**Mafalda Palma da Silva Viola Parreira Rocha**

Licenciada em Ciências da Engenharia e Gestão Industrial

# Risk of Employing an Evolvable Production System

Dissertação para obtenção do Grau de Mestre em Engenharia e Gestão Industrial

Orientador: António Carlos Bárbara Grilo, Professor Doutor, FCT-UNL
Coorientador: Javad Jassbi, Doutor, UNINOVA

Júri:

Presidente: Prof. Doutor Rogério Salema Puga Leal
Arguente(s): Prof. Doutor José Barata de Oliveira
Vogal(ais): Prof. Doutor António Carlos Bárbara Grilo

FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

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**Mafalda Palma da Silva Viola Parreira Rocha**

Graduate in Management and Industrial Engineering Science

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Dissertation for obtaining the Master's degree in Management and Industrial Engineering

Supervisor: António Carlos Bárbara Grilo, Professor PhD FCT-UNL
Co-supervisor: Javad Jassbi, PhD, UNINOVA

Evaluation Board:

President: Prof. Doutor Rogério Salema Puga Leal
Opponents: Prof. Doutor José Barata de Oliveira
Member(s): Prof. Doutor António Carlos Bárbara Grilo

FACULDADE DE CIÊNCIAS E TECNOLOGIA
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## Risk of Employing an Evolvable Production System

*To my parents, brother and André…*

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# Resumo

Presentemente as empresas estão a enfrentar grandes desafios devido à grande imprevisibilidade dos mercados. Desta forma estas necessitam de se manter na vanguarda da inovação, oferecendo produtos com novos tipos de características. Existem algumas estratégias e soluções desenvolvidas para diferentes níveis desde a estratégica à operacional. Ao nível operacional tem-se verificado um grande desenvolvimento no passado recente devido à constante evolução da tecnologia, mais especificamente nos sistemas de manufatura. Desta maneira, as empresas precisam de se adaptar aos paradigmas emergentes que geralmente, são de difícil implementação.

Um sistema ágil de manufatura poderá ser aplicado às empresas de forma a permitir que estas possam lidar com as constantes mudanças verificadas nos mercados. Assim sendo, os sistemas evolutivos de produção constituem um novo e emergente paradigma que oferece aos sistemas de manufatura a capacidade para lidar com estas mudanças. Este paradigma introduz o conceito de modularidade ao nível do chão de fábrica, oferecendo aos sistemas flexibilidade e dinâmica, recorrendo à constante evolução dos dispositivos de controlo. Esta nova abordagem fornece às companhias a possibilidade de alterar os seus sistemas de manufatura de forma rápida e sem paragens, adicionando e removendo componentes durante a execução e sem reprogramação. As vantagens e benefícios associados à sua utilização são conhecidos mas a sua aplicabilidade continua a ser bastante questionada. A maioria dos investigadores responsáveis pelo desenvolvimento desta abordagem estão maioritariamente focados na componente técnica, identificando as vantagens destes sistemas mas não analisando o risco associado à sua implementação de diferentes perspetivas, incluindo os responsáveis pelos sistemas de produção.

O principal objetivo deste trabalho é o desenvolvimento de uma metodologia e modelo capazes de identificar, classificar e quantificar o risco potencial associado à implementação de um sistema com estas características. De forma a quantificar o modelo proposto, um sistema inteligente de decisão foi desenvolvido um sistema de inferência difusa, para tratar a informação recolhida dos peritos, como não existem dados históricos sobre este tópico. O resultado constitui a avaliação de vulnerabilidades de implementar um sistema EPS nos fabricantes, com foco nas pequenas e médias empresas.

A presente dissertação fez uso do conhecimento e experiência de vários peritos envolvidos no projeto FP7 IDEAS, que foi considerado um caso de sucesso no desenvolvimento e investigação de sistemas desta natureza.

*Palavras-Chave: Sistemas Emergentes de Manufatura, Fatores de Risco, Sistema de Inferência Difuso, Análise de Vulnerabilidades*

# Abstract

Nowadays manufacturing companies are facing a more challenging environment due to the unpredictability of the markets in order to survive. Enterprises need to keep innovating and deliver products with new internal or external characteristics. There are strategies and solutions, to different organisational level from strategic to operational, when technology is growing faster in operational level, more specifically in manufacturing system. This means that companies have to deal with the changes of the emergent manufacturing systems while it can be expensive and not easy to be implement.

An agile manufacturing system can help to cope with the markets changeability. Evolvable Production Systems (EPS) is an emergent paradigm which aims to bring new solutions to deal with changeability. The proposed paradigm is characterised by modularity and intends to introduce high flexibility and dynamism at shop floor level through the use of the evolution of new computational devices and technology. This new approach brings to enterprises the ability to plug and unplug new devices and allowing fast reformulation of the production line without reprogramming. There is no doubt about the advantages and benefits of this emerging technology but the feasibility and applicability is still under questioned. Most researches in this area are focused on technical side, explaining the advantages of those systems while there are no sufficient works discussing the implementation risks from different perspective, including business owner.

The main objective of this work is to propose a methodology and model to identify, classify and measure potential risk associated with an implementation of this emergent paradigm. To quantify the proposed comprehensive risk model, an Intelligent Decision system is developed employing Fuzzy Inference System to deal with the knowledge of experts, as there are no historical data and sufficient research on this area. The result can be the vulnerability assessment of implementing EPS technology in manufacturing companies when the focus is more on SMEs.

The present dissertation used the experts' knowledge and experiences, who were involved in FP7 project IDEAS, which is one of the leading projects in this area.

*Keywords: Emergent Manufacturing Systems, Risk Factors, Fuzzy Inference System, Vulnerability Assessment*

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# Acronyms

| | |
|---|---|
| A | Ability to React |
| AI | Artificial Intelligence |
| AMS | Agile Manufacturing Systems |
| BMS | Bionic Manufacturing System |
| CI | Confidence Interval |
| EAS | Evolvable Assembly System |
| EPS | Evolvable Production System |
| EUPASS | Evolvable Ultra Precision Assembly Systems |
| FIS | Fuzzy Inference System |
| FMEA | Failure Mode, Effect Analysis |
| FMS | Flexible Manufacturing System |
| FTA | Fault Three Analysis |
| HMS | Holonic Manufacturing System |
| I | Impact of the Threat |
| IDEAS | Instantly Deployable Evolvable Assembly System |
| IS | Inference System |
| IT | Information Technology |
| MAS | Multiagent System |
| MF | Membership Function |
| P | Probability of Occur |
| P&P | Plug and Produce |
| PL | Production Line |
| PS | Production System |

| | |
|---|---|
| RA | Risk Assessment |
| RMS | Reconfigurable Manufacturing System |
| RPN | Risk Priority Number |
| SMEs | Small and Medium Enterprises |

# 1

# Introduction

## 1.1. Scope & Motivation

Over the years, manufacturing have been the foundation of strong and stable societies. Manufacturing has been designated as the mirror of developed and prosper societies, providing wealth to the population (Herrmann, Schmidt, Kurle, Blume, & Thiede, 2014). In Europe, according to EFFRA, in Factories of the Future – Multi-annual roadmap for the contractual PPP under Horizon 2020, in 2009 the sector employed 31 million persons and generated EUR 5 812 billions. This sector is responsible for 80% of the total exportations and contributes to 22.8% of employment rates (Commission, 2013).

Nevertheless, manufacturing enterprises face one of the most challenging times of the 21st century. Manufacturing companies are working on an unpredictable and uncertain environment whilst they have to deal with a more demanding society. This means they have to react continually to the request about the type and range of product that should be developed, the products lifespan and also the volume of each product according to the market expectation (R Frei, Ribeiro, Barata, & Semere, 2007). Despite this reality, according to Factories of the Future's Executive Summary, the European Commission believes that the manufacturing sector "is an indispensable element of the innovation chain" ((Commission, 2013)). This sector brings innovation not only to fabricate new products but to ease a new generation of technologies which enables the creation of new products. Enterprises need new solutions to cope with high volatile and unpredictable markets. Customers have high expectations towards new products. Customers are expecting more products with more specifications, more singularities and faster updates in the market but most of the companies, e.g. SMEs, cannot support the needed changes in the workshop level due to the limitation of current systems.

Evolvable Production System (EPS) paradigm is considered as a solution to tackle the challenges of Agile Manufacturing at workshop level. To make sure EPS could help enterprises to succeed, it is important to consider different points of view, mainly Technological and Managerial perspectives. From a Technological point of view, there are some successful prototypes, which approved EPS as a successful system to increase the ability and agility of manufacturing system, when there are some doubts about implementation strategy of such a new technology in workshops. This dissertation presents the results of a qualitative study that used an in-deep/multiple interview method when managers and specialists who are/were involved in related European projects were interviewed to identify the benefits and drawbacks of EPS and quantitative analysis to determine the solving order of the potential risks. The main goal is to understand what are the challenges of successful implementation of an EPS to assist manufacturing companies, in general, in their decision making process and to develop appropriate strategy in operational level. The work was advanced based on a closer look into project FP7 IDEAS (Ribeiro, Barata, Onori, et al., 2011). Project IDEAS aimed to develop an agent-based architecture to control the entire production Regardless of the differences, groups of experts involved in these two projects were interviewed, with both academic and industrial background.

Although the risk assessment is common to several areas, on manufacturing systems, this study concerns a stricter area. The majority of the risk assessment study, on the manufacturing systems, focus its attention on the problems resolution related with human hazards and/or with an already implemented process.

## 1.2. Objectives

The present dissertation focus the attention on the production systems paradigm evaluation gap. Most of the works focus their attention on two different aspects. First, the evaluation is done based on the evaluation of the already implemented process. Second, the evaluation is done according to the risk that a certain process represents to human.

**Research Question**

1. How to evaluate the risk of employing an Evolvable Production System based on a risk assessment method?
2. How to use experts' knowledge as a base to evaluate the risk of employing an Evolvable Production System?

**Hypothesis**

1. If the risk of employing an Evolvable Production System is evaluated based on the development of two models, a qualitative and a quantitative model based on experts' knowledge.
2. If the risk evaluation uses two fuzzy inference system to analyse the experts' answers, and prioritise their resolution.

The proposed dissertation main goal is to develop a structured gathering and analysis of the detected risks on the employment of an EPS. So, to achieve this goal, a methodology is developed. The proposed methodology presents a methodical approach to the gathering of risk factors. It is also presented a model that uses experts' evaluation and generates a risk level, according to the proposed methodology.

## 1.3. Methodology

The proposed methodology aims to create coherent and consistent method of approaching the challenges of employing an EPS in a real manufacturing environment. This work is organised as presented in Figure 1.1.

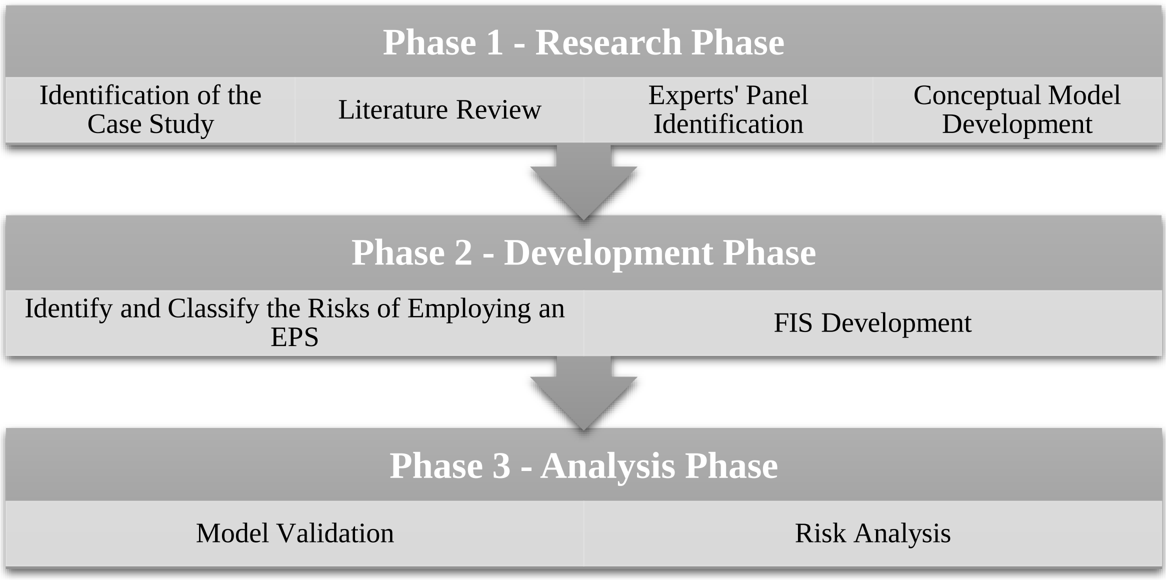



Figure 1.1 – Methodology’s process

On the research phase the case study selection is the base of the work presented in this dissertation, because it is the base for every subsequent choice. The literature review is the first step towards the detection of the potential risks of employing an EPS. In the literature, some risks linked to the employment of this emergent technology, or a similar one, which should be considered, are presented, in some practical cases. The experts’ panel is also chosen in accordance with the case study. It is important to extract information from experts that are really close to the employment of this emergent technology. The first phase final stage is the development of the conceptual model.

The second phase has three major stages. The identification and classification of the risk by the experts’ panel, the knowledge extraction stage and the development of the Fuzzy Inference System (FIS). The risks’ identification and classification is done based on a brainstorm meeting with the chosen experts’ panel. The knowledge extraction is done using a questionnaire developed based on the risks, gathered on the experts’ panel meeting, and for the parameters evaluation. Finally, after gathering all the information, it is possible to develop the FIS.

The third phase includes two stages. The first stage is model’s validation where two methods are used, the extreme conditions’ test and the behavioural examination. The second stage is the risk level analysis, which is based on the quantitative model results, considering the experts consensus level.

## 1.4. Conceptual Model

The proposed risk assessment model, aims to analyse the risks that are identified by the experts’ panel. This model helps to analyse three risk parameters, the impact of threat to companies; the ability that a company has to efficiently react to that threat; and finally the occurrence probability. Each risk is evaluated by each expert. The combination of those three parameters, through the application of the adequate analysis method, generates a Risk Priority Number (RPN).

A FIS is developed to aggregate the three defined parameters. This method is used due to two factors, first the lack of statistical data and second the evaluation of the risk is done based on verbal information. The model results, the RPN, are defined by experts, so it is necessary to aggregate that information.

To aggregate the information the RPN, generated by the first model, are aggregated, so each risk factor is defined by a RPN average and a standard deviation. In order to determine the risk level a second model is developed. This model aggregates both inputs and generates the risk level based on the combination. Then, based on the risk level the risk factors are ranked.

## 1.5. Dissertation Structure

This dissertation is organised as follows. Chapter 2 presents the main research area of this dissertation. This chapter introduces the Evolvable Production Systems concept and presents it characteristics. Chapter 3 presents a study of the necessary methods to gather information about the existent risk of employing an EPS. The quantitative methods presented in this chapter allows the possibility of assess the risk through the extraction of the knowledge from experts in the area.

Chapter 4 presents the methodology used in this dissertation. This methodology is developed with the purpose of extracting the knowledge from experts and analysing it. Chapter 5 suggests a quantitative model, based on FIS to analyse the risks data extracted from experts and to rank them according to it priority.

Chapter 6 presents the case which is the main motivation of this research work. In this chapter the methodology and the model results are presented, with all risks prioritised. Finally Chapter 7 presents a brief conclusion regarding the objectives of this work and proposes some points to be developed as a further work.

# 2

# Emergent Manufacturing Systems

Nowadays, enterprises need new solutions to cope with high volatile and unpredictable markets. Customers have high expectations towards new products. They prefer customisable and unique product. Despite these requirements, enterprises aim to be competitive in the market by bringing new ideas and options. Although the imposed goals for enterprises, it is mandatory to elaborate a new financial and production strategy. Figure 2.1 illustrates the evolution of the business paradigm and the stages of manufacturing systems (Oliveira, 2003) since the beginning of the 20$^{th}$ century passed through the Craft Industry, Mass Production and at this very moment, companies are facing the Mass Customisation Era (Ribeiro & Barata, 2011).

Mass Customisation brought new challenges to companies all over the world. Enterprises need to reduce the delivery time, making it necessary to adapt the production systems to produce faster than ever imagined. At this moment, agility is the main goal for all SMEs benefiting opportunities in the market. Agile Manufacturing Systems (AMS) is described in (Gunasekaran, 1998, 1999) as “the capability to survive in a competitive environment of continuous and unexpected change by reacting quickly and effectively to changing market, driven by customers-designed products and services”.

