence as moderate then, the variable (OC) will be equal to 3.

Table 2.1: Linguistic scale

Rank	**Description**	**Occurrence (OC)**	**Severity(S)**	**Detectability (D)**
1	Remote	Unlikely	No effect	Certainly detected fail
2	Low	Relatively few	Slight annoyance	Major defects are detected
3	Moderate	Occasional	Severus deterioration	Some defects are detected
4	High	Repeated	Very severs deterioration	Few defects are detected

Thus, given a risk R_k, its RPN_k is expressed by:

$$RPN_k = OC_k * S_k * D_k \tag{2.1}$$

The first problem with the classical FMEA consists in the parameters estimation which is not an easy task since in real world problems OC_k, S_k and D_k are pervaded with uncertainty which is not well described by qualitative linguistic scales. Moreover, to compute RPN values, the FMEA neglects the relative importance among OC, S and D since it assumes that they are equally important (by aggregating them via a simple multiplication) which is not always true. For instance, in nuclear and chemical plants, the severity is much more weighted than the occurrence and the detectability.

To overcame this weaknesses, several researchers propose to introduce fuzzy set theory [102] to evaluate the risk level. This theory is considered as a generalized function of the classical Boolean logic (i.e. each element can have only one or zero) known as crisp set. In fact, real values in the closed interval [0,1] can be assigned, it indicates partial degrees of membership of an element x in this interval. This generalized characteristic function is known as membership function defined by $\mu_{\hat{A}} : X \rightarrow [0,1]$ where $x \in X$. Each membership function is characterized by three parameters namely:

- *Linguistic term* (i.e. Low, moderate, etc.)
- *Function shape*(i.e. triangular, trapezoidal etc.)
- *Universe of discourse* (i.e.[0 1], [1 10] etc.)

The choice of these parameters depend on the physical meaning of the variable and they are generally defined by the experts in the field.

Using this theory, a fuzzy inference system is proposed by Mamadani et al. [70] to transform an uncertain input to a crisp output. This transformation is based on three main phases known as *fuzzification*, *fuzzy inference algorithm*, and *defuzzification*.

On the basis of this system, *Fuzzy FMEA* (F-FMEA) [19, 49, 91, 94] extends the classical FMEA by affecting to each risk R_k a linguistic description of its *occurrence* OC_k, *severity* S_k and *Detectability* D_k, then, it proceeds through a fuzzy inference system to calculate its *Risk Priority Number* (RPN_k).

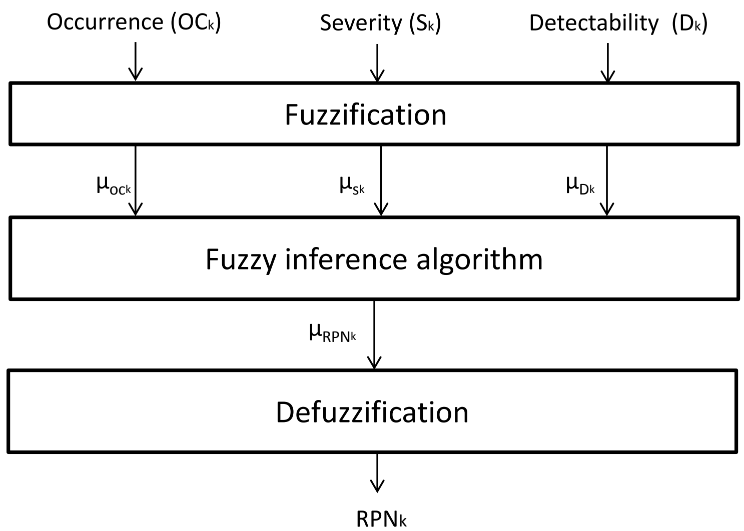

Figure 2.1: Overall view of fuzzy FMEA

Generally, the calculation the RPN value using fuzzy inference system proceeds as follows:

1. The three parameters namely the occurrence (OC_k), the severity (S_k) and the detectability (D_k) are fuzzified using appropriate membership function in order to generate the fuzzy number relative to each input respectively μ_{OC_k}, μ_{S_k}, μ_{D_k}. The main advantage of this step is that the different inputs can be expressed in crisp or uncertain manner. For example Figure 2.2 shows a set of trapezoidal membership functions with three linguistic terms (i.e. Low, Moderate and High). Thus, if we consider the crisp input $x_1 = 0.3$, then, its fuzzification μ_{x_1} is equal to 0.5 Low, 0.5 Moderate, 0 High (see Figure 2.2 (a)). And if we consider the uncertain input $x_1 = [0.1\ 0.3]$ then, its fuzzification μ_{x_1} is equal to 1 Low, 0.3 Moderate, 0 High (see Figure 2.2 (b)).

2. Then, once the inputs are decomposed into fuzzy number, a set of fuzzy If-Then rules (i.e. Fuzzy rule base) and an inference mechanism are used to process the three fuzzy inputs and produce the RPN fuzzy output (i.e. μ_{RPN_k}). Each rule consists of a condition and an action where the condition

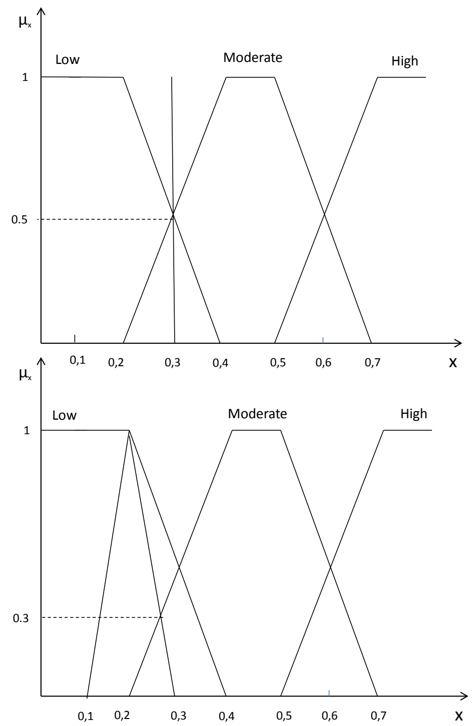

Figure 2.2: (a) Fuzzification of a crisp input (x=0.3). (b) Fuzzification of uncertain input (x= [0.1 0.3])

is interpreted from the input fuzzy set and the output is determined on the output fuzzy set. The most popular fuzzy rule suggested in literature is the one proposed by Mamdani [69] expressed as follows:

Rule 1: IF x is $\hat{A}_1$ AND y is $\hat{C}_1$ THEN z is $\hat{E}_1$
Rule 2: IF x is $\hat{A}_2$ AND y is $\hat{C}_2$ THEN z is $\hat{E}_1$
. . .
Rule r: IF x is $\hat{A}_4$ AND y is $\hat{C}_2$ THEN z is $\hat{E}_3$

where $\hat{A}_i$, $\hat{C}_i$ and $\hat{E}_i$ are respectively the set of linguistic terms describing the inputs x, y and z, and r is the number of rules.

Then, by using an inference mechanism an output fuzzy set is obtained from the rules and the input variables. From literature, the two most common inference mechanisms (I_M) frequently used are the **max-min** inference and the **max-prod** one.

3. Finally, a defuzzification method is used to convert μ_{RPN_k} into RPN_k value. In literature, Several defuzzification methods have been proposed as the *centroid*, *center of area*, and *maxima* methods [102]. However, the *centroid method* is the most used method in the context of the Fuzzy FMEA. This method is based on the computation of the center of gravity (COG) of the area delimited by the membership function of the output set.

Example 2.1 *Let us consider the membership function illustrated in Figure 2.3, proposed by Ben Romdhane et al. [19] to describe the linguistic scale of Table 2.1 relative to the inputs OC, S and D and to the output RPN. In fact, each linguistic variable is represented by a trapezoidal membership function.*

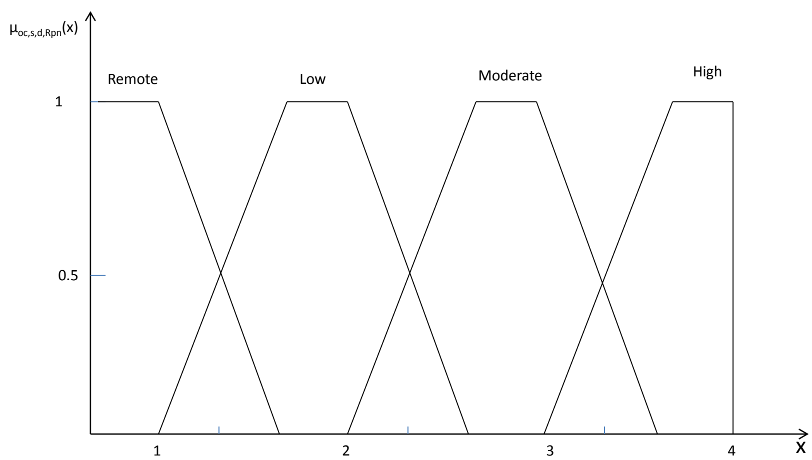

Figure 2.3: Set of four membership functions to represent FMEA parameters

Let us consider the three inputs OC=[1 3], S=4 and D=1. Thus, as shown in Figure 2.4, the fuzzification of OC corresponds to 0.66 Remote, 0.75 Low, the fuzzification of S corresponds to 1 High and the fuzzification of D corresponds to 1 Remote

Then, a fuzzy rule base with 128 rules are generated to relate the inputs (i.e. OC,S,and D) with the risk priority number RPN in the following form:

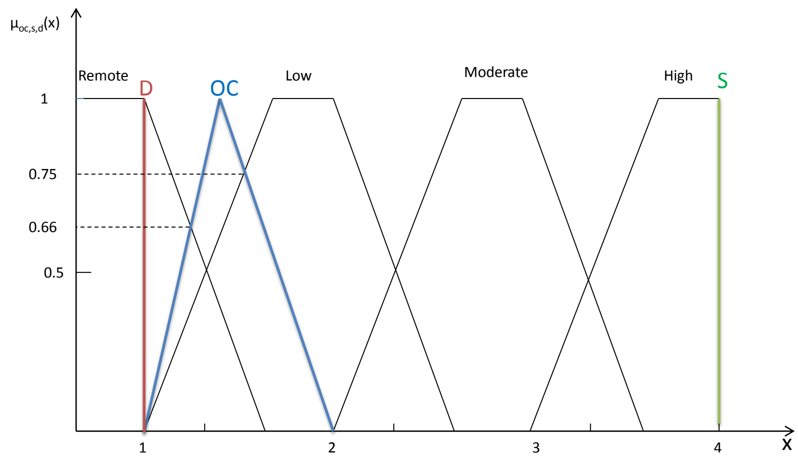

Figure 2.4: Fuzzification of the FMEA parameters

R_1: IF (OC is Low) AND (S is Low) AND (D is Low) THEN (RPN is Low)
R_2: IF (OC is Low) AND (S is Moderate) AND (D is Low) THEN (RPN is Moderate)
R_3: IF (OC is Low) AND (S is Moderate) AND (D is Moderate) THEN (RPN is Moderate)
R_4: IF (OC is Remote) AND (S is Remote) AND (D is Remote) THEN (RPN is Remote)
R_5: IF (OC is Remote) AND (S is High) AND (D is Remote) THEN (RPN is Moderate)
R_6: IF (OC is Low) AND (S is High) AND (D is Remote) THEN (RPN is high)
...

Then, the max-min inference mechanism is applied to generate the fuzzy output ($\mu_{RPN(x)}$). Figure 2.5 illustrates the application of the max-min inference mechanism with two fuzzy rules R_5: IF (OC is Remote) AND (S is High) AND (D is Remote) THEN (RPN is Moderate) *and R_6:* IF (OC is Low) AND (S is High) AND (D is Remote) THEN (RPN is high)*. As shown in Figure 2.5, from the rule R_5 the fuzzy output $\mu_{RPN_1(x)}$= 0.66 moderate is obtained and from R_6 the fuzzy output $\mu_{RPN_2(x)}$=0.75 high is obtained. Then, to obtain RPN fuzzy output $\mu_{RPN(x)}$ the max operator is applied between $\mu_{RPN_1(x)}$and $\mu_{RPN_2(x)}$ as illustrated in (c). Finally, the centroid method is applied to get the RPN value. In fact, the* *center of gravity of the area in (c)(see Figure 2.5) is equal to* $RPN^* = 3.15$.

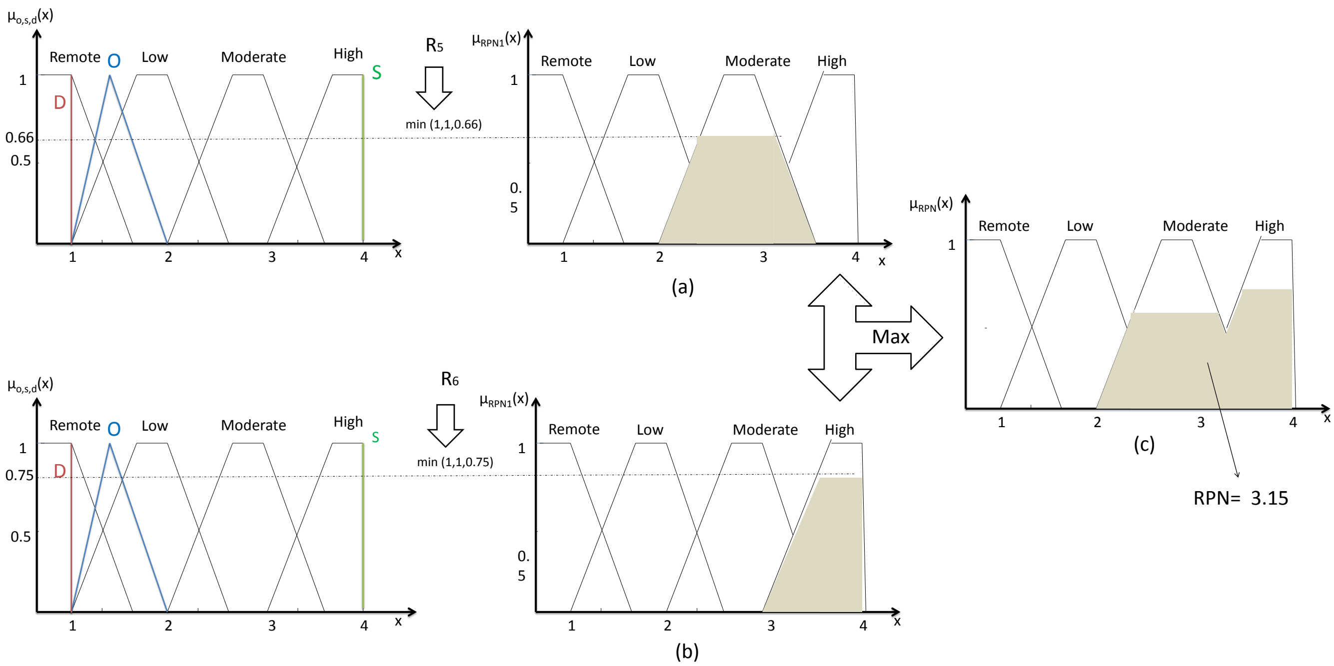

Figure 2.5: Inference mechanism to compute the finale RPN

Despite its success, fuzzy FMEA is limited by the qualitative linguistic description of the parameters and also by its restriction to a unique severity value regarding the whole studied system. In fact, in our case, several QSE objectives are handled so that any risk can alter the realization of these objectives in different ways and the definition of its severity by a single value is not realistic. To overcome this limitation the fuzzy FMEA is extended to our requirements as detailed below.

2.3 Multi-leveled Fuzzy FMEA (MLF-FMEA)

In this section, an extended fuzzy FMEA is proposed in order to deal with several QSE objectives. In fact, in accordance with our QSE integrated management system (see Figure 2.6), the deployment the different QSE objectives $(O_1 \cdots O_n)$

is proposed, which consists in dividing these objectives into several sub-objectives ($SO_1 \cdots SO_P$) using the process cartography. This division allows us to identify the existing risks ($R_1 \cdots R_K$), which will be analyzed by calculating their relative RPN values on each sub-objective ($RPN_1/SO_1 \cdots RPN_K/SO_P$). Finally, on the basis of these values the selection the most critical risks ($R_{s1} \cdots R_{sd}$) is proposed.

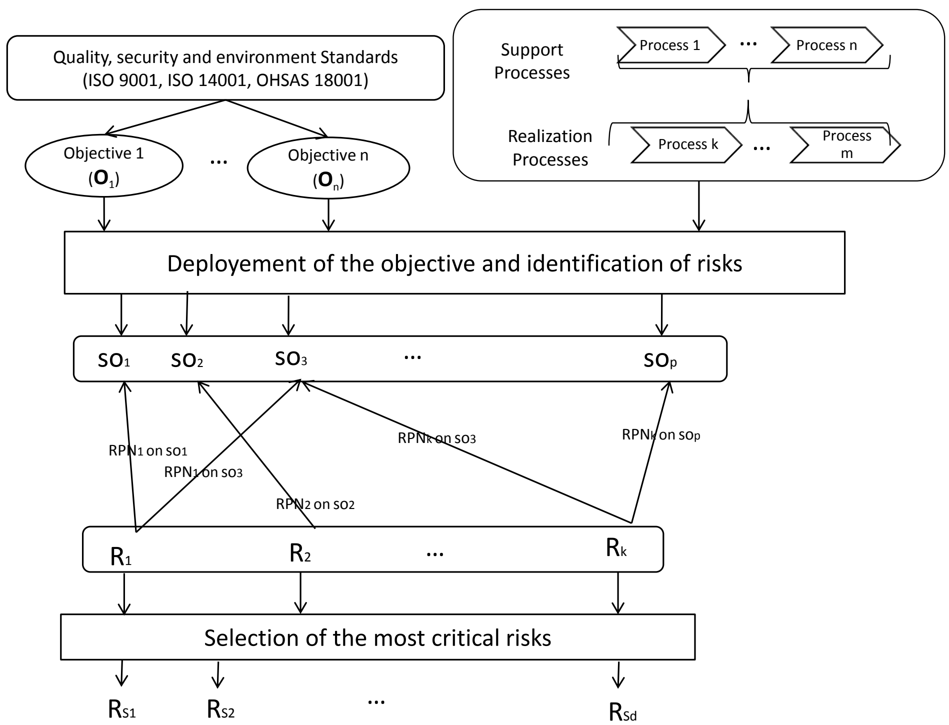

Figure 2.6: Risk identification and analysis phase

The extension, so called Multi-Leveled Fuzzy FMEA (MLF-FMEA), is outlined in Figure 2.7.

First, the improve of the parameter estimation phase is proposed by replacing the simple qualitative linguistic description used in FMEA by a quantitative one in the unit interval. To this end, several indicators are proposed relative to the occurrence, detectability and also to exploit the severity parameters to quantify the impact of each risk R_k on each QSE sub-objective (i.e. $S_{R_k/SO_1} \cdots \mathrm{S}_{R_k/SO_P}$). Then, an implementation of a fuzzy inference system on the basis of the three main steps of F-FMEA described above (i.e. fuzzification, fuzzy inference algorithm and defuzzification) is proposed in order to compute for each risk (R_k) a *Risk Priority Number* related to each sub-objective (i.e. $RPN_{k_1} \cdots RPN_{k_P}$). Finally, these RPNs are used as input to a multi-criteria analysis process, based on the Analytic Hierarchical Process (AHP) to detect the most critical ones.

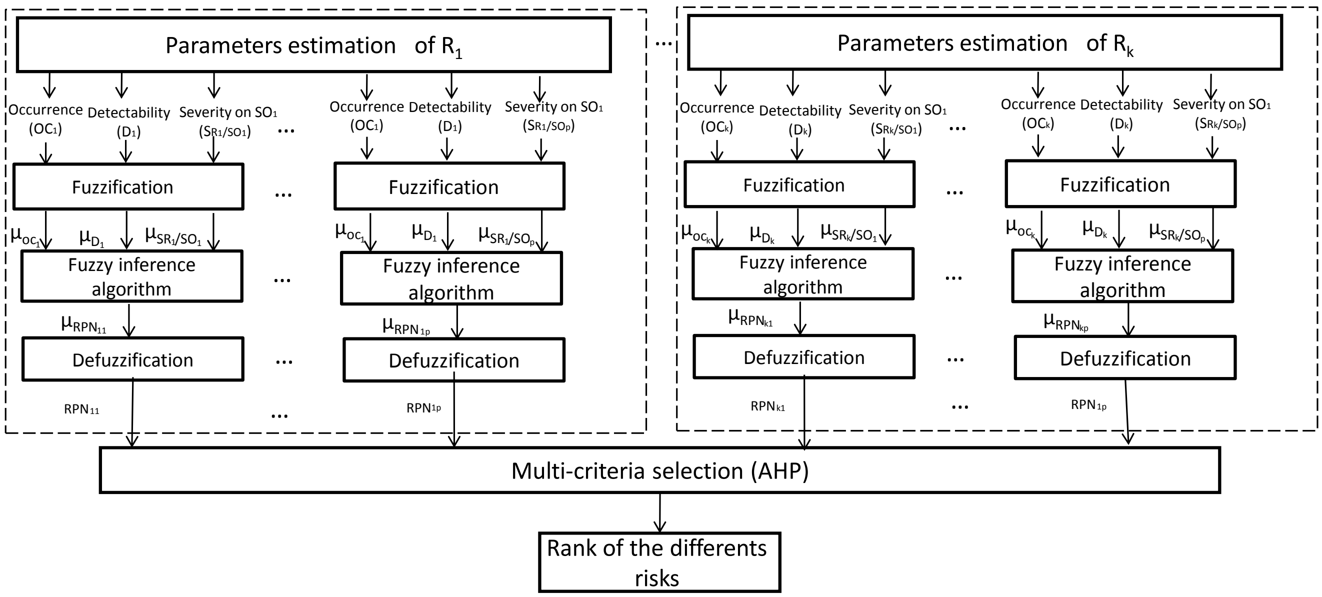

Figure 2.7: Overall view of MLF-FMEA

2.3.1 Parameters estimation

In this phase, the simplest qualitative linguistic description of parameters used in fuzzy FMEA are replaced by a quantitative one using the unit interval [0 1] such that:

- *Occurrence*(OC_k): Within the multiple indicators developed for the quantification of the occurrence, as the *Mean Time Between Failure* which is a basic measure of a system's reliability.

- *Detectability*(D_k): This parameter can easily be computed by a ratio of the detecting occurrence rate of the risk and its occurrence rate.

- *Severities*: To quantify the impact (severity) of each risk R_k on each QSE sub-objective (i.e. $S_{R_k/SO_1} \cdots S_{R_k/SO_P}$), several ratios involving the measure of the sub-objectives given a risk R_k and the expected values of the sub-objectives are computed. In fact, from a formal point of view, an objective can be seen through a set of expected values associated with a variable or factor since the three management systems (ISO 9001, ISO 14001, OHSAS 18001) require that each objective should be quantified and expressed by numerical values which can be expressed from customers requirement, standards or even regulations. Regarding the measure of the risk on the objectives it can be provided by physical sensors or by experts.

2.3.2 Fuzzy logic system for MLF-FMEA

Given K risks and P QSE sub-objectives, the parameters estimation phase will provide the inputs OC_k, D_k and S_{R_k/O_p} ($k \in \{1 \dots K\}$, $p \in \{1 \dots P\}$,). These inputs will be handled via a fuzzy inference system following the same principle than fuzzy FMEA. In fact, as shown in Figure 2.7, for each risk R_k, P fuzzy logic system are defined, each one has as input OC_k, D_k and S_{R_k/O_p} and as output RPN_{kp}. Each triplet will be fuzzified using appropriate membership functions, this latter will be defined in the same interval [0 1] as the parameters inputs. Then, once the inputs are fuzzified a set of fuzzy rules are defined in the following form:

Rule 1: IF OC_1 is $\hat{A}_1$ AND S_{R_1/O_1} is $\hat{B}_1$ AND D_1 is is $\hat{C}_1$ THEN RPN_{11} is $\hat{E}_1$
Rule 2: IF OC_1 is $\hat{A}_2$ AND S_{R_1/O_1} is $\hat{B}_1$ AND D_1 is is $\hat{C}_1$ THEN RPN_{11} is $\hat{E}_2$
...
Rule r: IF OC_k is $\hat{A}_4$ AND S_{R_k/O_p} is $\hat{B}_4$ AND D_k is is $\hat{C}_4$ THEN RPN_{kp} is $\hat{E}_4$

where $\hat{A}$, $\hat{B}$ and $\hat{C}$ are respectively the set of linguistic terms describing the inputs OC_k, D_k and S_{R_k/SO_p}, and $\hat{E}$ the set of linguistic terms describing the output RPN_{kp}. Then, the max-min inference mechanism is applied to generate each fuzzy output ($\mu_{RPN_{kp}(x)}$). Finally, the centroid method is applied to compute RPN_{kp} value.

Example 2.2 *In order to illustrate our approach an implementation in the petroleum field in TOTAL TUNISIA company is proposed. This company is certified in quality, security and environment management systems. In this illustrative example 3 QSE objectives (O_1, O_2, O_3) and 3 risks (R_1, R_2, R_3) are considered:*

- *O_1 (Quality) : Gain market share by providing superior all round by decreasing the product of non conformity level service to the customer. This objective is deployed into one sub-objective (i.e. SO_1: work stoppage $<=$ 10 hours).*

- *O_2 (Environement): Minimize the environmental waste by respecting the contamination rate of the air, water and ground according to the requirements and international standards. This objective is deployed into two sub-objectives (i.e. SO_2: Carbon concentration on the air $<=$ 10000 ppm and SO_3: Fuel concentration on the sea $<=$ 25000 ppm). For simplicity sake, SO_2 is used instead of SO_2 and SO_3 since R_1 and R_2 concern SO_2 and R_3 concerns only SO_3).*

- *O_3 (Security): Increase safety staff by decreasing the number of day off of employees. This objective is deployed into one sub-objective (i.e. SO_3: A total of days off $<=$ 15 days).*

- *R_1: A major fire and explosion on tanker truck carrying hydrocarbon,*

- *R_2: A fire in container*

- *R_3: the passage of a product in the discharge circuit from the separator to the sea.*

Figure 2.8 illustrates the membership functions defined by experts and used for both inputs and outputs (since they are defined by the same linguistic terms and the same universe of discourse). Regarding the fuzzy rule base, $4^3 = 64$ rules are defined for each risk in the following form:

IF (SO_1 is minor) AND (S_{R_1/SO_1} is minor) AND (D_1 is minor) THEN (RPN_{11} is minor)
IF (SO_1 is low) AND (S_{R_1/SO_1} is minor) AND (D_1 is minor) THEN (RPN_{11} is minor)
IF (SO_1 is moderate) AND (S_{R_1/SO_1} is minor) AND (D_1 is minor) THEN (RPN_{11} is low)
IF (SO_1 is high) AND (S_{R_1/SO_1} is high) AND (D_1 is minor) THEN (RPN_{11} is low)
...

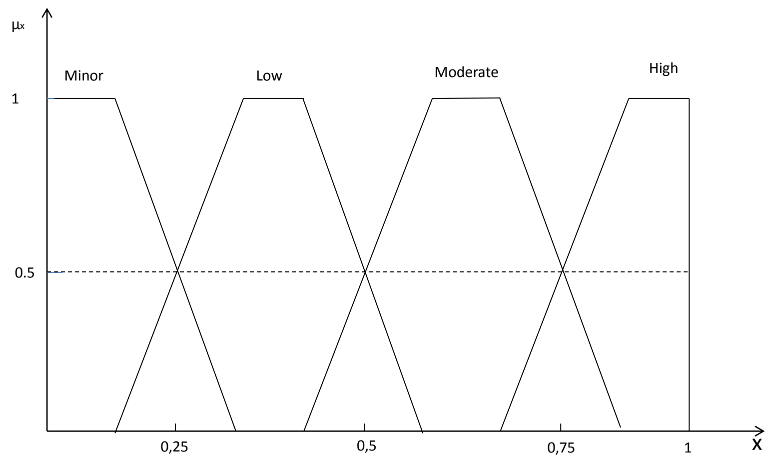

Figure 2.8: Constructed membership functions

The quantification of different inputs (i.e. occurrence, severities and detectability) are provided in Tables 2.2, 2.3 and 2.4.

Table 2.2: Occurrence values

	Risk occurence	$\Delta t(Days)$	Occurrence
R_1	[1 2]	3650 (10 years)	[0.0002 0.0005]
R_2	3	3650 (10 years)	0.0008
R_3	[1 2]	1825 (5 years)	[0.0005 0.0001]

Then, for each risk R_k (k=1 ... 3) and each objective SO_P (P=1 ... 3), RPN_{kp} given in Table 2.5 are computed using the max-min inference method and the centroid method for the defuzzification step.

2.3.3 Multi-criteria selection of the most critical risks

As shown in the previous section, each risk R_k can have several RPN values. Thus, the question that arises is *how detect the most critical ones?*

To answer this question the different risks have to be compared regarding each sub-objective SO_p. This is clearly a multi-objective problem. In literature, a variety of multi-criteria approaches can be distinguished such as weighting methods, outranking methods and interactive methods. We propose here to use

Table 2.3: Severity values

	Measure of risk on objective	Severity
Expected value of SO_1: <= 10 hours work stoppage		
R_1	2.5 hours work stoppage	$S_{R_1/SO_1} = 0.25$
R_2	3.5 hours work stoppage	$S_{R_2/SO_1} = 0.35$
R_3	6 hours work stoppage	$S_{R_3/SO_1} = 0.6$
Expected value of SO_2:Carbon concentration on the air <= 10000 ppm and Fuel concentration on the sea <= 25000 ppm		
R_1	Carbon concentration on the air = 6500 ppm	$S_{R1/SO_2} = 0.65$
R_2	Carbon concentration on the air = 6500 ppm	$S_{R_2/SO_2} = 0.65$
R_3	Fuel concentration on the sea = 6250 ppm	$S_{R_3/SO_2} = 0.25$
Expected value of SO_3: A total of 15 days off		
R_1	A total of 6 days off for injured staff	$S_{R_1/SO_3} = 0.4$
R_2	A total of 4 days off for injured staff	$S_{R_2/SO_3} = 0.26$
R_3	A total of 0 days off for injured staff	$S_{R_3/SO_3} = 0$

Table 2.4: Detectability values

	Detecting risk number	Risk occurrence	Detectability
R_1	1	[1 2]	[0.5 1]
R_2	2	3	0.66
R_3	1	[1 2]	[0.5 1]

the standard weighting method, which is the Analytic Hierarchical Process (AHP) [88] since it can be easily adapted to our requirements. In what follows some basics of this method are given.

2.3.3.1 Principles of Analytic Hierarchical Process (AHP)

The principle of AHP is to organize the critical aspects of a problem by decomposing it into a multi-level hierarchical structure (as shown in Figure 2.9) corresponding to a tree structure in which the first level (i.e. the root) corresponds to the objectives, the last one (i.e. the leaves) to the alternatives (i.e. the possible solutions) and the intermediate ones to the different criteria and their sub-criteria.

Table 2.5: Different RPN_{kp} values

	O_1	O_2	O_3
R_1	0.65	0.38	0.71
R_2	0.38	0.35	0.66
R_3	0.29	0.74	0.18

For each level of this tree (except the root), one or several decision matrices (DM) are defined based on pair-wise comparisons. Thus, for each level l with n elements (criteria or alternatives), m decision matrices ($n * n$) are defined, where m is the number of elements (i.e., criteria) of level $l-1$. Each value a_{ij} ($i \in \{1 \ldots n\}, j \in \{1 \ldots n\}$) in a decision matrix DM relative to the criteria C_i defines the degree of importance between i and j in the context of C_i. Such a value can be determined from Saaty's scale of measurement given in Table 2.6. Note that a_{ij}=a_{ji}, which means that all decision matrices are symmetric.

Table 2.6: Saaty's scale of measurement [88]

Intensity of importance	Significance
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments

Once the decision matrices are defined, the coherence of each one is ensured by computing its consistency ratio, as follows:

$$CR = \frac{CI}{RI} = \frac{\frac{\lambda_{max}-K}{K-1}}{RI} \tag{2.2}$$

where K and λ_{max} are, respectively, the number of compared elements and the maximum eigenvalue of the considered DM, and RI is the random index value defined according to the number of criteria (see Table 2.7 [88]).

Table 2.7: Table of random indexes

Number of criteria	2	3	4	5	6	7	8	9
RI	0	0.58	0.9	1.12	1.24	1.45	1.49	1.51

Values of CR <= 0.1 are considered acceptable, otherwise, the decision matrix should be revised [88].