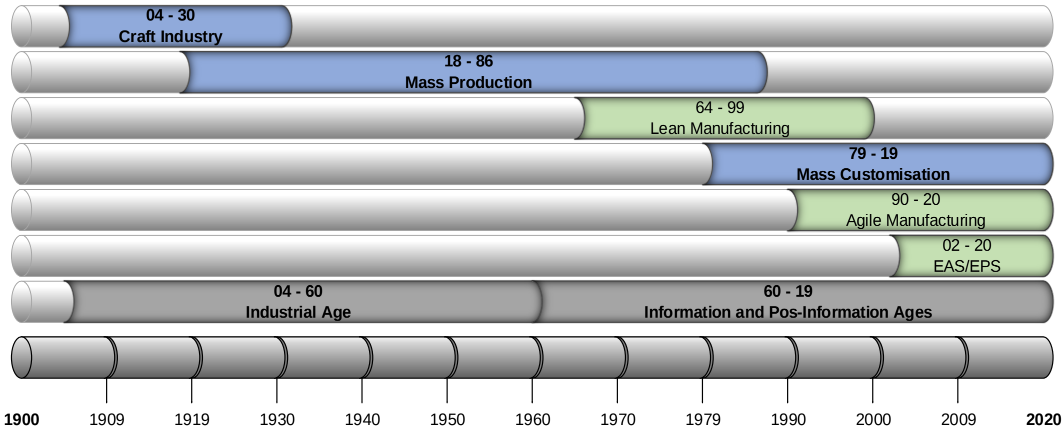



Figure 2.1 – Business paradigms

An AMS is responsible for several areas, from management to the Shop Floor (Oliveira, 2003). In order to implement this agility into a manufacturing environment, there are some new production paradigms that promise new approaches to control systems and resources used in the production of several products.

The new paradigms are: Flexible Manufacturing Systems (FMS) (El Maraghy, 2006; Elkins, Huang, & Alden, 2004), Holonic Manufacturing Systems (HMS) (Babiceanu & Chen, 2006; Gou, Luh, & Kyoya, 1997; Van Brussel, Wyns, Valckenaers, Bongaerts, & Peeters, 1998), Bionic Manufacturing Systems (BMS) (Ueda, 1992), Evolvable Assembly (EAS) (Regina Frei, Barata, & Onori, 2007; Mauro Onori, Barata, & Frei, 2006), Reconfigurable Manufacturing Systems (RMS) (El Maraghy, 2006; Koren et al., 1999; Mehrabi, Ulsoy, & Koren, 2000) and Evolvable Production Systems (EPS) (Ribeiro, Barata, Cândido, & Onori, 2010; Ribeiro, Barata, & Pimentao, 2011). In the following section, these new systems will be introduced.

## 2.1. Flexible Manufacturing Systems

According to literature, a Flexible Manufacturing Systems (FMS) paradigm is defined by the possibility offered to the system of sharing tools between different machines in order to increase the systems' ability to produce different products' variants. This ability allows increase the combinations between tolls and machines, raising the number of performed services provided by systems. All the machines are connected through a material handling system. Both, machines and material handling system, are controlled by a central system (El Maraghy, 2006; Elkins et al., 2004).

Although this is an approach used by several manufacturing systems there are still some issues that this paradigm cannot solve. The system self-organised, based on components, is the start point of the numerous approaches developed after the FMS improvement.

## 2.2. Holonic Manufacturing Systems

The Holonic Manufacturing Systems (HMS) appeared from the need for a paradigm that can help companies cope with markets unpredictability, low batches of products and mass customisation. The main idea of this paradigm is to create a highly dynamic and decentralised production systems. In other to implement this paradigm, there are being developed several holon-based architectures, such as PROSA (Van Brussel et al., 1998), ADACOR (Leitão & Restivo, 2006), and Rockwell Automation Agents (Vrba et al., 2011).

## 2.3. Bionic Manufacturing Systems

The Bionic Manufacturing Systems (BMS) are bio-inspired systems (Ueda, 1992). This paradigm is characterised by two ideas, hierarchy and self-organisation. BMS uses hierarchy similarly to the one founded in nature. This system is constantly changing information between each hierarchical layer, about it status in order to define a communication path. The other characteristic of this paradigm is the self-organised behaviour. This characteristic brings to the system a more autonomous management of the available resources (Ueda, 1992).

This paradigm is frequently used as the foundation for the development of the Multiagent Systems (further described in chapter 2.5.6), similarly to what happens with the HMS.

## 2.4. Reconfigurable Manufacturing Systems

The Reconfigurable Manufacturing Systems (RMS) paradigm has it main focus centred on the machine-tool reconfiguration. According to literature, although those systems are characterised by the use of numerous machines controlled by industrial controllers, the major contribution of this paradigm is focused on the reconfiguration of the pair machine-tool (Koren et al., 1999).

This paradigm has some similarities with the FMS paradigm, but they end in the point where RMS have the ability to facilitate the systems' reconfiguration through the addiction, removal or update of new components or machines into the system. In the literature it is possible to find more information about this systems (Galan, Racero, Eguia, & Garcia, 2007).

## 2.5. Evolvable Production Systems and Evolvable Assembly Systems

The Evolvable Production Systems (EPS) (Regina Frei et al., 2007; Neves & Barata, 2009; Ribeiro, Barata, & Pimentao, 2011) appeared in the beginning of the 21st century. This paradigm was developed to cope with the volatility of the human desires. This new approach aims to introduce agility, flexibility and a dynamic control system into Shop Floor environment. Those characteristics provide the system the ability of reconfiguration in run time. Products with short life cycles and rapid changeability of their characteristics are the main concerns which this paradigm has the goal to deal with.

The paradigm is characterised by numerous characteristics, and they are all interrelated in some way. The most striking characteristics of EPS are defined based on Emergence & Evolution, Self-Organisation, Pluggability, Fine Granularity, Process Oriented Modularity and Intelligent Systems. Those characteristics will be scrutinised in order to get an overview of the features which this paradigm leans on.

### 2.5.1. Emergence & Evolution

The term emergence is generated based on the phenomenon "where the global behaviour arises from the interaction between the local parts of the systems" (De Wolf & Holvoet, 2005). So, in order to a system to be considered emergent, there are some features that must exist, although different systems presents different emergent phenomena, all systems share common and interrelated properties which identifies them (De Wolf & Holvoet, 2005; Goldstein, 1999):

- "Radical novelty: emergents have features that are not previously observed in the complex system under observation. This novelty is the source of the claim that features of emergents are neither predictable nor deducible from lower or micro-level components. In other words, radically novel emergents are not able to be anticipated in their full richness before they actually show themselves."
- "Coherence or correlation: emergents appear as integrated wholes that tend to maintain some sense of identity over time. This coherence spans and correlates the separate lower-level components into a higher-level unity."
- "Global or macro level: since coherence represents a correlation that spans separate components, the locus of emergent phenomena occurs at a global or macro level, in contrast

to the micro-level locus of their components. Observation of emergents, therefore, is of their behaviour on this macro level.”

- “Dynamical: emergent phenomena are not pre-given wholes but arise as a complex system evolves over time. As a dynamical construct, emergence is associated with the arising of new attractors in dynamical systems (i.e., bifurcation).”
- “Ostensive: emergents are recognised by showing themselves, i.e., they are ostensively recognised. (…) Because of the nature of complex systems, each ostensive showing of emergent phenomena will be different to some degree from previous ones.”
- “Decentralised Control: Decentralised control is using only local mechanisms to influence the global behaviour. There is no central control, i.e. no single part of the system directs the macro-level behaviour. The actions of the parts are controllable. The whole is not directly controllable. This characteristic is a direct consequence of the radical novelty that is required for emergence. Centralised control is only possible if that central part of the system has a representation of the global behaviour (e.g. a plan).”
- “Robustness and Flexibility: The need for decentralised control and the fact that no single entity can have a representation of the global emergent, implies that such a single entity cannot be a single point of failure. Emergents are relatively insensitive to perturbations or errors. Increasing damage will decrease performance, but degradation will be ’graceful’: the quality of the output will decrease gradually, without sudden loss of function. The failure or replacement of a single entity will not cause a complete failure of the emergent. This flexibility makes that the individual entities can be replaced, yet the emergent structure can remain.”

Emergence and evolution are directly linked. The emergent paradigm bases it approach in features that offers to a systems the capability to evolve. The creation of new features with the combination of existing features and the dynamic behaviour, allows the system the ability to evolve according to new incoming requests.

### 2.5.2. Self-Organisation

According to (De Wolf & Holvoet, 2005) “Self-organisation is a dynamical and adaptive process where systems acquire and maintain structure themselves, without external control.”. The author refers ‘structure’ as any “spatial, temporal or functional structure”, and no ‘external control’ refers to “absence of direction, manipulation, interference, pressures or involvement” from foreign entities. This does not exclude input or output data, as long as those data does not have as purpose the control of the system. The term self-organisation has some important features that helps to understand the concept. Those features are: Increase in Order, Autonomy, Adaptability or Robustness with respect to Changes and Dynamical.

For a system, organisation can be seen as an increase, in the order of its behaviour, that gives it the capability to create a spatial, temporal or functional structure. In order to have this type of organisation the system need to be fully autonomous.

Autonomy is a concept necessary to explain the self-organisation of a system. A self-organised system does not have any external control, so in order for it to be fully autonomous, it should be able to control and install any device without external interference. Another very important part of autonomy concept is the notion of ‘boundary’. The systems boundaries must be clearly defined, making it necessary to differentiate the ‘inside’ from the ‘outside’.

For self-organising systems to cope with perturbations or changes, robustness is a required feature. For this type of systems, robustness is seen as a system that can adapt itself in presence of some entropy and maintain its organisation autonomously.

An essential property of self-organised system is a dynamic behaviour. In order to increase its order, adapt to changes and have an autonomous behaviour the system needs to be dynamic. This feature is considered from some authors ‘far-from-equilibrium’, which means a more fragile and sensitive system to changes in the environment, is more capable to react to new changes (De Wolf & Holvoet, 2005).

### 2.5.3. Pluggability

The ‘Plug and Produce (P&P)’ concept was an adaptation of the ‘Plug and Play’ performed for devices used in computing (Antzoulatos, Castro, Scrimieri, & Ratchev, 2014). In manufacturing, P&P aims to reduce the integration time between a new plugged resource and an already existent in the production line. Another characteristic of P&P is the ability of the system to plug a resource without human reconfiguration and without stoppages of the production.

### 2.5.4. Fine Granularity

The granularity of systems is measured by the extent of which the larger entity is subdivided. The analysis of the manufacturing system can be done in several levels, being the analysis of the system as a whole considered as a coarse granularity, where lots of important information does not rise into the higher level (Akillioglu & Onori, 2011). The EPS purpose is to perform a more detailed analysis of the production systems. So, it is necessary to reduce the granularity into a finer level such as the level of the component/device. At this level, it is possible to proceed to a more detailed analysis of the system and have a higher knowledge of the system’s problems. Each component/device is used as a module on the Shop Floor. Each module can be used and re-used in different locations, combined with other different modules offering several different topologies.

The granularity of a systems is measured by the extent of which the larger entity is subdivided, e.g., on Figure 2.2 is represented a manufacturing system. The analysis of the manufacturing system can be done in several levels, being the analysis of the system as a whole considered as a coarse granularity, where lots of important information does not arises into the higher level (Akillioglu & Onori, 2011).

EPS aim to make a more detailed analysis of the production systems, so to achieve that purpose it is necessary to reduce the granularity (Figure 2.2) into a finer one such as the level of the component/device. At this level is possible to proceed to a more detailed analysis of the system and have a higher knowledge of the system's problems.

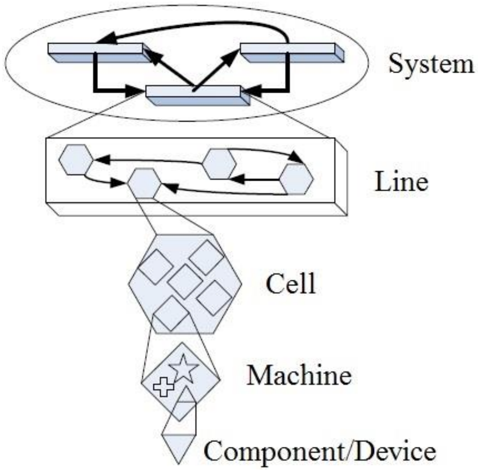


Figure 2.2 – Manufacturing Systems Levels (Akillioglu & Onori, 2011)

In this case (Figure 2.2) each component/device is used as a module on the Shop Floor. Each module can be used and re-used in different locations, combined other different modules offering several different topologies.

## 2.5.5. Process Oriented Granularity

In an EPS, the product is described as an instruction set. This set represents the skills that the product must perform in the system. The instruction set represents a process. In this sense, each module (component/device) is capable of offering the abilities to perform the previous instructions (Akillioglu & Onori, 2011). Each module is formed by two elements: the hardware (physical resource, a robot or an operator) and the controller. The controller is able to act and read all the different parameters provided by the hardware, using specific language. In the same controller, the intelligent entity is also running and it uses specific language to interact with the hardware. Thus, the higher level the entities are capable to act and read the hardware interfacing with native language of the hardware. This intelligent entity abstracts the resource and its skills, and informs the system about its existence and the skills that it will offer to the system. This approach allows a process-oriented behaviour.

### 2.5.6. Intelligence in the System

The intelligence given to an Evolvable Production Systems is achieved through the use of a Multiagent System (MAS). The MAS allows the systems to perform a self-analysis of not only the state of the tasks that must be carried out to produce the required product but also the state of the available skills to produce the final product. The MAS also allows a decentralised approach to the system. This technology is based on the use of distinct entities called agents. This agents' purpose is to abstract a resource or module, under its command. An agent is an autonomous entity capable to act and react to stimulus from the surrounding environment and they have some key characteristics, such as, proactivity, autonomy, reactivity and adaptability. Thus, the agent is capable to get information from the environment and based on it, the agent can decide and act to satisfy individual and global goals (Leitão, 2009).

## 2.6. Progress of Emergent Manufacturing Systems

The Mass Customisation era brings new challenges that companies are not ready to face. It is important to create new solutions for this new reality. According to the literature, the number of emergent manufacturing system is increasing with the goal of solve several emergent problems.

This path is initiated with the FMS with the purpose of offering the ability to be flexible, but the number of changes are increasing, so this paradigm cannot solve all the emergent problems. The design of the HMS, BMS, RMS, and finally EPS and EAS paradigms brought new solutions for problems like unpredictability of ordering, volume of production, among others.

The improvements of the BMS and HMS are mostly based on the development of new architectures and then those architectures are compared in order to see what are the differences and decide the next step (Regina Frei et al., 2007; Tharumarajah, 1996). On the contrary, FMS and RMS have now some implemented evidences of the paradigms capabilities, which are used to decide the path that should be followed (El Maraghy, 2006; Leitão, Barbosa, & Trentesaux, 2012). For FMS and RMS there are some developed studies towards the detection of challenges and points to improve the implementation quality of those paradigms (El Maraghy, 2006; Setchi & Lagos, 2004).

The EPS/EAS have a few implementations, and until now the followed path is decided according to the project results, instead of being decided according to the real needs (Antzoulatos et al., 2014; Ribeiro, Barata, Onori, et al., 2011). The first step towards this path is presented in the literature when are discussed the value proposition, and the cost characterisation and strategies for EPS (Maffei, Akillioglu, & Flores, 2013; Maffei, Neves, & Onori, 2013). But it is still a gap that need to be addressed, what should be the EPSs' next step? What should be improved in order to be commercialised? Those are the questions that this dissertation aims to provide some answers.

# 3

# Risk

*“**Risk** is a function of the **likelihood** of a given **threat-source**’s exercising a particular potential **vulnerability**, and the resulting **impact** of that adverse event on the organization.”* (Stoneburner, Goguen, & Feringa, 2002).

*“**Risk** includes the **likelihood** of conversion of that source into actual…**loss**, **injury** , or **some form of damage**.”* (Kaplan, Garrick, Kaplin, & Garrick, 1981).

## 3.1. Risk Concept

The risk definition was firstly defined as comprised of all known information. Although this was, initially, an interesting approach the concept started to be applied into several areas. So, the definition of risk started to change mostly due to it link to the area of study.

Although the risk definition has some particularities, according to the research area, the risk can be defined based on the combination of two key factors. Those two factors are the event’s probability and it undesirable or unexpected consequences (Aven, 2010; Kristensen, Aven, &

Ford, 2006). So the probability of the event and it severity define the risk (Zimmerman & Bier, 2010).

As can be seen in the previous definition, and for the majority of the cases, risk is seen from the negative point of view. Although, there are a few authors that present the risk as "an uncertain event or condition that, if it occurs, has a positive or negative effect" (Chapman & Ward, 1996; PMI, 2009; Young, 2013).

The authors also debate that any decision situation regarding "Risk", is always defined by a threat and an opportunity. So both perspectives need to be managed, i.e. focus the attention on one side does not mean that the other side should be neglected.

### 3.1.1. Risk Relation with Other Concepts

To fully understand the risk concept it is important analyse some correlated concepts, such as:

- Threat;
- Vulnerability;
- Uncertainty;
- Probability.

The first two concepts, the threat and the vulnerability, are related. The threat's definition is commonly expressed under the vulnerability perspective. According to the National Research Council (National Research Council, 2002), the concept of vulnerability is defined as "an error or a weakness in the design, implementation , or operation of a system". The same organisation defines the threat concept as "an adversity that is motivated to exploit a system vulnerability and capable of doing so,". So, the National Research Council also defines risk as "the likelihood that a vulnerability will be exploited, or that a threat may become harmful" according to the definition of both concept, threat and vulnerability.