Acceptable decision matrices can be used to evaluate the global scores relative to different elements in each level in a top-down manner until reaching the alternatives level. More precisely, for each element i in a level l a global score W_i relative to each criteria C_j $(j = 1 \dots m)$ (pertaining to level $l-1$) is computed using the decision matrix relative to this criteria as follows:

$$W_i = \frac{1}{n}\begin{bmatrix}\frac{1}{\sum_{j=1}^{m} a_{i1}} & \frac{1}{\sum_{j=1}^{m} a_{i2}} & \dots & \frac{1}{\sum_{j=1}^{m} a_{in}}\end{bmatrix} * \begin{bmatrix}a_{i1} & a_{i2} & \dots & a_{in}\end{bmatrix}' \tag{2.3}$$

2.3.3.2 Multi-criteria approach to select the most critical risks

In order to select the most critical risks, a three levels hierarchical structure (see Figure 2.9) are used, having as a main objective (Top level) the ranking of different risks. The second level relative to the comparative criteria, concerns the deployed QSE objectives $(SO_1 \dots SO_p)$, and the last one the identified risks $(R_1 \dots R_m)$. Thus as a first step, the different sub-objectives are compared in order to obtain their relative weights using Saaty's scale measurement. Then, the different values of RPN_{kp}, obtained from the previous step, will be calibrated in Saaty's scale by a pairwise comparisons. More formerly, for each pair of risks $\{R_j, R_k\}$, for each sub-objective SO_p, the impact of R_j on SO_p w.r.t. R_k is computed by dividing RPN_{jp} on RPN_{kp} (resp. RPN_{kp} on RPN_{jp}) if $RPN_{jp} \geq RPN_{kp}$ (resp. otherwise) and by rounding the obtained result by a value α in order to fit to the semantic of Saaty's scale.

Example 2.3 *Let us consider the RPN values illustrated in Table 2.5, to aggregate them using the three levels hierarchical structure of Figure 2.9, the decision matrix relative to QSE objectives given in Table 2.8 is proposed. For instance, we*

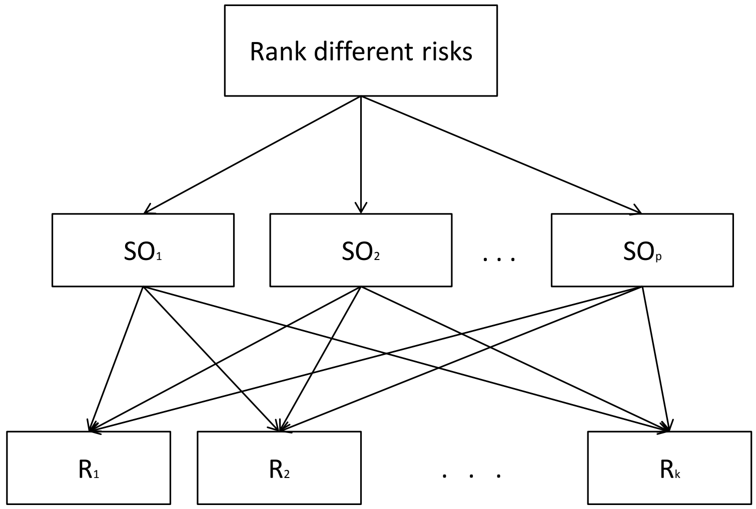

Figure 2.9: The hierarchical model to select critical risks

can note that SO_3 has a moderate importance w.r.t SO_1 and a stronger importance w.r.t SO_2 etc. On the basis of these values, the relative weight concerning each objective is defined. Thus, we can conclude that SO_2 is the most important criteria followed by SO_1, and finally SO_3. Once the criteria's weights are defined, the different values of RPN_{kp} will be re-scaled in Saaty's scale by computing for each couple $\{R_j, R_k\}$, for each objective SO_p, RPN_{kp}/RPN_{jp} if $RPN_{kp} \geq RPN_{jp}$ and RPN_{jp}/RPN_{kp} otherwise. Then, the ratio values are rounded using a threshold α (here we use $\alpha = 0.3$).

Table 2.9 illustrates this transformation which is used to construct the decision matrices relative to different risks regarding each objective (see Table 2.10). Using these values, Table 3.10 represents the different risk weights according to each objective. For instance, regarding the objective SO_1, R_1 is the most important risk ($W_1 = 0.498$), followed by R_2 ($W_2 = 0.268$) then, by R_3 ($W_3 = 0.203$).

2.4 Conclusion

In this chapter, a new approach extending the existing Fuzzy FMEA is proposed to implement the deployment of the objectives, the identification of risks and

Table 2.8: Decision matrix relative to QSE objectives

–	SO_1	SO_2	SO_3	Weights
SO_1	1	1/3	4	0.28
SO_2	3	1	5	0.63
SO_3	1/4	1/5	1	0.09

Table 2.9: Transformation of RPN_{jd} values into Saaty's scale

SO_1			SO_2			SO_3		
R$_j/R_k$	$\frac{RPN_{j1}}{RPN_{k1}}$	Saaty value	R$_j/R_k$	$\frac{RPN_{j2}}{RPN_{k2}}$	Saaty value	R$_j/R_k$	$\frac{RPN_{j3}}{RPN_{k3}}$	Saaty value
R_1/R_2	1.71	2	R_1/R_3	1.94	2	R_1/R_2	1.07	1
R_1/R_3	2.24	2	R_3/R_2	2.11	2	R_1/R_3	3.94	4
R_2/R_3	1.31	2	R_1/R_2	1.08	1	R_2/R_3	3.66	4

Table 2.10: Decision matrices relative to risks

	SO_1			SO_2			SO_3		
–	R_1	R_2	R_3	R_1	R_2	R_3	R_1	R_2	R_3
R_1	1	2	2	1	2	2	1	1	4
R_2	1/2	1	2	1/2	1	1	1	1	4
R_3	1/2	1/2	1	1/2	1	1	1/4	1/4	1

Table 2.11: Risk weights

R_i	SO_1 (0.28)	SO_2 (0.63)	SO_3 (0.09)	Weights
R_1	0.49	0.5	0.44	0.49
R_2	0.31	0.25	0.44	0.28
R_3	0.2	0.25	0.12	0.23

their analysis.

The proposed extension named, multi-leveled fuzzy FMEA(MLF-FMEA), affects for each risk R_k several RPN_{kp} regarding different QSE sub-objectives $(SO_1 \cdots SO_P)$.

Then, to select the most critical risks an aggregation using the *Analytic Hierarchical Process (AHP)* [88] is proposed since it can be easily adapted to our requirements. It is important to note that this approach can be applied in other fields where many objectives should be considered.

In next chapter, the fourth and the last step in the plan phase is proposed, consisting in evaluating each selected critical risk in order to assist the decision maker to define the appropriate treatments as preventive and corrective action.

Chapter 3

A Bayesian Approach to Construct Bow Tie Diagrams for Risk Evaluation

3.1 Introduction

Given the most critical risks (w.r.t Quality, Security and Environment management systems) generated by the multi-leveled Fuzzy FMEA proposed in chapter 2, we propose now to move one step further regarding the plan phase of our process-based approach which consists in evaluating each critical risk. More precisely, we propose to assists the decision maker by constructing for each critical risk a scenario (i.e causes and consequences).

Among scenario analysis models, this chapter proposes to use the bow tie diagram for risk analysis [30]. The choice of this tool can be explained by the fact that the whole scenario for each identified risk also called *top event* (TE) is clearly represented via two parts: the first corresponds to a *fault tree* defining all possible causes leading to the TE and the second represents an *event tree* to reach all possible consequences of the TE. In addition, bow tie diagrams allow to define in the same scheme *preventive barriers* to limit the occurrence of the TE and *protective barriers* to reduce the severity of its consequences.

The major problem with bow tie diagrams is that they are restricted to a graphical representation of different scenarios and that they ignore the dynamic aspect of real systems. To overcome this weakness, this chapter proposes a new Bayesian approach for constructing bow tie diagrams that reflect the real behaviour of the system. Moreover, the new numerical component that we have added in the building phase will be used to allow experts to interact with the system in real time via a multi-criteria approach: the analytic hierarchical process (AHP) in order to define different barriers (preventive and protective) in a dynamic way.

The remainder of this chapter is organized as follows: Section 2 presents a brief recall on the bow tie diagrams analysis. Section 3 proposes a Bayesian approach to construct the bow tie diagrams. Section 4 is dedicated to the barriers implementation. Finally section 5 presents an illustrative example.

Main results presented in this chapter are published in [9, 10, 11].

3.2 A brief recall on the bow tie diagrams analysis

Several techniques have been proposed to identify the accident scenario of a given risk, such as *barrier block diagrams* [92], *fault and event trees* [50] and *bow tie diagrams* [30]. An interesting comparison, between these techniques is proposed in [78, 92]. Among these techniques, the bow tie diagrams have proven their efficiency in several real world applications such as accident risk assessment [35, 36, 47, 62], risk management [28], safety barrier implementation [10, 36] and especially in the petroleum field [30]. The principle of this technique is to build a kind of tree, called bow tie due to its special form, for each identified risk R_i (also called *top event* (TE)) that represents the entire scenario based on two parts, as shown in Figure 3.1:

- The first part corresponds to the left part of the scheme and represents a *fault tree* (FT) that defines all possible causes of TE. These causes can be classified into two kinds: the first are the *initiator events* (IE), which are the principal causes of TE, and the second are the *undesired and critical events* ($IndE$ and CE) that are the causes of IE. The relationships between events and causes are represented by logical AND and OR gates. The AND gate means that the occurrence of an event requires the happening of all its related causes. However, the OR gate means that the occurrence of an event requires the happening of any of its related cause.

- The second part corresponds to the right part of the scheme, which represents an *event tree* (ET) that defines all possible consequences of TE. These consequences can be classified into three types: *second events* (SE), which are the principal consequences of TE, *dangerous effects* (DE), which are the dangerous consequences of SE, and *major events* (ME) of each DE.

Bow tie diagrams are also used to define *preventive barriers* to limit the occurrence of TE and also *protective barriers* to reduce the severity of its consequences. These barriers can be classified as *active* if they require a source of energy or a request (automatic or manual action) to fulfil their function (e.g., safety valve, alarm) or as *passive* if they do not require a source of energy or a request to fulfil their function (e.g., procedure, retention dike, firewall).

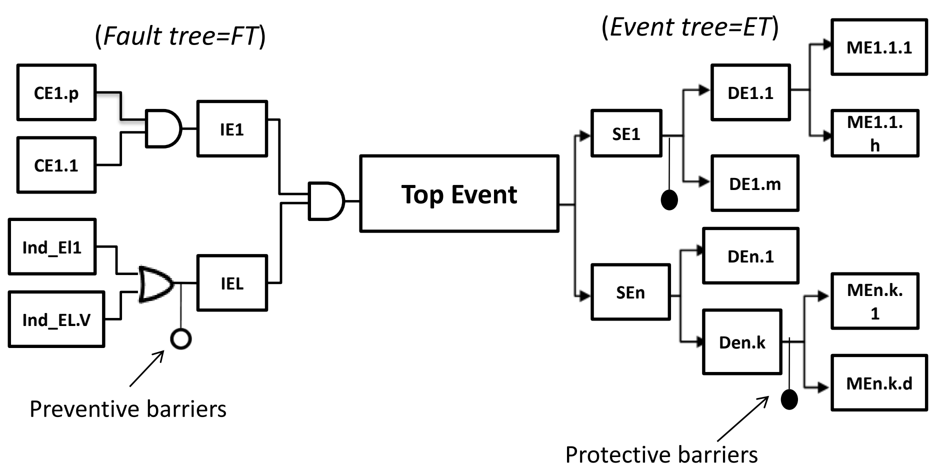

Figure 3.1: A bow tie diagram model

The construction of bow tie diagrams is mainly based on experts knowledge and follows the same basic rules as required in development of fault and event trees [38, 50] i.e. in a top top-down manner (from TE to $IndE$ and CE in the fault tree and from TE to ME in the event tree).

Clearly the restriction to expert experience to define bow ties represents a real limitation of this tool since it seems unrealistic to use static recommendation in real dynamic systems

To overcome this problem, some researches propose novel approaches to build bow ties [34, 39, 54, 65, 72, 71]. For instance, Delvosalle et al. [34] have proposed a new methodology based on crossing matrices (i.e. a kind of checklist filled by the experts). In addition, they have proposed to implement the preventive and protective barriers by examining the bow tie structure, then they estimate their performance by computing the frequency relative to TE and ME using the traditional conjunction operation for AND and OR gates [40, 41]. Nevertheless, these approaches still limited to experts knowledge and do not consider the dynamicity of real systems.

In the remaining, a Bayesian approach is proposed to learn bow ties from real data while enriching them by a new numerical component that allows us an implementation of preventive and protective barriers in a dynamic way.

3.3 A new algorithm to construct bow tie diagrams

The principle of our method is to consider bow ties as particular probabilistic graphical models namely, Bayesian networks [81] which are powerful tools for reasoning under uncertainty. Formally, Bayesian networks have two components: a graphical one which is a DAG (Directed Acyclic Graph) where nodes represent variables and edges to encode the (in)dependence relationships and a numerical component which quantifies different links by the conditional probability of each node in the context of its parents.

Following this principle, the same learning process of Bayesian networks will be reused to learn bow tie diagrams in an automatic manner. More precisely, first bow ties structure is learned from a set of observations i.e. a training set [1], and then to quantify it by learning a numerical component i.e. a set of conditional probability tables. This latter, allows us, on the one hand, to characterize the

[1]A set of data used to discover potentially predictive relationships

impact of different causes on the top event TE and, on the other hand, to study its repercussion on its consequences.

3.3.1 Learning bow ties structure

To learn the bow ties structure automatically from real data, this diagram will be considered as tree-structured graph, denoted by T, with two subtrees (i.e. the fault tree FT and the event tree ET) sharing TE as central node. T is defined on a set of n nodes $V = \{X1, \cdots, Xn\}$, s.t. each node X_i represents an event (e.g., IE, CE and SE). All these events are considered as binary (present or absent), thus, all variables in V have two states: True (T) or False (F). In the remaining, X_1 is considered as the top event TE.

Formally, bow ties learning problem can be formulated as follows: given a tree distribution T_d and a training set TS of N observations (s.t. $TS = \{x_1, x_2, \cdots, x_N\}$, where x_i is the i_{th} observation relative to all variables in TS), we should find the tree T^* that maximises the log likelihood of the data as follows [26]:

$$T^* = argmax \sum_{i=1}^{N} logT_d(x_i) \tag{3.1}$$

To learn the bow ties structure, first its skeleton is learned, then its arcs are oriented.

3.3.1.1 Learning bow ties skeleton

To learn the bow tie skeleton, the *Maximal Weight Spanning Tree (MWST)* algorithm proposed by Chow and Liu [26] is used. Our approach, outlined by Algorithm 3.1, uses a training set TS as input, and generates a spanning tree, denoted by $UT = \{U, E\}$, where U is the set of nodes, and E is the set of edges. The principle of this learning algorithm is to compute the mutual information I_{ij} between each pair of variables (X_i, X_j) in the training set as follows:

$$I_{ij} = \sum_{x_i x_j} P_{ij}(x_i, x_j) log(\frac{P_{ij}(x_i, x_j)}{P_i(x_i)P_j(x_j)} \tag{3.2}$$

where $P_{ij}(x_i, x_j)$ (resp. $P_i(x_i)$) is the proportion of observations in the training set TS and $X_i = x_i$ and $Y_i = y_i$ (resp. $X_i = x_i$).

Algorithm 3.1: Learning_undirected_tree_structure

```
Data: TS on a set of n variables V = {X_1, ..., X_n}
Result: UT={U,E}
begin
    for i ∈ {1, ..., n − 1} do
        for j ∈ {2, ..., n} do
            Compute the mutual information I_ij using equation (3.2)
            M[i][j] ← I_ij
    Let r be an arbitrarily chosen variable from V
    U ← r
    E ← ∅
    while |U| < n do
        Use M to find X_i in U and X_j in V-{U} s.t. I_ij is the highest mutual
        information (within all possible combinations)
        U ← U ∪ X_j
        E ← E ∪ (i − j)
end
```

Since the bow tie is composed of two trees (i.e. ET and FT), Algorithm 3.1 is ran twice to learn the skeleton of FT and ET separately from two distinct training sets: the first, denoted by TS_{FT}, is related the observed events leading to the TE, and the second, denoted by TS_{ET}, is relative to its consequences.

3.3.1.2 Orientation of bow ties

Using the bow tie skeleton generated in the previous phase, the orientation is realized while respecting the specificities of its two components i.e. ET and FT. Generally, this task is ensured semantically [11] using the fact that events in fault trees are similar to those in a polytree in which an event may arise from multiple causes (i.e., arcs are directed toward TE), unlike event trees in which the same event may cause multiple events (i.e., arcs will be directed back toward TE). Thus, the orientation task of FT and ET are addressed in a different way.

i) *Orientation of fault tree*

If we consider the FT diagram as a cause and effect diagram, then all the edges should be oriented as tail-to-head relations toward the TE. Indeed, all the events (i.e., $IndE$, CE and IE) represent a direct or indirect causes of the TE.

The problem, is that in real cases, not all the observed events in fault tree are causes of the TE. For instance, if we consider the events in Figure 3.2, it is clear that a gas leak E_1 and a fuel leak E_3 are the initiator events of an explosion TE, while the gas odour E_2 is an informative event about the gas leak E_1. Thus, its observation is useful even though it is not a cause of the TE.

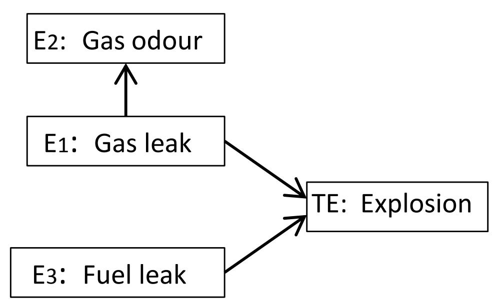

Figure 3.2: Example of an oriented fault tree

This structure represents a much richer dependency model than the classical fault tree, which is limited to eventual causes of the TE. Thus, our idea is to benefit from this dependency structure to represent the fault trees. To represent such a structure, Rebane et al. [86] proposed an algorithm to orient a polytree given a tree structure derived from the Chow and Liu algorithm [26]. They assumed that independence tests on various multiple parent nodes are available and that we have marginal independence between at least two parents of any node. The principle of this approach is to divide the polytree into one or several causal basins. A causal basin starts with an articulation point described by the following rule:

(a) A node Z is said to be an articulation point between nodes X and Y if an unoriented triplet of variables X, Y and Z ordered: X—Z—Y exists, where X and Y are independent. X is as a parent of Z, and Y is oriented as a parent of Z (i.e., X $\rightarrow$ Z $\leftarrow$ Y).

Then, once the articulation points are detected, the following rule should be applied:

(b) For any triplet X, Y and Z such that: X $\rightarrow$ Z—Y, if X and Y are independent, then Y is a parent of Z (i.e., Z $\leftarrow$ Y), otherwise, Y is a child of Z (i.e., Z $\leftarrow$ Y).

The rule (b) is applied until no more edges can be oriented.

In the case where the polytree is not be fully oriented, the unoriented edges can be oriented arbitrarily due to the Markov equivalence property[2]. However, even if arbitrary orientation has no impact in terms of calculations, it may compromise the readability of the final graph. To ovoid this problem, the expert knowledge is used to complete the orientation properly.

This orientation procedure should be applied to all edges except for those directly related to TE where a tail-to-head orientation is proposed since it is the major consequence in TS_{FT}. Algorithm 3.2 outlines the major steps used to orient the fault tree.

Algorithm 3.2: Orient_polytree

Data: Undirected Fault tree (UT), TE
Result: Oriented Fault tree
begin

Orient unoriented edge related to TE (i.e. $—TE$) towards the TE (i.e. $\rightarrow TE$),
Detect and orient any articulation point in UT using rule (a),
Use rule (b) to orient the remaining nodes until no edges can be oriented,
If any articulation point remains in UT. Then return to step 2,
If any undirected edges remain, use expert knowledge to complete the orientation,

end

ii) *Orientation of event tree*

[2]Two Bayesian networks are said to be Markov equivalent if and only if they have the same sets of adjacencies and V-structures [97].

Contrary to the FT, in the ET, the edges in ET should be oriented from TE toward different nodes in ME. To this end, the principle suggests that an undirected tree (UT) can be oriented by selecting a root and directing the different edges from it [75]. In our context, the TE is considered as the root. This task will be ensured by the function *orient_tree (UT={U,E} : undirected tree, TE: Top event)* which returns an oriented tree.

3.3.2 Learning bow ties parameters

Once the bow structure is learned, its quantification is realized by learning its parameters i.e. its numerical component which differs from the fault to the event tree.

3.3.2.1 Quantification of fault tree

For any node X_i in FT, conditional probability table (CPT) is assigned in the context of its parents (i.e., $P(X_i \mid Pa(X_i))$, where $Pa(X_i)$ denotes the parent set of X_i.

These tables generalize the logical AND and OR gates by defining in a numerical manner the behaviour of different events w.r.t their causes. For instance, if X_2 AND X_3 cause X_1, this means that in the CPT of X_1, $P(X_1 = T \mid X_2 = T, X_3 = T) = P(X_1 = F \mid X_2 = T, X_3 = F) = P(X_1 = F \mid X_2 = F, X_3 = T) = P(X_1 = F \mid X_2 = F, X_3 = F) = 1$ and that the remaining entries are null. The same relation can be represented with more flexibility by probability degrees pertaining to the unit interval.

To quantify the fault tree, a Bayesian approach based on informative priors is used. More precisely, to estimate $P(X_i = k \mid Pa(X_i) = j)$ (i.e., the probability that X_i is equal to k knowing that its parents denoted by $Pa(X_i)$ take the value j), the *maximum a posterior* (MAP) estimate is used and expressed by:

$$\hat{P}(X_i = k \mid Pa(X_i) = j) = \frac{N_{ijk} + \alpha_{ijk}}{\sum_k N_{ijk} + \alpha_{ijk}} \tag{3.3}$$

where N_{ijk} is the number of instances in the training set TS_{FT} where $X_i = k$ and $Pa(X_i) = j$ occur conjointly and α_{ijk} is a Dirichlet prior with a simple interpretation in terms of pseudo counts, i.e., we suppose that we saw the value k

of X_i for each value j of $Pa(X_i)$ α_{ijk} times. This value prevents us from declaring that an event $(X_i = k, Pa(X_i) = j)$ is impossible just because it was not seen in the training set. If we have no precise information on priors we can consider them as uniform.

3.3.2.2 Quantification of event tree

For any node X_i in ET (except ME), a value related to its severity w.r.t. its children (i.e., its consequences) is assigned denoted by $Ch(X_i)$. This value quantifies the impact of the realisation of X_i on any $X_j \in Ch(X_i)$. In literature, several methods have been proposed to evaluate the severity of an event, the most famous ones are *preliminary risk analysis* (PRA), *hazard and operability study* (HAZOP) and *failure mode and effects analysis* (FMEA). But, these methods are not appropriate with probabilistic graphical models. Thus, the severity of X_i on any of its child X_j is considered as the probability of that X_j occurs knowing that X_i is true (i.e., $P(X_j = T \mid X_i = T)$). This means that, for each X_i, a severity vector containing the different severity values toward its related children is assigned. To compute this value, the Bayes theorem is used as follows:

$$S_i[j] = P(X_j = T \mid X_i = T) = \frac{N_{ij}}{N_i} \tag{3.4}$$

where N_{ij} is the number of instances in TS_{ET} s.t. $X_i = T$ and $X_j = T$ occur conjointly and N_i is the number of instances in TS_{ET} s.t. $X_i = T$.

3.3.3 Global learning approach

The global approach learning bow tie diagram is summarized in Algorithm 3.3.

The resulting bow tie (structure and parameters), can be used to propose appropriate preventive and protective barriers in a dynamic way while taking into account available resources as described below.

3.4 Barriers implementation

Using the resulting bow tie from the previous phase, the behaviour of some events is observed and their impact on TE are studied in order to determine the real

Algorithm 3.3: Learning bow tie

```
Data: TS_FT; TS_ET; TE
Result: BT = {T, CPT, S}
begin
    % Learning structure
    UT_FT ← Learning_undirected_tree_structure(TS_FT,, TE)
    UT_ET ← Learning_undirected_tree_structure(TS_ET, TE)
    T_FT ← Orient_polytree(UT_FT)
    T_ET ← Orient_tree(UT_ET)
    T ← {T_FT, T_ET}
    % Learning parameters
    foreach X_i ∈ T_FT do
        compute P(X_i | Pa(X_i)) using equation (3.3)
        CPT[i] ← P(X_i | Pa(X_i))
    S ← ∅
    foreach X_i ∈ T_ET do
        foreach X_j ∈ Ch(X_i) do
            compute P(X_j = T | X_i = T) using equation (3.4)
            S_i[j] ← P(X_j = T | X_i = T)
        S ← S ∪ S_i
end
```

probability relative to its release and propose appropriate preventive and protective barriers at any moment. This choice is, obviously, constrained by several criteria such as *effectiveness*, *reliability*, *availability* and *cost*, which means that we have a multi-criteria problem. Thus, to select the appropriate barriers, the standard weighting method is used, which is the Analytic Hierarchical Process (AHP) [88] since it can be easily adapted to our requirements.

As shown in Figure 3.3, a three levels hierarchical model is proposed using in the second level the most common criteria relative to the selection of the barriers [30] namely, *effectiveness*, *reliability*, *availability* and *cost*. This hierarchical structure provides us with a set of barriers sorted by priority based on their global score. In the following, the function *AHP (B: a set of possible barriers, DM: the* *set of the required decision matrices)* is used to return a set of barriers sorted by priority.

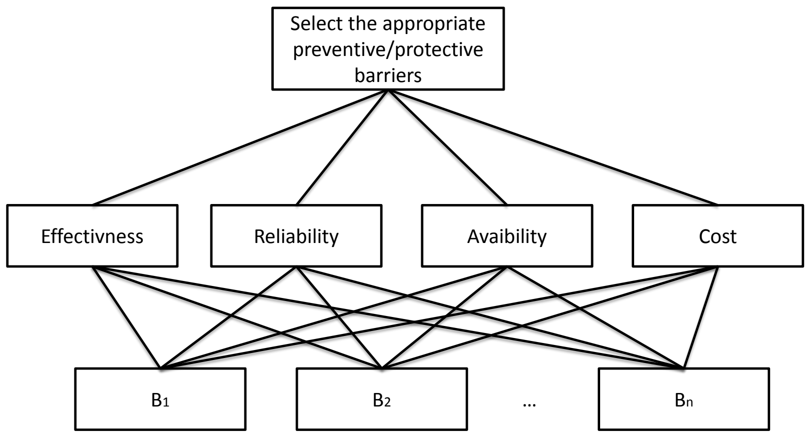

Figure 3.3: The hierarchical model used to select preventive and protective barriers

We now explain how to integrate this method to implement preventive and protective barriers.

3.4.1 Preventive barrier implementation

In order to detect the most efficient preventive barriers, first the impact of observations next to the nodes in the fault tree FT (referred to by e) on the top event TE are studied, i.e., we are interested in the value of $P(TE = T \mid e)$. This value can be determined in a polynomial way by applying the Pearl's propagation algorithm in *polytrees* [81, 83]. In this algorithm, the impact of each new piece of evidence is viewed as a perturbation that propagates through two messages, passing a collect-evidence pass in which messages are passed toward a particular node in FT, called the pivot (selected randomly), and a distribute-evidence pass where messages are passed from the pivot to the rest of the nodes in the FT.

Thus, different marginals are used, which are issued from the propagation phase to select the appropriate preventive barriers i.e., those that reduce the probability of the occurrence of the TE. At this stage, the decision maker can interact with the system by selecting the most critical IE_s. To this end, classifying them w.r.t. their relative impact on the TE is done because they represent the principle causes leading to TE. This task is completed by computing the probability of occurrence of TE for each $IE_i \in IE$ i.e., $P(TE = T \mid IE_i = T)$. This step is important, since it allows the decision maker to localise the most critical events by interacting with the system to define the appropriate set of interventions that reduce the occurrence of the TE. Indeed, the decision maker can propose a set of interesting and possible interventions, then, via a simulation, our system can determine their impact on the occurrence of TE.

Let $I = \{I_1 \cdots I_n\}$ be the set of all possible scenarios of interventions on events relative to FT s.t. $I_i = \{I_{i1}, \cdots, I_{in}\}$ is a set of events intervening on the scenario I_i. Then the set I is used to determine the most efficient interventions by testing the impact of each I_i on the occurrence of TE, i.e., $\forall I_i \in I$, $P(TE = T \mid I_{i1} = e_1, \cdots, I_{in} = e_n)$ is computed, where e_j is the probability relative to the event I_{ij} (i.e. I_{ij}=1 (resp. I_{ij}=0) means that I_{ij}=T (resp. I_{ij}= F), otherwise, if $e_j \neq 0$ or $e_j \neq 1$ then I_{ij}=e_j means that $P(I_{ij}) = e_j$).

Example 3.1 *Let us consider the fault tree shown in Figure 3.4, and suppose that the gas or fuel leak and source of ignition are the most critical IE_s since they have a higher influence on the TE and that the intervention in public constructions close to the station is not possible. Regarding this situation, suppose that the decision maker proposes two scenarios i.e. $I = \{I_1, I_2\}$ such that:*

- $I_1 = \{I_{11}$:*Wear and degradation of the pump*, I_{12} :*Incorrect reception or transfer operation*
  I_{13} :*Hotspot operations*$\}, \{e_1 = 0.8, e_2 = 1, e_3 = 0.6\}$, *and*

- $I_2 = \{I_{21}$:*Wear and degradation of the pump*, I_{22} =*Incorrect reception or transfer operation*,
  I_{23} :*Flame, Cigarette, Cell phone*$\}, \{e_1 = 0.9, e_2 = 0.9, e_3 = 0.5\}$

Then the propagation process leads to $P(TE = T \mid I_{11} = 0.8, I_{12} = 1, I_{13} = 0.6\} = 0.1965$ *and* $P(TE = T \mid I_{21} = 0.9, I_{22} = 0.9, I_{23} = 0.5\} = 0.235$, *which means that the scenario I_1 is more interesting.*

The best set of interventions, it then used to select the appropriate preventive

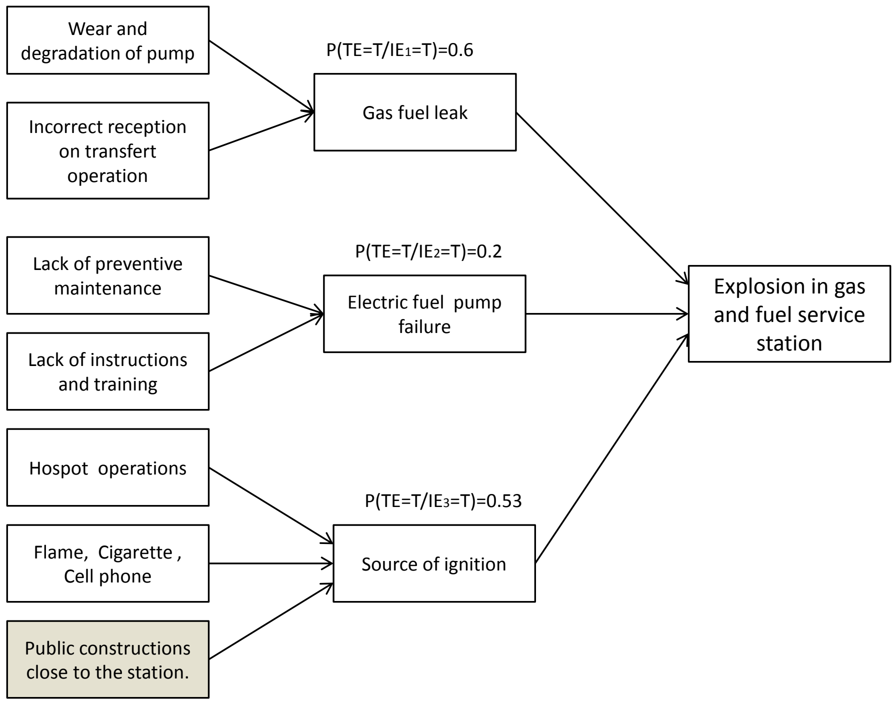

Figure 3.4: Fault tree relative to example 3.1

barriers via a multi-criteria selection by applying the AHP method. The global preventive barriers implementation algorithm is outlined by Algorithm 3.4.

3.4.2 Protective barrier implementation

Given the event tree, the decision maker can propose a set of interesting and efficient protective interventions and then compute their impact of each major event in similar way than preventive barriers. Formally, let I be the set of possible interventions related to ET, and let ME be the set of major events in ET. These two sets are used to determine the most effective interventions by testing the impact of each combination $I_i \in I$ on each event in ME i.e. $\forall I_i \in I$, $\forall ME_j \in ME$, $P(ME_j = T \mid I_{i1} = e_1, .., I_{in} = e_n)$ is computed. The particular structure of the event tree implies that all major events (the leaf level) are independent of each others [30] which means that $\forall I_i \in I$ we compute:

Algorithm 3.4: Preventive barrier implementation.

```
Data: T_FT, CPT
Result: PB*: proposed preventive barriers sorted by priority
begin
    foreach IE_i ∈ IE do
        compute P(TE = T | IE_i = T)
    Let I be a set of possible combination of interventions fixed by the decision maker.
    min ← 1
    foreach I_i ∈ I do
        compute P(TE = T | I_i1 = e_1, .., I_in = e_n)
        if min < P(TE = T | I_i1 = e_1, .., I_in = e_n) then
            I_i* ← I_i
    Let PB be the set of preventive barriers relative to the combination in I_i*
    Let DM be the set of the decision matrices relative to different criteria and their alternatives.
    % Select the appropriate preventive barriers
    PB* ← AHP(PB, DM)
end
```

$$P(ME_1, \cdots, Me_n \mid I_{i1} = e_1, \cdots, I_{in} = e_n) = \prod_{j=1}^{n} P(ME_j \mid I_{i1} = e_1, \cdots, I_{in} = e_n) \tag{3.5}$$

Then similarly to the implementation of preventive barriers, the AHP method is used in order to select the most appropriate ones by following the same hierarchy proposed in Figure 3.3. The whole selection procedure is outlined by Algorithm 3.5.

3.5 Illustrative example

Let us continue our illustrative example released in the petroleum field. In this example a unique risk relative to *a major fire and explosion on tanker truck carrying hydrocarbon* (TE) is considered. To construct the relative bow tie six

Algorithm 3.5: Protective barrier implementation

Data: T_{ET}, S
Result: PrB^*: proposed protective barriers sorted by priority
begin
    Let I_{pr} be a set of possible combination of interventions fixed by the decision maker.
    $min \leftarrow 1$
    foreach $I_{pri} \in I_{pr}$ **do**
        $P_{Me} \leftarrow 1$
        foreach $ME_{sj} \in ME_s$ **do**
            compute $P(ME_{sj} = T \mid I_{pri1} = e_1, .., I_{prin} = e_n)$
            $P_{Me} \leftarrow P_{Me} * P(ME_{sj} = T \mid I_{pri1} = e_1, .., I_{prin} = e_n)$
        if $min < P_{Me}$ **then**
            $I^*_{pri} \leftarrow I_{pri}$
    Let PrB be the set of protective barriers relative to the combination in I^*_{pri}.
    Let DM be the set of the decision matrices between the different criteria and their alternatives.
    % *Select the appropriate protective barriers*
    $PrB^* \leftarrow AHP(PrB, DM)$
end

events related to TE are identified:

- *Hydrocarbon gas leak* (HGL),
- *Source of ignition close to road* (SI),
- *Tank valve failure* (TVF),
- *Exhaust failure* (EF),
- *Gas odor* (GO),
- *construction site close to the truck parking* (CTP)),
- *Drilling a tank (DTA),and Presence of sparks* (PS).

And nine events representing its consequences:

- *Pool fire*(PF),
- *Thermal effects* (THE),
- *Toxic effects* (TO),
- *Production process in stop* (PPS),
- *Thermal damage to people* (TDP),
- *Damage to the other trucks* (DT),
- *Toxic damage to people* ($TODP$),
- *Damage on the environment* (DE),
- *Late delivery* (LD).

For simplicity sake, a restricted training set relative to causes (resp. consequences) TS_{FT} (resp. TS_{ET}) is considered, which is given in Table 6.5 (resp. Table 3.2).

Learning bow tie structure

The first step to learn the bow tie structure is to compute the mutual information between pairs of events (causes and consequences). The relative values to TS_{FT} (resp. TS_{ET}) are given in Table 3.3 (resp. Table 3.4), those in bold represent the best configurations (e.g., the more significant causes for TE are HGL and SI). Using these values, the bow tie diagram of Figure 3.5 is obtained.

Using these values, the bow tie diagram of Figure 3.5 is obtained.

Learning bow tie parameters

Once, the bow tie structure is defined, the parameters learning phase generates the numerical component relative to the FT (see Table 3.5) and severity degrees relative to ET (see Table 3.6).

Table 3.1: Training set relative to causes of a major fire and explosion on tanker truck carrying hydrocarbon TS_{FT}

DTA	GO	TE	EF	CTP	TVF	HGL	SI	PS	DTA	GO	TE	EF	CTP	TVF	HGL	SI	PS
T	T	T	T	T	F	T	T	T	F	T	T	T	T	T	T	T	T
T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	F	T	T	T	T	F	T	T	T	T	T	F	F	T	T	F	F
F	F	F	F	T	F	F	F	F	F	F	T	F	T	F	F	T	T
T	T	F	T	F	T	T	F	F	F	T	T	F	F	T	T	F	F
F	F	T	T	F	F	F	F	F	T	T	T	T	F	F	T	F	F
F	T	T	T	F	T	T	T	T	F	T	T	F	F	T	T	F	F
T	F	F	F	F	F	F	F	F	T	T	T	T	T	F	T	T	T
F	T	F	T	F	T	T	T	T	F	T	F	F	F	T	T	F	F
F	T	F	F	F	F	F	T	T	F	F	F	F	F	F	F	F	F
F	T	F	F	T	T	T	T	T	F	T	T	F	F	T	T	F	F
F	F	F	T	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	T	T	F	F	T	T	T	T	T	T	T	T	F	T	T	T	T
F	F	T	T	F	F	F	F	F	F	F	F	F	F	F	F	F	F
T	T	T	F	F	T	T	F	F	T	T	T	T	F	T	T	T	T
F	F	T	F	F	F	F	T	T	T	F	T	F	T	F	F	T	T
T	T	F	F	F	T	T	F	T	F	T	T	F	F	T	T	F	F
F	F	F	F	F	F	F	T	T	F	F	T	T	F	F	F	T	T
F	T	F	F	F	T	T	F	F	T	T	T	F	F	T	T	F	F
T	T	T	F	F	F	T	F	F	T	T	T	F	F	F	T	F	F
F	T	T	F	F	T	T	F	F	T	T	T	T	F	F	F	T	T
F	F	F	F	T	F	F	F	F	T	F	F	F	F	F	F	F	F
F	T	T	T	T	T	T	F	F	T	F	T	F	T	T	T	T	T
T	F	F	T	F	F	F	F	F	T	T	T	T	F	F	F	T	T
F	T	T	T	F	T	T	T	T	T	F	F	F	F	F	F	F	F
F	F	T	T	F	F	F	T	T	F	F	F	F	F	F	F	F	F

Table 3.2: Training set relative to consequences of a major fire and explosion on tanker truck carrying hydrocarbon TS_{ET}

TE	LD	DE	$TODP$	DT	TDP	PPS	TOE	PF	THE	TE	LD	DE	$TODP$	DT	TDP	PPS	TO	PF	THE
T	T	T	T	T	T	T	T	T	T	F	F	T	F	F	F	T	F	F	F
T	T	T	T	F	T	T	T	T	T	F	T	F	F	F	T	T	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	T	T	F	F	F	T	F	F
F	T	T	F	F	T	F	F	F	F	F	F	F	F	F	T	F	F	F	T
F	F	T	T	F	T	T	T	F	F	F	F	T	F	F	T	F	T	F	F
F	F	T	T	T	T	F	F	F	T	F	T	F	T	F	F	T	F	F	F
F	T	F	T	F	F	T	F	F	F	F	T	T	T	F	F	F	T	F	F
F	F	F	F	F	F	T	F	F	F	F	F	T	T	F	T	F	T	F	F
T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T
F	F	F	F	F	T	F	F	F	T	F	T	F	F	F	T	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	T	T	F	F	F	T	F	F	F
F	T	F	T	F	T	T	F	F	F	F	F	F	T	F	T	F	F	F	T
F	T	T	T	F	F	F	T	F	F	F	T	F	T	F	T	T	F	F	F
F	T	F	F	T	T	F	F	F	T	T	F	T	F	F	F	F	F	F	F
F	F	T	T	F	T	F	T	F	F	F	F	F	T	T	T	F	F	F	T
F	F	T	F	T	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F
T	T	T	T	T	T	T	T	T	T	F	F	F	T	F	F	F	T	F	F
F	F	T	T	F	F	F	T	F	F	T	T	T	T	F	T	T	T	T	T
F	T	T	F	T	F	T	T	T	T	F	F	F	F	F	T	F	F	F	F
F	F	F	F	T	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F
F	T	T	T	F	F	F	T	F	F	F	T	F	F	F	T	T	F	F	F
F	F	T	F	T	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F
F	F	T	T	T	F	F	T	F	F	T	T	T	T	F	T	T	T	T	T
F	T	T	F	F	T	T	F	F	F	F	T	T	F	F	F	T	F	F	F
F	F	F	T	T	F	F	F	F	F	F	F	T	T	F	T	F	T	F	F
T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T

3.5.1 Preventive barrier implementation

To implement the appropriate preventive barrier the first step is to calculate for each $IE_i \in E$ $P(TE = T \mid IE_i = T)$ as shown in Table 3.7. On the basis of these values the decision maker defines three scenario of of intervention i.e. $I = \{I_1, I_2, I_3\}$ such that $I_1 = \{I_{HGL} = 0.6, I_{TVF} = 1, I_{EF} = 1\}$, $I_2 = \{I_{SI} =$

Table 3.3: Mutual information values relative to TS_{FT}

	TE	SI	HGL	PS	TVF	CTP	EF	DTA	GO
TE	–	**0.097**	**0.109**	0.071	0.049	0.014	0.081	0.01	0.084
SI	**0.097**	–	0	**0.86**	0	**0.083**	**0.114**	0	0
HGL	**0.109**	0	–	0	**0.514**	0	0	**0.019**	**0.879**
PS	0.0709	**0.86**	0	–	0	0.073	0.096	0	0
TVF	0.049	0	**0.625**	0	–	0	0	0	0.471
CTP	0.014	**0.083**	0	0.073	0	–	0	0	0
EF	0.081	**0.114**	0	0.096	0	0	–	0	0
DTA	0.01	0	**0.019**	0	0	0	0	–	0.019
GO	0.084	0	**0.879**	0	0.471	0	0	0.012	–

Table 3.4: Mutual information values relative to TS_{ET}

–	TE	PF	THE	PPS	TOE	TDP	DT	LD	$TODP$	DE
TE	–	**0.485**	0.217	0.134	0.146	0.076	0.019	0.113	0.085	0.134
PF	0.485	–	**0.341**	**0.239**	**0.254**	0.076	0.051	0.212	0.085	0.134
THE	0.217	0.341	–	0	0	**0.25**	**0.167**	0	0	0
PPS	0.134	0.239	0	–	0	0	0	**0.385**	0	0
TOE	0.146	0.254	0	0	–	0	0	0	**0.327**	**0.294**
TDP	0.076	0.076	0.25	0	0	–	0	0	0	0
DT	0.057	0.113	0.259	0	0	0	–	0	0	0
LD	0.113	0.212	0	0.385	0	0	0	–	0	0
$TODP$	0.085	0.085	0	0	0.327	0	0	0	–	0
DE	0.134	0.134	0	0	0.294	0	0	0	0	–

$0.5, I_{EF} = 1, I_{TVF} = 1\}$, $I_3 = \{I_{SI} = 0.5, I_{DTA} = 0.8, I_{EF} = 1\}$.

Table 3.7 shows the impact of each scenario on TE and clearly $I^* = I_1$ since it decreases the occurrence of TE to 0.2834. Regarding this situation the following preventive barriers are proposed: *Education and Training Task to deal with HGL*

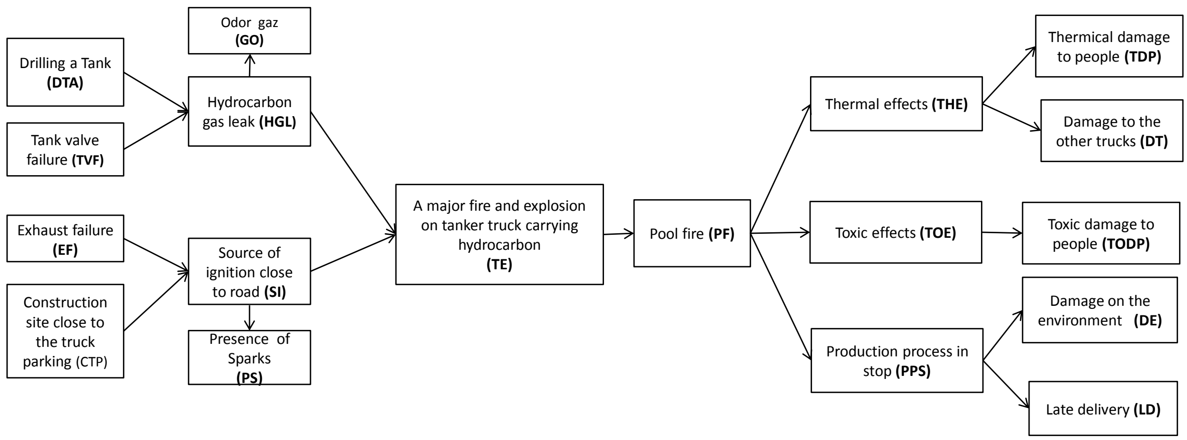

Figure 3.5: Resulted bow tie structure

(PB_1), *Fire simulation* (PB_2), *Prohibition to park the trucks close the site after loading* (PB_3), *Periodic preventive to minimize (TVF) and (EF)* (PB_4). To select the appropriate ones the analytic hierarchical process (AHP) is applied.

From Table 3.8, we can note that the effectiveness has a moderate importance than the availability, whereas the reliability has a stronger importance than the cost etc. On the basis of these values, the relative weight concerning each criteria are defined using equation 2.3 (see Table 3.8).

Thus, we can conclude that the effectiveness is the most important criteria followed by the availability, then the reliability and finally the cost. Once the criteria's weights are defined, all the alternatives are compared according to each criteria. The relative decision matrices are represented in Table 3.9.

Then on the basis of these values, Table 3.10 represents the different barrier's weights according to each criteria, for instance, regarding the criteria j=effectiveness, the barrier i= PB_1 is the most important one ($W_i^j = 0,47$), followed by i=PB_4 ($W_i^j = 0,284$), then i=PB_3 ($W_i^j = 0,171$) and finally i=PB_2 ($W_i^j = 0,075$).

On the basis of the Weights column in Table 3.10 we can conclude that the most interesting preventive barrier is PB_1:*Education and Training Task to deal with HGL*, followed by PB_4:*Periodic preventive to minimize (SI) and (HGL)*, then PB_3:*Prohibition to park the trucks close the site after loading* and finally

Table 3.5: Numerical component relative to FT

SI, HGL	T,T	F,T	T,F	F,F
$\hat{P}(TE = T \mid SI, HGL)$	0.7692	0.7222	0.7500	0.1765
EF, CTP	T,T	F,T	T,F	F,F
$\hat{P}(SI = T \mid EF, CTP)$	0.7143	0.6250	0.5882	0.1786
DTA, TVF	T,T	F,T	T,F	F,F
$\hat{P}(HGL = T \mid DTA, TVF)$	0.9000	0.8824	0.4000	0.0556
HGL	T		F	
$\hat{P}(GO = T \mid HGL)$	0.9655		0.0345	
SI	T		F	
$\hat{P}(PS = T \mid SI)$	0.9565		0.0435	
$\hat{P}(EF) = T$	0.3889			
$\hat{P}(CTP) = T$	0.2222			
$\hat{P}(TVF) = T$	0.4444			
$\hat{P}(DTA) = T$	0.4074			

Table 3.6: Severity degrees relative to ET

a	THE	TOE	PPS
$S(PF) = P(a = T \mid PF = T)$	1.000	1.000	1.000
a	TDP		DT
$S(THE) = P(a = T \mid THE = T)$	0.9474		0.5263
a	TODP		DE
$S(TOE) = P(a = T \mid TOE = T)$	0.9167		0.9853
$S(TE) = P(PF = T \mid TE = T)$	0.9000		
$S(PPS) = P(LD = T \mid PPS = T)$	0.8800		

Table 3.7: Propagation results

IE_i	$P(TE = T \mid IE_i = T)$
HGL	0.4113
SI	0.4516
I_i	$P(TE = T \mid I_{pi} = T)$
I_1	0.2834
I_2	0.2958
I_3	0.3374

Table 3.8: Decision matrices criteria

−	Effectiveness	Reliability	Availability	Cost	Weight
Effectiveness	1	2	3	4	0.427
Reliability	0.5	1	4	6	0.342
Availability	0.33	0.25	1	4	0.159
Cost	0.25	0.16	0.25	1	0.072

Table 3.9: Preventive barrier's decision matrices

	Effectiveness DM				Reliability DM			
−	PB_1	PB_2	PB_3	PB_4	PB_1	PB_2	PB_3	PB_4
PB_1	1	5	3	2	1	5	4	2
PB_2	0.2	1	0.33	0.25	0.2	1	0.5	0.33
PB_3	0.33	3	1	0.5	0.25	2	1	2
PB_4	0.5	4	2	1	0.5	3	0.5	1
	Availability DM				Cost DM			
−	PB_1	PB_2	PB_3	PB_4	PB_1	PB_2	PB_3	PB_4
PB_1	1	4	7	2	1	3	0.33	1
PB_2	0.25	1	4	0.33	0.33	1	0.2	0.33
PB_3	0.142	0.25	1	2	3	5	1	3
PB_4	0.5	3	0.5	1	1	3	0.333	1

Table 3.10: Weights of preventive barriers

PB_i	**Effectiveness** (0, 427)	**Reliability** (0, 342)	**Availability** (0, 159)	**Cost** (0, 072)	**Weights**
PB_1	0, 47	0, 502	0, 487	0, 2	**0.465**
PB_2	0, 075	0, 087	0, 158	0, 09	**0.096**
PB_3	0, 171	0, 212	0, 14	0.51	**0.206**
PB_4	0, 284	0, 199	0, 215	0.2	0.233

PB_2:*Fire simulation*. The choice between these barriers will be done by experts.

3.5.2 Protective barrier implementation

To select the appropriate protective barriers suppose that the decision maker proposes two scenarios i.e. $I = \{I_1, I_2\}$ such that $I_1 = \{I_{PF} = 0.5, I_{TOE} = 0.5, I_{THE} = 0.7\}$, $I_2 = \{I_{PF} = 0.6, I_{PPS} = 0.4, I_{THE} = 0.7\}$. Thus, from Table 3.11 we can see that the optimal combination $I^* = I_1$. Regarding this situation in the next step the following protective barriers are chosen: *a fix or tractable canal to prevent incident along the site (PrB_1), Blast protection window film (PrB_2), Setting up equipments to limit the thermal effects (PrB_3)*, and *Setting up equipments to limit the toxic effects (PrB_4)*. In the fourth step the analytic hierarchical process is applied in order to select the appropriate protective barriers. In this case of study, the protective barriers and preventive ones have identical criteria's weights (see Table 3.8), thus the protective barriers are compared according to each criteria, The relative decision matrices are represented in Table 3.12.

Table 3.11: Severity propagation results

$P(ME_j = T \mid I_i = T)$	TDP	DT	LD	$TODP$	DE	$\prod P(ME_j = T \mid I_i = T)$
I_1	0.2834	0.1236	0.1547	0.1987	0.2987	0.00032
I_2	0.2955	0.1478	0.0898	0.3547	0.4447	0.00061

On the basis on the Weights column in Table 3.13 we can conclude that the

Table 3.12: Protective barrier's decision matrices

	Effectiveness DM				Reliability DM			
–	PrB_1	PrB_2	PrB_3	PrB_4	PrB_1	PrB_2	PrB_3	PrB_4
PrB_1	1	5	0.5	0.2	1	4	5	5
PrB_2	0.2	1	0.2	0.125	0.25	1	4	4
PrB_3	2	5	1	5	0.2	25	1	1
PrB_4	5	8	0.2	1	0.2	0.25	1	1

	Availability DM				Cost DM			
–	PrB_1	PrB_2	PrB_3	PrB_4	PrB_1	PrB_2	PrB_3	PrB_4
PrB_1	1	0.33	0.2	0.2	1	1	3	3
PrB_2	3	1	0.33	0.33	1	1	2	2
PrB_3	5	3	1	1	0.33	0.5	1	1
PrB_4	5	3	1	1	0.33	0.5	1	1

most interesting protective barrier is PrB_1: *a fix or tractable canal to prevent incident along the site*, followed by PrB_3: *setting up equipments to limit the thermal effects*, then PrB_4: *setting up equipments to limit the toxic effects* and finally PrB_2: *blast protection window film.* The choice between these barriers will be done by experts.

Table 3.13: Relative weight concerning each protective barriers

PrB_i	**Effectiveness** $(0,427)$	**Reliability** $(0,342)$	**Availability** $(0,159)$	**Cost** $(0,072)$	**Weights**
PrB_1	$0,169$	$0,56$	$0,068$	0.3931	**0.319**
PrB_2	$0,050$	0.253	$0,156$	$0,319$	**0.165**
PrB_3	$0,455$	$0,087$	$0,388$	$0,144$	**0.296**
PrB_4	$0,326$	$0,1$	$0,388$	$0,144$	**0.22**

3.6 Conclusion

In this chapter a new approach to construct bow tie diagrams which reflect the real behavior of exiting system is proposed. This approach is divided into two phases:

1. The first phase concerns the construction of the whole scenario of each identified risk. To deal with, two parts are proposed, first a learning algorithm is proposed to construct the whole scenario from IE to ME, and the second is a numerical component allowing us to characterize the impact of different causes on the top event TE and to study its repercussion while considering its severity and those of its consequences. To learn our bow tie diagrams the algorithm 3.3 is proposed. This latter uses Chow and Liu [26] algorithm, this choice was motivated by the fact that this algorithm provides us a spanning tree from a training set, which characterizes both FT and ET structure learning.

2. The second phase proposes a dynamic way to implement preventive and protective barriers in bow tie diagrams. Our proposal is based on a statistical computation allowing us to have a realistic view of the system behavior and on the analytic hierarchical process (AHP) in order to take into consideration different selection criteria. This approach allows us to overcome the problem lied to the static selection of preventive and protective barriers.

In the next chapter the implementation of the *Do* phase is proposed by defining the appropriate QSE management plans. To this end, a transformation procedure of the already existing bow ties into a multi-objective influence diagram is proposed. This diagram [74] is one of the most commonly used graphical decision models for reasoning under uncertainty.

Chapter 4

A Multi-objective Approach to Generate the Optimal Management Plans

4.1 Introduction

Once the *plan phase* is achieved by defining the whole scenario of each identified risk via bow ties diagrams, we can move to the *DO phase* in order to define of the appropriate management plans QSE. Each management plan QSE is a set of decisions (i.e action) required by the three standards regarding all the objectives.

To this end, a new multi-objective approach is proposed to generate the optimal QSE management plans. The basic idea is to transform the already constructed bow ties into a *multi-objective influence diagram (MID)* [74] which is one of the most commonly used graphical decision models for reasoning under uncertainty. This tool is an extension of classical influence diagrams (ID) in order to handle multiple objectives by gathering them in a unique value node. More precisely, a mapping of constructed bow tie diagrams, into a MID is proposed, in order to evaluate it and generate the optimal management plans.

The remainder of this chapter is organized as follows: Section 2 presents related works concerning risk management approaches to solve decision problems. Section 3 presents multi-objective influence diagrams. Section 4 proposes a multi-objective approach to define the appropriate QSE management plans. Finally, in section 5 we continue our illustrative example.

Main results presented in this chapter are published in [12, 13, 14].

4.2 Risk management approaches to solve decision problems

In literature, many researches have been carried out in order to extend the existing risk management approaches in order to solve decision problems, most of these researches are based on the law 2003-699 [53] relative to the introduction of probability concepts in any risk analysis. In fact, the major of the proposed approaches are based on tree-based techniques which offer a flexible structure to be used with probability concepts. More precisely, they are particularly focalized on *Bayesian networks* [81]. These approaches can be divided into three classes:

- The principle of the first class is to *transform* a risk analysis tool into a Bayesian network. This idea was first introduced by Bibbio et al. [23] which propose a mapping from fault tree analysis into Bayesian networks. In the same context, léger et al. [68] propose to extend the technical bow tie analysis to a global system, including human beings and organizations.

- The principle of the second class is the *fusion* of a risk analysis tool and a Bayesian network. We can mention in particular the work of Trucco et al. [96] where Bayesian networks are used as an extension of the fault tree in order to introduce the social activity in the evaluation of the latter.

- The third class does not require any risk analysis tools. In fact, each identified risk will be directly modeled by a Bayesian network as proposed by Palaniappan [80].

The first problem with these methods in that they handle a unique management area, so they cannot be applied in the context of a fully integrated management system. Moreover, the fact that these methods are based on Bayesian networks presents a real weakness since this graphical model is not really appropriate to generate optimal decisions. In fact, the powerful of Bayesian networks consists in their ability in reasoning under uncertainty and not in decision making area. Thus, our objective is to model a more efficient risk management tool by using an appropriate graphical decisional model. More precisely, as shown in Figure 4.1, *influence diagrams* is used which are an extensions of Bayesian networks able to provide optimal solutions while maximizing decision makers utilities. Moreover, given the multi-objective aspect of our problem, *multi-objective influence diagrams* (MIDs) will be used, which are a new variant of influence diagrams dedicated to such a problems. Thus, our idea is to map constructed *bow ties* into a MID, then, to evaluate it in order to generate the appropriate QSE management plans. In what follows, a brief recall on the multi-objective influence diagrams is given.

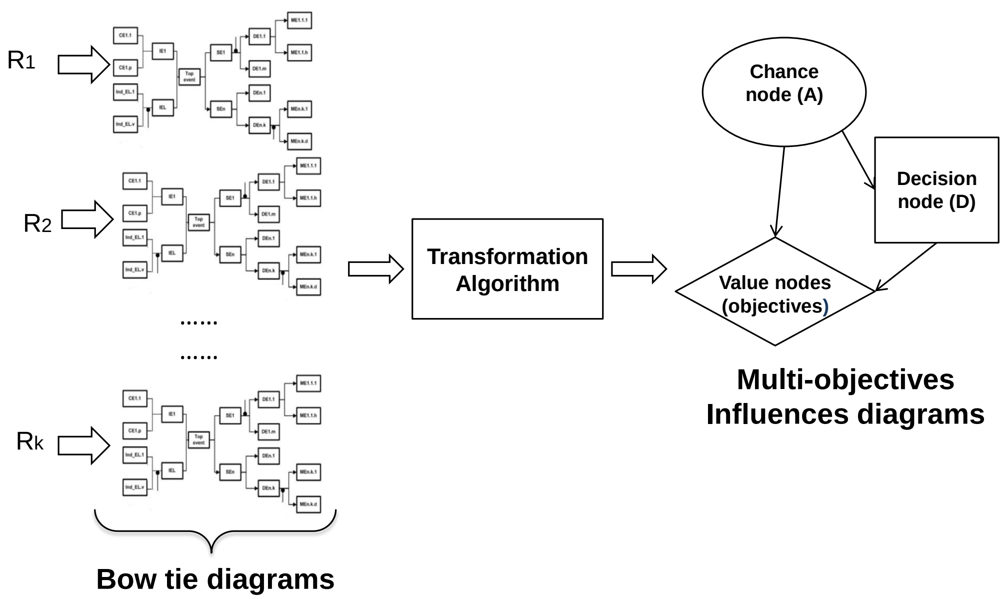

Figure 4.1: Transformation to multi-objective influence diagram

4.3 Multi-objective influence diagrams

Multi-objective influence diagrams (MID) [74] are an extension of standard influence diagrams (ID) [52] allowing the modelisation of multiple objectives decision problems. Similarly to standard influence diagrams, multi-objective influence diagrams have two components:

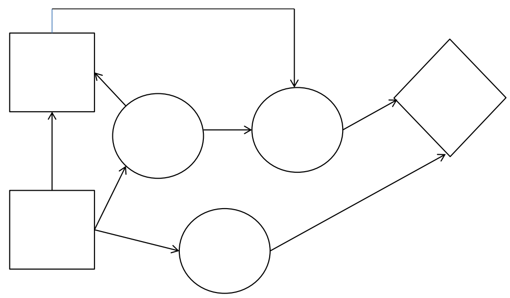

Figure 4.2: Typology of Multi-objective influence diagrams

1. *Graphical component* (or qualitative component) which is a directed acyclic graph (DAG) denoted by $G = (N, A)$ where A is the set of arcs in the graph and N its node set. As shown in Figure 4.2 the node set N is partitioned into subsets C, D and V such that:

    - $C = \{C_1, \cdots, C_n\}$ is a set of chance nodes which represents relevant uncertain factors for decision problem. Chance nodes are represented by circles.
    - $D = \{D_1, \cdots, D_m\}$ is a set of decision nodes which depicts decision options. These nodes should respect a temporal order. Decision nodes are represented by rectangles.
    - $V = \{V_1, \cdots, V_k\}$ is a set of value nodes which represents utilities to be maximized, contrary to the classical ID, in the case of MID several objectives can be gathered in the same value node which is represented by lozenge.

    Arcs in A have different meanings according to their targets. We can distinguish:

    - *conditional arcs* (into chance and value nodes), those that have as target chance nodes represent probabilistic dependencies.

- *informational arcs* (into decision nodes) which imply time precedence.

Two assumptions, are in general considered with multi-objective influence diagrams i.e. *regularity* which means that value nodes cannot have children and and there is a directed path that contains all of the decision nodes and *no-forgetting* property which means that a decision node and its parents should be parents to all subsequent decision nodes.

2. *Numerical component* (or quantitative component) evaluating different links in the graph. Namely, each conditional arc which has as target a chance node C_i is quantified by a conditional probability distribution of C_i in the context of its parents $Pa(C_i)$. Such conditional probabilities should respect the probabilistic normalization constraints:

   - If $Pa(C_i) = \emptyset$ (C_i is a root) then, a priori probability relative to C_i should satisfy:

$$\sum_{c_{ij} \in \omega_{c_i}} P(c_{ij}) = 1 \tag{4.1}$$

   - If $Pa(C_i) \neq \emptyset$ then the relative conditional probability relative to C_i in the context of its parents Pa(Ci) should satisfy:

$$\sum_{c_{ij} \in \omega_{c_i}} P(c_{ij} \mid Pa(C_i)) = 1 \tag{4.2}$$

Once the MID constructed it can be used to identify the optimal decisions satisfying all the objectives. This can be ensured via the evaluation algorithm proposed by Micheal et al. [74] which allows to generate the best strategy yielding to the highest expected utility. The basic modifications required to evaluate a (MIDs) compared to a (IDs) are defined in the:

1. *Chance node removal*: To remove a chance node two cases have to be considered.

   Case A: is performed when no decision nodes have been removed prior to the removal of the current chance node. In this case, for each unique combination of alternatives and outcomes of the other influences to the value node, the expectation operation is performed on each outcome of the chance node being removed. The expectation operation is performed on each objective.

Case B: is performed when one or more decision nodes have been removed prior to the current chance node. For this case, each possible outcome of the chance node can be associated with a set of one or more noninferior decision rules. A decision rule is simply defined as a particular decision alternative chosen when a certain outcome of a chance node occurs, it is only considered inferior if another solution has values that are equal or better for all objectives being considered.

Example 4.1 *Suppose a chance node weather is being removed following the removal of a decision node what to bring during the solution procedure of an influence diagram. The chance node weather has two possible outcomes, cloudy or rainy, and the decision node what to bring has three alternatives, raincoat, umbrella, or nothing. Assume that each alternative of what to bring is noninferior for either outcome of weather. In this case, each outcome of weather has a set of three noninferior decision rules associated with it. Therefore, there are nine possible combinations of decision rules to which the expected value must be applied. This situation is shown in Table 4.1.*

2. *Decision Node Removal*: The required modification is that the simple maximizing operation must be replaced with an operation that can determine the set of noninferior solutions.

Otherwise, the extension to (MIDs) has no effect on the arc reversal and the barren node (a node without a successor) removal transformations.

The algorithm proposed by Micheal et al. [74] is outlined by Algorithm 4.1.

To demonstrate how algorithm 4.1 is performed, an illustrative example for optimal placement of horizontal wells [85] is illustrated in this section.

Example 4.2 *Let us consider the influence diagram shown in Figure 4.3, where two decisions have to be considered the first is type of drilling which has three*

Table 4.1: Example of combinations of decision rules

Weather	What to bring
Rainy	Umbrella
	Raincoat
	Nothing
Cloudy	Umbrella
	Raincoat
	Nothing

Rainy	Cloudy
1) Umbrella	Umbrella
2)Umbrella	Raincoat
3)Umbrella	Nothing
4)Raincoat	Umbrella
5)Raincoat	Raincoat
6)Raincoat	Nothing
7)Raincoat	Umbrella
8)Raincoat	Raincoat
9)Raincoat	Nothing

states: sidetrack, drill up and drill down and the second is azimuthal test which has two states: yes and no. The objectives for this problem are to minimize cost, well productivity index, and wellbore configuration. These three objectives are conflicting. In fact, when the cost increases, well productivity index, and wellbore configuration decrease. This problem also considers the uncertainties of sand location which have two states: sand is above the drill-bit and sand is below the drill-bit, drilling zone, Horizontal Section Length A, Horizontal Section Length B, and test results. Figure 4.3 depicts this decision problem in an influence diagram and Table 4.3 shows the values of the three objectives for selected outcomes.