The third concept is uncertainty. Every decision process is associated to a degree of uncertainty. The uncertainty of any event reflects the level of knowledge regarding a particular subject. So, the uncertainty degree is smaller as greater the knowledge, relevant to make a decision, about that particular subject (Holton, 2004; Willows, Reynard, Meadowcroft, & Connell, 2003).

As already mentioned, the likelihood, or the probability of an event occur is a key factor on the risk analysis. This is the fourth presented concept. According to several authors, it is possible define and give a value to a probability using a classical approach or making usage of a Bayesian approach, depending of the context and the type of data that we have to describe the probability

(Aven, 2010; Kristensen et al., 2006). Each event, in any case, has an associated probability to occur. From the statistical point of view, probability to occur defines a ratio between number of occurrences and the number of times where this event could occur.

In the classical way, based on the statistical approach, the risk is objectively defined as a parameter that can be measured. In this sense, the experts should calculate approximately the best value, based on data previously retrieved from occurrences of the event, hard data. If the measured event has infinity occurrences, the probability to occur represents the number of occurrences during a timeframe (Aven, 2010; Kristensen et al., 2006; Sutton, 2014).

When the objective is to measure the occurrences of an event where the probability is subjective, and with an associated uncertainty, the Bayesian approach is the most suitable one. In this case, and because of the uncertainty, the evaluation should be done based on experts' opinion. The experts should be chosen according to the subjects' experience and knowledge. With the knowledge and background, the experts are responsible to evaluate the risk and give the most indicated value which represents the probability to occur (Aven, 2010; Kristensen et al., 2006; Sutton, 2014).

### 3.1.2. Areas of the Risk Research and Practice

The risk concept, as already mentioned, is defined in accordance with the research area. Although the number of areas under analysis is growing, there are more areas to be analysed. Those research areas are:

- Economic risk;
- Health, safety and environment;
- Information technology and information security;
- Insurance;
- Business and management;
- Human services;
- High reliability organisations ;
- Finance;
- Security;
- Human factors;
- Psychology of risk taking;
- Maintenance.

The presented areas are already being developed, and several studies are done. This dissertation proposes a new research area, the risk of implementing an emergent manufacturing paradigm, where the risk analysis methodology can adapted and implemented. Although, in order to implement any risk methodology, it is important to analyse the options.

## 3.2. Risk Assessment and Risk Management

*"**Risk assessment** is a means to characterize and reduce uncertainty to support our ability to deal with catastrophe through **risk management**."* (Zimmerman & Bier, 2010)

In the beginning of the risk analysis formulations, risk assessment and risk management were defined as two totally separate functions, in terms of it regulation (National Research Council, 1983). The regulatory agencies took steps, over time, to define a flawless distinction between both concepts. Which means the scientific discoveries should not be influenced by factors, such as, political, economic or technical considerations (Zimmerman & Bier, 2010). However both concepts should not be separated with respect to risk analysis implementation.

Nevertheless, over time new concepts emerge in the risk analysis. Environmental sociology and social psychology started to introduce both ideas in the risk assessment, the risk perception and the risk communication. Those two concepts strongly influenced the risk assessment‘s nature. In the end of the $20^{th}$ century, the two processes, the risk assessment and management were officially merged (Zimmerman, 1998).

In order to understand the relation between both concepts, and how they interact, it is desirable analyse them under the systems' perspective. On the systems' standpoint both concepts, risk assessment and risk management boundaries are seen as flexible and both concepts complement each other (Zimmerman & Bier, 2010). Analysing Figure 3.1, it is possible to understand this complementarity.

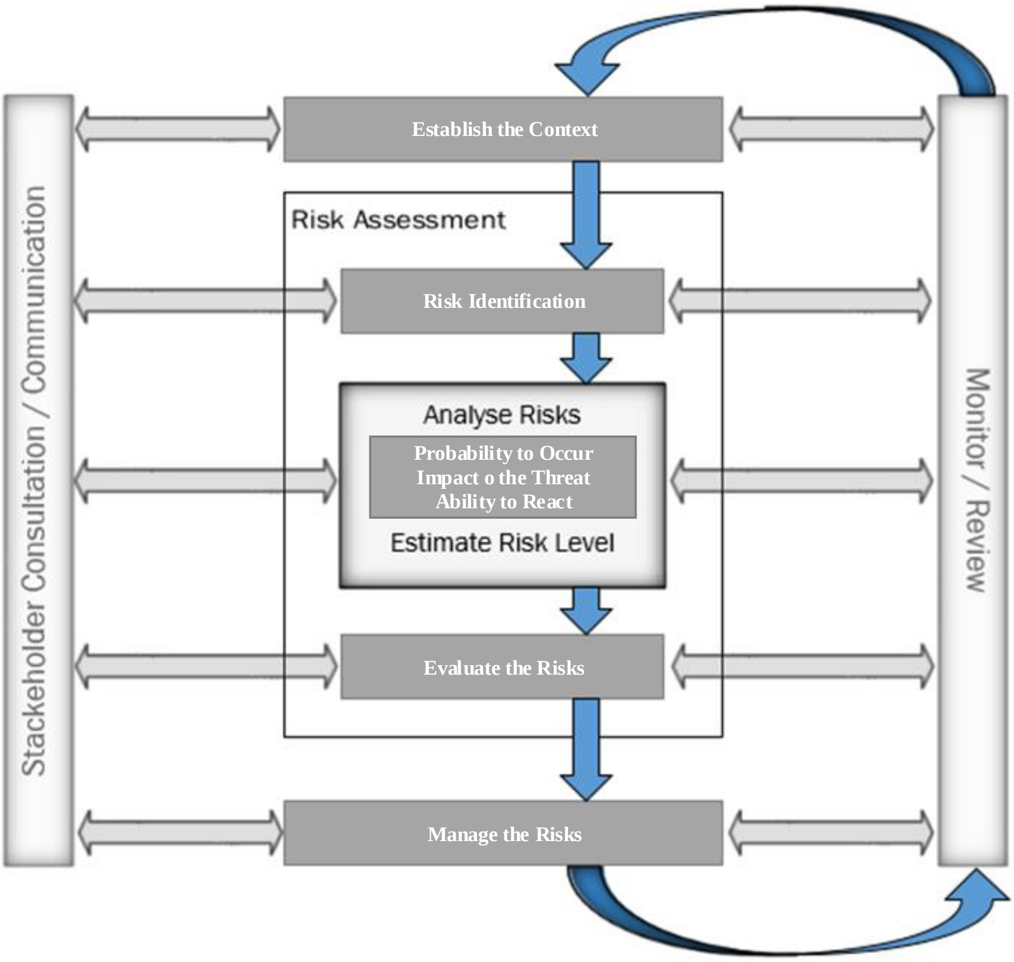



Figure 3.1 – Risk assessment and risk management processes adapted from (Bitaraf, 2011)

The approach presented in Figure 3.1, aims to embrace all the entities in the risk analysis, i.e., aims to involve not only the risk analysis' specialists, but also the stakeholders in the process. The adopted risk management process is iterative, composed by six different stages in a loop. So, in more detail, the risk assessment and risk management processes follow the stages (Bitaraf, 2011):

- **Establish the context: T**he context definition means the definition of objectives, suitable decision criteria and the risk assessment program. Those factors need to be approved by the stakeholders;
- **Risk Identification:** Where all the possible risks are identified and selected, in order to be evaluated and managed;
- **Analyse of Risks:** In this stage, all the previously selected risks are analysed, in order to understand how they can be evaluated;

- **Evaluation of the Risks:** This constitutes the last stage in the Risk Assessment part. In this stage the evaluation of the risks is done and as result of this stage is possible collect the values that results from the usage of the model;
- **Manage the Risks:** the last process stage is the definition of a strategy to manage the risks.

During all stages, the stakeholders and the reviewers are invited to give feedback. Both external entities are defined according to (Bitaraf, 2011):

- **Stakeholders Consultation/Communication:** In the process of risk management, stakeholders need to be an active part in the entire process. They should be informed of all process' progresses;
- **Monitor / Review:** During all the stages, to ensure the process success, a reviewer should monitor the steps. This step is important in order to guarantee it correct evolution and to avoid unexpected/undesired evolutions. In the last stages it is important to define a different type of monitoring process, i.e., a monitoring which allows the review to understand if it is relevant to do one more iteration, or on the contrary, the process should end.

The risk assessment methods can be defined as:

- Qualitative ;
- Quantitative.

The qualitative risk analysis uses adjective to help to describe the system. This type of method is less efficient in the provide information than the Quantitative Risk Analysis method. On the other hand the Quantitative Risk Analysis method uses mathematical or statistical methods to describe the risk. This type of method makes use of numerical values to assign to risk components in order to determine the risk management process. (Wawrzyniak, 2006).

To assess risk two techniques are widely used (Kales, 1998):

- Fault Tree Analysis (FTA);
- Failure Modes and Effects Analysis (FMEA).

On this dissertation case the three variables under analysis, the probability of occurrence, the impact of the threat and the ability to react need to be analysed together. So, the most suitable technique, although with some adaptations, is the FMEA.

# 3.3. Failure Modes and Effects Analysis

## 3.3.1. Failures Mode and Effects Analysis Applications

Managers and engineers work in a constant base to minimise or even eradicate the risk in projects, processes and/or services. (Stamatis, 2003). Since the beginning of the use of this methodology, it has been applied to several areas such as processes, services, projects, systems and equipment, etc. In order to address different problem, in different areas and with so many requirements, there are three distinct FMEA approaches:

- Systems Failures Mode and Effects Analysis;
- Process Failures Mode and Effects Analysis;
- Design Failures Mode and Effects Analysis.

This differentiation is only made to better address a specific problem in each area.

## 3.3.2. Failures Mode and Effects Analysis Methodology

### 3.3.2.1. Failures Mode and Effects Analysis – Implementation Steps

The FMEA methodology is defined by the following steps:

- Definition of case study;
- Set a multidisciplinary experts group;
- Identify the potential failure modes;
- Identify the effects;
- Identify the cause of the failure.

To help with the methodology are usually used four support tools (Pereira & Requeijo, 2008). Those are:

- Flowcharts;
- Brainstorming;
- Tree diagrams;
- Control plan.

Those support tools contributes to better illustrate the risk analysis processes.

#### 3.3.2.2. Risk Assessment and Classification

To prioritise the risk it is used the Risk Priority Number (RPN) which allows the risk evaluation through three parameters severity (S), probability of the failure occurs (O) and the probability of detect the failure (D) (Chang & Cheng, 2010). Each parameter is evaluated according to Table 3.1, Table 3.2 and Table 3.3. The Severity evaluation criteria is given by Table 3.1.

Table 3.1 – Conventional RPN evaluation criteria for severity (Chang & Cheng, 2010)

| Effect | Criteria: severity of effect | Rank |
|---|---|---|
| Hazardous | Failure is hazardous, and occurs without warning. It suspends operation of the system and/or involves non-compliance with government regulations | 10 |
| Serious | Failure involves hazardous outcomes and/or non-compliance with government regulations or standards | 9 |
| Extreme | Product is inoperable with loss of primary function. The system is inoperable | 8 |
| Major | Product performance is severely affected but functions. The system may not operate | 7 |
| Significant | Product performance is degraded. Comfort or convince functions may not operate | 6 |
| Moderate | Moderate effect on product performance. The product requires repair | 5 |
| Low | Small effect on product performance. The product does not require repair | 4 |
| Minor | Minor effect on product or system performance | 3 |
| Very Minor | Very minor effect on product or system performance | 2 |
| None | No effect | 1 |

The probability of the failure to occur evaluation criteria is given by Table 3.2.

Table 3.2 - Conventional RPN evaluation criteria for occurrence (Chang & Cheng, 2010)

| Probability of failure | Possible failure rates | Rank |
|---|---|---|
| Extremely high: failure almost inevitable | ≥1 in 2 | 10 |
| Very high | 1 in 3 | 9 |
| Repeated failures | 1 in 8 | 8 |
| High | 1 in 20 | 7 |
| Moderately high | 1 in 80 | 6 |
| Moderate | 1 in 400 | 5 |
| Relatively low | 1 in 2000 | 4 |
| Low | 1 in 15,000 | 3 |
| Remote | 1 in 150,000 | 2 |
| Nearly impossible | ≥1 in 1,500,000 | 1 |

The probability of detect the failure evaluation criteria is given by Table 3.3.

Table 3.3 – Conventional RPN evaluation criteria for detection (Chang & Cheng, 2010)

| Effect | Criteria: severity of effect | Rank |
|---|---|---|
| Absolute uncertainty | Design control does not detect a potential cause of failure or subsequent failure mode; or there is no design control | 10 |
| Very remote | Very remote chance the design control will detect a potential cause of failure or subsequent failure mode | 9 |
| Remote | Remote chance the design control will detect a potential cause of failure or subsequent failure mode | 8 |
| Very low | Very low chance the design control will detect a potential cause of failure or subsequent | 7 |
| Low | Low chance the design control will detect a potential cause of failure or subsequent failure mode | 6 |
| Moderate | Moderate chance the design control will detect a potential cause of failure or subsequent failure mode | 5 |
| Moderately high | Moderately high chance the design control will detect a potential cause of failure or subsequent failure mode | 4 |
| High | High chance the design control will detect a potential cause of failure or subsequent failure mode | 3 |
| Very high | Very high chance the design control will detect a potential cause of failure or subsequent failure mode | 2 |
| Almost certain | Almost certain Design control will almost certainly detect a potential cause of failure or subsequent failure mode | 1 |

Through the use of the traditional approach the RPN is determined by:

$$RPN = S \times O \times D$$

The risk with the highest RPN is the first that should be addressed.

Although the classifications are the most used, the work developed under this dissertation could not use them, due to their complexity, specificity and restrictiveness. So, the developed work need a simpler language, a softer, and more tolerant and flexible approach which experts can use to evaluate the risks. The fuzzy logic is a method which allows this approach.

## 3.4. Fuzzy Logic

Most of the time the "classes of objects encountered in the real world" cannot be sharply defined by only one class. One object can be a member of two deferent groups, e.g., bacteria or starfish have an ambiguous status in the animals' class (Zadeh, 1965). The same ambiguity arises in several other different subjects. Professor Lofti A. Zadeh started the development of a new theory which allows the handling of imprecise, uncertain or even vague information. The fuzzy sets' theory aims to aims to translate the human semantics and cognitive capacities into mathematical domain.

In order to build a fuzzy logic systems is necessary follow a procedure. Figure 3.2 represents the three stages of a fuzzy logic model. The stages, represented in grey, are the fuzzification, the inference mechanism and finally the defuzzification.


Figure 3.2 – Fuzzy logic model's stages (Nunes, 2010)

The fuzzification, the first stage of the model, is the process of transforming 'Crisp' inputs, numerical or linguistic data, in fuzzy sets. The second stage is the inference mechanism, which has the purpose of apply rules, fuzzy logic operators or fuzzy IF-THEN rules, to the aggregated input. The defuzzification is the final stage of this process. This stage has the purpose of covert the fuzzy output into 'Crips' output, numerical or linguistic data, to be understood by the users (Nunes, 2010).

## 3.4.1. Fuzzy Sets

In classical sets' theory the decision making process is defined in two ways: the object belong to the set or it does not belong. This type of set is designated as a "Crisp" set. Let a "Crisp" set, defined by C, which belong to a universe $X$, with a generic element $x$ ($X = \{x\}$). The "Crisp" set membership function is defined by $\mu_C : X \rightarrow \{0,1\}$, i.e.:

$$\mu_C(x) = \begin{cases} 1, & if\ x \in C \\ 0, & if\ x \notin C \end{cases} \quad (3.1)$$

According to Zadeh (Zadeh, 1965), not everything in the real world have often a sharp membership criteria. Let's analyse the example of Figure.3.3. Can a person be designated '*young*' only when his/her age is below 20 years old? Isn't a person with 25 years old young? Or 30 years old?

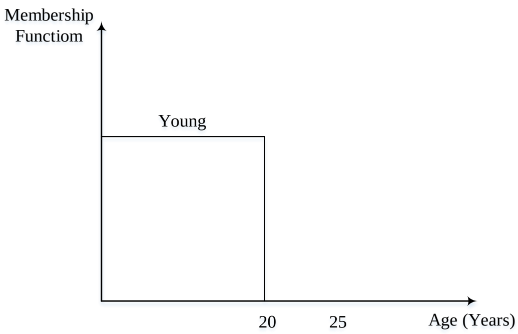



Figure.3.3 – Classical set representation

Consistent with Zadeh's sets theory, a fuzzy set is a class of objects "with a continuum of grades of membership". A person with 25 years old can be considered '*young*', but the grade of membership for those persons can be smaller than a person with 20 years old but higher than a person with 30 years old. Figure 3.4 illustrates a membership function of the linguistic variable '*young*'. This membership function as a continuum shape between 0 and 1.