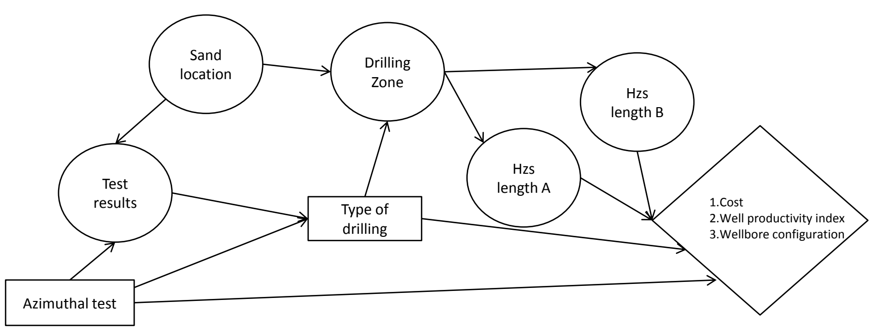

Figure 4.3: Influence diagram for optimal placement of horizontal wells

Table 4.2: Multi-objective values

Azimuthal Test	Test											
Type of drilling?	Sidetrack				Drill up				Drill down			
Horizontal Section Length A	1000		1200		1000		1200		1000		1200	
Horizontal Section Length B	0	100	0	100	0	100	0	100	0	100	0	100
Productivity Index	40	40	45	45	35	35	40	40	32	34	32	34
Cost	-340	-340	-340	-340	-250	-250	-250	-250	-220	-220	-220	-220
Wellbore Configuration	80	85	90	100	70	75	80	85	50	55	65	70

Algorithm 4.1: *Transformation of bow ties into a regular MID structure*

Data: Regular MID

Result: Optimal management plans

begin

1. Check the regular *property of MID.*
2. remove barren nodes (i.e. nodes without successors).
3. If a chance node exists with the value node as its sole successor then remove it and update the utility function of the value node.
4. If any node remains in the diagram then return to step 3 otherwise terminate the algorithm.
5. If there is a decision node which is a direct predecessor of the value node such that the remaining predecessors of the value node are informational predecessors of the decision node, then:
- remove it,
- update the utility function of the value node,
- remove any barren node.
If any node remains in the diagram then return to step 3 otherwise terminate the algorithm.
6. Find a chance node C_i which is a direct predecessor to the value node such that it has no decision node as successor.
7. Find a chance node C_j which is a direct successor of C_i such that there is no other directed path between C_i and C_j and reverse the arc between C_i and C_j. If C_i has any other successors repeat step 6.
8. Remove the chance node C_i
with the arc reversal transformation (probability table transformation).
9. If any node remains in the diagram return to step 3 otherwise terminate the algorithm.

end

The first step in algorithm 4.1 is to remove the chance node Hsz lengthB and

Hsz lengthA in either order (see Figure 4.4 b) and c) since they have solely the multi-objective value node as direct successor. This removal process represents case A of Transformation because the chance node is removed before any decision node. In this case, the expected value operation is applied to each objective of the multi-objective value node over each possible outcomes for Hsz lengthB and Hsz lengthA. Then, the Drilling Zone node would be removed (see Figure 4.4.d). In order to remove the Sand Location node (see Figure 4.4.e), the arrow between Test Results and Sand Location nodes must first be reversed. Finally, the Test Results node would be removed (Figure 4.4.f). Figure 4.4 shows the solution diagrams, signifying the decision rules. Table 4.3 shows the different decision rules.

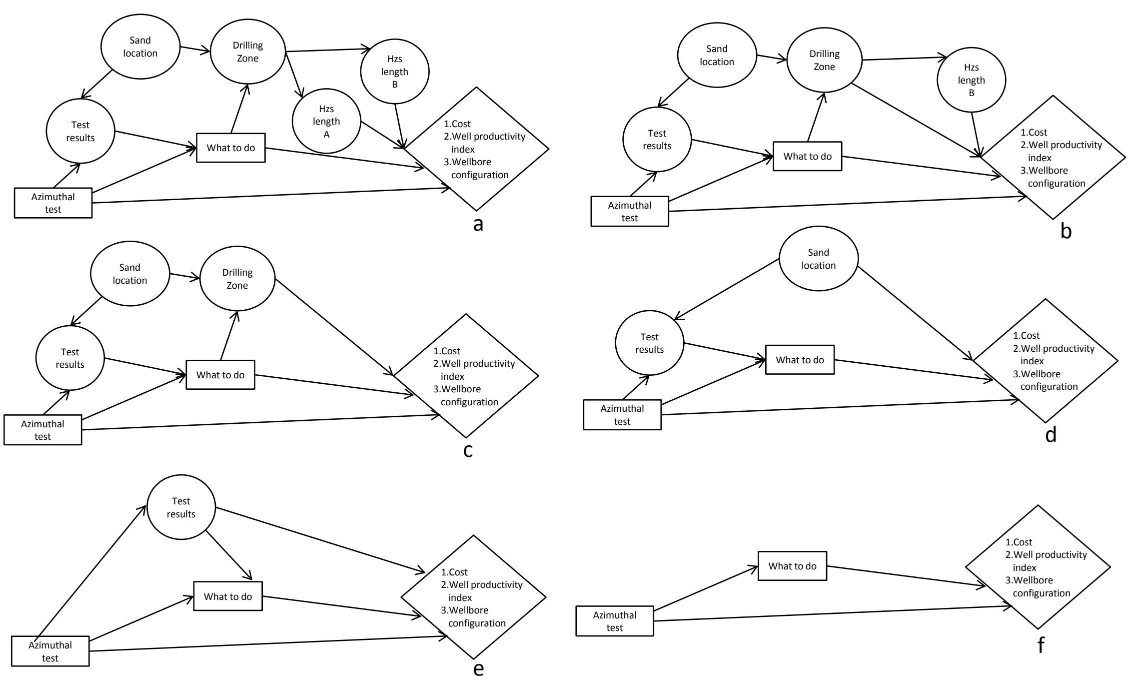

Figure 4.4: Evaluation procedure for optimal placement of horizontal wells

From Table 4.3 we can conclude that DR1, DR2 and DR6 the non-inferior solution, thus, the optimal decision can be What to do=Sidetrack, Azimuthal Test= yes or What to do=Drill Up, Azimuthal Test= yes or What to do=Drill Down, Azimuthal Test= no.

Table 4.3: Final results of evaluating MID for optimal placement of horizontal wells

Decision rules	cost	Wellbore Configuration	Well Productivity	What to do?	Azimuthal Test
DR1	-331.00	85.5348	42.5109	Sidetrack	Yes
DR2	-259.00	77.6264	38.7847	Drill Up	Yes
DR3	-332.00	50.2245	28.6831	Drill Down	Yes
DR4	-331.00	50.2245	32.5109	Sidetrack	No
DR5	-359.20	47.6254	30.7342	Drill Up	No
DR6	-232.00	60.2245	34.6831	Drill Down	No

4.4 A multi-objective approach to define appropriate QSE management plans

In order to generate the optimal management plans satisfying all the objectives, first a mapping from existing bow ties (generated by the plan phase) to build a multi-objective influence diagram is proposed. Our idea is to gather all the QSE required objectives in the same value node. Then, each selected risk and its respective scenario occurrence from initiators to final consequences will represent the chance nodes. Finally, the barriers will be transformed into as decision nodes in order to define the appropriate management plans. Algorithm 4.2 outlines this transformation procedure.

- Let $BT_1..BT_n$ be the set of bow ties and $O_1..O_k$ the set of objectives.
- Let R_i be top event of BT_i and F_i be its occurrence.
- Let IE_i (resp. $InfE_i$, CE_i, $IndE_i$, SE_i, DE_i, ME_i) be the set of initiator (resp. informative, critical, undesired, second, dangerous, major) events in BT_i.
- Let Cq_i (resp. Cs_i, Ce_i) be the consequence on quality (resp. security, environment) in BT_i.
- Let X_i and Y_i be any set of events in BT_i, then, $Ar(X_i, Y_i)$ is a function which returns the set of arcs relative to all links between X_i and Y_i in BT_i.

For instance $Ar(IE_i, CE_i)$ is the set of arcs relative to all links between IE_i and CE_i in BT_i.

Algorithm 4.2: Transformation of bow ties into a *regular* MID structure

Data: $BT_1..BT_n$; $O_1..O_k$; $ArCq_1..ArCq_n$; $ArCs_1..ArCs_n$; $ArCe_1..ArCe_n$; $ArpB$; ord

Result: Regular MID

begin

- $C \leftarrow \emptyset$, $D \leftarrow \emptyset$, $V \leftarrow \emptyset$, $A \leftarrow \emptyset$
- Gather all the QSE objectives O_i (i=1..k) in the same value node V_{QSE}
- $V \leftarrow V_{QSE}$

for $i \leftarrow 1..n$**do**

  % Create R_i and F_i and connect them
  $C \leftarrow C \cup R_i \cup F_i$
  $A \leftarrow A \cup (R_i \rightarrow V_{QSE}) \cup (F_i \rightarrow R_i)$
  % Create all the events and connect them
  $C \leftarrow C \cup IE_i \cup CE_i \cup IndE_i \cup SE_i \cup DE_i \cup ME_i$
  $\forall IE_{ij} \in IE_i, A \leftarrow A \cup (IE_{ij} \rightarrow F_i)$
  $\forall SE_{ij} \in SE_i, A \leftarrow A \cup (F_i \rightarrow SE_{ij})$
  $A \leftarrow A \cup Ar(IE_i, CE_i) \cup Ar(IE_i, IndE_i) \cup Ar(SE_i, DE_i) \cup Ar(DE_i, ME_i)$
  % Create Cq_i, Cs_i, Ce_i and connecte them
  $C \leftarrow C \cup Cq_i \cup Cs_i \cup Ce_i,$
  $A \leftarrow A \cup (Cq_i \rightarrow R_i) \cup (Cs_i \rightarrow R_i) \cup (Ce_i \rightarrow R_i)$
  $\forall ArCq_{ij} \in ArCq_i, A \leftarrow A \cup (ArCq_{ij} \rightarrow Cq_i)$
  $\forall ArCs_{ij} \in ArCs_i, A \leftarrow A \cup (ArCs_{ij} \rightarrow Cs_i)$
  $\forall ArCe_{ij} \in ArCe_i, A \leftarrow A \cup (ArCe_{ij} \rightarrow Ce_i)$
  % Handel barriers
  $D \leftarrow D \cup PreB_i \cup ProB_i$
  $\forall PreB_{ij} \in PreB_i, \forall ProB_{ij} \in ProB_i, A \leftarrow A \cup (PreB_{ij} \rightarrow PE(PreB_{ij})) \cup (ProB_{ij} \rightarrow SE(ProB_{ij}))$

% Additional links
$A \leftarrow A \cup ArpB$
% Connect decision nodes while respecting the precedence order.
$n_1 \leftarrow nb(D)$
for $k \leftarrow 1..(n_1 - 1)$ **do**
  for $l \leftarrow (k+1)..n_1$ **do**
    $A \leftarrow A \cup (D_{ord(k)} \rightarrow D_{ord(l)})$

end

- Let $ArCq_i$ (resp. $ArCs_i$, $ArCe_i$) the set of major events which has a possible links to Cq_i (resp. Cs_i, Ce_i) in BT_i.
- Let $PreB_i$ (resp. $ProB_i$) be the set of *preventive* barriers (resp. *protective*) barriers in BT_i. Let $PE(.)$ (resp. $SE(.)$) be a function which returns the set of *precedent* (res. *successive*) events of any barrier in BT_i.
- Let D the set of all barriers. Let $ArpB$ the set of additional arcs relative to the links between each element of D to each event.
- Let ord be the order relative to different decision nodes relative to existing barriers in $BT_1..BT_n$, this order can be defined by experts.
- Let nb(.) be a function returning the nb of elements of a given set. Algorithm 4.2 outlines the major steps of our approach.

It is important to note that Algorithm 4.2 provides a regular influence diagram satisfying the no-forgetting property.

Once the MID structure is constructed, the experts assign the numerical values for each node in the MID. Then, algorithm 4.1 generates the optimal QSE management plans.

4.5 Illustrative example

Let us continue our example where three objectives (O_1: Gain market share by providing superior all-round service to the customer, O_2: Minimize the environmental waste and O_3: Increase safety staff) have been considered. In this step, two Bow tie diagrams will be considered, the first relative to R_1: A major fire and explosion on tanker truck carrying hydrocarbon and the second relative to R_2: A fire in container. Table 4.4 illustrates the events and barriers relative to R_1 and R_2.

The bow tie diagrams relative to BT_1 and BT_2 are respectively shown in Figures 4.5 and 4.6.

The input data of the transformation procedure (i.e. Algorithm 4.2) are:

- BT_1, BT_2, O_1, O_2, O_3

Table 4.4: Events and barriers relative to R_1 and R_2

−	BT_1	BT_2
Initiator events	*Hydrocarbon gas leak* (HGL) *Source of ignition*(SI)	*Hydrocarbon gas leak in the container*(HLC) *Source of ignition close the container*(SIC)
informative events	*gaz odor*(GO) *presence of spark*(PS)	*gaz odor*(GO) *presence of spark*(PS)
Undesired events	**leading to HGL**: *Tank valve failur*(TVF) *Drilling a tank*(DTA) **leading to SI**: *Exhaust failure*(EF) *Construction site close* *to the truck parking*(CTP) *Driver smoking a cigarette*(DC)	**leading to HLC**: *Wear and degradation of gas tank*(WDT) *Incorrect reception or transfer operation*(INR) **leading to SIC**: *hotspot operatio*(HO) *Flame,cigarettes* *GSM*(FCG)
Secondary event:	*Pool fire*(PF)	*Container explosion*(CE)
Dangerous events	*Thermal effects*(THE) *Toxic effects*(TOE) *Production process in stop*(PPS)	*Thermal effects*(THE) *Toxic effects*(TOE) *Production process in stop*(PPS)
Major events	**due to THE**: *Damage to people*(DP1) *Damage to other truck*(DT) **due to TOE**: *Damage to persons*(DP2) *Damage on the environment*(DE) **due to PPS**: *Late delivery*(LD)	**due to THE**: *Damage to people*(DP1) *Damage to other truck*(DT) **due to TOE**: *Damage to persons*(DP2) *Damage on the environment*(DE) **due to PPS**: *Late delivery*(LD))
Preventive barriers	*Periodic preventive* *maintenance tank valve* (PMV) *Periodic preventive maintenance* *to minimize exhaust failure*(PME) *Education and Training Task*(ETT) *Prohibition to park the trucks close*(PME) *to the site after loading*(PPT) *Fire simulation*(FS)	*Establish re permit*(EFP): *Setting instructions*(SI): *Successive training*(ST):
Protective barriers	*A fix or tractable canal to* *prevent incident a long the site* (FTC) *Blast protection window film*(BPM) *Personal Protective equipment to* *limit thermal effects*(PPET) *Personal Protective equipment* *to limit toxic effects*(PPETO)	*Personal Protective equipment to* *limit thermal effects*(PPET) *Personal Protective equipment* *to limit toxic effects*(PPETO)

- $ArCq_1 = ArCq_2 = \{LD, DT\}$ since *Late delivery* (LD) and *Damage to trucks* (DT) have consequences on quality
- $ArCs_1 = ArCs_2 = \{TDP, TODP\}$ since *Toxic damage on persons* (TDP)

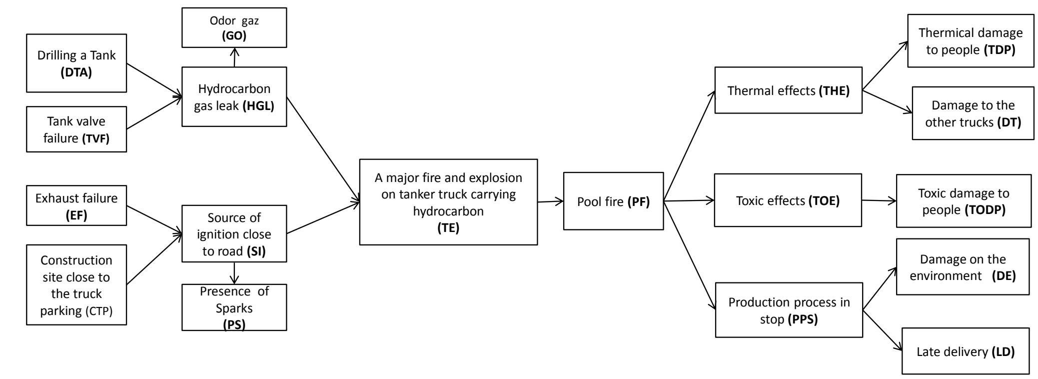

Figure 4.5: Bow tie analysis of R_1

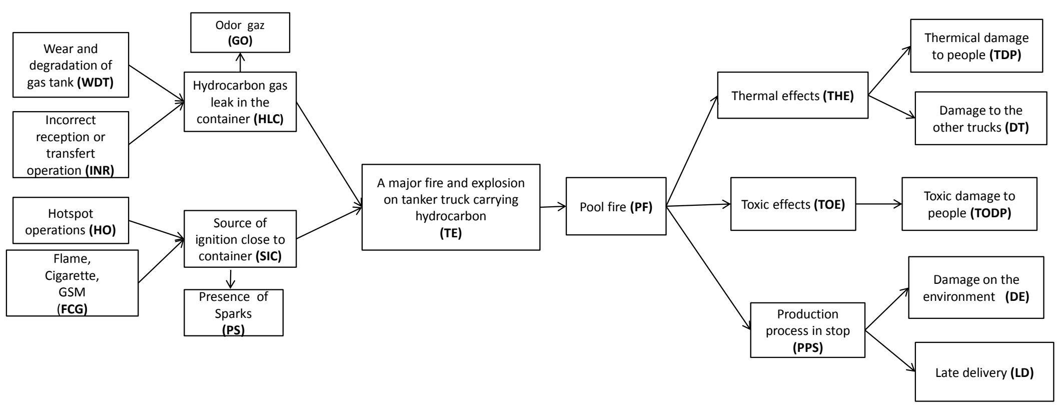

Figure 4.6: Bow tie analysis of R_2

and *Thermic damage on persons* (TODP) have consequences on security

- $ArCe_1 = ArCe_2 = \{DE, DT\}$ since *Damage on the environment* (DE) and *Damage on trucks* (DT) have consequences on the environment

- The additional arcs defined in $ArpB$ are (FS, Ce_1), (ST, TVF) and (ST, Cs_2) since *Fire simulation* (FS) is considered as pollutant for the environment (Ce_1), *Successive trainings* (ST) can increase *Tank valve failure rates* (TVF) and successive trainings (ST) can have an impact on security (Cs_2)

- In order to respect the precedence order relative to different decision nodes relative to existing barriers in BT_1 and BT_2 (i.e. PVM, PME, ETT, PPT, FS, FTC, BPW, PPET, PPETO, ST, EFP, SIN), the following set $ord=\{6,4,5,3,2,7,8,1,9,10,11,12\}$ will be considered.

Using these inputs, Algorithm 4.2 proceeds as follows:

- gathers all the Q,S,E objectives in the same value node V_{QSE},
- creates the chance nodes R_1 and F_1,
- connects R_1 to V_{QSE} and F_1 to R_1,
- creates *HGL*, *SI*, *GO*, *PS*, *TVF*, *DTA*, *EF*, *CTP*, *DC*, *PF*, *TE*, *TOE*, *PPS*,*TDP*, *DT*, *TODP*, *DE* and *LD* as chance nodes,
- connects (*HGL* and *SI*) to F_1, F_1 to *PF*, (*DTA* and *TVF*) to *HGL*, (*EF*,*CTP* and *DC*) to *SI*, *PF* to (*TE*, *TOE* and *PPS*), *TE* to (*TDP* and *DT*), *TOE* to (*TODP* and *DE*), and *PPS* to *LD*,
- creates three chance nodes Cq_1, Cs_1, Ce_1 and connects them to R_1,
- connects (*LD* and *DT*)to Cq_1, (*TDP* and *TODP*) to Cs_1 and (*DT* and *DE*) to Ce_1,
- creates the decision nodes *PMV* (resp. *PME*, *ETT*, *PPT*, *FS*, *FTC*, *BPW*, *PPET* and *PPETO*) and connects them to *TVF* (resp. *EF*, *DC*, F_1, F_1, *PF*, *PF*, *TDP*, *TODP*),
- creates the chance node R_2 and F_2,
- connects R_2 to V_{QSE} and F_2 to R_2,
- creates *HLC*, *SIC*, *WDT*, *INR*, *HO*, *FCG* and *CE* as chance nodes
- connects (*HLC* and *SIC*) to F_2, F_2 to *CE*, (*WDT* and *INR*) to *HLC*, (*HO* and *FCG*) to *SIC* , *CE* to (*TE*, *TOE* and *PPS*),
- creates three chance nodes Cq_2, Cs_2, Ce_2 and connects them to R_2,
- connects (*LD* and *DT*) to Cq_2, (*TDP* and *TODP*) to Cs_2 and (*DT* and *DE*) to Ce_2,
- creates the decision node *EFP* (resp. *SIN* and *ST*) and connects it to *HO* (resp. *FCG*, *INR*),
- proceeds with the additional links and connects *FS* to Ce_1, *ST* to Cs_2 and *ST* to *TVF*,
- connects *PPET* to *FS*, *FS* to *PPT*, *PPT* to *PME*, *PME* to *ETT*, *ETT* to *PMV*, *PMV* to *FTC*, *FTC* to *BPW*, *BPW* to *PPETO*, *PPETO* to *ST*, *ST* to *EFP* and *EFP* to *SIN* and adds the *no-forgetting arcs* between the decision nodes.

The resulted MID is represented by Figure 4.7 where:

- $C = \{R_1, F_1, HGL, SI, TVF, DTA, EF, EF, CTP, DC, PF, TE, TOE, PPS, TDP, DT, TODP, DE, LD, Cq_1, Cs_1, Ce_1, R_2, F_2, HLC, SIC, WDT, INR, HO, FCG, CE, Cq_2, Cs_2, Ce_2\}$,
- $D = \{PMV, PME, ETT, PPT, FS, FTC, BPW, PPET, PPETO, EFP, SIN, ST\}$ where all decision nodes are binary (i.e. can take True (T) or False (F)), Moderate (M) or Frequent (F)). Note, that the no-forgetting arcs between decision nodes are not represented in Figure 4.7
- $V = \{V_{QSE}\}$

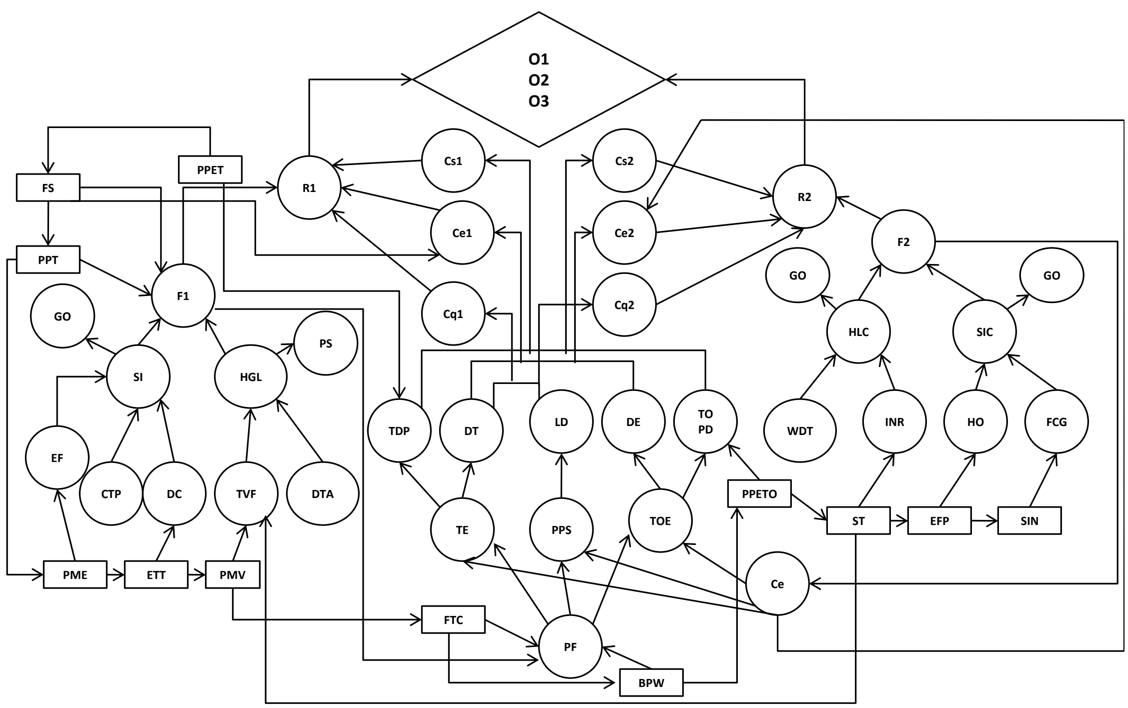

Figure 4.7: The resulted MID

Once the *quantification phase* is achieved, the evaluation algorithm (Algorithm 4.1) is applied and proceeds as follows:

1. the first step is to remove the barren nodes PS and GO since they don't have any successors

2. R_1 and R_2 chance node are removed randomly since they have the multi-objective value node as direct successor

3. Cq_1, Cq_2, Cs_1, Cs_2, Ce_1 and Ce_2, chance nodes are removed randomly.

4. Cq_1, Cq_2, Cs_1, Cs_2, Ce_1 and Ce_2, chance nodes are removed randomly.

5. TDP, DT, LD, DE and $TODP$ chance nodes are removed randomly.

6. Inverse the arcs between F_1 and PF, and F_2 and CE.

7. F_1 and F_2 chance nodes are removed in either order.

8. SI, HGL, HLC, SIC chance nodes are removed randomly.

9. EF, CTP, DC, TVF, DTA, WDT, INR,INR, INR and FCG chance nodes are removed in either order.

10. SIN, EFP, ST, $PPETO$, BPW, FTC, PMV, ETT, PME, PPT, FS, $PPET$ and EF decision nodes are removed.

It is important to note the different chance nodes removal represents case A of transformation because the chance node is removed before any decision node. The final output of this algorithm is the optimal management plans satisfying all the objectives while maximizing decision makers utilities. These decisions corresponds to the different management plans QSE. For our illustrative example the optimal management plans are:

- Management plan 1={PPET=T,FS=F, PPT=T, PME=T, ETT=T, PMV=F, FTC=T, BPW=T, PPETO=T, ST=F, EFP=T, SIN=T}.

- Management plan 2={PPET=F,FS=T, PPT=T, PME=T, ETT=T, PMV=T, FTC=F, BPW=T, PPETO=T, ST=T, EFP=T, SIN=T}.

It is clear that if we limit our analysis to BT_1 and BT_2, we cannot define the appropriate management plans regarding all the objectives. This is not the case with the resulted MID since its evaluation enabled us to generate the appropriate management plans satisfying all the objectives QSE while maximizing decision makers utilities.

4.6 Conclusion

This chapter proposes a multi-objective approach to generate the optimal management plans. This implementation concerns the *Do* phase of our process-based approach for implementing an integrated management system. To this end, a transformation of the already constructed bow tie diagrams into a multi-objective influence diagram is proposed. This choice was motivated by the fact that this diagram is one of the most appropriate graphical decision model for reasoning under uncertainty. In addition, it allows the manipulation of different objectives which feats well with our problem since we deal with the three standards QSE. The evaluation of the resulted MID provides the appropriate management plans QSE, which should be executed in the *Check and Act* phase as detailed in Chapter 5.

Chapter 5

Proposition of a performance measurement system

5.1 Introduction

Once the *Do phase* is achieved by carrying out the quality, security and environment management plans, in this chapter their effective implementation are proposed.

To ensure this task, a performance measurement system (PMS) should be implemented. This latter is composed by several performance indicators, which are a variable indicating the effectiveness and/or efficiency of a management plan against a given norm or target [42]. The implementation of PMS is structured around two main phases: The design phase which concerns the identification of the performance structure by decomposing the overall objectives into elementary ones and the exploitation phase which concerns the expression of the elementary and the overall objectives performance.

To consider these two phases, many approaches have been proposed such as ECOGRAI [22], the activity based costing/activity based modeling (ABC/ABM) [25], system measurement analysis and reporting technique (SMART) [31], the process performance measurement system (PPMS) [64] and the quantitative model performance measurement system (QMPMS) [93]. All these approaches studied the implementation of PMS from various view points especially the design and the exploitation phases. Nevertheless, these approaches are not appropriate to deal with our proposed process-based approach to integrate the three management systems.

To deal with, a new approach ensuring the implementation of a whole performance measurement system including the design and the exploitation phases is proposed in this chapter. These approach will satisfy the *Check and Act* phase proposed to implement our process-based approach.

The remainder of this chapter is organized as follows: Section 2 presents a review of existing performance measurement system. Section 3 presents a new approach to design performance measurement system. Section 4 proposes the quantification of the performance measurement system. Finally section 5 presents an illustrative example.

5.2 Review of existing performance measurement systems

From a global point of view, a performance measurement system (PMS) can be seen as a set of performance indicators leading to quantify the satisfaction of the objectives. Generally each PMS is associated with two models namely the break down model and the aggregation model [27] defined as follows:

1. **The break down model** which concerns the identification of the performance structure where the considered global objectives called the strategic objectives is broken down into two levels namely the tactical and the operational levels. In literature, the major of PMS has proposed frameworks structuring the performance structure such as ABC/ ABM [25], SMART [31] and PPMS [64] which propose several criteria to break down the objectives. However, Neely et al. [77] has complained that these frameworks are too superficial. In fact, most of the researches discuss the issues of implementation, and suggest few principles and guidelines, nevertheless the tools and method needed for performing tasks during the design phase are neglected [77]. Moreover, Cliville et al. stress the fact that an management plan should be associated with the PMS to reach the different objectives [27].

2. **The aggregation model** which concerns the expression of overall performance degree on the basis of the break down model. In literature, two types of approaches are distinguished, the first is the mono criterion procedure where the performance is expressed according to a common criterion, such as cost, efficiency etc. In the second one, many criteria are considered. In this context, some approaches have been carried out, such as the performance criteria system (PCS) [46] which expresses the elementary performances using a qualitative pairwise matrix, then the overall performance expression is aggregated using the *Weighted Arithmetic Mean* (WAM) operator. The major problem with this approach is that it only quantifies the hierarchical relations and totally ignores the interaction between criteria and elements at the same level. To overcome this weakness, the quantitative model performance measurement system (QMPMS) [93] uses the WAM operator associated with a corrective factors, to take into consideration the interaction at the same level. Also, Cliville et al. [27] have proposed a new multi-criteria approach based on the Macbeth methodology [17] with the choquet integral operator to generalize the WAM operator and to consider the interaction between criteria. The major problem with both solutions is their lack of consistency between the determination of weights and the expression of elementary performances, the former being expressed on a ratio scale not consistent with the interval scale of the latter.

Thus our idea, is to overcome the weakness of existing systems, by proposing a new approach to construct and quantify a performance measurement system in the context of an integrated management system QSE.

In the next section, a new approach to construct a performance measurement system is presented.

5.3 A new approach to construct performance measurement system

For AFNOR, a performance indicator is a quantified data, which measures the effectiveness or the efficiency of whole or part of a process or a system, compared to a standard, a plan or an accepted objective, within the framework of a company strategy [7]. Thus, from this definition we can say that a set of coherent indicators is composed of a set of objectives, a set of measurements and a set of action leading to reach the objectives. The main industrial practices to design a PMS are based on methodologies that allow linking strategic objectives with their relative tactical and operational indicators [76]. These relations are generally structured in a tree composed of independent indicators as shown in the following example.

Example 5.1 *For instance, let O_1: increase service rate be one of the objectives of a company, then as shown in Figure 5.5 O_1 is broken down into three tactical objectives which are average delay, Order receive time and Shipments accuracy. Then, each tactical objective is broken down into several operational indicators (i.e. elementary performance indicators), in fact average delay is broken down into Operator skill and Equipment availability, Order receive time is broken down into Bottleneck productivity and Work in progress level, and Shipments accuracy is broken into Product quality*

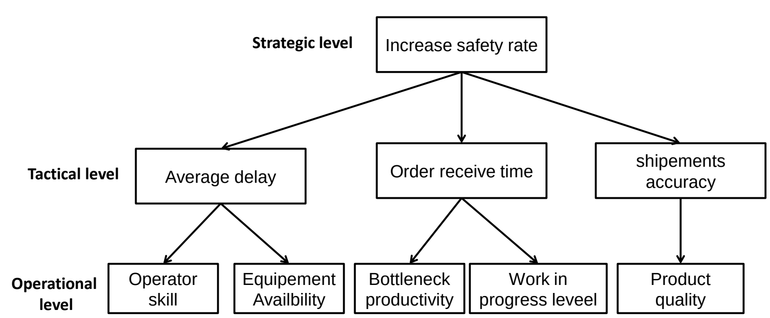

Figure 5.1: The tree structure of the service rate global objective

The major problem in designing a PMS can be defined in two points:

1. The first is the identification of their corresponding tactical objectives from a strategic objective, and from each tactical objective, their corresponding operational indicators

2. The second concerns the identification of the links between the elementary performance and overall one.

To deal with the first point, our idea is to use the identified elements from the *plan phase*. More precisely, the QSE objectives $(O_1 \cdots O_n)$ are considered as the strategic objectives, then their relative sub-objective $(SO_1 \cdots SO_P)$ as the tactical objectives and the selected risks $(Rs_1 \cdots Rs_d)$ as operational indicators for each sub-objective.