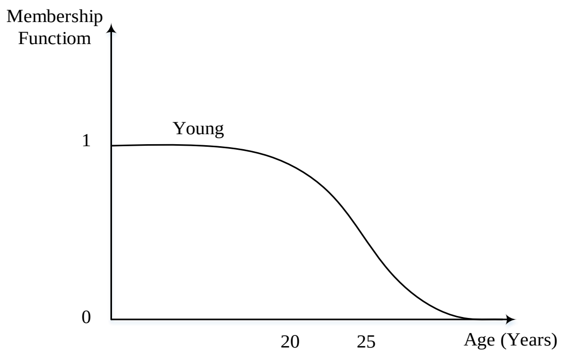



Figure 3.4 – Fuzzy set's representation

The membership function ($\mu_A$) of a fuzzy set A is defined by:

$$\mu_A: X \longrightarrow [0; 1] \tag{3.2}$$

So, each element $x$ from $X$ has a membership grade $\mu_A \in [0; 1]$. Being $A$ described by the coordinated pair:

$$\mu_A = \{(x. \mu_A(x)): x \in X\} \tag{3.3}$$

Let *X* be a discrete domain, where A is represented by:

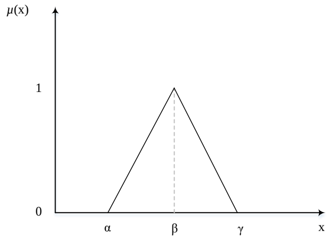
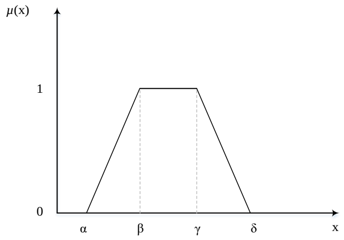
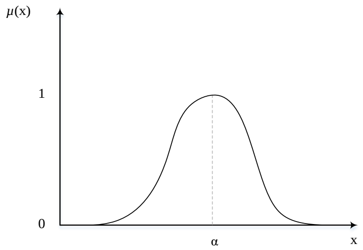
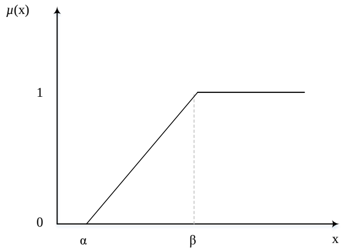
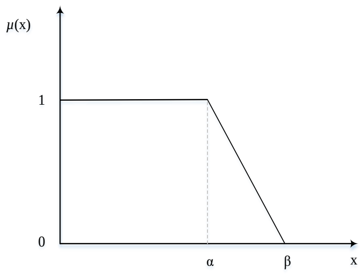
$$\sum_{x \in X} \frac{\mu_A(x)}{x} \tag{3.4}$$

Instead that, let X be a continuous domain, than A will be represented by:

$$\int_X \frac{\mu_A(x)}{x} \tag{3.5}$$

The definition of the membership function can be done in two different ways. The first one is the aggrupation of the membership grade with the respective element. The second method consists in the definition of a generic function which represents the membership grade ($\mu_A$) of each *x* element of the universe *X*. The most common continuous membership functions are the triangular shape, trapezoidal shape, Gaussian shape, or also called bell shape, the S shape and the Z shape. In Table 3.4 are illustrated the membership function with its characteristic equation. The discrete membership functions can have similar shapes.

Table 3.4 – Types of membership functions of continuous fuzzy sets

| Membership Function | Characteristic Equation |
|---|---|
| Triangular Shape<br><br> | $\Lambda : X \longrightarrow [0;1]$<br>$\Lambda(x,\alpha,\beta,\gamma) = \begin{cases} 0, & x < \alpha \\ \frac{x-\alpha}{\beta-\alpha}, & \alpha \leq x \leq \beta \\ \frac{\gamma-x}{\gamma-\beta}, & \beta \leq x \leq \gamma \\ 1, & x > \gamma \end{cases}$ |
| Trapezoidal Shape<br><br> | $\Pi : X \longrightarrow [0;1]$<br>$\Pi(x,\alpha,\beta,\gamma,\delta) = \begin{cases} 0, & x < \alpha \\ \frac{x-\alpha}{\beta-\alpha}, & \alpha \leq x \leq \beta \\ 1, & \beta \leq x \leq \gamma \\ \frac{\delta-x}{\delta-\gamma}, & \gamma \leq x \leq \delta \\ 0, & x \geq \delta \end{cases}$ |
| Gaussian Shape<br><br> | $\Omega : X \longrightarrow [0;1]$<br>$\Omega(x,\alpha,\sigma) = e^{\left(\frac{-x(x-\alpha)^2}{2\sigma^2}\right)}$ |
| S Shape<br><br> | $\Sigma : X \longrightarrow [0;1]$<br>$\Sigma(x,\alpha,\beta,\gamma,\delta) = \begin{cases} 0, & x < \alpha \\ \frac{x-\alpha}{\beta-\alpha}, & \alpha \leq x \leq \beta \\ 1, & x \geq \beta \end{cases}$ |
| Z Shape<br><br> | $Z : X \longrightarrow [0;1]$<br>$Z(x,\alpha,\beta,\gamma,\delta) = \begin{cases} 1, & x < \alpha \\ \frac{x-\alpha}{\beta-\alpha}, & \alpha \leq x \leq \beta \\ 0, & x \geq \beta \end{cases}$ |

## 3.4.2. Fuzzy Sets' Properties

The fuzzy sets have three properties: **Support**, **Core** and the **α-cut**. Figure 3.5 illustrates those properties.

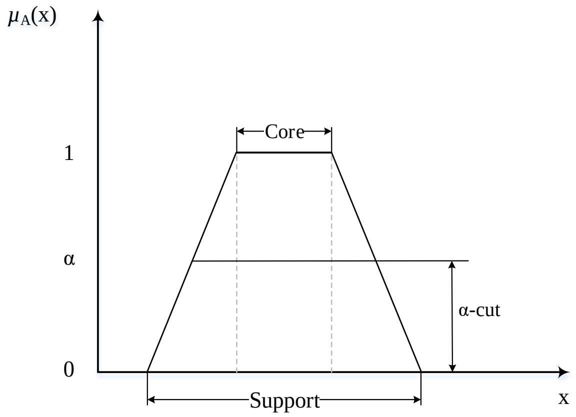



Figure 3.5 – Fuzzy sets' properties

Let A be a fuzzy set, in universe $X$, the support of the fuzzy set is defined by:

$$Support\ (A) = \{x \in X :\ \mu_A(x) > 0\} \tag{3.6}$$

The core of the fuzzy set A is defined by:

$$core(A) = \{x \in X :\ \mu_A(x) = 1\} \tag{3.7}$$

The α-cut is represented by:

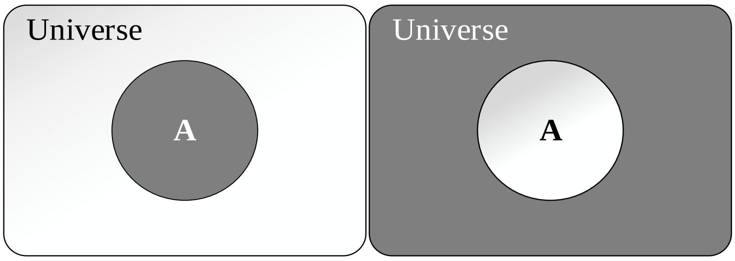
$$\alpha_A = \{x \in X :\ \mu_A(x) \geq \alpha\} \tag{3.8}$$

Another important property of fuzzy sets is the convexity property. One fuzzy set A is considered convex if the membership function respects the equation $\forall_{x_1,x_2 \in X} \forall_{\lambda \in [0,1]}:\ \mu_A(\lambda x_1 + (1-\lambda)x_2) \geq min\big(\mu_A(x_1), \mu_A(x_2)\big)$ (3.9).

$$\forall_{x_1,x_2 \in X} \forall_{\lambda \in [0,1]}:\ \mu_A(\lambda x_1 + (1-\lambda)x_2) \geq min\left(\mu_A(x_1), \mu_A(x_2)\right) \tag{3.9}$$

## 3.4.3. Fuzzy Sets' Operations

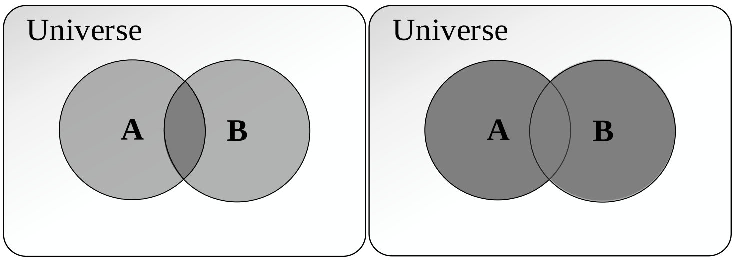
An object can belong to a class of objects due to one or several characteristics. This same object can also belong to several other classes. It is possible to build fuzzy sets from two or more sets, through basic operation. In classical logic, the use of Venn diagrams is very common to illustrate operations between sets in a universe $X$. Figure 3.6 illustrates ole of the operation between sets, the complementary. The grey elements represent the operations between the sets and the universe $X$.




Set A Set A Complementary

Figure 3.6 – Complementarity representation using Venn's diagrams

There are two other basic operations between sets. The intersection and the union between set A and set B (Figure 3.7).




Intersection of A and B Union of A and B

Figure 3.7 – Intersection and union representation using Venn's diagrams

There are some other notion of the classic theory which may be extended to fuzzy sets, the notion of equality and *subset*. Let A and B, two *subsets* of universe $X$. Two sets are equal $A = B$ iff:

$$\forall_{x \in X} : \ \mu_A(x) = \mu_B(x) \tag{3.10}$$

The set A is a *subset* of set B $A \subseteq B$ iff:

$$\forall_{x \in X} : \ \mu_A(x) \leq \mu_B(x) \tag{3.11}$$

Although in classic theory the operation between sets are defined without any ambiguity, in fuzzy sets that is not quiet truth. Despite of basic operators, fuzzy logic also allows logic operators and a set of fuzzy operators. The fuzzy operators are the union operators (conorma-t), mean operators and intersection operators (norm-t). Those operators offer a variety of data aggregation behaviours, allowing the simulation of numerous aggregation types. Figure 3.8 illustrates the continuum of fuzzy operators, with some examples of operators who "typically define the upper and lower behaviour in each category" (Nunes, 2010).

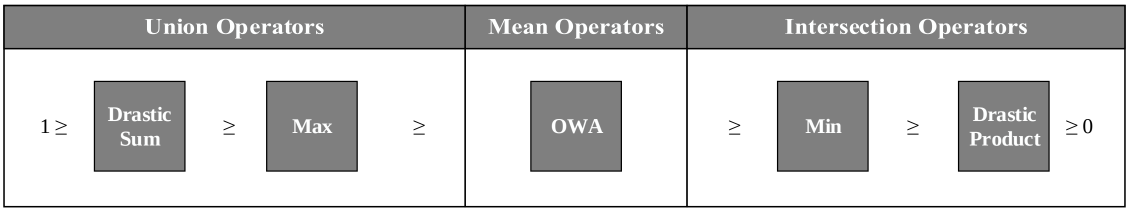



Figure 3.8 – Fuzzy operators' continuum (Nunes, 2010)

The fuzzy operators are distributed into two groups, the parametric and the non-parametric which means that the result can or cannot rest on the value of the parameter. Parametric operators offer a higher flexibility than a non-parametric operator although it is computationally more demanding (Nunes, 2010). Table 3.5 presents the parametric and non-parametric operators according with the union, mean and intersection operators.

Table 3.5 – Fuzzy aggregation' operators

| Union Operators (*conorma-t*) | Mean Operators | Intersection Operators (*norma-t*) |
|---|---|---|
| **Non Parametric** | | |
| Drastic Product | Arithmetic Mean | Drastic Sum |
| Limited Product | Geometric Mean | Limited Sum |
| Einstein Product | Harmonic Mean | Einstein Sum |
| Algebraic Product | | Algebraic Sum |
| Hamacher Product | | Hamacher Sum |
| Max | | Min |
| **Parametric** | | |
| Hamacher Intersection | 'AND' Fuzzy | Hamacher Intersection |
| Yager Intersection | 'OR' Fuzzy | Yager Intersection |
| Schweizer e Skar Intersection | OWAS | Schweizer e Skar Intersection |
| Dubois e Prade Intersection | | Dubois e Prade Intersection |

## 3.4.4. Linguistic Variables

The use of natural language is a usual occurrence when human wants to summarise any information. Language can be seen as a system where words, phrases and sentences are seen as "atomic and composite labels". Being a word $x$ in natural language $L$ which summarise the description of a fuzzy set $A(x)$, in the universe $X$, where $A$ represents the meaning of $x$. For example, if the noun 'car', where it meaning is defined by the fuzzy set $A(car)$ and the adjective '$yellow$', where it meaning is defined by $A(yellow)$, than the meaning of '$yellow$' car is set by the intersection of $A(car)$ and $A(yellow)$ (Zadeh, 1973).

In this case if the colour of an object is considered a variable, it values, yellow, blue, etc. may be considered the fuzzy labels of objects' universe. It is important to highlight that a natural language label in much less shard than a numerical one, i.e., for the previews example the wavelength of a particular colour is much more precise than it label 'yellow'. (Zadeh, 1973).

## 3.4.5. Fuzzy Rule Representation

A fuzzy rule representation presents itself as a set of fuzzy relations which respects the following rule:

$$\boldsymbol{If}\ x_1\ is\ A_1\ and\ x_2\ is\ A_2\ \boldsymbol{Then}\ \mathrm{y}\ is\ \mathrm{B} \tag{3.12}$$

Where $A_1$, $A_2$ and $B$ are defined by the membership function $\mu_{A_1}(x_1)$, $\mu_{A_2}(x_2)$ and $\mu_B(y)$ the fuzzy relation is:

$$R = I(T(A_1, A_2), B) \tag{3.13}$$

Where I is the fuzzy implication function and T is the representation of a general T-norm (Table 3.5) conjunction base (Jager, 1995).

## 3.4.6. Inference Mechanism

The inference mechanism is responsible for the combination of fuzzy inputs. Table 3.6 presents a group of fuzzy implication methods from several authors as Zadeh, Mamdani, Yager and other.

Table 3.6 – Fuzzy implications (Lucena, 2012)

| Implication | $I(a,b)$ |
|---|---|
| Lukasiewicz | $\min(1-a+b,1)$ |
| Zadeh | $\min\left(1-a+b, nin(a,b)\right)$ |
| Kleene | $max(1-a,b)$ |
| Reichenbach | $1-a+ab$ |
| Gödel | $\begin{cases} a, & \geq b \\ 1, & c.c \end{cases}$ |
| Dubois and Prade | $\begin{cases} 1-a, & b=0 \\ b, & a=1 \\ 1, & c.c. \end{cases}$ |
| Goguen | $\begin{cases} 1, & a=0 \\ min\left(\frac{b}{a},1\right), & c.c \end{cases}$ |
| Gaines | $\begin{cases} 1, & a \leq b \\ 0, & c.c \end{cases}$ |
| Wu1 | $\begin{cases} 1, & a<b \\ min(1-a,b), & c.c \end{cases}$ |
| Wu2 | $\begin{cases} 0, & a<b \\ b, & c.c \end{cases}$ |
| Yager | $b^2$ |
| Willmott | $min\left(max(1-a,b), max(a,1-b,\min(b,1-a))\right)$ |
| Mamdani | $\min(a,b)$ |
| Larsen | $ab$ |

During the development of this dissertation the inference mechanism used was the Mamdani's inference mechanism.

# 4

# Evaluation Methodology

A research approach can be defined as a plan or a research procedure that guides, through a general assumption to detail methods of data collection, analysis and interpretation. The development of a plan, or procedure, involves several decisions, so the researcher should decide what the best approach to study the proposed topic is. Decisions are based on the assumptions made by the researcher, to deal with constrains, in order to develop inquiries (research design) and data collection, analysis and interpretation (research methods) (Creswell, 2013). The choice of the research approach, according to Creswell, should be made based on the nature of the research problem, the researchers' personal experience and on the audience of the study, i.e.

Creswell defines, in his book, three approaches to research, the Qualitative, the Quantitative and the Mixed methods (Creswell, 2013). Qualitative and quantitative methods are most of the time viewed as distinct or even polar opposite categories, but they only "represent different ends on a continuum". Mixed methods researches are a combination of both methods to incorporate elements from each qualitative and quantitative approaches (Creswell, 2013). The work developed in this dissertation is a mix methods research where qualitative model presented as an isomorph risk system and quantitative model is developed based on FIS to quantify the mode and support risk measurement and aggregation. The FIS model is used because the model is defined based on imprecise data, related to the verbal information.

## 4.1. Proposed Methodology

This work has the purpose of analyse the applicability of an EPS in real shop floor. In order to understand what kind of risks, companies will face during the employment of EPS, this dissertation presents a methodology to analyse the points that will need to be worked on to deliver a better final product. The development of this methodology is organised in three phases:

- Research Phase;
- Development Phase;
- Analysis Phase.

Figure 4.1 represents the necessary phases to develop the methodology the current work, as well as the key steps towards the conclusion of the study.