Concerning the second point, two types of relations are proposed:

- **Hierarchical relations** by relating the strategic objective to their relative tactical ones, and the tactical objectives to the different risks.
- **Horizontal relations** by identifying the mutual interaction between the elements of the PMS. For instance, in the context of QSE integrated management system, the tactical objectives are usually in interaction. For example increasing the production capacity to satisfy the quality requirements is harmful for environment and security objectives since it can increase the pollution and injury rate.

Example 5.2 *Let us consider a strategic objective O_1, and suppose that this objective is divided into two sub-objectives SO_1 and SO_2 which are mutually interacted. In addition, suppose that two risks R_1 and R_2 having impact on both of sub-objectives are identified. Thus, the corresponding PMS structure is illustrated in Figure 5.2. For instance, R_{11} and R_{12} are respectively the operational indicators relative to R_1 and R_2 for the sub-objective SO_1.*

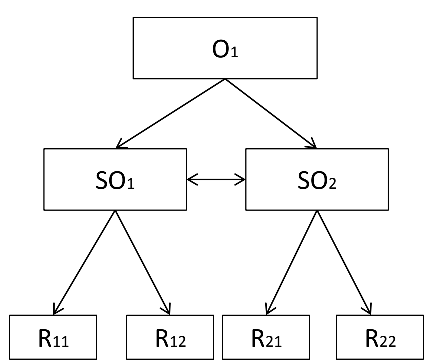

Figure 5.2: Corresponding PMS structure to example 5.2

Once the PMS structure is defined, the effectiveness of each management plan has to be evaluated in order to select the appropriate one. To this end, a quantification of the PMS has to be ensured.

5.4 Quantification of the performance measurement system

The quantification of a PMS consists in the expression of the overall performance of the strategic objective given to a management plan. To this end, several approaches have been proposed in [27, 46, 93]. From these studies, two main subproblems concerning the quantification can be distinguish which are:

1. *Elementary performance expression*: which consists in expressing the performance relative to each operational indicator given to a management plan.
2. *Overall objective performance expression*: which consists in expressing the performance relative to each strategic objective from the elementary performance expressions.

5.4.1 Elementary performance expressions

To express the performance ($P^A_{O_P}$) relative to an operational indicator O_P given to a management plan A, two values have to be carried out:

1. the measure m^A_{OP} relative to the operational indicator OP given to a management plan A.
2. the measure $m_{max_{O_P}}$ relative to the maximal satisfaction degree of the operational indicator O_P.

Then these two values are compared. Generally, this comparison is ensured via the ratio (i.e $\frac{m_{max_{O_P}}}{m^A_{OP}}$) and the difference operator (i.e $m^A_{OP} - m_{max_{O_P}}$)

Example 5.3 *Let us consider the PMS structure illustrated in Figure 5.2 and a management plan A. As shown in Table 5.1, to calculate the performance relative to the operational indicator R_{11} given to the management plan A, we set the* *measure relative to* R_{11} *given to A using the risk priority number* ($RPN^A_{R_{11}}$) *and its relative maximal satisfaction* $RPN_{max_{R_{11}}}$. *Then, the corresponding performance is calculated using the ratio scale* $P^A_{R_{11}} = \frac{RPN_{max_{R_{11}}}}{RPN^A_{R_{11}}}$. *This ratio is defined along the same universe [0 1], where the value 0 means a total satisfaction of the objective while 1 means absolute non-satisfaction.*

Table 5.1: Elementary performance of R_{11}

$RPN^A_{R_{11}}$	$RPN_{max_{R_{11}}}$	$P^A_{R_{11}}$
0.45	0.34	0.75

It is important to note that the calculated performance expressions are considered as commensurable since all the risks are evaluated in the same scale.

5.4.2 Overall objective performance expression

Once the performance relative to each operational indicator is defined, an aggregation operation is ensured to express the satisfaction degree relative to the overall objectives (i.e. strategic objectives). To this end, the elementary performance is synthesized into a global performance.

The main aggregation operator is the weighted average mean (WAM). In lot of propositions, an expert chooses the weight directly. However, in majority of cases the weights are determined via other method, the choice of the appropriate one depends on the comparison operator used to express the satisfaction of each elementary performance. For instance, the weights determined by the Analytic Hierarchical Process (AHP) method, are used in the case of ratio comparison [90], and the weights determined by the MACBETH multi-criteria method are used in the case of differences comparison [17, 21]. However, these methods are adapted for independent criteria and are not able to take into account synergy, contradictions, redundancy between criteria which is often observed in the context of an integrated management system.

Thus, the choice of the appropriate aggregation operator must be on one hand significant for the scale type considered and on the other hand significant for the post processing to elaborate the overall performance [67]. Thus, *the Analytic*

Network Process (ANP) is used. In fact, this method allows us to be significant with the same ratio scale used to express the elementary performance, moreover, it considers dependent criteria.

In what follows, a brief recall on this method is given.

5.4.3 Analytic network process (ANP)

The Analytic Network Process (ANP) [89] is a generalization of the Analytic Hierarchical Process (AHP), it has been developed by saaty in order to overcome the problem related to the interconnection between decision factors at the same level since the AHP model assumes a one-way hierarchical relation between the different levels. More precisely, the ANP replaces the hierarchical structure with a network which gives a more flexible way to the decision maker to compare between the criteria and alternatives. The structural difference between a hierarchy and a network is depicted in Figure 5.3. In fact, the levels in AHP will be replaced by clusters in ANP, each cluster is composed of a set of elements (i.e criteria, alternatives). The elements in a cluster may influence some or all the elements of any cluster, in fact, a hierarchy is a special case of a network with connections going only in one direction.

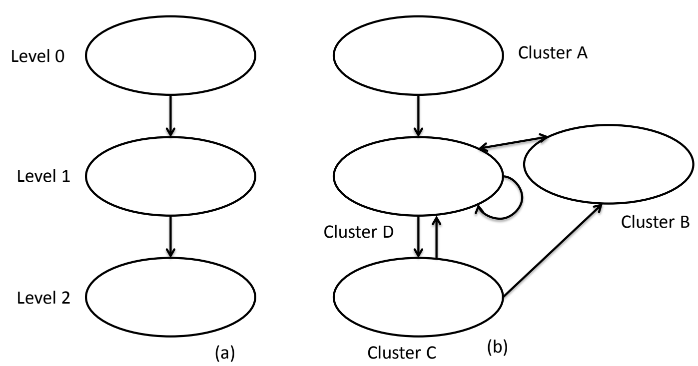

Figure 5.3: Structural difference between a hierarchy and a network // (a) a Hierarchy (b) a Network

The process of ANP comprises three majors steps:

1. **Model construction and problem structuring**: The problem here should be stated clearly and decomposed into a network G=(C,A), where C is a set of clusters and A a set of relations between the different elements. These relations have different meanings according to their targets, namely inner dependency between the elements in the same cluster and outer dependency between elements in different clusters.

2. **Pairwise comparison matrices and priority vectors**: Once the structure is defined, one or several decision matrices are constructed using a pairwise comparison between related elements, here the decision maker can express his preference between each pairs of elements verbally, this description would be then translated into numerical values using the fundamentals comparison scales used by the AHP shown in Table 2.6. Then the weight W_i of each element is calculated using equation 2.3.

3. **Unweighted supermatrix formation**: The unweighted supermatrix is constructed from the weights W_i derived from the different pairwise comparisons. The column relative to an element contains the priorities of all elements that influence it.

4. **Cluster matrix construction**: The clusters themselves should be compared to establish their relative weights and use it to weight the corresponding blocks of the unweighted supermatrix. A cluster impacts another cluster when it is linked to it i.e when at least one element in the source cluster is linked to an element in the target cluster. The clusters linked to the source cluster are pairwise compared for the importance of their impact on it.

5. **Weighted supermatrix formation**: The weighted supermatrix is obtained by multiplying each unweighted supermatrix column by the corresponding element's cluster weight.

6. **Limit supermatrix formation**: Finally,the limit supermatrix is calculated by multiplying the weighted supermatrix by itself numerous times until the columns stabilize and become identical in each block. From this

matrix, the weight relative to each element regarding each other element is obtained.

Example 5.4 *As an example, let us consider the network illustrated in Figure 5.4 where the cluster criteria is composed of three elements namely quality, cost and reliability and the cluster alternative is composed of two elements namely D_1, D_2 and D_3*

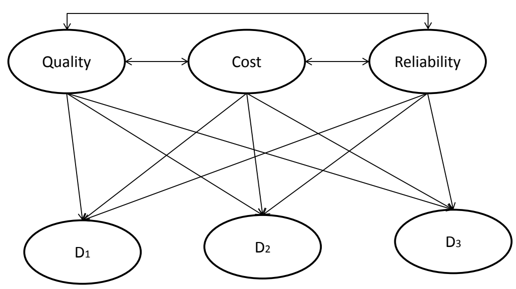

Figure 5.4: Overall Goal: Selection of the appropriate decision

Each criterion in this example has a link to the three alternatives to indicate the flow of influence from the criterion to the alternatives. Pairwise comparisons are made to determine the relative influence which the criterion has on the relative preferences of the alternatives. Also, each criterion in this example has a link to the other criterion to indicate the flow influence between each one. In fact, each criterion can have preference on the other ones, for example, the quality choice is more beneficial for the reliability than the cost etc. The process of ANP proceeds as follows:

1. *The three alternatives are compared with respect to criteria quality, cost and reliability in Table 5.2. The vector weights column illustrates the weight relative to each alternative with the respect to each criterion.*

2. *The three criteria are compared with respect to each criterion in Table 5.3. The vector weights column illustrates their relative weights.*

3. *From Table 5.2 and 5.3 the unweighted supermatrix illustrated in Table 5.4 is obtained.*

Table 5.2: Pairwise comparisons of the three decisions with respect to each criterion

Cost	D_1	D_2	D_3	Vector Weights
D_1	1	0.15	0.5	0,09731
D_2	7	1	4	0,71931
D_3	2	0.2	1	0,18338
Quality	D_1	D_2	D_3	Vector Weights
D_1	1	0.166	1	0,12711
D_2	6	1	6	0,74426
D_3	1	0.166	1	0,12864
Reliability	D_1	D_2	D_3	Vector Weights
D_1	1	5	3	0,63983
D_2	0.2	1	0.5	0,12006
D_3	0.33	2	1	0,18338

Table 5.3: Pairwise comparisons of the three criteria with respect to each criterion

Quality	*Quality*	*Cost*	*Reliability*	Vector Weights
Quality	–	–	–	0
Cost	–	1	0.5	0,33
Reliability	–	2	1	0,66
Cost	*Quality*	*Cost*	*Reliability*	Vector Weights
Quality	1	–	1	0,5
Cost	–	–	–	–
Reliability	1	–	1	0,5
Reliability	*Quality*	*Cost*	*Reliability*	Vector Weights
Quality	1	3	–	0.75
Cost	0.33	1	–	0,25
Reliability	–	–	–	–

4. *The weighted supermatrix is constructed by considering that criteria cluster and alternatives cluster have an equal importance, which means that their*

Table 5.4: unweighted supermatrix

−	*Quality*	*Cost*	*Reliability*	D_1	D_2	D_3
Quality	0	0.5	0.75	0	0	0
Cost	0.333	0	0.25	0	0	0
Reliability	0.666	0.5	0	0	0	0
D_1	0.127	0.097	0.639	1	0	0
D_2	0.744	0.719	0.12	0	1	0
D_3	0.128	0.183	0.183	0	0	1

relative weights are equal to 0.5. Consequently, the weighted supermatrix shown in Table 5.5 is obtained.

Table 5.5: weighted supermatrix

−	*Quality*	*Cost*	*Reliability*	D_1	D_2	D_3
Quality	0	0.25	0.375	0	0	0
Cost	0.165	0	0.125	0	0	0
Reliability	0.333	0.25	0	0	0	0
D_1	0.063	0.048	0.0319	1	0	0
D_2	0.372	0.359	0.06	0	1	0
D_3	0.064	0.091	0.09	0	0	1

5. *The final limit supermatrix is obtained by multiplying this matrix by itself numerous times until the columns stabilize and become identical in each block (see Table 5.6).*

Once the supermatrix is formed in the previous step, the weights of each alternative is calculated. For instance the weights of D_1*,* D_2 *and* D_3 *regarding the criteria quality are respectively* $W_{D_1}^{Quality} = 0.244$*,* $W_{D_2}^{Quality} = 0.588$ *and* $W_{D_3}^{Quality} = 0.147$.

Table 5.6: Limit supermatrix

−	*Quality*	*Cost*	*Reliability*
Quality	0.000	0.000	0.000
Cost	0.000	0.000	0.000
Reliability	0.000	0.000	0.000
D_1	0.244	0.219	0.438
D_2	0.588	0.595	0.355
D_3	0.147	0.170	0.168

5.4.4 Aggregation of the elementary performance expression

Thus, our idea here is to calculate the overall objectives performance expression using the Analytic network Process (ANP) by aggregating each elementary performance with its corresponding weight.

5.5 Illustrative example

Let us continue our illustrative example released in the petroleum field where three objectives have been considered namely:

- O_1 (Quality) : Gains market share by providing superior all round by decreasing the product of non conformity level service to the customer.
- O_2 (Environment): Minimizes the environmental waste by respecting the contamination rate of the air, water and ground according to the requirements and international standards.
- O_3 (Security) : Increase safety staff by decreasing the number of day off of employees.

Construction of the performance measurement system

As said previously, the objective O_1 is deployed to one sub-objective (i.e O_{11}: hours work stoppage $<=$ 10 hours), the objective O_2 into two sub-objectives (i.e.

O_{21}: Carbon concentration on the air $<=$ 10000 ppm and O_{22}:Fuel concentration on the sea $<=$ 25000 ppm) and O_3 into one sub-objective (i.e. O_{31} :A total of days off $<$ 15), from these sub-objectives two risks have been identified (i.e. R_1: A major fire and explosion on tanker truck carrying hydrocarbon, and R_2: A fire in container). In this example, both risks do not have any impact on O_{22}, consequently it will be ignored for the rest of the example. In addition, as shown in Table 5.7 the decision maker has identified three mutual beneficial interactions between:

1. O_{12} and O_{11} since decreasing the carbon concentration in the air decrease hours work stoppage.
2. O_{12} and O_{31} since decreasing the carbon concentration in the air decrease the total days off.
3. O_{31} and O_{11} since decreasing total days off decrease hours work stoppage.

N means that no interaction is observed and '+' means a positive interaction.

Table 5.7: Mutual interactions between the tactical objectives

	O_{11}	O_{12}	O_{31}
O_{11}	N	N	N
O_{21}	+	N	+
O_{31}	+	N	N

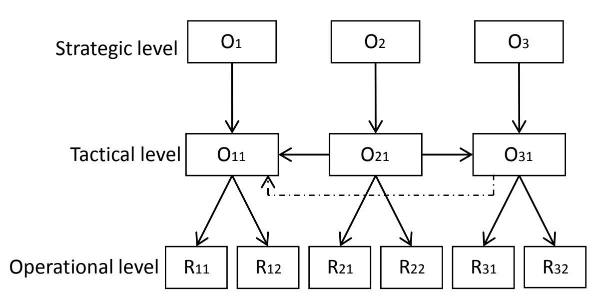

Figure 5.5: Performance measurement system structure

To reach the strategic objectives, two management plans have been proposed in section 4.5 i.e A_1, A_2.

Quantification of the performance measurement system

As shown in Table 5.8, the elementary performances relative to A_1 (P^{A_1}) (resp. A_2 (P^{A_2})) are calculated using the ratio comparison between the maximal satisfaction (RPN_{max}) and the measure of (RPN^{A_1})(resp. RPN^{A_2}).

Table 5.8: Different RPN values relative to each state

–	RPN^{A_1}	RPN^{A_2}	(RPN_{max})	P^{A_1}	P^{A_2}
R_{11}	0.45	0.32	0.22	0.48	0.68
R_{12}	0.28	0.27	0.18	0.64	0.66
R_{21}	0.22	0.28	0.16	0.72	0.57
R_{22}	0.25	0.18	0.15	0.6	0.83
R_{31}	0.31	0.38	0.24	0.77	0.77
$R32$	0.47	0.35	0.19	0.4	0.54

Once the elementary performance expressions are defined, an aggregate operation is ensured to express the overall performance relative to each strategic objective. To this end, as shown in Table 5.9, first the operational indicators are compared regarding each tactical objective. For example, the decision maker considers that R_{11} has a strong importance than R_{12} regarding O_{11} etc. Then, in Table 5.10 the transversal relations are compared between the tactical objectives. For example the decision maker considers O_{21} has a more moderate importance than O_{31} regarding the satisfaction of O_{11}.

Once the DM matrices are constructed, the weights relative to each compared element are calculated and the unweighted supermatrix is constructed as illustrated in Table 5.11. For instance regarding O_{11}, the weight relative to O_{12} is $W_{O_{12}}$= 0.666, to O_{31} is $W_{O_{31}}$= 0.333, to R_{11} is $W_{R_{11}}$= 0.833 and to R_{12} is $W_{R_{12}}$= 0.166.

Then, the decision maker performs a pairwise comparison between the tactical objectives cluster C_{TO} and the operational indicators cluster C_{OP} by considering

Table 5.9: Decision matrices relative to the risk with respect to the tactical objectives

	O_{11}			O_{21}			O_{31}	
–	R_{11}	R_{12}	-	R_{21}	R_{22}	–	R_{31}	R_{32}
R_{11}	1	5	R_{21}	1	0.2	R_{31}	1	0.33
R_{12}	0.2	1	R_{22}	5	1	R_{32}	3	1

Table 5.10: Decision matrices relative to the tactical objectives with respect to themselves

	O_{11}			O_{21}			O_{31}		
–	O_{11}	O_{21}	O_{31}	O_{11}	O_{21}	O_{31}	O_{11}	O_{21}	O_{31}
O_{11}	–	–	–	–	–	–	–	–	–
O_{21}	–	1	2	–	–	–	–	1	–
O_{31}	–	0.5	1	–	–	–	–	–	–

Table 5.11: Unweighted supermatrix

-	O_{11}	O_{21}	O_{31}	R_{11}	R_{12}	R_{21}	R_{22}	R_{31}	R_{32}
O_{11}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
O_{21}	0.666	0.000	1	0.000	0.000	0.000	0.000	0.000	0.000
O_{31}	0.333	0.000	0.00	0.000	0.000	0.000	0.000	0.000	0.000
R_{11}	0.833	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
R_{12}	0.166	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000
R_{21}	0.000	0.833	0.000	0.000	0.000	1.000	0.000	0.000	0.000
R_{22}	0.000	0.166	0.000	0.000	0.000	0.000	1.000	0.000	0.000
R_{31}	0.000	0.000	0.25	0.000	0.000	0.000	0.00	1.000	0.000
R_{32}	0.000	0.000	0.75	0.000	0.000	0.000	0.0	0.000	1.00

that C_{OP} is more important than C_{TO} which is translated to the value 4 according to saaty scale. Thus, $W_{C_{OP}}$ is equal to 0.75 and $W_{C_{TO}}$ is equal to 0.25. Then on the basis of these values the weighted supermatrix shown in Table 5.12 is constructed.

Table 5.12: Weighted supermatrix

-	O_{11}	O_{21}	O_{31}	R_{11}	R_{12}	R_{21}	R_{22}	R_{31}	R_{32}
O_{11}	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
O_{21}	0.22	0.000	0.33	0.000	0.000	0.000	0.000	0.000	0.000
O_{31}	0.11	0.000	0.00	0.000	0.000	0.000	0.000	0.000	0.000
R_{11}	0.55	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
R_{12}	0.106	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000
R_{21}	0.000	0.833	0.000	0.000	0.000	1.000	0.000	0.000	0.000
R_{22}	0.000	0.166	0.000	0.000	0.000	0.000	1.000	0.000	0.000
R_{31}	0.000	0.000	0.166	0.000	0.000	0.000	0.00	1.000	0.000
R_{32}	0.000	0.000	0.50	0.000	0.000	0.000	0.0	0.000	1.000

Finally, the limit supermatrix is obtained by multiplying the unweighted supermatrix by it self four times as shown in Table 5.13.

Table 5.13: Limit supermatrix

-	O_{11}	O_{21}	O_{31}	R_{11}	R_{12}	R_{21}	R_{22}	R_{31}	R_{32}
O_{11}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
O_{21}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
O_{31}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
R_{11}	0.55	0.000	0.00	0.100	0.000	0.000	0.000	0.000	0.000
R_{12}	0.106	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000
R_{21}	0.106	0.833	0.274	0.000	0.000	1.000	0.000	0.000	0.000
R_{22}	0.213	0.166	0.054	0.000	0.000	0.000	1.000	0.000	0.000
R_{31}	0.042	0.000	0.166	0.000	0.000	0.000	0.0	1.000	0.000
R_{32}	0.018	0.000	0.500	0.000	0.000	0.000	0.0	0.000	1.000

From the final matrix, the relative weight of each operational indicator with respect to each tactical objective is obtained. For instance regarding the objective O_{11} the relative weights are $W_{R_{11}}^{O_{11}}$=0.55, $W_{R_{12}}^{O_{11}}$=0.106, $W_{R_{21}}^{O_{11}}$=0.106, $W_{R_{22}}^{O_{11}}$=0.213, $W_{R_{31}}^{O_{11}}$=0.042, $W_{R_{32}}^{O_{11}}$=0.018, $W_{R_{21}}^{O_{21}}$=0.833, $W_{R_{22}}^{O_{22}}$=0.166, $W_{RPN_{21}}^{O_{31}}$=0.274, $W_{R_{22}}^{O_{31}}$=0.054, $W_{R_{31}}^{O_{31}}$=0.166, $W_{R_{32}}^{O_{31}}$=0.5. In addition, since the strategic objective O_1(resp. O_2,

O_3) is only related to O_{11}(resp. O_{21}, O_{31}), thus $W_{O_{11}}^{O_1} = W_{O_{21}}^{O_2} = W_{O_{31}}^{O_3} = 1$.

Once the different weights are defined, the global satisfaction relative to each strategic objective given A_1 and A_2 are calculated as follows:

$P_{O_1}^{A_1} = R_{11}^{A_1} \times W_{R_{11}}^{O_{11}} + R_{12}^{A_1} \times W_{R_{12}}^{O_{11}} + R_{11}^{A_1} \times W_{R_{21}}^{O_{11}} + R_{22}^{A_1} \times W_{R_{22}}^{O_{11}} + R_{31}^{A_1} \times W_{R_{31}}^{O_{11}} + R_{32}^{A_1} \times W_{R_{32}}^{O_{11}}$.

$P_{O_1}^{A_2} = R_{11}^{A_2} \times W_{R_{11}}^{O_{11}} + R_{12}^{A_2} \times W_{R_{12}}^{O_{11}} + R_{11}^{A_2} \times W_{R_{21}}^{O_{11}} + R_{22}^{A_2} \times W_{R_{22}}^{O_{11}} + R_{31}^{A_2} \times W_{R_{31}}^{O_{11}} + R_{32}^{A_2} \times W_{R_{32}}^{O_{11}}$.

$P_{O_2}^{A_1} = R_{21}^{A_1} \times W_{R_{21}}^{O_{21}} + R_{22}^{A_1} \times W_{R_{22}}^{O_{21}}$.

$P_{O_2}^{A_2} = R_{21}^{A_2} \times W_{R_{21}}^{O_{21}} + R_{22}^{A_2} \times W_{R_{22}}^{O_{21}}$.

$P_{O_3}^{A_1} = R_{21}^{A_1} \times W_{R_{21}}^{O_{31}} + R_{22}^{A_1} \times W_{R_{22}}^{O_{31}} + R_{31}^{A_1} \times W_{R_{31}}^{O_{31}} + R_{32}^{A_1} \times W_{R_{32}}^{O_{31}}$.

$P_{O_3}^{A_2} = R_{21}^{A_2} \times W_{R_{21}}^{O_{31}} + R_{22}^{A_2} \times W_{R_{22}}^{O_{31}} + R_{31}^{A_2} \times W_{R_{31}}^{O_{31}} + R_{32}^{A_2} \times W_{R_{32}}^{O_{31}}$.

Table 5.14 illustrates the different performance values relative to each strategic objective given A_1 and A_2.

Table 5.14: Global satisfaction degrees relative to each decision

	O_1	O_2	O_3
P^{A_1}	0.2629	0.356	0.1247
P^{A_2}	0.3708	0.548	0.689

Thus, from table 5.14 we can conclude that the management plan A_2 is more appropriate than A_1, since it has a better performance on each strategic objective.

5.6 Conclusion

This chapter proposes an implementation of the *Act and Check phase* of our process-based approach for integrating Quality, Security and Environment management systems. To this end, construction and the quantification of a performance measurement system (PMS) is proposed since its allows us to measure the effectiveness of the defined management plans in the *Do* phase. In fact, on the basis of these measures, the most appropriate ones are selected.

In next chapter, a global implementation of the proposed process-based approach for an integrated QSE management system in a real case study is proposed.

Chapter 6

Global Implementation of the Process Based Approach for IMS-QSE: Real Case of Study in the Petroleum Field

6.1 Introduction

In this Chapter, an effective implementation of the proposed process-based approach for implementing an integrated Quality, Security and Environment management system is proposed.

The implementation of the global approach has been released in the petroleum field in TOTAL TUNSIA company.

The remainder of this chapter is organized as follows: Section 2 presents the implementation if the risk identification and deployment of the objectives. Section 3 presents the implementation of the risk analysis step. Section 4 presents the implementation of the risk evaluation step. Section 5 presents the definition of the global management plan QSE. Section 6 presents the implementation of the proposed performance measurement system. Finally, section 7 presents the proposed tool to implement our process-based approach algorithms.

6.2 Risk identification and deployment of the objectives

The inputs relative to this phase are:

- **Process cartography**: Figure 6.1 illustrates the process cartography relative to some activities (due to confidential reasons only some activities are represented) related to TOTAL TUNSIA company. In this cartography ten activities are represented namely *Marketing, Prospecting, Studies, Commercial, Realization of orders, Outbound logistics, Inbound logistics, planning, Purchase, Provision.*

- **QSE objectives**: Three objectives are considered namely O_1: Gain market share by providing superior all around service to the customer, O_2: Minimize the environmental waste and O_3:Increase safety staff.

From these inputs, 50 risks ($R_1 \cdots \mathrm{R}_{50}$) related to *the Realization of orders* activity have been identified as shown in Table 6.2. These risks are in relation with six deployed objectives namely O_1:{SO_1: Late delivery, SO_2: Damage on the other trucks}, O_2:{SO_3: Thermal damage to people, SO_4 : Toxic damage to people }, O_3 : {SO_5:Damage on the air, SO_6:Damage on the sea}.

6.3 Risk Analysis

The inputs relative to this phase are the ML-FMEA inputs parameters, which are a set of indicators quantifying:

- Occurrence (OC): computed by a calculated *average of occurrence number by year.*

- Detectability (D): computed by a ratio of the *detecting occurrence rate of the risk* and *its occurrence rate.*

- Severity (S) on SO_1: computed by a ratio of the *Time required to deliver the product* and *Time released to deliver the product.*

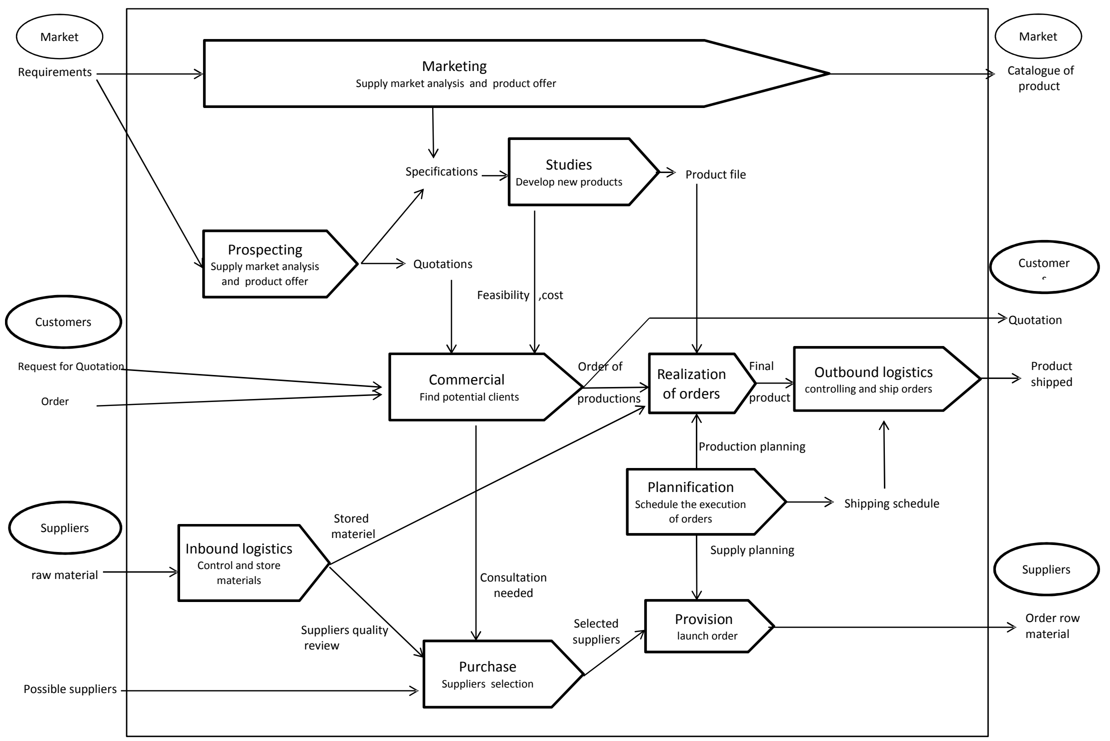

Figure 6.1: Process cartography relative to TOTAL TUNISIA company

Table 6.1: Identified risks

R_1:Explosion of a boat
R_2: A major fire and explosion on tanker truck carrying
R_3:UVCE after LPG leak at the oil wharf (compartment of a 1200 T gas)
R_4:Fire in container (compartment of a 1200 T gas)
R_5:BLEVE of a sphere of 4000 m3 of LPG (Gas Total Gas and North)
R_6:Spreading occurs due to the effects induced by perforation of a 10 m3 tank
R_7:Overflow tank (50 m3) during reception
R_8:Tank fire or explosion due to a crime (or malicious intrusion)
R_9:Break tank
R_{10}:Leak on bottom of tank 10 m3
R_{11}:Collapse of the screen and float presence of an explosive atmosphere above the screen floating socket
R_{12}:Loss of seal at the screen and float presence of an explosive atmosphere above the screen floating socket
R_{13}:Presence of an explosive atmosphere above the screen floating in a tank filling operation
R_{14}:Electrostatic discharge when gauging or sampling during or immediately after the reception operation
R_{15}:Leak dress or tank accessories 250 L
R_{16}:Dispersal of products following collision between two vehicles (trucks, trolley, cars) 500L
R_{17}:Dispersal of products following collision between a crane and a Fixed installation (500L)
R_{18}:Electric shock due to a lack of grounding in a truck unloading
R_{19}: Spreading occurs due to an overflow of 800 L tanker
R_{20}: Spreading of the product following the truck tank piercing
R_{21}: Spreading due to the loss of a tank truck
R_{22}: Out of the loading arm 250 L
R_{23}:Leak on loading arm 250L
R_{24}:Fuel spill during a maintenance operation on the group counter CPC 100L
R_{25}:Spreading due to the loose of a tank truck
R_{26}:Explosion following heating by air intake(cavitation) pump towable
R_{27}:Explosion due to significant heating of a transfer pump due to a mechanical problem Cavitation (airintake)
R_{28}:Seal or gasket leak on a transfer pump 250 L
R_{29}:Drain transfer pump body 250 L in a truck
R_{30}: Spreading of the product following the truck tank piercing
R_{31}: Leakage on flexible 3 "50L
R_{32}: Leakage on flexible 6" 80L
R_{33}: Leakage on flexible 6" 350L
R_{34}: Leakage on pipes 4" 1000 L
R_{35}:Leakage on pipes 6" 1000 L
R_{36}:Leakage on pipes 8" 1000 L
R_{37}:Spreading occurs following a pipeline rupture by mechanical shock
R_{38}:Leak on flange gasket line 100L
R_{39}:Blocking an open valve open or valve leak on 50L
R_{40}:Drain pipe stitching on 50L
R_{41}: Leak drip leg 100L
R_{42}: Overflow of a drip leg 100L
R_{43}: Valves leak due to wear 250 L
R_{44}: Leak occurs in the circuits of a separator
R_{45}: Unconfined Vapour Cloud Explosion (UVCE) following the gas leak
R_{46}: Passage of product in the exhaust system of separator to the sea
R_{47}: Transformer explosion
R_{48}: Electrical short circuit (UVCE) following the gas leak
R_{49}: Leakage of diesel from generator 50 L
R_{50}: Lightning causing an explosion or fire in the transformer station and / or the main switchboard

- Severity (S) on SO_2: computed by a ratio of the *Trucks prices* and *Trucks repair cost*.
- Severity (S) on SO_3: computed by a ratio of the *days off number due to thermal damage* and *Number of paid days off*. .
- Severity (S) on SO_4: computed by a ratio of the *days off number due to toxic damage* and *Number of paid days off*.
- Severity (S) on SO_5: computed by a ratio of the *Carbon concentration in the air* and *threshold concentration of CO2 in the air according to ISO 12884:2000 standard* [1].
- Severity (S) on SO_6: computed by a ratio of the *Fuel concentration on the sea* and *threshold concentration of Fuel concentration on the sea according to ISO 12884:2000 standard* [1].