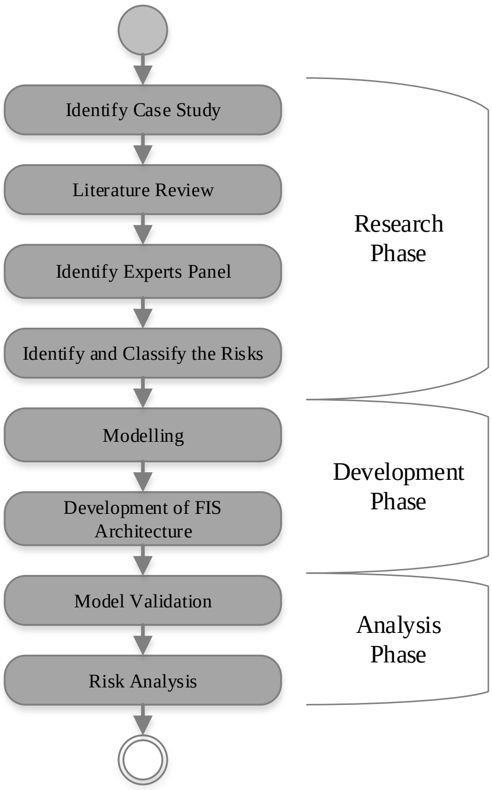



Figure 4.1 – Research flowchart

## 4.2. Research Phase

The Research Phase has the main purpose of set a consistent method to analyse all the available potential sources of information about the risks of employing an EPS. So, this phase is divided in four stages:

- The identification of the case study;
- The literature review;
- The identification of experts' panel;
- Modelling.

Each stage represents an important step towards the study conclusion. The first stage, the selection of the case study, is the base of all developed work. So it is important to analyse all the potential projects and decide which project concentrates the largest amount of relevant information about the potential risks of employing an EPS. The projects, developed in EPS, are at this moment the best information source, due to the amount of experiments that are developed to create the final product. This process is responsible to identify weaknesses associated with the EPS employment, divided in several areas, like the paradigm, the software among others.

The literature review, the second stage, is presented in Chapter 2 and 3. This stage is an import part to find the most suitable methodologies to analyse the risks of EPS' paradigm.

The third stage is the development of the conceptual model, where a systematic approach is employed to follow a consistent method to the problem.

The last stage of this phase is the identification of the experts' panel. The experts' panel should have sufficient knowledge in EPS, with academia and/or business background.

## 4.3. Development Phase

The Development Phase has three different stages:

- Identification and Classification of *Risks*;
- Fuzzy Inference System Development.

### 4.3.1. Identification and Classification of *Risks*

Both identification and classification of risks are done using the in-depth interview method. In-depth interviewing is a qualitative research technique. It involves an intensive interview of small groups of persons, which have a privileged view over a specific subject (Boyce & Neale, 2006). This methodology is the most appropriate due to the lack of information available in the literature. This methodology is developed in two stages, according to Figure 4.2.

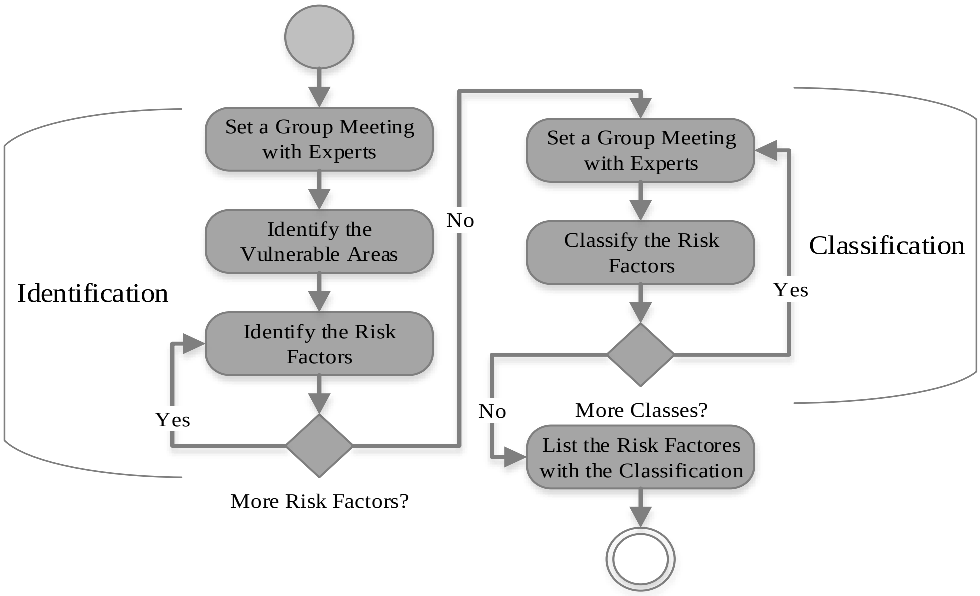



Figure 4.2 – Methodology used to identify and classify the risk factors

The identification phase has two simple steps. The first one is to set a group meeting with the set experts' panel. On this meeting experts' are asked to identify the most vulnerable areas, and according to it, the activities which represent a risk factors for the employment of an EPS. These steps are repeated until the experts are satisfied, which means, the process will be repeated until experts detect risks to be analysed.

When all the vulnerable areas are explored, the risk factors are ready to be classified, according to the classes presented on Chapter 5. These classifications are defined according to experts' opinion. The classification process is similar to the identification process. After all risk factors are classified, they are listed and ready for the next step, the Fuzzy Inference System Development.

### 4.3.2. Fuzzy Inference System Development and Knowledge Extraction

The second process is the development and verification of a Fuzzy Inference System (FIS). FIS is a powerful tool to deal with imprecise data and it could work efficiently when lack of information exists. So, this is the main reason to utilise it. The development of the FIS, to determine the risk factors RPN, follows the framework of Figure 4.3. This framework has three parts:

- Input;
- Fuzzy inference system;
- Output.

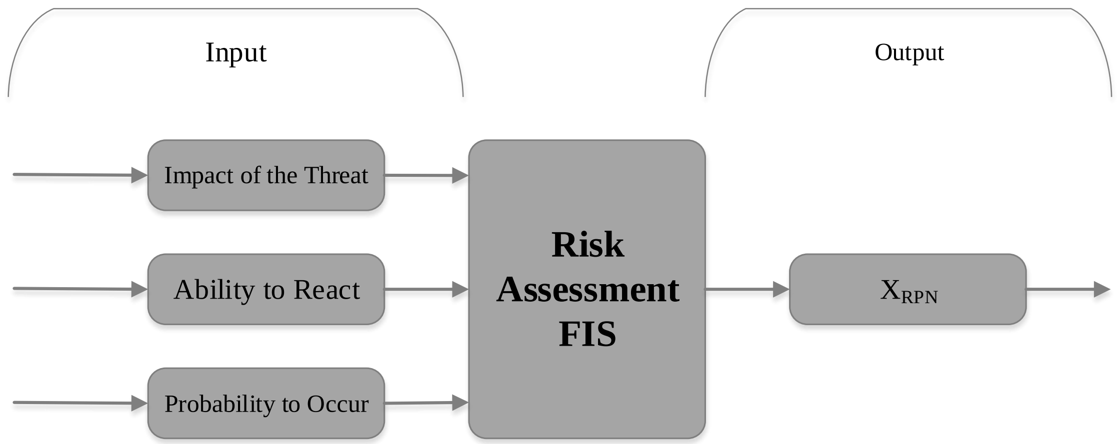



Figure 4.3 – FIS framework for the RPN determination, per risk factor

The framework presented in Figure 4.3 is designed to use the experts' evaluation and transform it into a RPN. After each risk factor $RPN_{ij}$, where *i* represents each risk factor identification number and *j* represents the expert's identification number, all RPNs from the same risk factor are aggregated, in order to analyse them. The aggregated RPNs are now define by $RPN_i(\bar{X}_{RPN_i}, S_{RPN_i})$. So, to analyse this information it is designed an auxiliary model that uses the aggregated data, $RPN_i(\bar{X}_{RPN_i}, S_{RPN_i})$ where $\bar{X}_{RPN_i}$ is the experts' average opinion and $S_{RPN_i}$ is the consensus level and rank all the risks. The consensus-based model framework is represented by Figure 4.4.

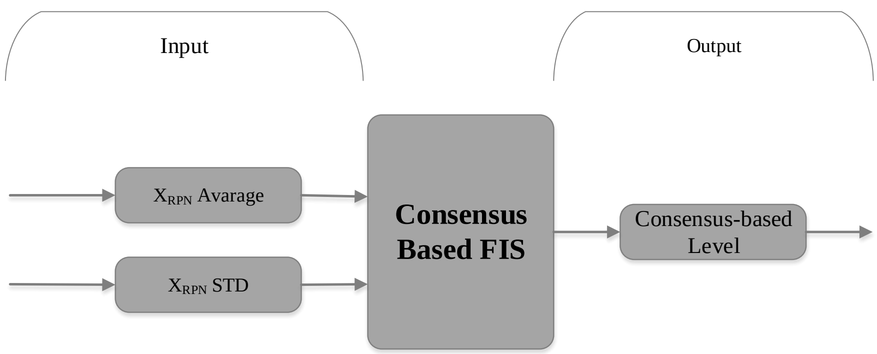



Figure 4.4 – FIS framework of the consensus-based model

## 4.4. Analysis Phase

Finally the Analysis Phase is divided in three stages:

- Model Validation;
- Risk Analysis.

The model's validation is done in three different ways. The first method is the extremes conditions' test, the second is a behavioural analysis and the third is the face validity. The extremes condition's test consists in applying extreme conditions to the model and analyse the result. If the output is not the expected one, it is necessary to make adjustments. The behavioural analysis consists on the behaviour examination of the system according to the input parameters changes. The last method is the face validity, which consists on the validation of the FIS rules combination (represented by surfaces). This method uses logic, to verify the rules and also is validated by experts.

The risk analysis is developed based on two different approaches. The first approach is based on the analysis of the risk assessment model, through the analysis of the confidence interval. The second analysis is done using the results of the consensus-based model.

# 5

# Evaluation Model's Development

The Evaluation Model Chapter is presented in four subchapters:

- Presumption;
- Conceptual Model;
- Quantitative Model;
- Data Aggregation and Consensus-based Model.

Presumption subchapter presents the considered assumptions in the development of the main model.

The Conceptual Model subchapter presents factors and their relations, which can represent the risks of employing an EPS, or any similar technology.

The Quantitative Model subchapter presents the model development process. The model aims to evaluate the risk factors according to the parameters defined in the Conceptual Model subchapter, and generate a Risk Priority Number (RPN). The developed model generates, per expert, a RPN result for each risk factor.

The Data Aggregation and Consensus-based Model is the last subchapter which presents a model that rank all the risk factors, resultant from the aggregated RPN, provided by the main model.

## 5.1. Presumption

The model's definitions requires the establishment of some assumption. Those premises are:

- The implementation of an EPS only makes sense if the PL is redundant, i.e. each station has a twin station, which offers the same skills, which allow the system adopt alternative paths, e.g. Figure 5.1 has four stations, station 1 and 2, and on the other side of the PL are station 3 and 4, in this case the station 1 and 2 should provide the same "services" to the product, giving the system the possibility to evolve, in accordance to the production needs. This characteristic allows the system to evolve and be more dynamic;
- The second principle is that the risk factor list is created based on the perception of the risk by a group of experts of two different areas, experts in EPS paradigm and experts in risk;
- The last presumption is based on the premise that each risk is independent from the other risks, i.e. it occurs regarding the occurrence of any other risk.

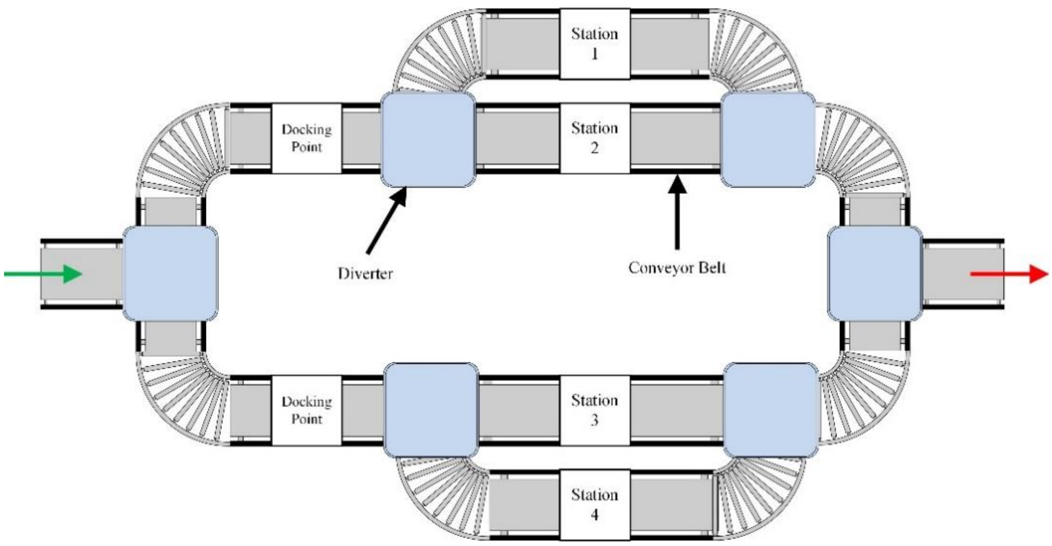



Figure 5.1 – Production line (adapted from (A. Rocha, 2013))

## 5.2. Conceptual Model

The Conceptual Model subchapter is presented in two subchapters:

- Risk Factors;
- Risk Measurement Parameters.

The Risk Factors subchapter presents the risk factors, obtained in accordance with the process defined in the Evaluation Methodology chapter. The subchapter Risk Measurement Parameters presents the explanation of the parameters used to define the two proposed models.

### 5.2.1. Risk Factors

The risk factors used to evaluate the risk of employing an EPS are not discussed enough in the literature. The risk analysis of employing this emergent paradigm is a new approach to the study of the EPS, as most of the woks are focused on technical issues including control systems considering the mentioned gap it was necessary to analyse the value of this new approach for production system (PS), elaborated in Chapter 2, and then search for potential failures. To identify the risk factors, the best solution is to interview experts, on EPS, to collect them. The risk factors of employing an EPS in a production line (PL) are defined, in accordance to experts, by:

- $R_1$: Insufficient financial resources to remodel the PL – a traditional budget plan may not be adequate for the improvement of the existent PL in order to implement an EPS;
- $R_2$: Insufficient financial resources to build a new PL – a traditional budget plan may not be adequate to build a new PL in order to implement an EPS;
- $R_3$:Inaccurate choice of hardware – the choice of the hardware may not be accurate, due to lack of information related with the software needs;
- $R_4$: Inadequate facilities – the choice of the facilities may not consider the hard and software needs;
- $R_5$: Incapability to produce – the system may lose the ability to produce due to an occurrence of a natural disaster;
- $R_6$: Shutdown of all PS – the system may lose the ability to produce due to an occurrence of a power cut;
- $R_7$: Inadequate quantity of controllers – the number of controllers may not be enough for the PL need;
- $R_8$: Inadequate capacity of the controller – the choice of the controllers' capacity may not correspond to the software need, so the system performance may decrease;
- $R_9$: Delay in the delivery of the hardware – delays in the hardware delivery may represent a delay in the implementation of the PL;

- $R_{10}$: Information leakage – the system may have weaknesses in terms of security, i.e. the system may be vulnerable to hackers;
- $R_{11}$: Data inconsistency – the system may have data inconsistencies due to the easy access to tamper it database information;
- $R_{12}$: Shut down of the entire system – the system may stop due to malfunction of some PL's component;
- $R_{13}$: Decrease of the entire system's performance – the system's performance may decrease due to the malfunction of some PL's component;
- $R_{14}$: Unperformed maintenance in the PL – the number of persons formed on this new technology may not be enough to create a team that can perform the necessary maintenance to the system;
- $R_{15}$: Insufficient maintenance performed in the PL – the number of persons formed on this new technology may not be enough to create a team that can perform the necessary maintenance to the system for every existent errors;
- $R_{16}$: Unspecialised system's integrators – the number of persons formed on this new technology may not be enough to create a team who can integrate all the system's parts, or the system with existent ones;
- $R_{17}$: Inertia to start the paradigm's transition – companies do not see radical changes as a risk that they are willing to take without knowing the risk and the gains of it, so change an entire PS is seen as a huge risk;
- $R_{18}$: Inadequate design of the PL – the number of persons formed on this new technology may not be enough to create a team to design the most adequate PL for this type of paradigm;
- $R_{19}$: Failure of the entire PL – the hardware capacity may compromise the PL's normal functioning;
- $R_{20}$: Decrease of the entire system's performance – the hardware capacity may compromise the PL's normal performance;
- $R_{21}$: Human error – the integration of this system with other PS may be susceptible to human errors;
- $R_{22}$: Inadequate integration with the existing control systems – the integration of this system with an existing control system may be susceptible to human errors, making it inadequate;
- $R_{23}$: Inadequate integration with the existing statistical analysis tools – the integration of this system with an existing statistical analysis tool may be susceptible to human errors, making it inadequate;

- $R_{24}$: Inadequate integration with the existing visualisation tools – the integration of this system with an existing visualisation tool may be susceptible to human errors, making it inadequate;
- $R_{25}$: Inadequate integration with the existing simulation tools – the integration of this system with an existing simulation tool may be susceptible to human errors, making it inadequate;
- $R_{26}$: Inadequate integration between EPS and managerial subsystem – the integration of this system with an existing managerial subsystem may be susceptible to human errors, making it inadequate;
- $R_{27}$: Incompatibility with the existing control systems – this new technology may not be integrated with the majority of the existing control systems due to software incompatibilities;
- $R_{28}$: Incompatibility with the existing statistical analysis tools – this new technology may not be integrated with the majority of the existing statistical analysis tools due to software incompatibilities;
- $R_{29}$: Incompatibility with the existing visualisation tools – this new technology may not be integrated with the majority of the existing visualisation tools due to software incompatibilities;
- $R_{30}$: Incompatibility with the existing simulation tools – this new technology may not be integrated with the majority of the existing simulation tools due to software incompatibilities;
- $R_{31}$: Incompatibility between EPS and managerial subsystem – this new technology may not be integrated with the majority of the existing managerial subsystem due to software incompatibilities;
- $R_{32}$: Inefficient connection between agents, entities – the system may temporarily stop working as a result of losses of connectivity between components, due to software or physical problems, i.e. the system needs to be connected so that the system's agents and entities can communicate with each other and guide the product for the best possible path;
- $R_{33}$: Inexistent connection between agents, entities – the system may stop working as a result of lack of connectivity between components, due to software or physical problems, i.e. the system needs to be connected so that the system agents and entities can communicate with each other and guide the product for the best possible path;
- $R_{34}$: Optimal performance is not guaranteed – the system presents to the product the best path according to the actual state of the system, so each time a product leaves a station and goes to another one the best path may be different because of the system's differences;
- $R_{35}$: Entry and exit order of products cannot be assured – the constant analysis of the system provides different paths to the products during production process, making almost impossible the prediction of the exit order based on the entry order;

- $R_{36}$: Increases human error in implementation– the system's complexity may lead to human errors in the software development;
- $R_{37}$: Overload controllers – the system's complexity may overload the controllers with the information exchange between the system's agents and entities;
- $R_{38}$: Unpredictable behaviour of the system – the constant analysis of the system provides different paths to the products during production process, being difficult the prediction of the system's behaviour.