The values relative to each parameter for each risk are illustrated in Table 6.3.

From these inputs, 10 risks are selected namely:

- RS_1: A major fire and explosion on tanker truck carrying hydrocarbure.
- RS_2: Fire in container (compartment of 1200 T gas).
- RS_3: Overflow tank ($50m^3$) during reception.
- RS_4: Break tank.
- RS_5: Disposal of products following collision between two vehicles.
- RS_6: Disposal of products following collision between a crane and a fixed installation (500L).
- RS_7: Spreading due to the loss of a tank truck.
- RS_8: Spreading of the product following the truck tank piercing.
- RS_9: Unconfined vapor cloud explosion (UVCE) following the gas leak.
- RS_{10}: Passage of product in the exhaust system of separator.

Table 6.2: Identified risks and their relative measures

Identified Risks	OC	D	S on SO_1	S on SO_2	S on SO_3	S on SO_4	S on SO_6	S on SO_6
R_1	0.01	0.09	0.36	0.7	0.9	0.14	0.3	0.8
R_2	0.32	0.7	0.46	0.7	0.9	0.34	0.7	0.1
R_3	0.09	0.11	0.17	0.18	0.25	0.0.3	0.27	0.39
R_4	0.4	0.45	0.49	0.73	0.82	0.30	0.57	0.1
R_5	0.08	0.18	0.14	0.28	0.36	0.18	0.27	0.17
R_6	0.03	0.05	0.13	0.15	0.16	0.18	0.02	0.09
R_7	0.23	0.35	0.49	0.73	0.82	0.30	0.57	0.29
R_8	0.29	0.003	0.69	0.43	0.42	0.39	0.37	0.2
R_9	0.49	0.54	0.44	0.23	0.46	0.19	0.07	0.17
R_{10}	0.08	0.07	0.11	0.21	0.22	0.19	0.17	0.16
R_{11}	0.11	0.13	0.21	0.13	0.12	0.17	0.11	0.009
R_{12}	0.11	0.1	0.1	0.15	0.22	0.23	0.21	0.008
R_{13}	0.11	0.05	0.21	0.05	0.02	0.03	0.01	0.008
R_{14}	0.11	0.15	0.11	0.05	0.12	0.03	0.01	0.18
R_{15}	0.1	0.04	0.04	0.14	0.02	0.007	0.008	0.04
R_{16}	0.35	0.31	0.45	0.34	0.21	0.22	0.27	0.18
R_{17}	0.25	0.27	0.4	0.45	0.34	0.21	0.22	0.18
R_{18}	0.17	0.19	0.17	0.19	0.14	0.16	0.51	0.004
R_{19}	0.07	0.05	0.07	0.15	0.17	0.06	0.06	0.19
R_{20}	0.17	0.05	0.07	0.05	0.07	0.08	0.07	0.004
R_{21}	0.11	0.14	0.07	0.12	0.17	0.18	0.13	0.09
R_{22}	0.17	0.15	0.007	0.005	0.007	0.008	0.007	0.004
R_{23}	0.09	0.15	0.009	0.007	0.008	0.001	0.004	0.002
R_{24}	0.04	0.07	0.17	0.15	0.001	0.002	0.01	0
R_{25}	0.1	0.14	0.17	0.15	0.07	0.08	0.07	0.04
R_{26}	0.12	0.07	0.07	0.15	0.17	0.18	0.07	0.01
R_{27}	0.04	0.07	0.27	0.35	0.27	0.28	0.17	0.14
R_{28}	0.14	0.07	0.17	0.15	0.17	0.18	0.17	0.12
R_{29}	0.17	0.07	0.17	0.05	0.17	0.18	0.12	0.11
R_{30}	0.24	0.17	0.37	0.15	0.27	0.28	0.17	0.14
R_{31}	0.04	0.07	0.001	0.01	0.01	0.01	0.01	0.01
R_{32}	0.04	0.07	0.001	0.01	0.01	0.01	0.01	0.01
R_{33}	0.06	0.07	0.001	0.01	0.01	0.01	0.01	0.01
R_{34}	0.07	0.07	0.001	0.01	0.01	0.01	0.01	0.01
R_{35}	0.09	0.07	0.001	0.01	0.01	0.01	0.01	0.01
R_{36}	0.03	0.07	0.001	0.01	0.01	0.01	0.01	0.01
R_{37}	0.14	0.15	0.07	0.05	0.07	0.08	0.07	0.14
R_{38}	0.11	0.07	0.02	0.15	0.15	0.08	0	0
R_{39}	0.07	0.09	0.17	0	0	0	0	0
R_{40}	0.24	0.17	0.37	0	0	0	0	0
R_{41}	0.04	0.14	0.17	0	0	0	0	0
R_{42}	0.09	0.14	0.07	0	0	0	0	0
R_{43}	0.01	0.07	0.11	0	0	0	0	0
R_{44}	0.05	0.20	0.25	0	0	0	0	0.19
R_{45}	0.09	0.24	0.24	0.15	0.27	0.28	0.17	0.14
R_{46}	0.08	0.12	0.37	0.15	0.27	0.28	0.17	0.34
R_{47}	0.08	0.12	0.37	0.25	0	0	0.19	0
R_{48}	0.01	0.03	0.37	0.15	0.27	0.28	0.17	0
R_{49}	0.01	0.03	0.37	0.15	0.27	0.28	0.17	0
R_{50}	0.01	0.03	0.37	0.15	0.27	0.28	0.17	0

6.4 Risk evaluation

The inputs relative to this phase are the training sets illustrated from Table 6.3 to Table 6.22 relative to each selected risk ($RS_1 \cdots RS_{10}$). From these inputs, the different bow tie diagrams shown from Figure 6.2 to Figure 6.11 are obtained and their relative barriers are illustrated in Table 6.23.

Table 6.3: Training set relative to causes of a major fire and explosion on tanker truck carrying hydrocarbon

DTA	GO	RS_1	EF	CTP	TVF	HGL	SI	PS	MsE	DTA	GO	RS_1	EF	CTP	TVF	HGL	SI	PS	MsE
T	T	T	T	T	F	T	T	T	F	F	T	T	T	T	T	T	T	T	T
T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	F	T	T	T	T	F	T	T	T	T	T	T	F	F	T	T	F	F	F
F	F	F	F	T	F	F	F	F	T	F	F	T	F	T	F	F	T	T	T
T	T	F	T	F	T	T	F	F	T	F	T	T	F	F	T	T	F	F	F
F	F	T	T	F	F	F	F	F	T	T	T	T	T	F	F	T	F	F	F
F	T	T	T	F	T	T	T	T	T	F	T	T	F	F	T	T	F	F	F
T	F	F	F	F	F	F	F	F	F	T	T	T	T	T	F	T	T	T	T
F	T	F	T	F	T	T	T	T	F	F	T	F	F	F	T	T	F	F	F
F	T	F	F	F	F	F	T	T	F	F	F	F	F	F	F	F	F	F	F
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F	F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	F	F	F	F
F	T	T	T	T	T	T	F	F	T	T	F	T	F	T	T	T	T	T	T
T	F	F	T	F	F	F	F	F	T	T	T	T	T	F	F	F	T	T	T
F	T	T	T	F	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F
F	F	T	T	F	F	F	T	T	T	F	F	F	F	F	F	F	F	F	F

Table 6.4: Training set relative to consequences of a major fire and explosion on tanker truck carrying hydrocarbon

RS_1	LD	DA	$TODP$	DT	TDP	PPS	TOE	PF	THE	RS_1	LD	DA	$TODP$	DT	TDP	PPS	TO	PF	THE
T	T	T	T	T	T	T	T	T	T	F	F	T	F	F	F	T	F	F	F
T	T	T	T	F	T	T	T	T	T	F	T	F	F	F	T	T	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	T	T	F	F	F	T	F	F
F	T	T	F	F	T	F	F	F	F	F	F	F	F	F	T	F	F	F	T
F	F	T	T	F	T	T	T	F	F	F	F	T	F	F	T	F	T	F	F
F	F	T	T	T	T	F	F	F	T	F	T	F	T	F	F	T	F	F	F
F	T	F	T	F	F	T	F	F	F	F	T	T	T	F	F	F	T	F	F
F	F	F	F	F	F	T	F	F	F	F	F	T	T	F	T	F	T	F	F
T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T
F	F	F	F	F	T	F	F	F	T	F	T	F	F	F	T	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	T	T	F	F	F	T	F	F	F
F	T	F	T	F	T	T	F	F	F	F	F	F	T	F	T	F	F	F	T
F	T	T	T	F	F	F	T	F	F	F	T	F	T	F	T	T	F	F	F
F	T	F	F	T	T	F	F	F	T	T	F	T	F	F	F	F	F	F	F
F	F	T	T	F	T	F	T	F	F	F	F	F	T	T	T	F	F	F	T
F	F	T	F	T	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F
T	T	T	T	T	T	T	T	T	T	F	F	F	T	F	F	F	T	F	F
F	F	T	T	F	F	F	T	F	F	T	T	T	T	F	T	T	T	T	T
F	T	T	F	T	F	T	T	T	T	F	F	F	F	F	T	F	F	F	F
F	F	F	F	T	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F
F	T	T	T	F	F	F	T	F	F	F	T	F	F	F	T	T	F	F	F
F	F	T	F	T	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F
F	F	T	T	T	F	F	T	F	F	T	T	T	T	F	T	T	T	T	T
F	T	T	F	F	T	T	F	F	F	F	T	T	F	F	F	T	F	F	F
F	F	F	T	T	F	F	F	F	F	F	F	T	T	F	T	F	T	F	F
T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T

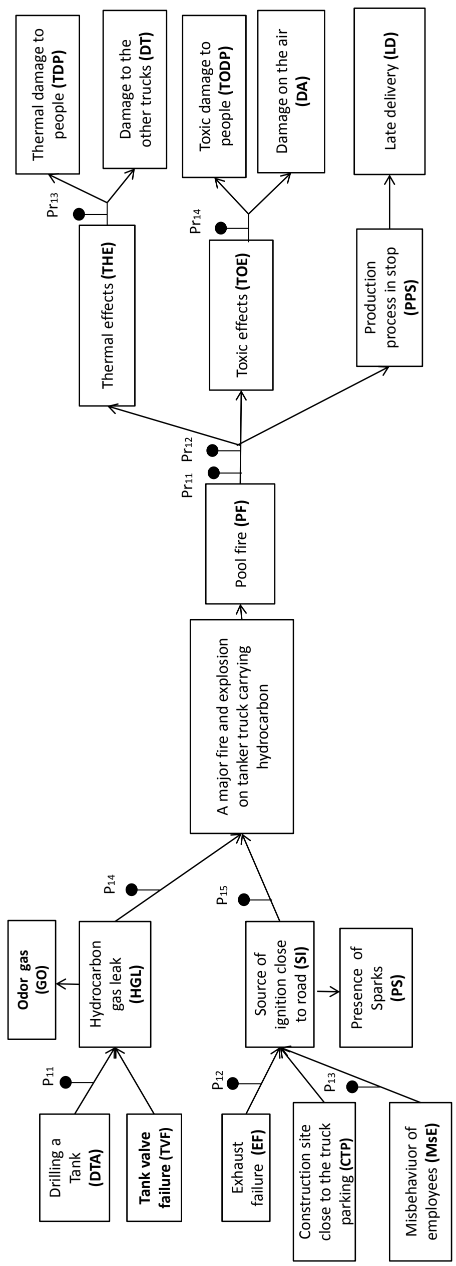

Figure 6.2: Bow tie diagram relative to a major fire and explosion on tanker truck carrying hydrocarbon

Table 6.5: Training set relative to causes of fire in container

WDT	GO	RS_2	IRO	HOP	FL	HGL	SI	PS	MsE	WDT	GO	RS_2	IRO	HOP	FL	HGL	SI	PS	MsE
F	T	T	T	F	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F
F	T	T	F	F	T	T	F	F	T	T	T	T	T	F	F	F	T	T	T
F	F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	F	F	F	F
T	T	T	F	F	T	T	F	F	F	T	T	T	T	F	T	T	T	T	T
F	F	T	F	F	F	F	T	T	F	T	F	T	F	T	F	F	T	T	T
F	F	T	T	F	F	F	T	T	T	F	F	F	F	F	F	F	F	F	F
F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	F	F	F	F	F
T	T	F	F	F	T	T	F	T	T	F	T	T	F	F	T	T	F	F	F
F	F	T	T	T	T	F	T	T	T	T	T	T	F	F	T	T	F	F	F
T	T	T	T	T	F	T	T	T	F	F	T	T	T	T	T	T	T	T	T
F	F	F	F	F	F	F	T	T	T	F	F	T	T	F	F	F	T	T	T
T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	F	F	F	T	F	F	F	F	T	F	F	T	F	T	F	F	T	T	T
T	T	F	T	F	T	T	F	F	T	F	T	T	F	F	T	T	F	F	F
F	F	T	T	F	F	F	F	F	T	T	T	T	T	F	F	T	F	F	F
F	T	T	T	F	T	T	T	T	T	F	T	T	F	F	T	T	F	F	F
T	F	F	F	F	F	F	F	F	F	T	T	T	T	T	F	T	T	T	T
F	T	F	T	F	T	T	T	T	F	F	T	F	F	F	T	T	F	F	F
F	T	F	F	F	F	F	T	T	F	F	F	F	F	F	F	F	F	F	F
F	T	F	F	T	T	T	T	T	T	F	T	T	F	F	T	T	F	F	F
F	T	T	F	F	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T
F	F	T	T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	T	F	F	F	T	T	F	F	T	T	T	T	F	F	T	T	F	F	F
T	T	T	F	F	F	T	F	F	T	T	T	T	F	F	F	T	F	F	F
F	T	T	T	T	T	T	F	F	T	T	F	T	F	T	T	T	T	T	T
T	F	F	T	F	F	F	F	F	T	T	T	T	T	F	F	F	T	T	T

Table 6.6: Training set relative to consequences of fire in container

RS_2	LD	DA	$TODP$	DT	TDP	PPS	TOE	CE	THE	RS_2	LD	DA	$TODP$	DT	TDP	PPS	TO	CE	THE
F	T	F	T	F	F	T	F	F	F	F	T	T	T	F	F	F	T	F	F
F	F	F	F	F	F	T	F	F	F	F	F	T	T	F	T	F	T	F	F
F	F	T	F	F	T	F	F	F	T	F	T	T	F	F	F	T	F	F	F
F	T	F	F	T	T	F	F	F	T	T	F	T	F	F	F	F	F	F	F
T	T	T	T	T	T	T	T	T	T	F	F	T	F	F	F	T	F	F	F
F	T	T	F	F	T	F	F	F	F	F	F	F	F	F	T	F	F	F	T
F	F	T	T	F	T	F	T	F	F	F	F	F	T	T	T	F	F	F	T
T	T	T	T	F	T	T	T	T	T	F	T	F	F	F	T	T	F	F	F
F	T	F	T	F	T	T	F	F	F	F	F	F	T	F	T	F	F	F	T
F	T	T	T	F	F	F	T	F	F	F	T	F	T	F	T	T	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	T	T	F	F	F	T	F	F
F	F	T	F	T	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F
F	F	T	T	T	F	F	T	F	F	T	T	T	T	F	T	T	T	T	T
T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T
T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T
F	F	T	T	F	F	F	T	F	F	T	T	T	T	F	T	T	T	T	T
F	T	T	F	T	F	T	T	T	T	F	F	F	F	F	T	F	F	F	F
F	F	T	F	T	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F
F	F	T	T	F	T	T	T	F	F	F	F	T	F	F	T	F	T	F	F
T	T	T	T	T	T	T	T	T	T	F	F	F	T	F	F	F	T	F	F
F	F	F	F	T	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F
F	T	T	T	F	F	F	T	F	F	F	T	F	F	F	T	T	F	F	F
F	T	T	F	F	T	T	F	F	F	F	T	T	F	F	F	T	F	F	F
F	F	F	T	T	F	F	F	F	F	F	F	T	T	F	T	F	T	F	F
F	F	F	F	F	T	F	F	F	T	F	T	F	F	F	T	T	F	F	F
F	F	T	T	T	T	F	F	F	T	F	T	F	T	F	F	T	F	F	F

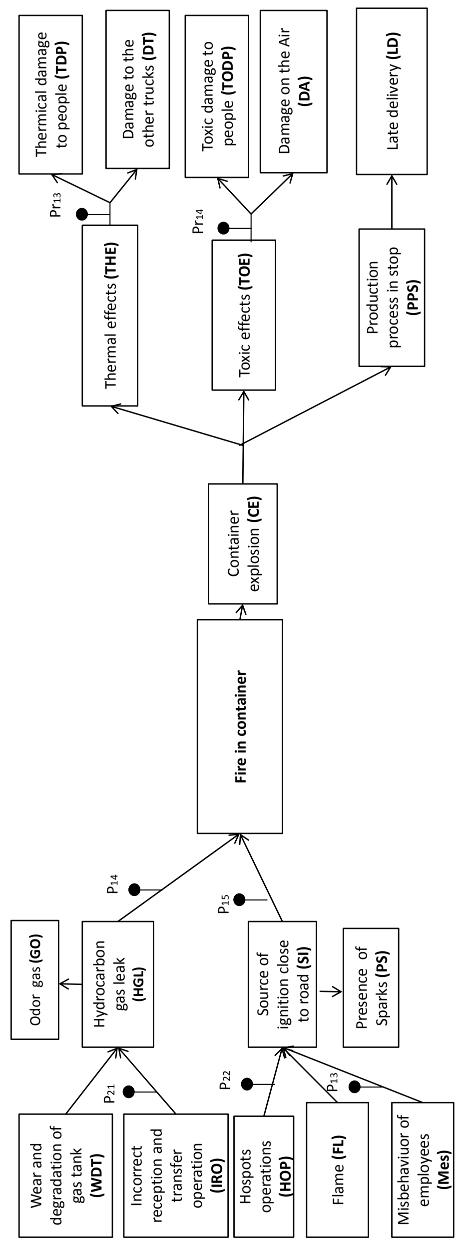

Figure 6.3: Bow tie diagram relative to a fire in container

Table 6.7: Training set relative to causes of Overflow tank (50 m3) during reception)

EXT	IBV	RS_3	FIL	LOC	FTC	FTS	FM	HE	FCC	CPS	EXT	IBV	RS_3	FIL	LOC	FTC	FTS	FM	HE	FCC	CPS
F	F	T	T	T	T	F	T	T	T	T	T	T	T	F	F	T	T	F	F	F	F
T	T	T	T	T	F	T	T	T	F	T	F	T	T	T	T	T	T	T	T	T	F
F	F	F	F	F	F	F	T	T	T	T	F	F	T	T	F	F	F	T	T	T	F
T	F	F	F	F	F	F	F	F	F	T	F	F	F	F	F	F	F	F	F	F	F
F	T	T	T	F	T	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F	F
F	T	T	F	F	T	T	F	F	T	F	T	T	T	T	F	F	F	T	T	T	F
F	F	F	F	T	F	F	F	F	F	T	T	F	F	F	F	F	F	F	F	F	F
T	T	T	F	F	T	T	F	F	F	T	T	T	T	T	F	T	T	T	T	T	T
F	T	F	F	T	T	T	T	T	T	F	F	T	T	F	F	T	T	F	F	F	F
F	T	T	F	F	T	T	T	T	T	F	T	T	T	T	F	T	T	T	T	T	T
F	F	T	T	F	F	F	T	T	T	F	F	F	F	F	F	F	F	F	F	F	F
F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	F	F	F	F	F	F	F
F	F	T	T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	T	F	F	F	T	T	F	F	T	F	T	T	T	F	F	T	T	F	F	F	F
T	T	T	F	F	F	T	F	F	T	F	T	T	T	F	F	F	T	F	F	F	F
F	T	T	T	T	T	T	F	F	T	F	T	F	T	F	T	T	T	T	T	T	F
T	F	F	T	F	F	F	F	F	T	T	T	T	T	T	F	F	F	T	T	T	F
F	F	T	F	F	F	F	T	T	F	F	T	F	T	F	T	F	F	T	T	T	T
T	T	F	F	F	T	T	F	T	T	T	F	T	T	F	F	T	T	F	F	F	F
F	F	F	F	T	F	F	F	F	T	T	F	F	T	F	T	F	F	T	T	T	F
T	T	F	T	F	T	T	F	F	T	T	F	T	T	F	F	T	T	F	F	F	T
F	F	T	T	F	F	F	F	F	T	F	T	T	T	T	F	F	T	F	F	F	F
F	T	T	T	F	T	T	T	T	T	F	F	T	T	F	F	T	T	F	F	F	F
T	F	F	F	F	F	F	F	F	F	F	T	T	T	T	T	F	T	T	T	T	F
F	T	F	T	F	T	T	T	T	F	F	F	T	F	F	F	T	T	F	F	F	F
F	T	F	F	F	F	F	T	T	F	F	F	F	F	F	F	F	F	F	F	F	F

Table 6.8: Training set relative to consequences of Overflow tank (50 m3) during reception

RS_3	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA	RS_3	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA
F	T	F	T	F	F	T	F	F	F	F	F	T	T	T	F	F	F	T	F	F	F
F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F	F	F
F	T	F	F	T	T	F	F	F	T	T	F	F	T	F	F	F	F	F	F	F	F
T	T	T	T	T	T	T	T	T	T	F	T	F	T	F	F	F	T	F	F	F	T
F	T	T	F	F	T	F	F	F	F	F	F	F	F	F	F	T	F	F	F	T	F
F	F	T	T	F	T	F	T	F	F	F	F	F	F	T	T	T	F	F	F	T	F
T	T	T	T	F	T	T	T	T	T	F	T	T	F	F	F	T	T	F	F	F	T
F	T	F	T	F	T	T	F	F	F	F	F	F	F	T	F	T	F	F	F	T	F
F	T	T	T	F	F	F	T	F	F	F	F	T	F	T	F	T	T	F	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F
F	F	T	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
F	F	T	T	T	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	F	T	T	T	T	T	T
T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
F	T	T	F	T	F	T	T	T	T	F	F	F	F	F	F	T	F	F	F	F	F
F	F	T	F	T	F	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	T	T	F	T	T	T	F	F	F	F	F	T	F	F	T	F	T	F	F	F
T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	F	F	F	T	F	F	T
F	F	F	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
F	T	T	T	F	F	F	T	F	F	F	F	T	F	F	F	T	T	F	F	F	F
F	T	T	F	F	T	T	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	F	T	T	F	F	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	F	F	F	T	F	F	F	T	F	F	T	F	F	F	T	T	F	F	F	F
F	F	T	T	T	T	F	F	F	T	F	F	T	F	T	F	F	T	F	F	F	F

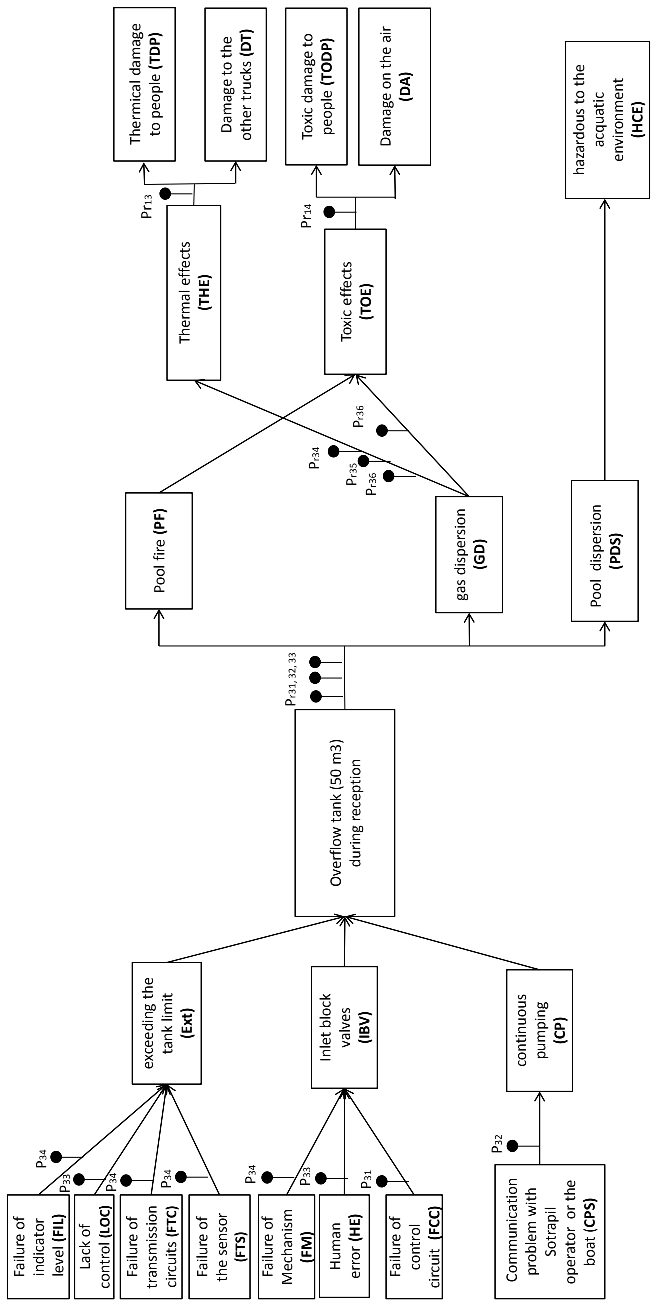

Figure 6.4: Bow tie diagram relative to an overflow tank (50 m3) during reception

Table 6.9: Training set relative to causes of Dispersal of products following collision between two vehicles (trucks , trolley, cars) 500L

LOS	LCD	RTP	LAT	MTC	FCW	RS_4	LOS	LCD	RTP	LAT	MTC	FCW	RS_4
T	T	T	F	F	T	T	F	F	F	T	T	T	T
F	T	F	F	T	T	T	T	T	T	F	F	T	T
T	F	F	F	F	F	F	F	F	F	T	F	F	F
F	T	T	T	F	T	T	T	T	T	T	T	F	F
F	T	T	F	F	T	T	T	T	T	F	T	T	T
F	F	T	T	F	F	F	T	T	T	F	F	F	F
F	F	T	T	T	T	F	T	T	T	T	T	T	T
T	T	T	T	T	F	T	T	T	F	T	F	T	T
F	F	T	T	F	F	F	F	F	F	F	F	F	F
F	T	F	F	F	T	T	F	F	T	F	T	T	T
F	T	T	F	F	T	T	F	F	T	F	T	T	T
F	F	F	F	T	F	F	F	F	F	T	T	F	F
F	F	F	F	F	F	F	T	T	T	T	F	F	T
F	F	F	T	F	F	F	F	F	T	F	F	F	F
T	T	T	F	F	F	T	F	F	T	F	T	T	T
F	T	T	T	T	T	T	F	F	T	F	T	F	T
T	F	F	T	F	F	F	F	F	T	T	T	T	T
F	F	T	F	F	F	F	T	T	F	F	T	F	T
T	T	F	F	F	T	T	F	T	T	T	F	T	T
F	F	F	F	T	F	F	F	F	T	T	F	F	T
T	T	F	T	F	T	T	F	F	T	T	F	T	T
F	F	T	T	F	F	F	F	F	T	F	T	T	T
F	T	T	T	F	T	T	T	T	T	F	F	T	T
T	F	F	F	F	F	F	F	F	F	F	T	T	T
F	T	F	T	F	T	T	T	T	F	F	F	T	F
F	T	F	F	F	F	F	T	T	F	F	F	F	F

Table 6.10: Training set relative to consequences of Dispersal of products following collision between two vehicles (trucks , trolley, cars) 500L

RS_4	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA	RS_4	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA
F	T	T	T	F	F	F	T	F	F	F	F	T	F	F	F	T	T	F	F	F	F
F	T	T	F	F	T	T	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	F	T	T	F	F	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	F	F	F	T	F	F	F	T	F	F	T	F	F	F	T	T	F	F	F	F
F	F	T	T	F	T	F	T	F	F	F	F	F	F	T	T	T	F	F	F	T	F
T	T	T	T	F	T	T	T	T	T	F	T	T	F	F	F	T	T	F	F	F	T
T	T	T	T	T	T	T	T	T	T	F	T	F	T	F	F	F	T	F	F	F	T
F	T	T	F	F	T	F	F	F	F	F	F	F	F	F	F	T	F	F	F	T	F
F	T	F	T	F	T	T	F	F	F	F	F	F	F	T	F	T	F	F	F	T	F
F	T	T	T	F	F	F	T	F	F	F	F	T	F	T	F	T	T	F	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F
F	F	T	T	T	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	F	T	T	T	T	T	T
F	T	F	T	F	F	T	F	F	F	F	F	T	T	T	F	F	F	T	F	F	F
F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F	F	F
F	T	F	F	T	T	F	F	F	T	T	F	F	T	F	F	F	F	F	F	F	F
F	F	T	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
F	F	T	T	T	T	F	F	F	T	F	F	T	F	T	F	F	T	F	F	F	F
F	T	T	F	T	F	T	T	T	T	F	F	F	F	F	F	T	F	F	F	F	F
F	F	T	F	T	F	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	T	T	F	T	T	T	F	F	F	F	F	T	F	F	T	F	T	F	F	F
T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	F	F	F	T	F	F	T
F	F	F	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F

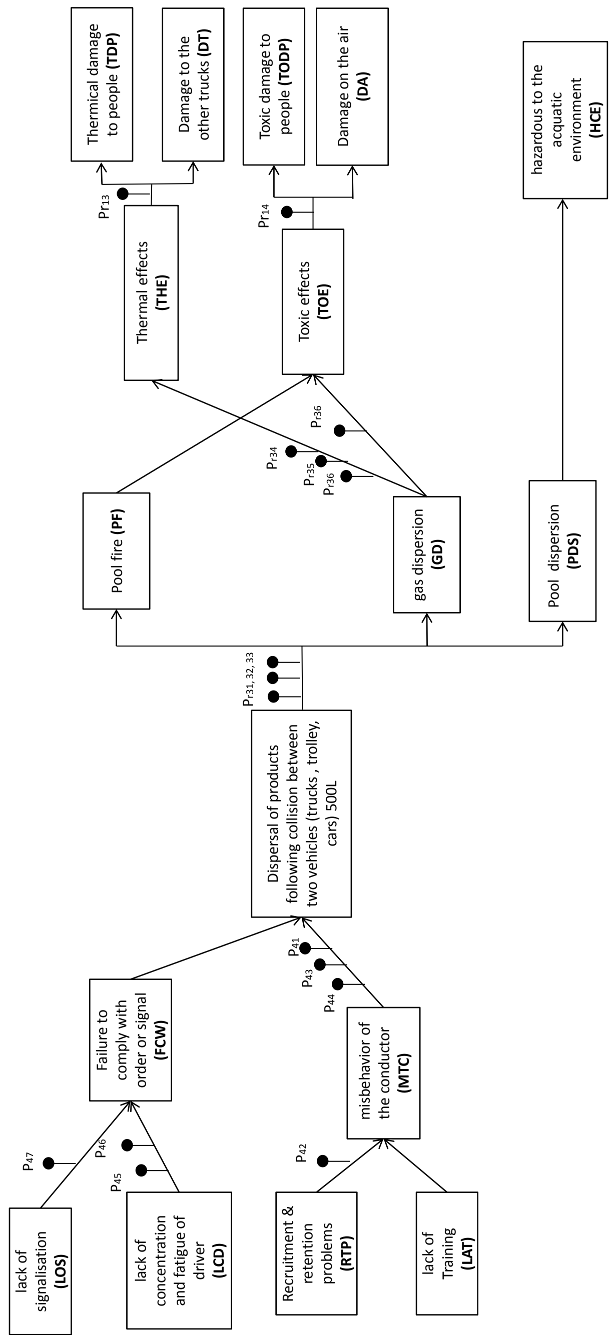

Figure 6.5: Bow tie diagram relative to a dispersal of products following collision between two vehicles (trucks , trolley, cars) 500L

Table 6.11: Training set relative to causes of Dispersal of products following collision between a crane and a Fixed installation (500L)

NCI	PPC	LRP	LRA	RS_5	LAG	NCI	PPC	LRP	LRA	RS_5	LAG
F	T	F	F	F	F	F	T	F	F	F	F
T	F	F	F	T	F	F	T	F	T	T	T
T	T	T	T	T	F	F	T	F	T	F	T
F	T	F	F	F	F	F	T	T	T	T	T
T	F	F	F	F	T	T	F	F	T	F	T
F	F	T	T	F	F	F	T	T	T	T	T
F	F	T	T	T	T	T	T	F	F	T	T
F	F	F	F	F	F	F	F	T	F	F	F
T	T	F	T	T	T	T	T	T	T	F	F
T	F	F	T	T	T	T	T	F	T	T	T
T	T	F	F	F	T	T	T	F	F	F	F
T	T	T	T	F	T	T	T	T	T	T	T
T	F	F	T	T	F	F	T	F	T	T	T
F	F	T	F	F	F	F	F	T	T	F	F
F	F	F	F	F	T	T	T	T	F	F	T
F	F	F	T	T	F	T	T	T	F	T	T
F	F	T	F	F	F	F	T	T	F	F	T
F	T	F	T	T	F	F	T	T	F	T	T
T	T	F	F	F	F	F	T	F	T	T	T
T	T	F	T	T	T	T	T	F	F	T	T
F	F	F	F	F	F	F	F	F	T	T	T
F	T	F	T	T	T	T	F	F	F	T	F
F	F	F	F	F	T	T	F	F	F	F	F
T	T	T	F	T	T	T	F	T	F	T	T
T	T	F	F	F	F	F	F	F	F	F	F
F	F	F	T	T	F	F	T	F	T	T	T

Table 6.12: Training set relative to consequences of Dispersal of products following collision between a crane and a Fixed installation (500L)

RS_5	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA	RS_5	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA
F	F	F	F	F	T	F	F	F	T	F	F	T	F	F	F	T	T	F	F	F	F
F	F	T	T	F	T	F	T	F	F	F	F	F	F	T	T	T	F	F	F	T	F
T	T	T	T	F	T	T	T	T	T	F	T	T	F	F	F	T	T	F	F	F	T
F	T	T	T	F	F	F	T	F	F	F	F	T	F	F	F	T	T	F	F	F	F
F	T	T	F	F	T	T	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	F	T	T	F	F	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
T	T	T	T	T	T	T	T	T	T	F	T	F	T	F	F	F	T	F	F	F	T
F	T	T	F	F	T	F	F	F	F	F	F	F	F	F	F	T	F	F	F	T	F
F	T	F	T	F	T	T	F	F	F	F	F	F	F	T	F	T	F	F	F	T	F
F	T	T	T	F	F	F	T	F	F	F	F	T	F	T	F	T	T	F	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F
F	F	T	T	T	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	F	T	T	T	T	T	T
F	T	T	F	T	F	T	T	T	T	F	F	F	F	F	F	T	F	F	F	F	F
F	F	T	F	T	F	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	T	T	F	T	T	T	F	F	F	F	F	T	F	F	T	F	T	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	T	T	T	F	F	F	T	F	F	F
F	T	F	F	T	T	F	F	F	T	T	F	F	T	F	F	F	F	F	F	F	F
F	F	T	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
F	F	T	T	T	T	F	F	F	T	F	F	T	F	T	F	F	T	F	F	F	F
T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	F	F	F	T	F	F	T
F	F	F	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F	F	F

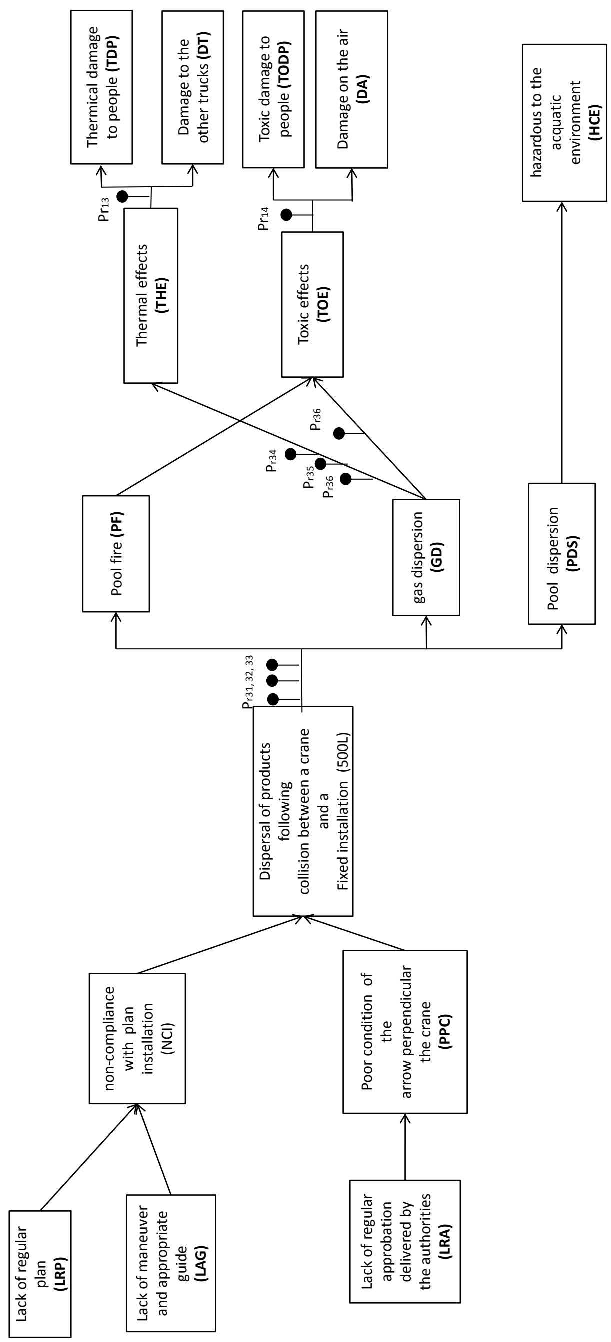

Figure 6.6: Bow tie diagram relative to a dispersal of products following collision between a crane and a fixed installation (500L)

Table 6.13: Training set relative to causes of spreading of the product following the truck tank piercing

Cor	WDN	STN	RS_6	DCN	BTP	IMG	LAS	MND	LTM	LAC	Cor	WDN	STN	RS_6	DCN	BTP	IMG	LAS	MND	LTM	LAC
F	T	T	T	F	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F	F	F
F	T	T	F	F	T	T	F	F	T	T	T	T	T	F	F	F	T	T	T	F	T
F	F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	F	F	F	F	T	F
T	T	T	F	F	T	T	F	F	F	T	T	T	T	F	T	T	T	T	T	T	T
F	F	T	F	F	F	F	T	T	F	T	F	T	F	T	F	F	T	T	T	T	T
F	F	T	T	F	F	F	T	T	T	F	F	F	F	F	F	F	F	F	F	F	F
F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	F	F	F	F	F	F	T
T	T	F	F	F	T	T	F	T	T	F	T	T	F	F	T	T	F	F	F	F	T
F	F	T	T	T	T	F	T	T	T	T	T	T	F	F	T	T	F	F	F	F	F
T	T	T	T	T	F	T	T	T	F	F	T	T	T	T	T	T	T	T	T	T	T
F	F	F	F	F	F	F	T	T	T	F	F	T	T	F	F	F	T	T	T	F	F
T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	F	F	F	T	F	F	F	F	T	F	F	T	F	T	F	F	T	T	T	T	T
T	T	F	T	F	T	T	F	F	T	F	T	T	F	F	T	T	F	F	F	F	F
F	F	T	T	F	F	F	F	F	T	T	T	T	T	F	F	T	F	F	F	F	F
F	T	T	T	F	T	T	T	T	T	F	T	T	F	F	T	T	F	F	F	F	T
T	F	F	F	F	F	F	F	F	F	T	T	T	T	T	F	T	T	T	T	T	T
F	T	F	T	F	T	T	T	T	F	F	T	F	F	F	T	T	F	F	F	T	T
F	T	F	F	F	F	F	T	T	F	F	F	F	F	F	F	F	F	F	F	T	F
F	T	F	F	T	T	T	T	T	T	F	T	T	F	F	T	T	F	F	F	F	F
F	T	T	F	F	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	T	T
F	F	T	T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	T	F	F	F	T	T	F	F	T	T	T	T	F	F	T	T	F	F	F	F	F
T	T	T	F	F	F	T	F	F	T	T	T	T	F	F	F	T	F	F	F	F	F
F	T	T	T	T	T	T	F	F	T	T	F	T	F	T	T	T	T	T	T	F	F
T	F	F	T	F	F	F	F	F	T	T	T	T	T	F	F	F	T	T	T	F	F

Table 6.14: Training set relative to consequences of spreading of the product following the truck tank piercing

RS_6	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA	RS_6	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA
T	T	T	T	T	T	T	T	T	T	F	T	F	T	F	F	F	T	F	F	F	T
F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F	F	F
F	T	T	F	F	T	T	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	F	T	T	F	F	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	T	T	F	F	T	F	F	F	F	F	F	F	F	F	F	T	F	F	F	T	F
F	T	F	T	F	T	T	F	F	F	F	F	F	F	T	F	T	F	F	F	T	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
F	F	T	T	T	T	F	F	F	T	F	F	T	F	T	F	F	T	F	F	F	F
T	T	T	T	F	T	T	T	T	T	F	T	T	F	F	F	T	T	F	F	F	T
F	T	T	T	F	F	F	T	F	F	F	F	T	F	F	F	T	T	F	F	F	F
F	T	T	F	T	F	T	T	T	T	F	F	F	F	F	F	T	F	F	F	F	F
F	F	T	F	T	F	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
F	F	T	T	T	T	F	F	F	T	F	F	T	F	T	F	F	T	F	F	F	F
T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	F	F	F	T	F	F	T
F	F	F	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F	F	F
F	F	T	T	F	T	T	T	F	F	F	F	F	T	F	F	T	F	T	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	T	T	T	F	F	F	T	F	F	F
F	T	F	F	T	T	F	F	F	T	T	F	F	T	F	F	F	F	F	F	F	F
F	F	T	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	F
F	F	T	T	F	T	F	T	F	F	F	F	F	F	T	T	T	F	F	F	T	F
F	T	T	T	F	F	F	T	F	F	F	F	T	F	T	F	T	T	F	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F
F	F	T	T	T	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	F	T	T	T	T	T	T
T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	F	F	F	T	F	F	T
F	F	F	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
F	F	F	F	F	T	F	F	F	T	F	F	T	F	F	F	T	T	F	F	F	F

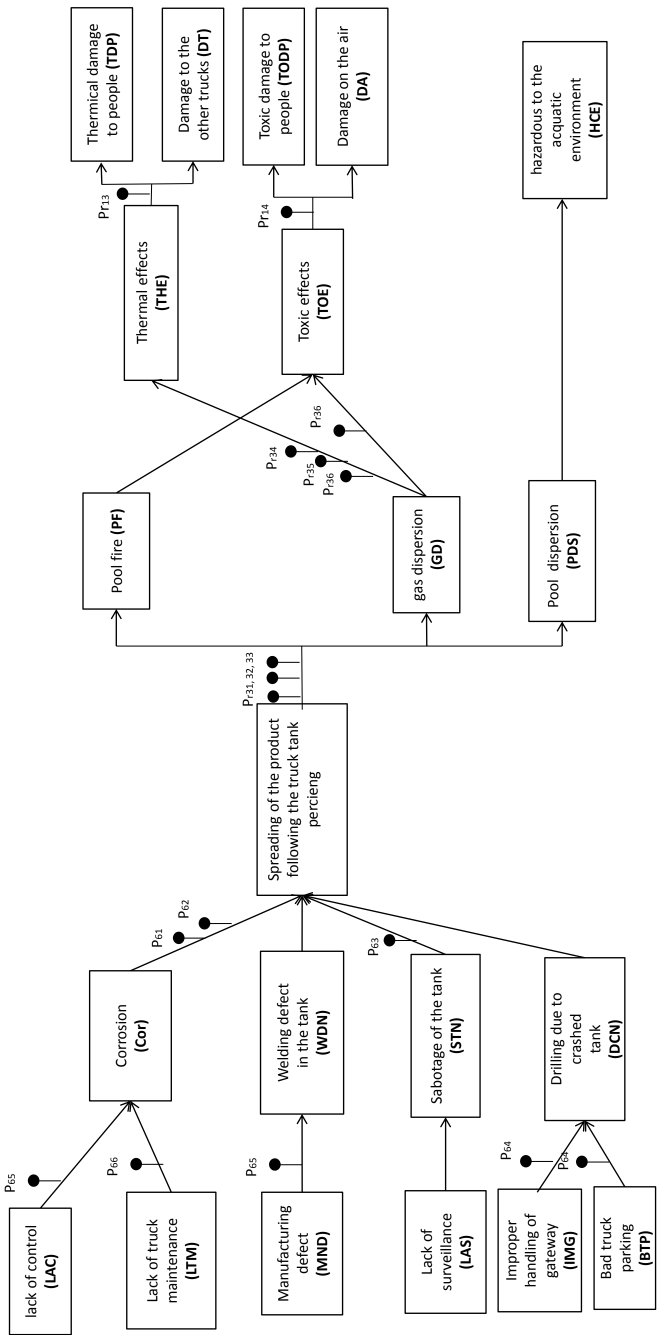

Figure 6.7: Bow tie diagram relative to a spreading of the product following the truck tank piercing

Table 6.15: Training set relative to causes of spreading due to the loss of a tank truck

CAF	LAC	LTM	WDN	MND	STN	LAS	VT	FOS	RS_7	CAF	LAC	LTM	WDN	MND	STN	LAS	VT	FOS	RS_7
F	T	T	T	F	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F
F	T	T	F	F	T	T	F	F	T	T	T	T	T	F	F	F	T	T	T
F	F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	F	F	F	F
T	T	T	F	F	T	T	F	F	F	T	T	T	T	F	T	T	T	T	T
F	F	T	F	F	F	F	T	T	F	T	F	T	F	T	F	F	T	T	T
F	F	T	T	F	F	F	T	T	T	F	F	F	F	F	F	F	F	F	F
F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	F	F	F	F	F
T	T	F	F	F	T	T	F	T	T	F	T	T	F	F	T	T	F	F	F
F	F	T	T	T	T	F	T	T	T	T	T	T	F	F	T	T	F	F	F
T	T	T	T	T	F	T	T	T	F	F	T	T	T	T	T	T	T	T	T
F	F	F	F	F	F	F	T	T	T	F	F	T	T	F	F	F	T	T	T
T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	F	F	F	T	F	F	F	F	T	F	F	T	F	T	F	F	T	T	T
T	T	F	T	F	T	T	F	F	T	F	T	T	F	F	T	T	F	F	F
F	F	T	T	F	F	F	F	F	T	T	T	T	T	F	F	T	F	F	F
F	T	T	T	F	T	T	T	T	T	F	T	T	F	F	T	T	F	F	F
T	F	F	F	F	F	F	F	F	F	T	T	T	T	T	F	T	T	T	T
F	T	F	T	F	T	T	T	T	F	F	T	F	F	F	T	T	F	F	F
F	T	F	F	F	F	F	T	T	F	F	F	F	F	F	F	F	F	F	F
F	T	F	F	T	T	T	T	T	T	F	T	T	F	F	T	T	F	F	F
F	T	T	F	F	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T
F	F	T	T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	T	F	F	F	T	T	F	F	T	T	T	T	F	F	T	T	F	F	F
T	T	T	F	F	F	T	F	F	T	T	T	T	F	F	F	T	F	F	F
F	T	T	T	T	T	T	F	F	T	T	F	T	F	T	T	T	T	T	T
T	F	F	T	F	F	F	F	F	T	T	T	T	T	F	F	F	T	T	T

Table 6.16: Training set relative to consequences of spreading due to the loss of a tank truck

RS_7	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA	RS_7	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA
F	F	T	T	T	T	F	F	F	T	F	F	T	F	T	F	F	T	F	F	F	F
T	T	T	T	F	T	T	T	T	T	F	T	T	F	F	F	T	T	F	F	F	T
F	T	T	T	F	F	F	T	F	F	F	F	T	F	F	F	T	T	F	F	F	F
F	T	T	F	T	F	T	T	T	T	F	F	F	F	F	F	T	F	F	F	F	F
F	F	T	F	T	F	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	F	T	F	T	F	F	F	T	F	F	F	T
F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F	F	F
F	T	T	F	F	T	T	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	F	T	T	F	F	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	T	T	F	F	T	F	F	F	F	F	F	F	F	F	F	T	F	F	F	T	F
F	T	F	T	F	T	T	F	F	F	F	F	F	F	T	F	T	F	F	F	T	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
F	F	T	T	T	T	F	F	F	T	F	F	T	F	T	F	F	T	F	F	F	F
T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	F	F	F	T	F	F	T
F	F	F	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F	F	F
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F	T	F	T	F	F	T	F	F	F	F	F	T	T	T	F	F	F	T	F	F	F
F	T	F	F	T	T	F	F	F	T	T	F	F	T	F	F	F	F	F	F	F	F
F	F	T	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	F	F	F	T	F	F	T
F	F	F	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
F	F	F	F	F	T	F	F	F	T	F	F	T	F	F	F	T	T	F	F	F	F
F	F	T	T	F	T	F	T	F	F	F	F	F	F	T	T	T	F	F	F	T	F
F	T	T	T	F	F	F	T	F	F	F	F	T	F	T	F	T	T	F	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F
F	F	T	T	T	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	F	T	T	T	T	T	T

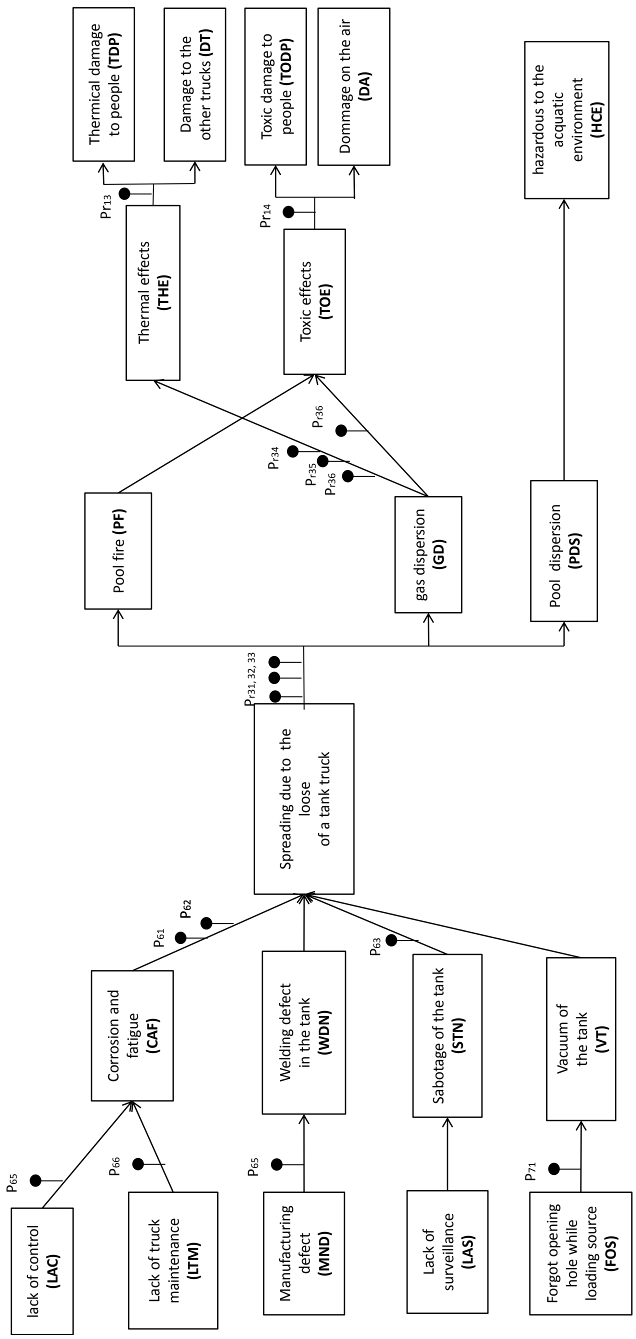


Figure 6.8: Bow tie diagram relative to a Spreading due to the loss of a tank truck

Table 6.17: Training set relative to causes of unconfined vapour cloud explosion (UVCE) following the gas leak

DTA	GO	RS_8	EF	CTP	TVF	HGL	SI	PS	MsE	DTA	GO	RS_8	EF	CTP	TVF	HGL	SI	PS	MsE
T	T	T	T	T	F	T	T	T	F	F	T	T	T	T	T	T	T	T	T
T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	F	T	T	T	T	F	T	T	T	T	T	T	F	F	T	T	F	F	F
F	F	F	F	T	F	F	F	F	T	F	F	T	F	T	F	F	T	T	T
T	T	F	T	F	T	T	F	F	T	F	T	T	F	F	T	T	F	F	F
F	F	T	T	F	F	F	F	F	T	T	T	T	T	F	F	T	F	F	F
F	T	T	T	F	T	T	T	T	T	F	T	T	F	F	T	T	F	F	F
F	T	T	F	F	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T
T	F	F	F	F	F	F	F	F	F	T	T	T	T	T	F	T	T	T	T
F	T	F	T	F	T	T	T	T	F	F	T	F	F	F	T	T	F	F	F
F	T	F	F	F	F	F	T	T	F	F	F	F	F	F	F	F	F	F	F
F	T	F	F	T	T	T	T	T	T	F	T	T	F	F	T	T	F	F	F
F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	F	F	F	F	F
F	F	T	T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
T	T	T	F	F	T	T	F	F	F	T	T	T	T	F	T	T	T	T	T
F	F	T	F	F	F	F	T	T	F	T	F	T	F	T	F	F	T	T	T
T	T	F	F	F	T	T	F	T	T	F	T	T	F	F	T	T	F	F	F
T	F	F	F	F	F	F	F	F	F	T	T	T	T	T	F	T	T	T	T
F	T	F	F	F	T	T	F	F	T	T	T	T	F	F	T	T	F	F	F
T	T	T	F	F	F	T	F	F	T	T	T	T	F	F	F	T	F	F	F
F	T	T	F	F	T	T	F	F	T	T	T	T	T	F	F	F	T	T	T
F	F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	F	F	F	F
F	T	T	T	T	T	T	F	F	T	T	F	T	F	T	T	T	T	T	T
T	F	F	T	F	F	F	F	F	T	T	T	T	T	F	F	F	T	T	T
F	T	T	T	F	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F
F	F	T	T	F	F	F	T	T	T	F	F	F	F	F	F	F	F	F	F

Table 6.18: Training set relative to consequences of unconfined vapour cloud explosion (UVCE) following the gas leak

RS_8	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA	RS_8	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA
F	F	T	T	T	T	F	F	F	T	F	F	T	F	T	F	F	T	F	F	F	F
T	T	T	T	F	T	T	T	T	T	F	T	T	F	F	F	T	T	F	F	F	T
F	T	T	T	F	F	F	T	F	F	F	F	T	F	F	F	T	T	F	F	F	F
F	T	T	F	T	F	T	T	T	T	F	F	F	F	F	F	T	F	F	F	F	F
F	F	T	F	T	F	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	F	T	F	T	F	F	F	T	F	F	F	T
F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F	F	F
F	T	T	F	F	T	T	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	F	T	T	F	F	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	T	T	F	F	T	F	F	F	F	F	F	F	F	F	F	T	F	F	F	T	F
F	T	F	T	F	T	T	F	F	F	F	F	F	F	T	F	T	F	F	F	T	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
F	F	T	T	T	T	F	F	F	T	F	F	T	F	T	F	F	T	F	F	F	F
T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	F	F	F	T	F	F	T
F	F	F	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F	F	F
F	F	T	T	F	T	T	T	F	F	F	F	F	T	F	F	T	F	T	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	T	T	T	F	F	F	T	F	F	F
F	T	F	F	T	T	F	F	F	T	T	F	F	T	F	F	F	F	F	F	F	F
F	F	T	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	F	F	F	T	F	F	T
F	F	F	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
F	F	F	F	F	T	F	F	F	T	F	F	T	F	F	F	T	T	F	F	F	F
F	F	T	T	F	T	F	T	F	F	F	F	F	F	T	T	T	F	F	F	T	F
F	T	T	T	F	F	F	T	F	F	F	F	T	F	T	F	T	T	F	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F
F	F	T	T	T	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	F	T	T	T	T	T	T

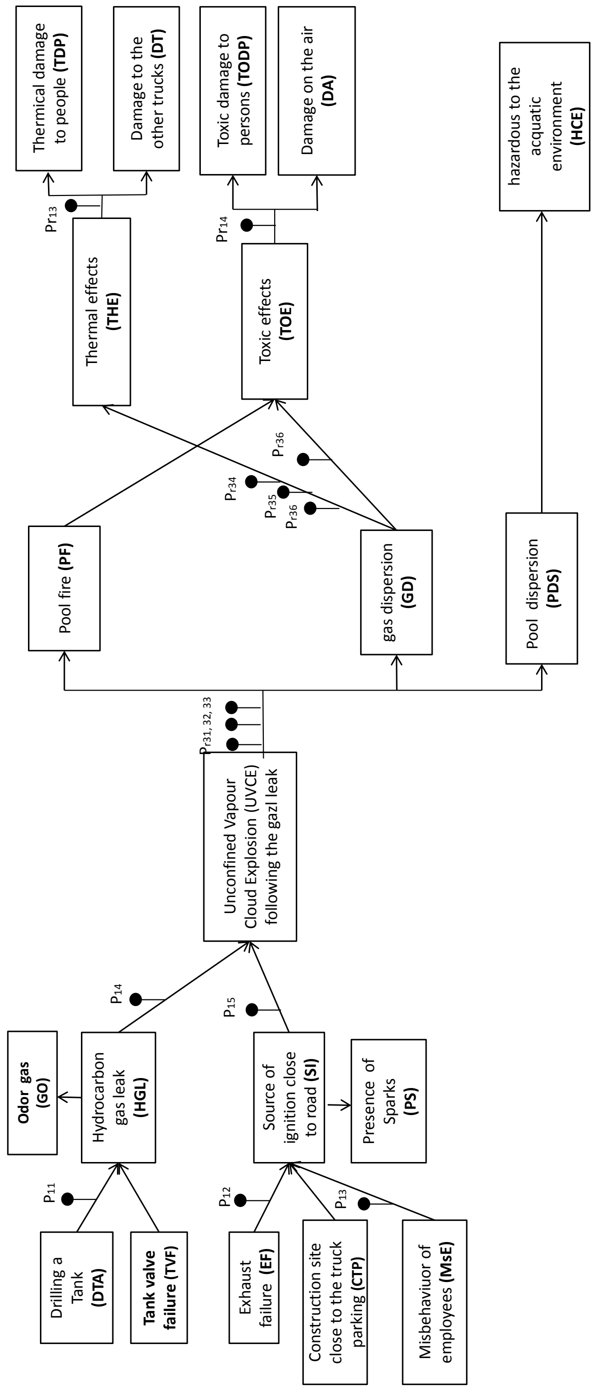


Figure 6.9: Bow tie diagram relative to an unconfined vapour cloud explosion (UVCE) following the gas leak

Table 6.19: Training set relative to causes of Break tank

RCS	EPH	RS_9	EWF	VP	DIP	CTP	TA	RCS	EPH	RS_9	EWF	VP	DIP	CTP	TA
T	T	T	T	T	F	T	T	T	F	F	T	T	F	T	T
T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
F	F	T	T	T	T	F	T	T	T	T	T	T	F	T	F
F	F	F	F	T	F	F	F	F	T	F	F	T	F	T	F
T	T	F	T	F	T	T	F	F	T	F	T	T	F	T	T
F	F	T	T	F	F	F	F	F	T	T	T	T	T	T	T
F	T	T	T	F	T	T	T	T	T	F	T	T	F	T	F
F	T	T	F	F	T	T	T	T	T	T	T	T	T	F	F
T	F	F	F	F	F	F	F	F	F	T	T	T	T	T	T
F	T	F	T	F	T	T	T	T	F	F	T	F	F	F	F
F	T	T	F	F	T	T	F	F	T	T	T	T	T	T	F
F	F	F	F	T	F	F	F	F	F	T	F	F	F	F	F
F	T	T	T	T	T	T	F	F	T	T	F	T	F	T	F
T	F	F	T	F	F	F	F	F	T	T	T	T	T	T	T
F	T	T	T	F	T	T	T	T	T	T	F	F	F	F	F
F	F	T	T	F	F	F	T	T	T	F	F	F	F	F	F
F	T	F	F	F	F	F	T	T	F	F	F	F	F	F	F
F	T	F	F	T	T	T	T	T	T	F	T	T	F	T	F
F	F	F	T	F	F	F	F	F	T	F	F	F	F	F	F
F	F	T	T	F	F	F	F	F	F	F	F	F	F	F	F
T	T	T	F	F	T	T	F	F	F	T	T	T	T	T	T
F	F	T	F	F	F	F	T	T	F	T	F	T	F	T	F
T	T	F	F	F	T	T	F	T	T	F	T	T	F	T	F
T	F	F	F	F	F	F	F	F	F	T	T	T	T	T	T
F	T	F	F	F	T	T	F	F	T	T	T	T	F	T	F
T	T	T	F	F	F	T	F	F	T	T	T	T	F	T	F

Table 6.20: Training set relative to consequences of Break tank

RS_9	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA	RS_9	PF	THE	TDP	DT	$TODP$	DT	TOE	GD	HCE	DA
F	F	T	T	T	T	F	F	F	T	F	F	T	F	T	F	F	T	F	F	F	F
T	T	T	T	F	T	T	T	T	T	F	T	T	F	F	F	T	T	F	F	F	T
F	T	T	T	F	F	F	T	F	F	F	F	T	F	F	F	T	T	F	F	F	F
F	T	T	F	T	F	T	T	T	T	F	F	F	F	F	F	T	F	F	F	F	F
F	F	T	F	T	F	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	F	T	F	T	F	F	F	T	F	F	F	T
F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F	F	F
F	T	T	F	F	T	T	F	F	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	F	T	T	F	F	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	T	T	F	F	T	F	F	F	F	F	F	F	F	F	F	T	F	F	F	T	F
F	T	F	T	F	T	T	F	F	F	F	F	F	F	T	F	T	F	F	F	T	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
F	F	T	T	T	T	F	F	F	T	F	F	T	F	T	F	F	T	F	F	F	F
T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	F	F	F	T	F	F	T
F	F	F	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T	F	F	F	F
F	F	T	T	F	T	T	T	F	F	F	F	F	T	F	F	T	F	T	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	T	T	T	F	F	F	T	F	F	F
F	T	F	F	T	T	F	F	F	T	T	F	F	T	F	F	F	F	F	F	F	F
F	F	T	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	F	F	F	T	F	F	T
F	F	F	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
F	F	F	F	F	T	F	F	F	T	F	F	T	F	F	F	T	T	F	F	F	F
F	F	T	T	F	T	F	T	F	F	F	F	F	F	T	T	T	F	F	F	T	F
F	T	T	T	F	F	F	T	F	F	F	F	T	F	T	F	T	T	F	F	F	F
F	T	F	T	F	F	T	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F
F	F	T	T	T	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	F	T	T	T	T	T	T

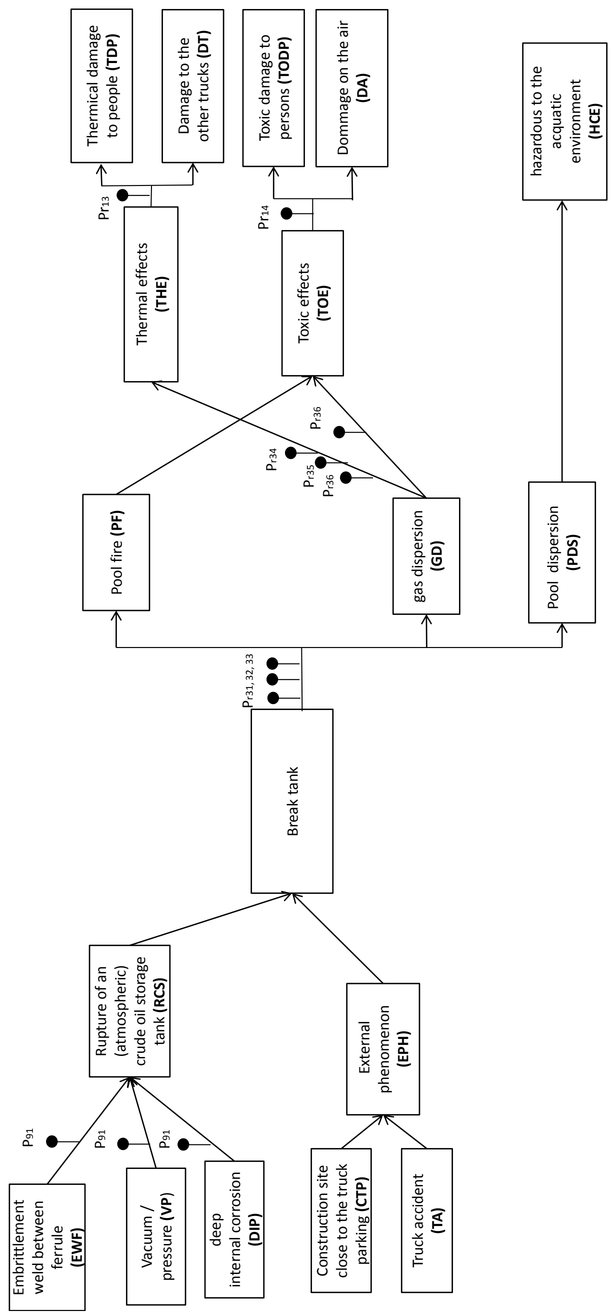


Figure 6.10: Bow tie diagram relative to a Break tank

Table 6.21: Training set relative to causes of a passage of product in the exhaust system of separator to the sea