All the risk factors are obtained through the use of the methodology proposed in Chapter 4, and the factors are represented by $R_i, where\ i = \{1, 2, \dots, 38\}$. Some of the presented risk factors are related with the way this new technology is perceived. In order to make a structured analysis to the technology, the risks are aggregated in two different ways. In a more technical perspective, the risk factors are classified by vulnerable areas, also identified by experts, in accordance with the proposed methodology. Under managerial perspective, the risk factors are classified by risk classes. The Vulnerable Areas (*V*) are defined, according to experts' perception, by:

- $V_1$: Financial Liquidity – area related with the financial capacity that the company has to invest in the employment of this new paradigm;
- $V_2$: Natural Disasters – area related with the response to an occurrence of a natural disaster;
- $V_3$: Power Cuts – area related with the response to an occurrence of a power cut;
- $V_4$: Specific Hardware – area related with choice of the adequate hardware for the software;
- $V_5$: Hardware's Delivery Delays – area related with the delays in the deliveries;
- $V_6$: Security – area related with the security of the hardware with respect to external attacks;
- $V_7$: Faulty Hardware – area related with the risk that a faulty hardware can reduce the PL performance;
- $V_8$: Manpower – area related with the human action on the PL;
- $V_9$: Hardware Capacity – area related with the capacity hardware to perform the necessary tasks;
- $V_{10}$: Systems' Integration – area related with the integration between EPS and existent software;
- $V_{11}$: Network Connection – area related with the existence of network connection to allow the system to work;
- $V_{12}$: System's Performance – area related with the systems' performance;
- $V_{13}$: System's Complexity – area related with the risks that can appear due to systems' complexity.

The vulnerable areas are represented by $V_i, where\ i = \{1, 2, \dots, 13\}$. According to the proposed methodology, the risk factors can now be associated with the vulnerable areas. Figure 5.2 presents a schematic representation of the association made by experts, between these two sets.

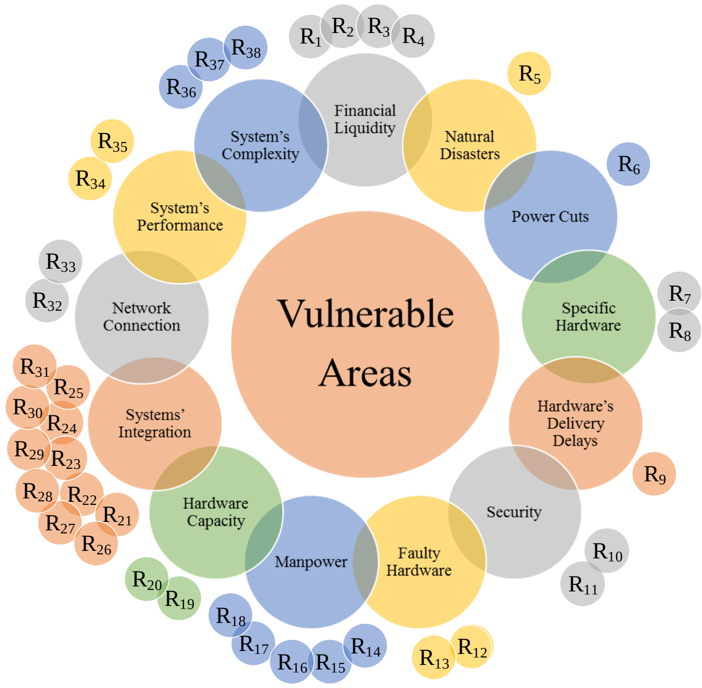



Figure 5.2 – Conceptual Model 1

With this representation is possible to identify some areas more susceptible than others (Figure 5.2). Through a detailed analysis to Figure 5.2 it is possible to observe that the Systems' Integration presents the higher number of possible risks of employing an EPS, a total of 11 risk factors, followed by the Manpower and Financial Liquidity areas with smaller numbers, 5 and 4 respectively, leaving the remaining ones with an average of 2 risk factors per area.

The distribution of the risks per vulnerable area is not the only available option. In terms of management there is other method to classify the risk factors. The second method to classify the risk factors, further detailed in the Evaluation Methodology Chapter, is by the definition of classes. The identified classes are:

- $C_1$: Human – Risk related to activities performed by human;
- $C_2$: Hardware – Risk related to the hardware used to support the PL;
- $C_3$: Software – Risk related to the software used to support the PL;
- $C_4$: Paradigm – Risk related to an EPS approach;
- $C_5$: Environmental – Risk related to the surrounding environment.

The classes are represented by $C_i, where\ i = \{1, \dots, 5\}$. According to the proposed methodology the risk factors can now be associated with the classes. Figure 5.3 presents a schematic representation of the association made by experts, between the risk factors and the risk classification.

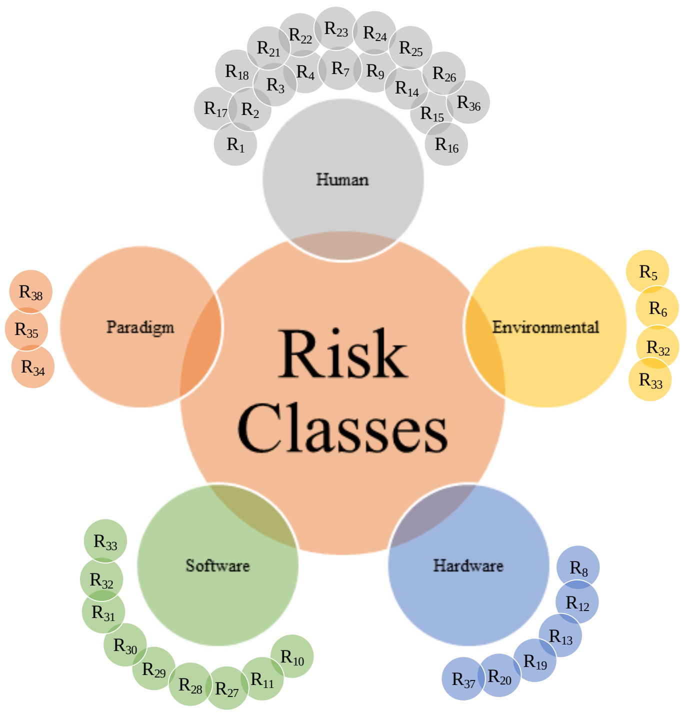



Figure 5.3 – Conceptual Model 2

Through a detailed observation of Figure 5.3 it is possible to note that the Human class is the most susceptible to a failure from all classes, presenting a stunning 18 risk factors. The next is the Software class, with half of the risk factors, only 9. Hardware class presents 6 risk factors and finally the Environmental and the Paradigm classes present 4 and 3 risks respectively.

Summarising, from both preliminary aggregations of the risk factors in the vulnerable areas group or in the risk classification group it is possible to take some conclusions. The System's Integration area or the Human and Software classes are the most potential threaten due to the high number of risk factors present in each group. Although this information can be perceived only by a simple observation of Figure 5.2 and Figure 5.3 the "threat's level" of the risk factors, the "real value of the risk" need to be measured.

## 5.2.2. Risk Measurement Parameters

The implementation of new PS may be matter of concern for most of the manufacturing companies. After the detection of the risk factors it is necessary to define a method that can measure them properly. The most common parameters to evaluate the risk of a certain activity are the impact that the risk has on the production line when it occurs and the regularity of the occurrence. Those two parameters are described in the literature as Impact of the Threat (*I*) and Probability to Occur (*P*).

Although these two parameters are the most commonly used, there is a third parameter that companies must consider, which is presented in a form of question, what is the company ability to react to a threat? This is a question that must be answered by companies before they start doing changes in the PL. So to assess the risk factors, the used model must contemplate three parameters, the Impact of the Threat, the Probability to Occur and finally the Ability to React (*A*).

There are several method to assess the risk, as described in Chapter 3. Traditional FMEA can be used in this case, but a simple multiplication of the three parameters is not enough to characterise the final RPN. So to simplify the developed model evaluates the risk factors, per expert, based on the questionnaire answers from Annex I, this model is an adaptation from the traditional FMEA. The model use the traditional concept and create a Fuzzy FMEA model which is a more adequate method to analyse the risk factors. Based on it, a qualitative model is defined for this study.

## 5.3. **Quantitative Model**

The Quantitative Model Chapter presents the necessary steps to design a proper model to assess the risk factors previously identified. According to that information a Risk Assessment Model is designed. In the development of this model is used the MATLAB Fuzzy Toolbox.

### 5.3.1. Risk Assessment Model

The Risk Assessment Model developed in this work, based on the introduced quantitative model, used Fuzzy Inference System (FIS) as described in the Evaluation Methodology Chapter. The FIS is defined by a fuzzy input, fuzzy output and for an inference mechanism (IM). Before the FIS definition, it is necessary to describe the evaluation method. The model’s characterisation starts with the definition of the parameters characterised in the previous subchapter. The evaluation method of each parameter is made through the use of natural language, categorised by:

- Very Low – VL;
- Low – L;
- Moderate – M;
- High – H;

- Very High – VH.

These five categories terminology is used to describe the input and output parameters, and are commonly used in this area (Khanmohammadi, Rezaie, Jassbi, & Tadayon, 2012). The categories are stabilised as five, according to experts perception the number of options to evaluate the I, A and P are enough to demonstrate their concerns on this new technology. Although the used terminology is the same, the meaning of each category is slightly different per parameter. So it is necessary to clarify this subject. Table 5.1 presents the categories' explanation to parameter Impact.

Table 5.1 – Categories' explanation to parameter Impact

| Scale | Description |
|---|---|
| VL | The impact of the threat is almost inexistent |
| L | The impact of the threat is non-significant |
| M | The impact of the threat is moderately significant |
| H | The impact of the threat is considerably significant |
| VH | The impact of the threat compromises the EPS's success |

Table 5.2 presents the categories' representation to parameter Ability.

Table 5.2 – Categories' explanation to parameter Ability

| Scale | Description |
|---|---|
| VL | The ability to react is almost inexistent |
| L | The ability to react is low |
| M | The ability to react is medium |
| H | The ability to react is significant |
| VH | The ability to react is good enough to address the problem |

Finally, Table 5.3 presents the categories' representation to parameter Probability.

Table 5.3 – Categories' explanation to parameter Probability

| Scale | Description |
|---|---|
| VL | The probability to occur is almost inexistent |
| L | The probability to occur is non-significant |
| M | The probability to occur is moderately significant |
| H | The probability to occur is considerably significant |
| VH | The probability to occur compromises the EPS's success |

After the inputs' categories are explained, it is necessary to do the same procedure to the output parameter. Table 5.4 presents the categories' representation to the output parameter, RPN.

Table 5.4 – Categories' explanation to the RPN

| Scale | Description |
|---|---|
| VL | The risk is almost inexistent |
| L | The risk is low but should be addressed |
| M | The risk is medium, average |
| H | The risk is considerable and must be addressed immediately |
| VH | The risk compromises the success of the employment of the EPS |

According to the methodology the first step the categorisation of the inputs and outputs based on the natural language, is accomplished. The second step in the modelling design is the creation of fuzzy sets to the inputs and the outputs.

According to Guyonnet et al., the definition of any distribution should be made based on the collection of statistical data, and fit the theoretical distribution into a relative frequencies histogram. Although, in risk assessments the data collection is insufficient to apply this type of procedures (Guyonnet et al., 2003).

This case is no exception. The quantity of the collected data is not enough to use a statistical based method, so it is necessary to define the shape that best describe these type of systems. Most of the papers in literature prefer the triangular shape, due to its simplicity, to define the values but a large number of authors use also the Gaussian shape, which is commonly used as it is the most natural choice to describe experts' opinion (Markowski & Mannan, 2008), to describe the risk assessment model. This model, similarly to other developed models, uses the Gaussian shape in the input and output parameters development.

The developed Gaussian shape is given by:

$$\mu = e^{\left(\frac{-x(x-c)^2}{2\sigma^2}\right)} \tag{5.1}$$

Where $\mu$ represents the category's membership function (MF). Each category has a representative MF. Figure 5.4 presents the representative fuzzy set for the input and output parameters $\left(I, A, P\ and\ RPN_{ij}\right)$.

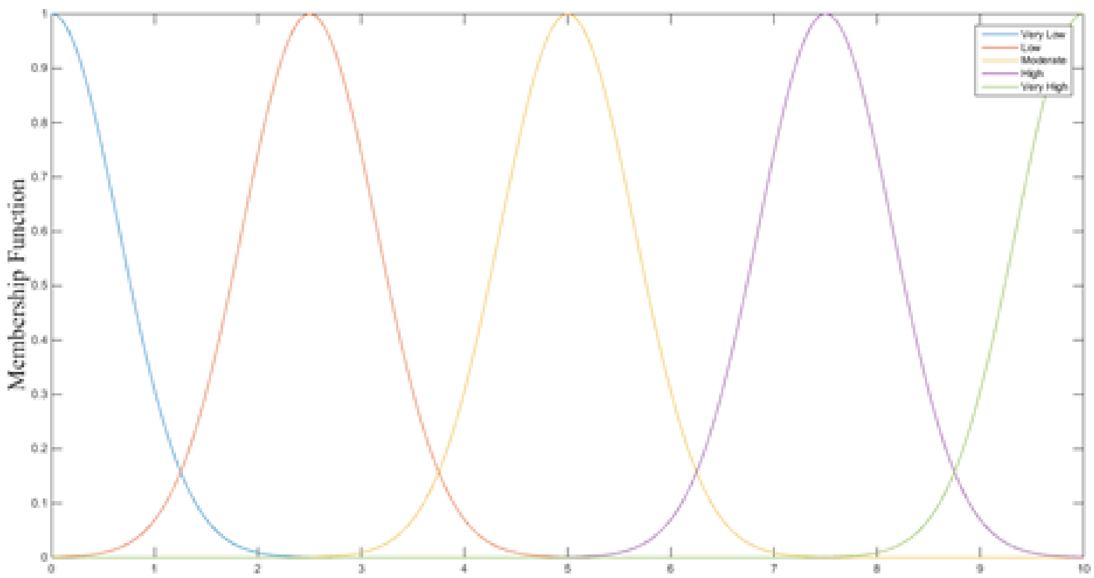



Figure 5.4 – Categories' MFs fuzzy set for input and output parameters $(I, A, P \text{ and } RPN_{ij})$

The curves, from left to right, are the MF's representation for the categories VL, L, M, H and VH (Figure 5.4) of the fuzzy set. This representative fuzzy set is equal for the output and the input parameters of this model.

In accordance with the proposed methodology, the next stage is the definition of the IM. The IM used in the Mamdani's method, usually on the design of this models. The rules definition is the subsequent step for this model.

The phase of finding the final list is an iterative process made by the experts and it validates the final model

## 5.3.2. Risk Assessment Model Validation

The model's validation process is an iterative procedure where two parts of the model are analysed, as introduced in the methodology. The first test performed is the extreme condition test. This test aims to force the model to extreme conditions and verify the results. Ideally the results should be equal to the maximum/minimum/medium values of the output, but due to the approximations made by the iteration of the mathematical model reproduced by the software used, the tests' values should be close to the optimal ones.