RS_{10}	VFO	BV	STN	HER	LIS	LOT	LOF	LAS	RS_{10}	VFO	BV	STN	HER	LIS	LOT	LOF	LAS
T	T	F	F	F	T	F	F	T	F	T	F	F	T	F	F	F	F
T	T	T	T	F	T	T	T	T	T	F	T	T	F	F	F	T	T
F	T	T	T	F	F	F	T	F	F	F	F	T	F	F	F	T	T
T	F	T	T	T	T	F	F	F	F	F	F	T	F	F	F	F	F
F	F	T	F	T	F	F	F	T	T	F	F	F	T	F	F	F	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T
T	T	T	T	T	T	T	T	T	T	F	T	F	T	F	F	F	T
F	F	T	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T
F	T	T	F	F	T	T	F	F	F	F	F	T	T	F	F	F	T
T	F	F	F	F	F	F	F	F	T	T	F	T	F	T	F	F	F
F	T	T	F	F	T	F	F	F	F	F	F	F	F	F	F	T	F
F	T	F	T	F	T	T	F	F	F	F	F	F	F	T	F	T	F
F	F	T	T	F	F	F	T	F	F	T	F	T	T	T	F	T	T
F	F	T	T	T	T	F	F	F	T	F	F	T	F	T	F	F	T
T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	F	F	F
F	F	F	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F
F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	F	T	F
F	F	T	F	F	T	F	F	F	T	F	F	T	T	F	F	F	T
F	F	T	T	F	T	T	T	F	F	F	F	F	T	F	F	T	F
F	T	F	T	F	F	T	F	F	F	F	F	T	T	T	F	F	F
F	T	F	F	T	T	F	F	F	T	T	F	F	T	F	F	F	F
F	F	T	F	T	T	F	F	F	T	F	F	F	T	T	F	F	F
T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T
T	T	T	T	T	T	F	T	F	F	T	F	F	F	T	F	F	T
T	T	F	F	F	T	F	F	F	T	T	F	F	F	T	F	F	F
F	T	F	F	F	T	F	F	T	F	F	F	T	T	F	F	F	F
F	T	F	T	F	F	F	F	F	F	T	T	T	F	F	F	T	F
F	F	F	T	F	F	F	F	T	F	T	F	T	T	F	F	F	F
F	F	T	F	F	F	F	F	F	T	T	F	F	F	T	F	F	F
T	F	F	T	F	F	T	F	T	T	T	F	T	T	T	T	T	F
T	T	T	T	T	T	T	F	T	T	T	F	T	T	T	T	T	T

Table 6.22: Training set relative to consequences of a passage of product in the exhaust system of separator to the sea

RS_{10}	HCE	LD	PPS	RS_{10}	HCE	LD	PPS
T	T	F	F	F	T	F	F
F	T	T	F	F	F	T	T
F	F	T	F	F	F	T	T
T	F	T	T	T	T	F	F
F	F	T	F	T	F	F	F
F	F	T	T	F	F	F	T
T	T	T	T	T	T	T	T
F	F	T	F	F	F	F	F
F	F	T	F	F	T	F	F
F	T	T	F	F	T	T	F
T	F	F	F	F	F	F	F
F	T	T	F	F	T	F	F
F	T	F	T	F	T	T	F
F	F	T	T	F	F	F	T
F	F	T	T	T	T	F	F
T	T	T	T	T	T	T	T
F	F	F	F	T	T	F	F
F	F	F	F	F	F	T	F
F	F	T	F	F	T	F	F
F	F	T	T	F	T	T	T
F	T	F	T	F	F	T	F
F	T	F	F	T	T	F	F
F	F	T	F	T	T	F	F
T	T	T	T	T	T	T	T
T	T	T	T	T	T	F	T
T	T	F	F	F	T	F	F
F	T	F	F	F	T	F	F
F	T	F	T	F	F	F	F
F	F	F	T	F	F	F	F
F	F	T	F	F	F	F	F
T	F	F	T	F	F	T	F
T	T	T	T	T	T	T	F

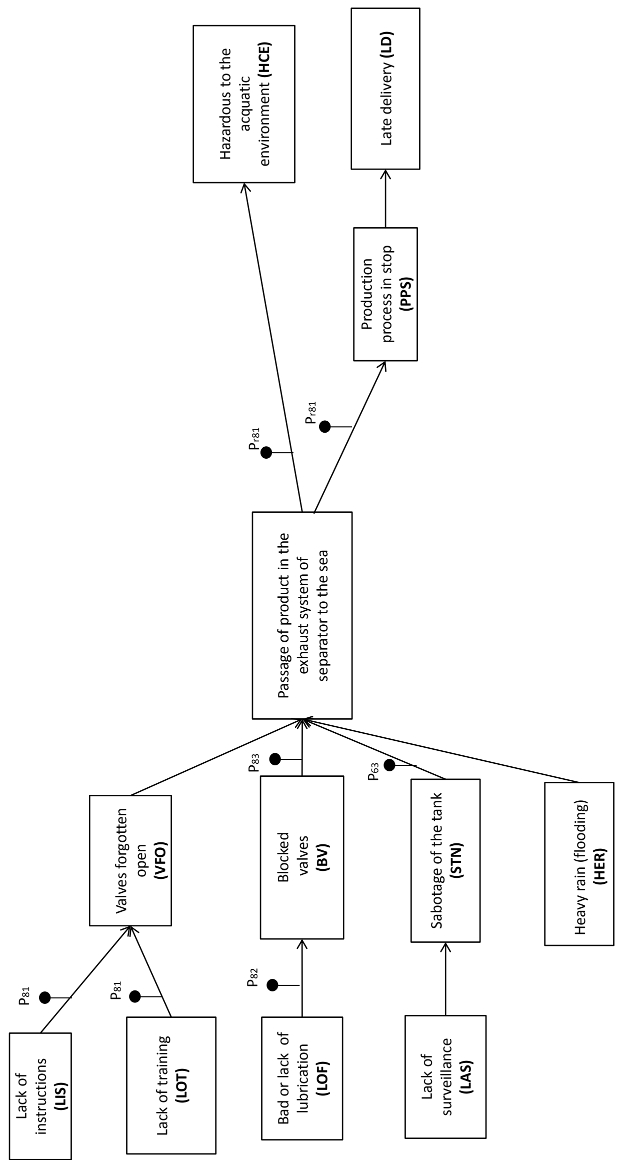


Figure 6.11: Bow tie diagram relative to a passage of product in the exhaust system of separator to the sea

Table 6.23: Selected preventive and protective barriers

Code	Preventive barriers	Code	Protective barriers
P_{11}	Education and Training Task to deal with HGL.	Pr_{11}	A fix or tractable canal to prevent incident along the site
P_{12}	Periodic preventive to minimize (SI).	Pr_{12}	Blast protection window film
P_{13}	Setting fire instruction.	Pr_{13}	Setting up equipments to limit the thermal effects.
P_{14}	Fire simulation.	Pr_{14}	Setting up equipments to limit the toxic effects
P_{15}	Prohibition to park the trucks close . the site after loading	Pr_{31}	Control of ignition sources
P_{21}	Successive training for reception and transfer operation.	Pr_{32}	hydrocarbon detector with alarm
P_{22}	Establish fire permit.	Pr_{33}	Retention basins and clarifiers
P_{31}	Enslavement of the motorized valve at high flow (NTH).	Pr_{34}	Plane Installation against fire
P_{32}	Establishment of a "Stop-pumping" system with an embedded indicator level.	Pr_{35}	Flame detectors
P_{33}	Formation and instructions.	Pr_{81}	Regular control of separator
P_{34}	Periodic Preventive Maintenance I.		
P_{41}	Speed limit and continued awareness of the traffic dangers.		
P_{42}	Driving training		
P_{43}	Trucks fitted with lights and horn		
P_{44} P_{45}	GPS Trucks and cars navigator Sanction procedures		
P_{46}	Calculation and compliance with driving hours		
P_{47}	study of risks circulation problems		
P_{61}	Control the truck state		
P_{62}	Periodic trucks audit		
P_{63}	Implementation of surveillance camera		
P_{64}	Instruction and training		
P_{65}	Quality control plan		
P_{66}	Maintenance of trucks		
P_{81}	Training and regular inspection of the settlers		
P_{82}	Implementation of a pressure relief valve		
P_{83}	implementation of motorized valve on the exhaust system		
P_{71}	Implementation of a pressure relief valve		
P_{91}	Periodic preventive maintenance for oil storage tank		

Table 6.24: Generated management plans

$Managementplan(A_i)$	Barriers
(A_1)	$P_{11}, P_{13}, Pr_{13}, P_{15}, P_{22}, Pr_{32}, P_{44}, P_{45}, P_{46}, P_{62}, P_{65}, P_{71}, P_{91}$
(A_2)	$P_{12}, Pr_{14}, Pr_{13}, P_{21}, P_{22}, Pr_{31}, P_{41}, P_{45}, P_{47}, P_{62}, P_{65}, P_{82}, P_{83}$
(A_3)	$P_{15}, Pr_{14}, Pr_{13}, P_{21}, P_{22}, Pr_{32}, P_{41}, P_{44}, P_{47}, P_{62}, P_{65}, P_{71}, P_{83}$
(A_4)	$P_{11}, P_{12}, P_{13}, Pr_{81}, P_{64}, P_{66}, P_{61}, Pr_{34}, Pr_{35}, P_{62}, P_{65}, P_{71}, P_{83}$
(A_5)	$P_{11}, Pr_{13}, P_{13}, Pr_{81}, P_{64}, P_{66}, Pr_{32}, P_{41}, Pr_{35}, P_{62}, P_{65}, P_{71}, P_{83}$

6.5 Definition of global management plan QSE

The inputs relative to this phase are:

- The sub-objectives $(SO_1, SO_2, SO_3, SO_4, SO_5, SO_6)$,
- The constructed bow tie diagrams $(BT_1, BT_2, BT_3, BT_4, BT_5, BT_6, BT_7, BT_8, BT_9, BT_{10})$.

From these inputs algorithms 4.1 and 4.2 generate the management plans $(A_1, A_2, A_3, A_4, A_5)$ illustrated in Table 6.24.

6.6 Proposition of a performance measurement system

The inputs relative to this phase are:

- The sub-objectives $(SO_1, SO_2, SO_3, SO_4, SO_5, SO_6)$,
- The selected risks $(RS_1, RS_2, RS_3, RS_4, RS_5, RS_6, RS_7, RS_8, RS_9, RS_{10})$,
- The defined management plans $(A_1, A_2, A_3, A_4, A_5)$.

From these inputs the performance relative to each QSE objective (O_1, O_2, O_3) given each management plan $(A_1, A_2, A_3, A_4, A_5)$ are obtained (see Table 6.25)

Table 6.25: Global satisfaction degrees relative to each management plan

	O_1	O_2	O_3
P^{A_1}	0.3629	0.456	0.4247
P^{A_2}	0.3708	0.548	0.389
P^{A_3}	0.68	0.224	0.570
P^{A_4}	0.47	0.3708	0.470
P^{A_5}	0.42	0.4708	0.476

Thus, according to Table 6.25, we can conclude that for O_1 the management plan A_3 is the best alternative followed by A_4, then A_5, then A_2 and finally A_1. For O_2 the management plan A_2 is the best alternative followed by A_5, then A_1, then A_4 and finally A_3. For O_3 the management plan A_3 is the best alternative followed by A_5, then A_4, then A_1 and finally A_2.

But which management plan is more appropriate to our QSE system? In fact, as shown in Table 6.25 each objective has its own preference, this is clearly a multi-objective problem. To this end, each calculated performance degree $P^A_{O_i}$ is compared to its corresponding satisfactory value S_{O_i}. This value represents the threshold value to be satisfied with a given objective. These comparisons are made using the subtraction operator between $P^A_{O_i}$ and it corresponding S_i which is noted ϵ_i^A (i.e. $\epsilon_i^A = P^A_{O_i}$ - S_i).

Let S_1=0.6, S_2=0.7 and S_3=0.55 be respectively the satisfactory value relative to O_1, O_2 and O_3. Table 6.26 illustrates the comparisons between each $P^A_{O_i}$ and its relative S_i. Finally, for each management plan, ϵ_i^A is aggregated using the sum operator $\sum_{i=1}^{3} \epsilon_i^A$.

Finally, the *min operator* is applied to select the most efficient management plan. Thus according to Table 6.26 we can conclude that the management plan A_3 is the most appropriate one.

Table 6.26: comparison between the desirable performance and the performance of each decision

Act_m	O_1	O_2	O_3	$\sum \epsilon^m$
ϵ^{A_1}	0.2371	0.244	0.1253	0.6064
ϵ^{A_2}	0.2292	0.152	0.161	0.5422
ϵ^{A_3}	-0.08	0.476	-0.02	0.376
ϵ^{A_4}	0.13	0.3292	0.1	0.5592
ϵ^{A_5}	0.18	0.2292	0.074	0.4832

6.7 Proposed tool to implement our process-based approach algorithms

In this section, the software tool implemented with Delphi 2010 and MATLAB R2010a is proposed. The main menu of our tool is illustrated in Figure 6.12. Now its different options will be explained.

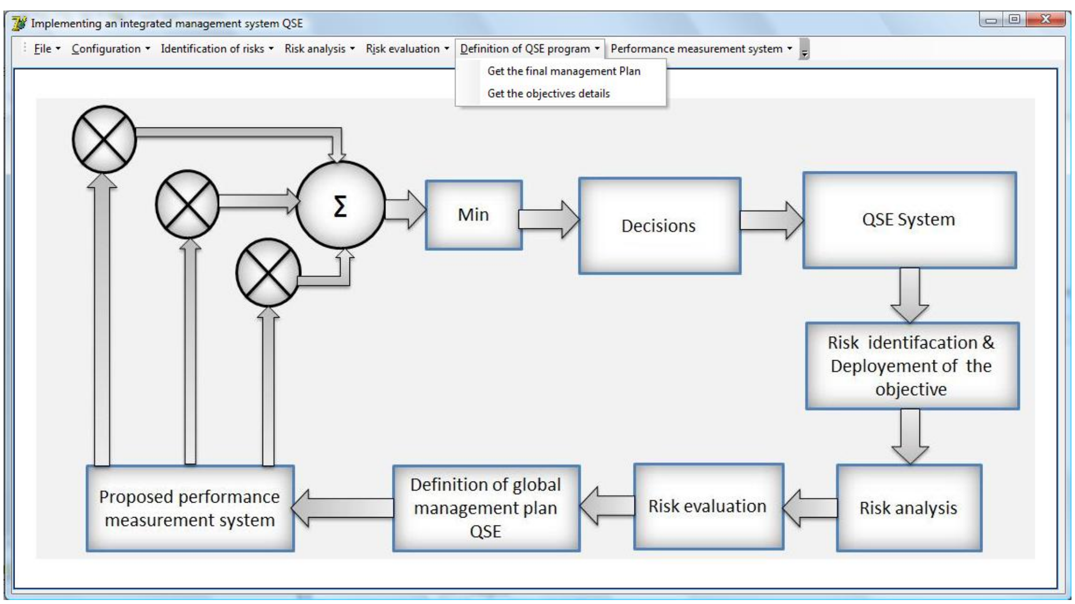


Figure 6.12: Main Menu

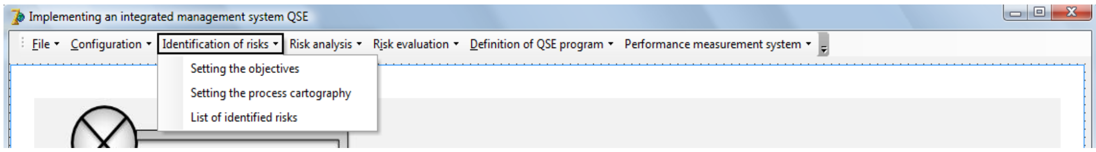


Figure 6.13: Risks identification option

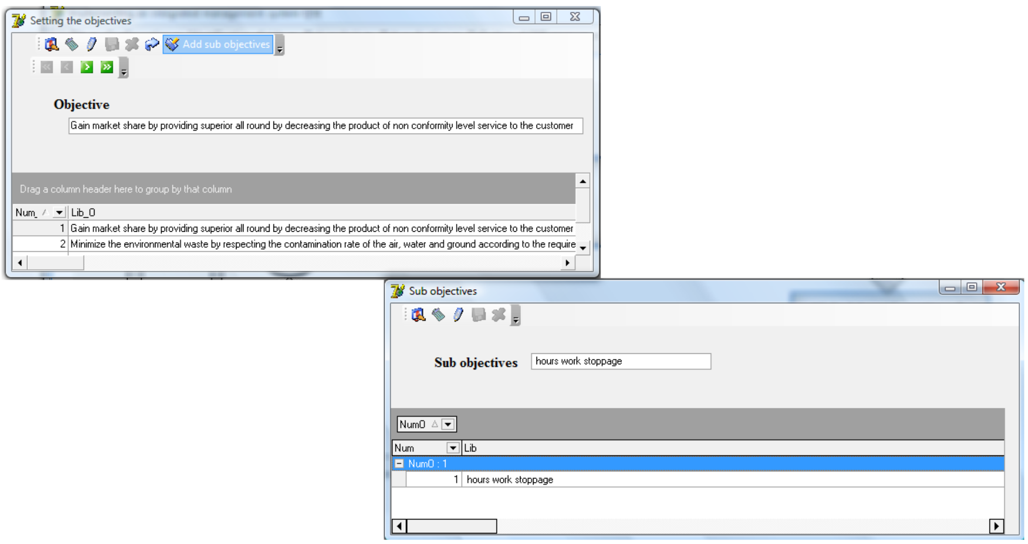


Figure 6.14: setting the strategic and tactical objectives

- Risk Identification

  This option (see Figure 6.13) allows to set the strategic and tactical objectives, set the process cartography and its related elements, display the identified risks.

  For instance, Figure 6.14 illustrates the principal frames set the strategic and tactical objectives.

- Risk analysis

  This option (see Figure 6.17) allows to set the RPN of each identified risk, define the Fuzzy system parameters, define the AHP parameters.

  For instance, Figure 6.16 illustrates the principal frame to measure fire in

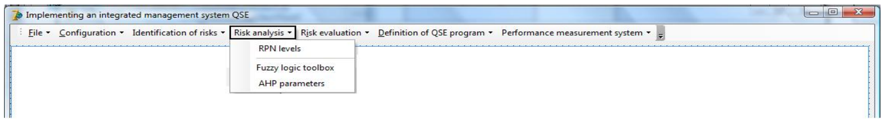


Figure 6.15: Risks analysis option

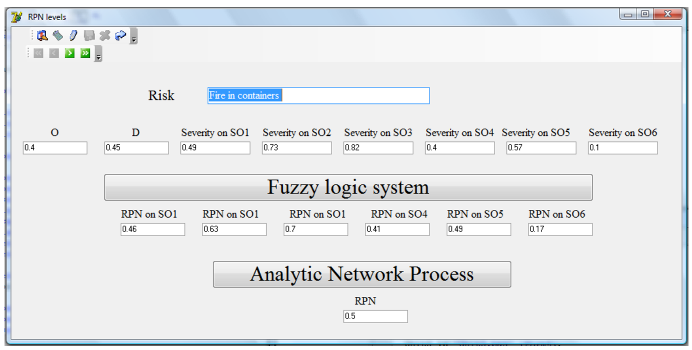


Figure 6.16: Measure of RPN value

container's RPN level.

- Risk evaluation

  This option (see Figure 6.17) allows to display bow ties structure constructed from training sets, calculate and display bow ties parameters, setting barriers.

  For instance, Figure 6.18 illustrates the principal frame to display bow tie diagrams

- Definition of QSE programs

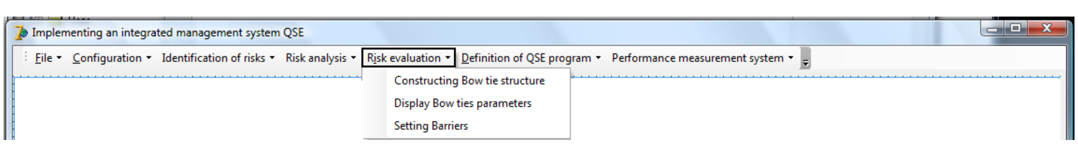


Figure 6.17: Risks evaluation option

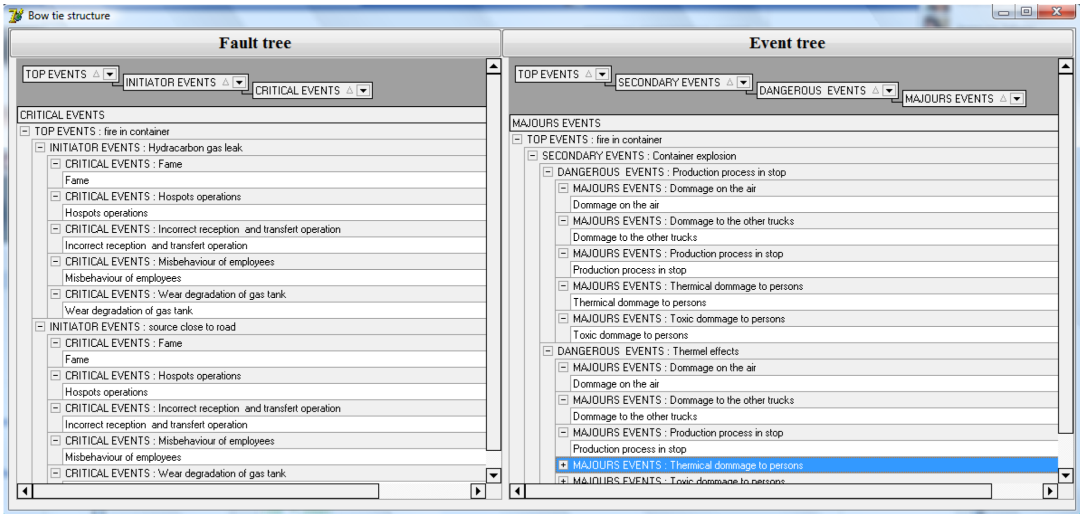


Figure 6.18: bow tie diagrams

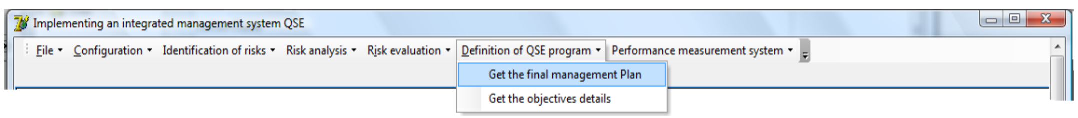


Figure 6.19: Definition of QSE program option

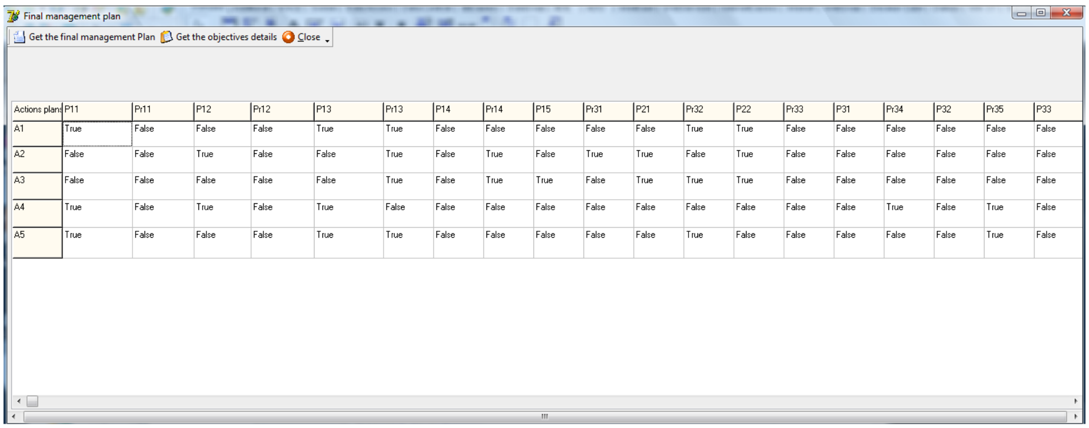
This option (see Figure 6.21) allows to display the final management plan, get the objectives details.

For instance, Figure 6.22 illustrates the principal frame to display the final management plan.

- Performance measurement system

This option (see Figure 6.21) allows to set performance structure, quantify the PMS, display management plan's performance, display selected management plan.

For instance, Figure 6.22 illustrates the principal frame to display the performances relative to each management plan.



Actions plans	P11	Pr11	P12	Pr12	P13	Pr13	P14	Pr14	P15	Pr31	P21	Pr32	P22	Pr33	P31	Pr34	P32	Pr35	P33
A1	True	False	False	False	True	True	False	False	False	False	False	True	True	False	False	False	False	False	False
A2	False	False	True	False	False	True	False	True	False	True	True	False	True	False	False	False	False	False	False
A3	False	False	False	False	False	True	False	True	True	False	True	True	True	False	False	False	False	False	False
A4	True	False	True	False	True	False	False	False	False	False	False	False	False	False	False	True	False	True	False
A5	True	False	False	False	True	True	False	False	False	False	False	True	False	False	False	False	False	True	False

Figure 6.20: Final management plan

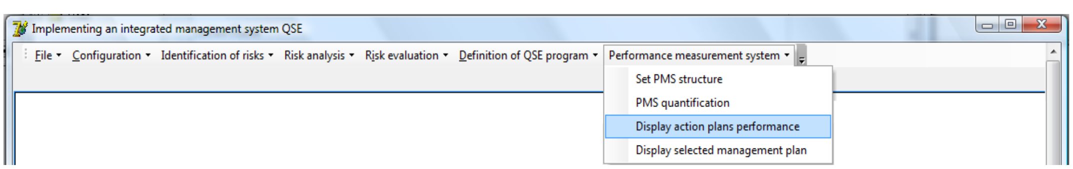
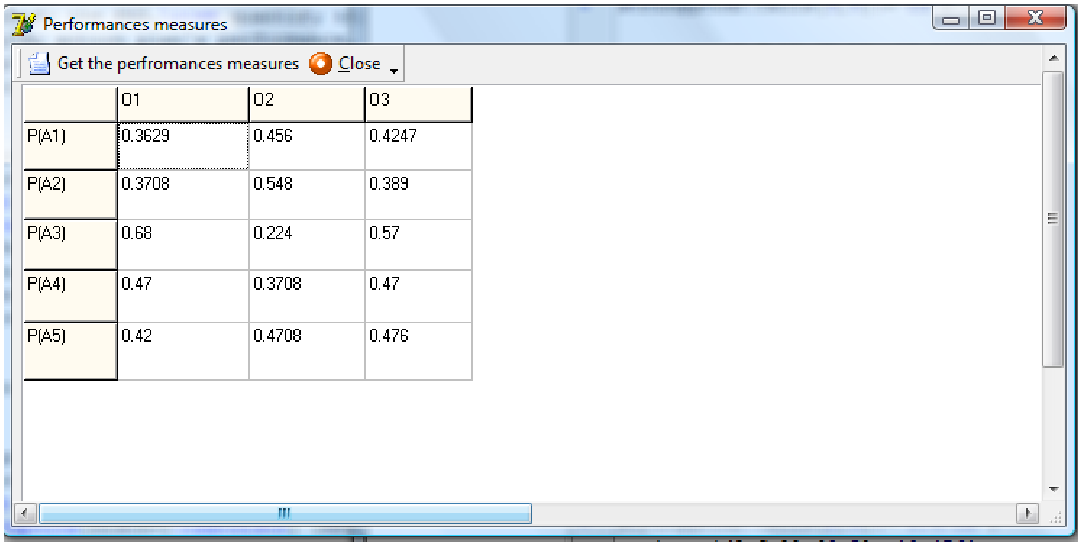


Figure 6.21: Performance measurement system option



	O1	O2	O3
P(A1)	0.3629	0.456	0.4247
P(A2)	0.3708	0.548	0.389
P(A3)	0.68	0.224	0.57
P(A4)	0.47	0.3708	0.47
P(A5)	0.42	0.4708	0.476

Figure 6.22: Performance relative to each management plan

6.8 Conclusion

In this chapter, an effective implementation of the proposed process-based approach for implementing an integrated Quality, Security and Environment management system is proposed.

Indeed, in the first part of this chapter, the implementation of the different phases of our process-based approach is illustrated in real case study released in the petroleum field in TOTAL TUNSIA company. In the second part of this chapter, our proposed tool to implement our process-based approach algorithms is presented.

General Conclusion

The main purpose of this thesis is to propose an integrated management system Quality, Security and Environment (QSE) that considers the interactions between these three systems. Indeed, the three international standards ISO 9001 [8], ISO 14001 *ISO 14001* and OHSAS 18001 [3] management systems relating to QSE management systems govern all management concepts and their implementation. Generally, The implementation of these standards is done separately which leads to a parallel management systems without any coordination and with several redundant procedures since the three standards (i.e. Quality, Security, Environment) share close management techniques and principles. Thus, the main objective of this thesis is the development of a new process-based approach for implementing an integrated management system: Quality, Security and Environment.

We first proposed, in Chapter 1, a global process-based approach for integrating the three management systems proposed QSE. Our approach overcomes the weakness of existing systems since it ensures a total integration of the three management systems by respecting the three levels of integration proposed by Jorgensen et al. [57] i.e. *correspondence*, *coordination* and *integration*. To satisfy these three levels, three integrating factors namely *risk management*, *process approach* and *monitoring system* are implemented around the PDCA (Plan, Do, Check, Act) scheme which is a standard ensuring the continuous improvement in quality systems [14, 16]. The proposed process-based approach have been recognized by the national Portuguese standard [45] to integrate the three management systems. In addition, our approach is under study by the International Organization for Standardization (ISO) to integrate a new international standard.

The second main contribution of this work concerns the proposition of an effective implementation of the three phases of our process-based approach. This can be summarized as follows:.

PLAN PHASE: to implement this phase, Chapter 2 proposes to deploy the different QSE objectives and to identify their related risks then to analyze them in order to select the most critical ones. To this end, a new approach extending the existing Fuzzy FMEA [19, 49, 91, 94] is proposed, named, multi-leveled fuzzy FMEA(MLF-FMEA). This approach allows us to analyze each identified risk regarding each QSE objective, then to select the most critical ones, a multi-criteria analysis is proposed using the Analytic Hierarchical Process method (AHP) [88]. Once the most critical risks are selected, Chapter 3 propose to evaluate them by construing their relative bow tie diagrams to assist the decision maker in order to define the appropriate treatments as preventive and corrective actions. To construct bow tie diagrams which reflect the real behaviour of studied systems, first, a learning algorithm is proposed to construct the whole scenario of each risk in an automatic way from real training sets. The principle of the proposed approach is to consider bow ties as particular Bayesian networks [81]. Then, a dynamic way to implement preventive and protective barriers is proposed. Our proposal is based on a statistical computation allowing us to have a realistic view of the system behavior and on the Analytic Hierarchical Process (AHP)[88] in order to take into consideration the different criteria selection [9, 10, 11].

Do PHASE: Once the whole scenario of each selected risk and its relative preventive and protective barriers are defined, Chapter 4 proposes an algorithm to transform the whole bow ties into a multi-objective influence diagram (MID) [74], which is one of the most commonly used graphical decision models. In fact, the evaluation of this graphical tool have allowed us to generate a set of optimal management plans satisfying the already defined QSE objectives [12, 13, 14].

Check and Act PHASE: Once the different management plans are carried out, Chapter 5 proposes to measure their effectiveness regarding the QSE objectives in order to select the most appropriate one. To this end, a performance measurement system (PMS) appropriate is designed to our process-based approach.

The proposed approach was illustrated on a real case study released in the petroleum field in TOTAL TUNSIA company using a software tool developed with Delphi 2010 and MATLAB R2010a.

An interesting future work is to propose an embedded system to implement some steps of our process-based approach. In fact, the identification and the analysis of risks can integrate a decision support system with integrated embedded components for monitoring and evaluation of risks such as wireless equipment, sensors, and programming components etc.

Another line of research is to use the possibility theory [103] rather than the probability theory in risk management process. In fact, this latter is only appropriate when all numerical data are available which not always possible. In fact, possibility theory offers a natural and a simple model to handle uncertain information. It is an appropriate framework for experts to express their opinions about uncertainty numerically using possibility degrees or qualitatively using total pre-order on the universe of discourse.

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