The second test is the face validity. Firstly, the generated behaviour of the system, represented by the graph, is analysed to identify any irregular trend, then this analysis is confirmed with the analysis of the input parameters' individual behaviour.

The last test is a behavioural analysis. To perform this test and verify the reasonability of the behaviour, two input factors are kept constants and the other one is smoothly increased. With this process is possible to understand the behaviour of the system and discover possible unexpected trends that should be solved.

To start the rules development, ten rules are defined. Table 5.5 presents this first group of rules.

Table 5.5 – List of first group of rules for the Risk Assessment Model

| Rules Number | *I* | *Op.* | *A* | *Op.* | *P* | RPN |
|---|---|---|---|---|---|---|
| 1 | Moderate | and | Moderate | and | Moderate | Moderate |
| 2 | Moderate | and | Moderate | and | Very Low | Moderate |
| 3 | Very High | and | Very Low | and | High | High |
| 4 | Very High | and | Very Low | and | Very High | Very High |
| 5 | Very High | and | Moderate | and | Very High | High |
| 6 | Moderate | and | Low | and | Moderate | Moderate |
| 7 | High | and | Very Low | and | Very High | High |
| 8 | Very Low | and | – | and | Very Low | Very Low |
| 9 | Very Low | and | Moderate | and | Very High | Moderate |
| 10 | High | and | Very Low | and | High | High |

Each rule is defined according to the three input parameters. The combination of each parameter should be translated in a logical output, the risk. For example, Rule 4 is defined by:

$$(\boldsymbol{I = Very\ High}) \wedge (\boldsymbol{A = Very\ Low}) \wedge (\boldsymbol{P = Very\ High}) \rightarrow \boldsymbol{R = Very\ High}$$

Rule 8 is a particular case, where two parameters are defined and one it is not defined.

$$(\boldsymbol{I = Very\ Low}) \wedge (\boldsymbol{P = Very\ Low}) \rightarrow \boldsymbol{R = Very\ Low}$$

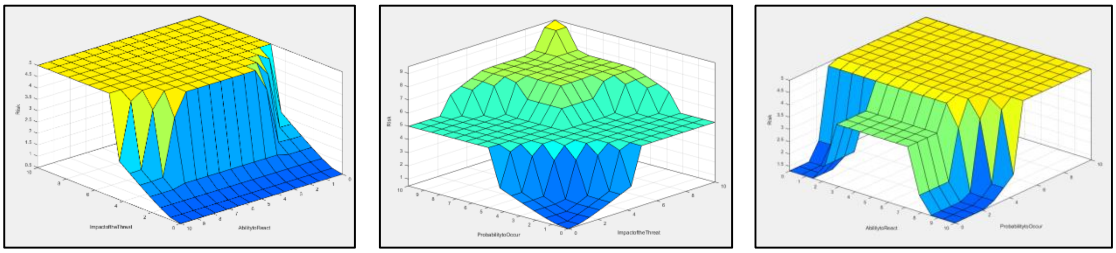
This case indicates that whatever is the value allocated to parameter *A* the value of the risk is not altered. After the implementation of this rules it is necessary to validate the model.

The first validation is the extreme conditions test. Table 5.6 presents the test results.

Table 5.6 – Results of the extreme conditions' test

| Impact | Ability | Probability | Risk |
|---|---|---|---|
| 0 | 10 | 0 | 0,49 |
| 5 | 5 | 5 | 0,50 |
| 10 | 0 | 10 | 9,51 |

The performed tests presents fine results, all three results are close to the expected ones (Table 5.6). The second validation is the behavioural test. Figure 5.5 presents three examples of face validity test generated based on the ten rules groups from Table 5.5.



(a) (b) (c)

Figure 5.5 – Face validity tests with the three combinations of the input factors; (a) *I* vs. *A*; (b) *I* vs. *P*; (c) *A* vs. *P*

Through the face validity test is possible to verify some irregularities. Figure 5.5 only presents a few of the generated surfaces. In test (b) the risk value increases with the increment of parameters I and A, but tests (a) and (c) the risk increases and decreases it value with the increment of one of the parameters (Figure 5.5). This represents a problem because it does not respect the assumption made earlier.

To better understand the presented problem it is necessary to perform a verification of the parameters behaviour, through a behavioural test. This test identify the parameter or parameters that are affected by the current system behaviour. Figure 5.6 presents nine cases of system's behaviour according to the evolution of one input. With these examples it is possible to identify some problems, represented as unexpected trends.

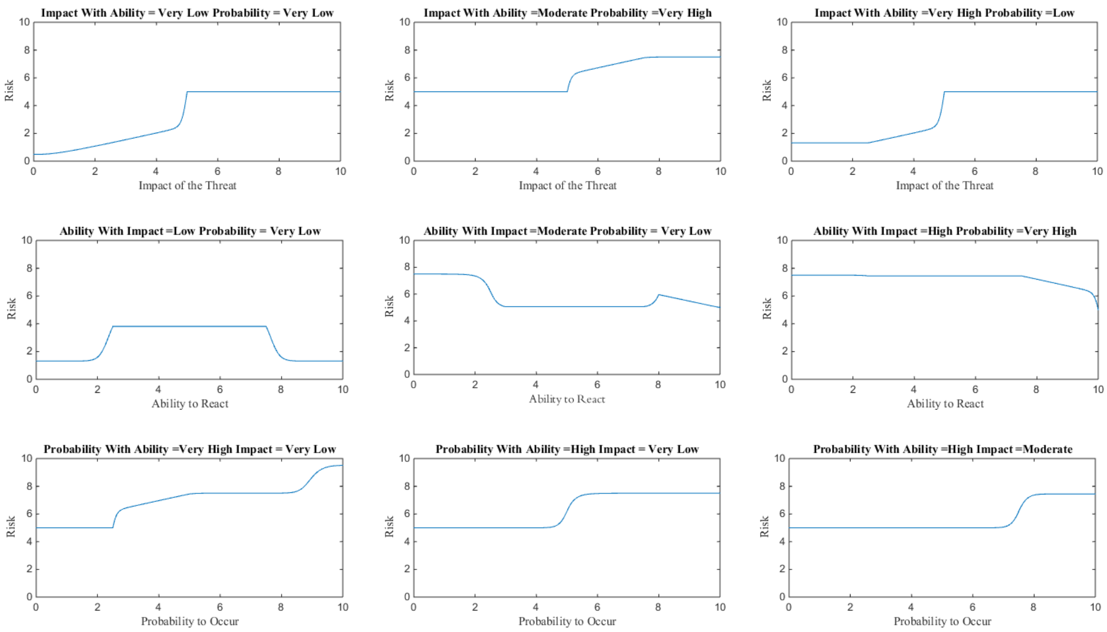



Figure 5.6 – Behavioural test related to the ten rules list

The parameters I and P are not presenting any problems by themselves, as can be seen in the first and third rows of Figure 5.6 the behaviour is consistently raising, but the parameter a needs some adjustments, since it does not present a consistent behaviour. So experts need to add, remove or edit few rules. So, some rules are added to correct the previews imperfections and a few others that appeared later. In the end of this process the system has twenty four rules, presented in Table 5.7. Table 5.7 presents the final list of rules for the model's IS.

Table 5.7 – Final list of rules for the Risk Assessment Model

| Rules Number | *I* | *Op.* | *A* | *Op.* | *P* | RPN |
|---|---|---|---|---|---|---|
| 1 | Moderate | and | Moderate | and | Moderate | Moderate |
| 2 | Moderate | and | Moderate | and | Very Low | Moderate |
| 3 | Very High | and | Very Low | and | High | High |
| 4 | Very High | and | Very Low | and | Very High | Very High |
| 5 | Very High | and | Moderate | and | Very High | High |
| 6 | Moderate | and | Low | and | Moderate | Moderate |
| 7 | High | and | Very Low | and | Very High | High |
| 8 | Very Low | and | – | and | Very Low | Very Low |
| 9 | Very Low | and | Moderate | and | Very High | Moderate |
| 10 | High | and | Very Low | and | High | High |
| 11 | Moderate | and | Very Low | and | Very Low | Moderate |
| 12 | Very Low | and | Very Low | and | Moderate | Moderate |
| 13 | Very High | and | Very Low | and | Moderate | High |
| 14 | High | and | Very High | and | Moderate | Moderate |
| 15 | Very High | and | Very High | and | Very Low | Moderate |
| 16 | Very High | and | Very High | and | Very High | High |
| 17 | Moderate | and | Very High | and | Very High | Moderate |
| 18 | Very High | and | Low | and | Moderate | High |
| 19 | Very High | and | Low | and | High | High |
| 20 | Very High | and | Low | and | Very High | High |
| 21 | Moderate | and | Low | and | Very High | High |
| 22 | Very Low | and | Very Low | and | Very High | Moderate |
| 23 | Very Low | and | Very High | and | Moderate | Low |
| 24 | Very Low | and | Moderate | and | Moderate | Low |

All the defined rules, presented in Table 5.7, are defined by experts on EPS, as mentioned in the Evaluation Methodology Chapter. After the new rules addiction all the validation process need to be repeated. The extreme conditions test do not present any alteration, so the new group of rules do not affect the model when it is subject to extreme inputs.

The second performed test generates the surfaces presented by Figure 5.7, Figure 5.8 and Figure 5.9.

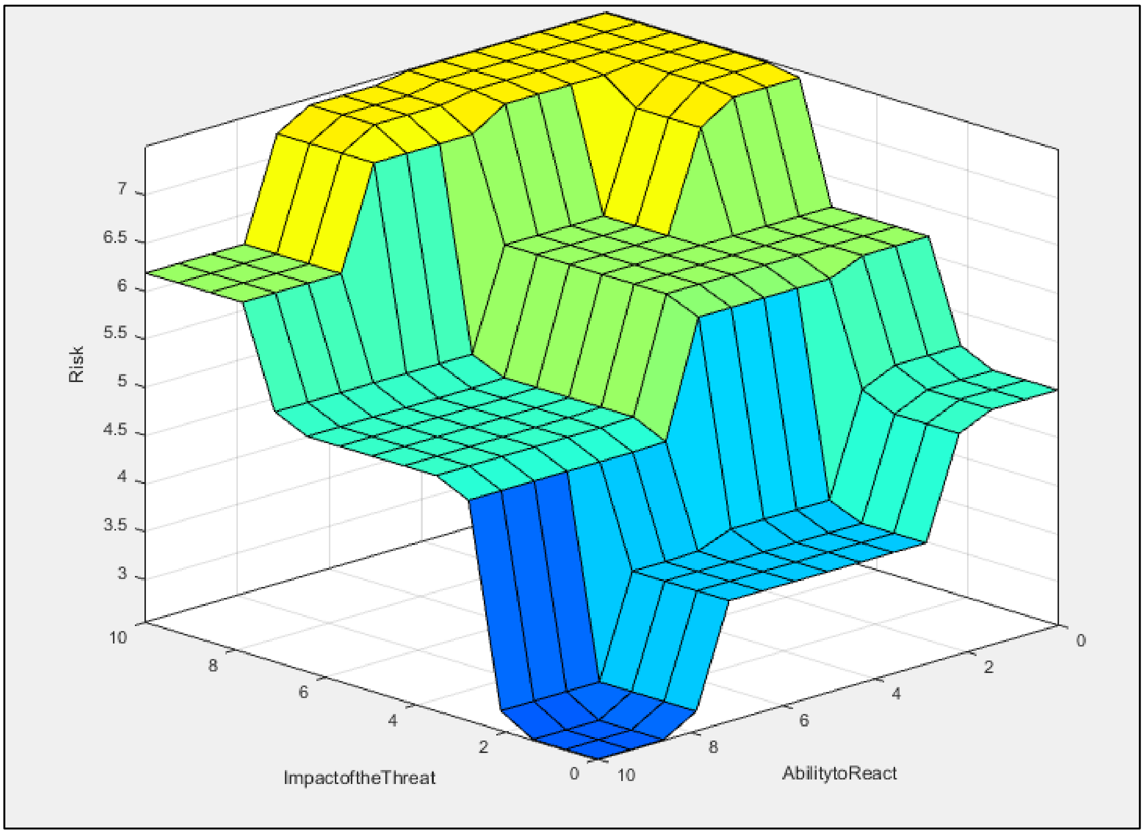



Figure 5.7 – Face validity test on the combination of parameters I and A

Figure 5.7 does not present any imperfection in the surface and has a particularity. The risks value increases with the rise of the impact value and with reduction of the ability value. This is an expected behaviour of the surface. This is also an indicator of the proper functioning of the defined rules. Figure 5.8 does not have any imperfection in the surface, after the implementation of the new rules.

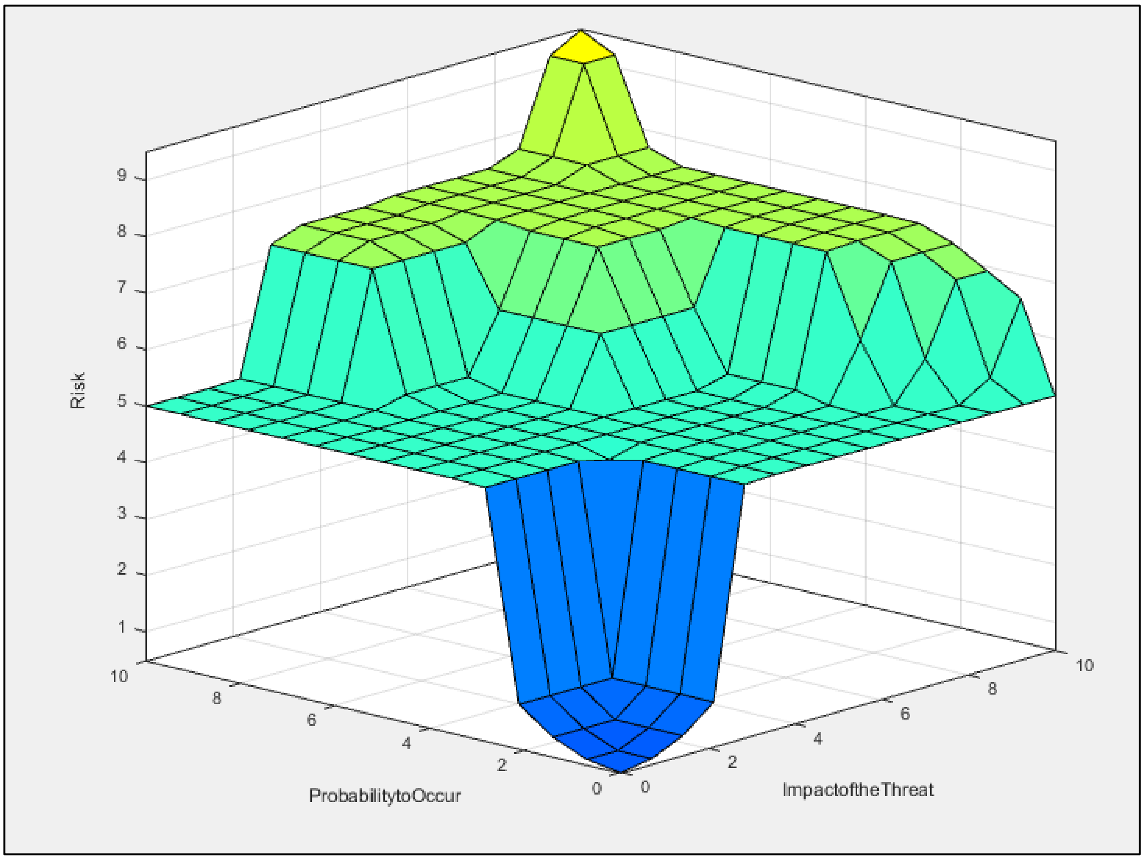



Figure 5.8 – Face validity test on the combination of parameters I and P

On the contrary, Figure 5.8 presents the rise of the risk values with the increment of the probability and impact values. This is also an expected behaviour, since one of the initial assumption is that the RPN value increases when the I and the P values are incremented.

Figure 5.9, similarly to the Figure 5.7 and Figure 5.8, has no imperfections in the surface, after the implementation of the new rules.

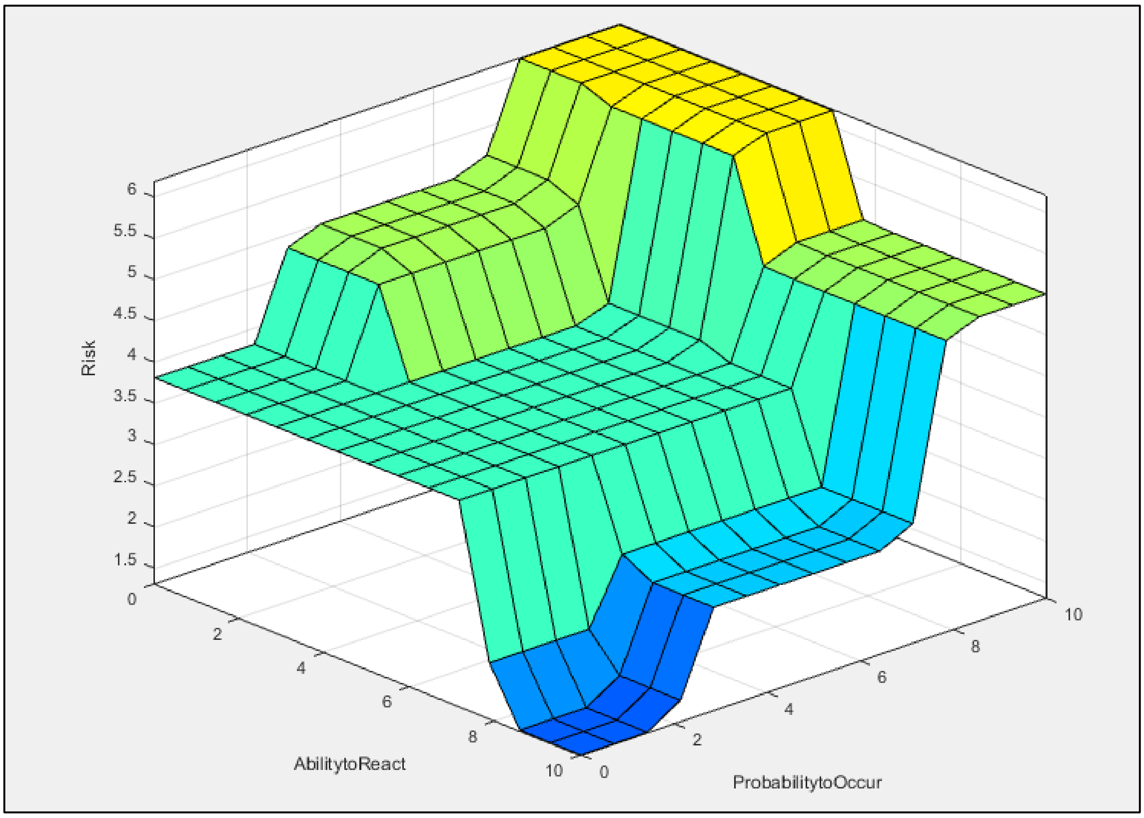



Figure 5.9 – Face validity test on the combination of parameters P and A

Figure 5.9, similarly to Figure 5.7, has the particularity described. The RPN values increase with the increment of the P values and with the reduction of the A values. This is an expected behaviour due to the assumptions made in the previous chapter.

To be confident with that choice is done a second verification of each parameter behaviour. Figure 5.10 presents nine graphics that are representative that analysis. Each row represents a parameter, the first row has the graphical representation of the impact, the second row has the ability and third row has the probability parameter. The constant trend of the graph indicates an adequate behaviour of the system, for instance in the first case, when the ability and probability are fixed in very low and low respectively, the behaviour of the system has a positive tendency increasing the impact value.

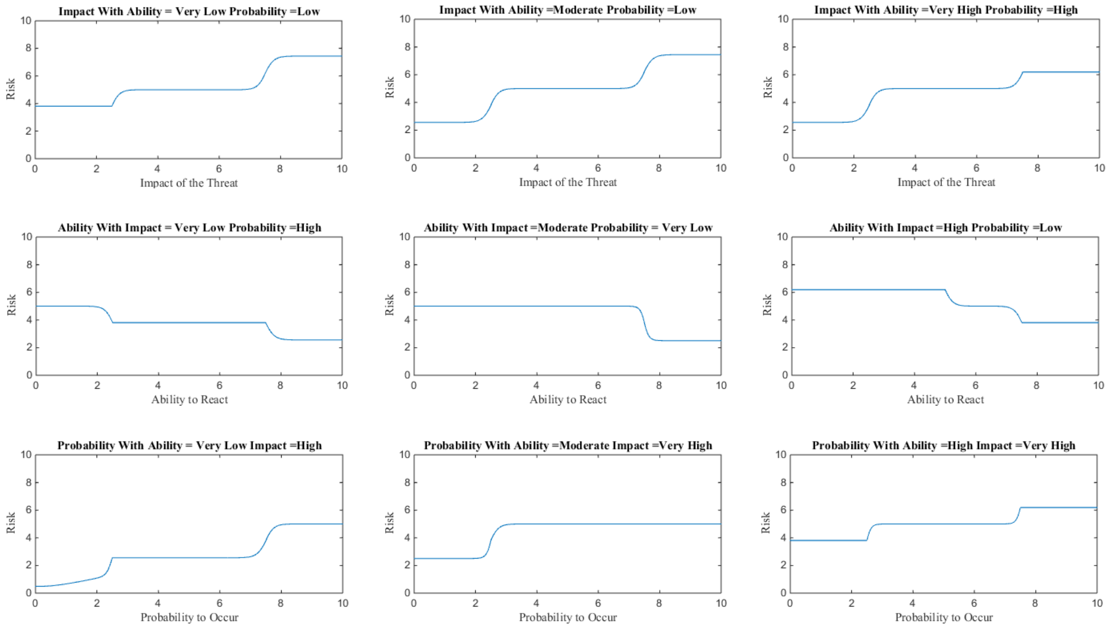



Figure 5.10 – Validation test (iteration 2)

The new rules, not only correct the existent problems, from the first iteration, but also provides a more precise output. This new rules provide also a more realistic perspective over the problem, allowing the model to be more realistic.

## 5.4. Data Aggregation and Consensus-based Model

The Data Aggregation and Consensus-based Model, has the purpose of analysing the data, generated from the Risk Assessment Model. The Risk Assessment Model generates a value for the risk factor per experts. This analysis main objective is to examine the risk of each variable considering all experts' opinion. So it is necessary to determine a consensual value to be ranked.

All experts' opinions are considered equally important, so they have the same weight on the aggregation process. Based on this information, it is considered that the calculation of a simple average and standard deviation, is enough to determine the risk factors rank, once that risks' independency is a presumption of this model. Based on this, the average ($\bar{X}_{RPN}$) is calculated by:

$$\bar{X}_{RPN_i} = \frac{\sum_{i=1}^{n} x_i}{n} \quad (5.2)$$

And it is also determined the sample standard deviation ($S_R$) based on:

$$S_{RPN_i}^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{X}_{RPN})^2}{n-1} \Longrightarrow S_{RPN_i} = \sqrt{S_{RPN_i}^2} \quad (5.3)$$

This model is also developed using FIS. In this model are considered two inputs, Risk Average $(\bar{X}_{RPN_i})$ and the Risk Standard Deviation $(S_{RPN_i})$. The $\bar{X}_{RPN_i}$ is defined by a fuzzy set similar of the input and output parameters in the Risk Assessment Model, but the $S_{RPN_i}$ is defined differently because this parameter does not need to have as much specification as the rest of the parameters. Table 5.9 presents the categories definition for the $S_{RPN_i}$ parameter.

The output of this model is the consensus risk level of the risk factors. This consensus risk level represents the risk level considering all experts opinion and their differences. The fuzzy set used to define this parameter is the same as the $\bar{X}_{RPN_i}$ paramter.

Table 5.8 – Categories' explanation to parameter $S_{RPN_i}$

| Scale | Description |
|---|---|
| L | Low number of the standard deviation – High level of the confidence in the average number. |
| M | Moderate number of the standard deviation – Moderate level of the confidence in the average number. |
| H | High number of the standard deviation – Low level of the confidence in the average number. |

So the $S_{RPN_i}$ parameter is also represented by the fuzzy set presented by Figure 5.11, where are defined it MFs.

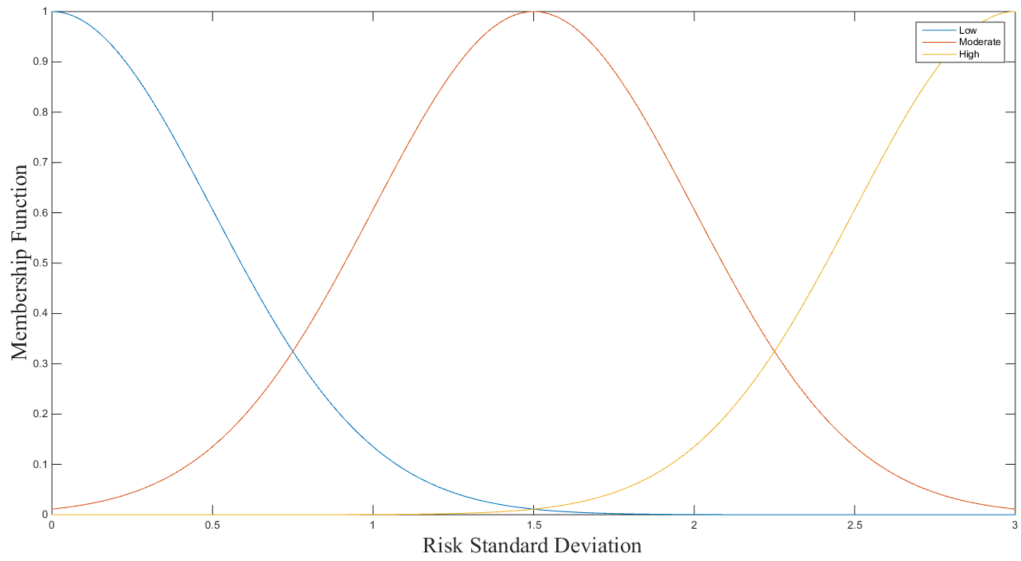



Figure 5.11 – $S_{RPN_i}$ MFs

Similarly to the Risk Assessment Model methodology the FIS is developed. The inference mechanism on the FIS similar to the Risk Assessment Model. The rules for this FIS are defined in Table 5.9. The rules are defined based on the assumption, as lower the standard deviation value is, more reliable the average value of the risk is.

Table 5.9 – List of rules for the Consensus-based Model

| Rule Number | Risk Average | *Op.* | Risk Standard Deviation | Risk Rank |
|---|---|---|---|---|
| 1 | Very High | and | Low | Very High |
| 2 | Very Low | and | High | Very Low |
| 3 | Very Low | and | Low | Low |
| 4 | Very High | and | High | High |

After implement the first group of rules it is necessary to validate the model. The validation process is similar to the procedure used before. The first validation test is the extreme conditions test. Table 5.10 presents the test's results.

Table 5.10 – Results of the consensus-based model extreme conditions' test

| Risk Average | Risk Standard Deviation | Risks Rank |
|---|---|---|
| 0 | 3 | 0,49 |
| 5 | 5 | 5,00 |
| 10 | 0 | 9,51 |

The extreme condition test a good result, being the final results close to the optimal ones. The next test is the behavioural analysis, as proposed in the methodology. Figure 5.12 presents the generated surface, based on Table 5.10 groups of rules.

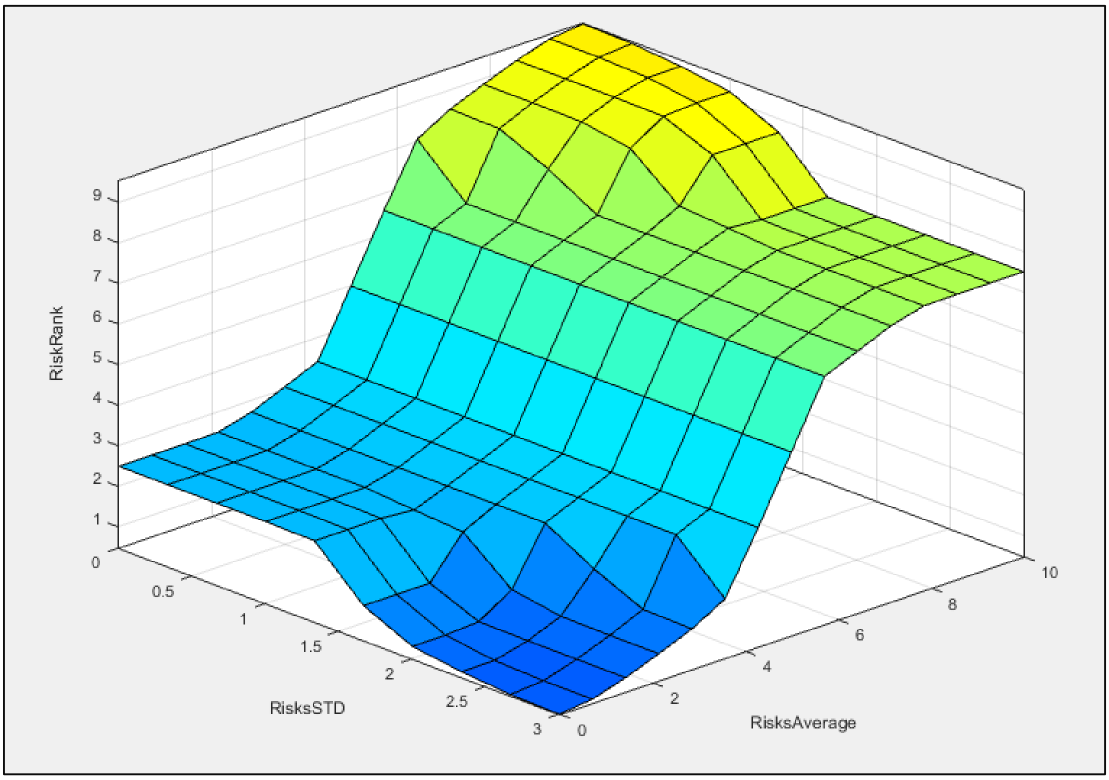



Figure 5.12 – Face validity test on the combination of factors $\bar{X}_{RPN_i}$ and $S_{RPN_i}$

In Figure 5.12 is possible to verify that the surface has no visible imperfections. This surface also presents a particularity, the experts' consensus value rise when the $\bar{X}_{RPN_i}$ value rise and the Risk $S_{RPN_i}$ value decrease, as expected.

To be confident with that choice, it is made a second verification of the behaviour of each parameter. Figure 5.13 presents six graphics that are representative of the behaviour of each parameter. Each row represents a parameter, the first row has the graphical representation of the $\bar{X}_{RPN_i}$ factor and the second row has the $S_{RPN_i}$ factor.

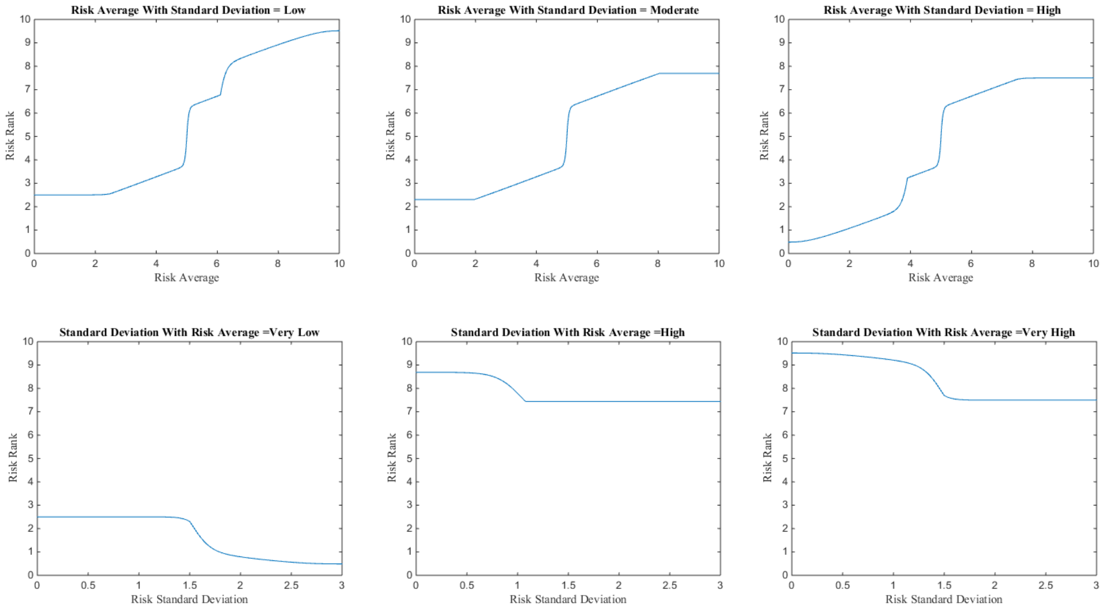



Figure 5.13 – Behavioural test related to the final rules list

As already done to the previous model, a behavioural analysis is done. In all cases it is possible to see the tendencies. For instance, in the first graph, the risk rank has a positive trend increasing the risk average. The constant trends do not generate any irregularity, so there is no evidence that the model is not valid.

So after the risk factor analysis with the risk assessment model, the consensus-based risk model uses the aggregated data, based on the sample average and on the sample standard deviation, and determines the best approach to better solve the potential risks.

# 6

# Risk of Employing an Evolvable Production System (Case Study)

The Risk of Employing an Evolvable Production System (Case Study) chapter is organised as follow:

- Project IDEAS;
- Experts Evaluation and Risk Assessment Quantitative Model Implementation;
- Consensus-based Model – Application;
- Results' Analysis.

In the Project IDEAS a brief description of the project is presented, as well as the motivation behind it choice. In the following subchapters are determined the risk list, and the two developed models are used to determine the final RPN for each risk factors presented in the questionnaire and rank them.

## 6.1. Project IDEAS

IDEAS project (Ribeiro, Barata, Onori, et al., 2011) emerged from a first approach, the EUPASS project (M. Onori, Alsterman, & Barata, 2005), where the Evolvable Production Systems paradigm is presented for the first time. These projects are developed with the purpose of empowering companies, with a sophisticated and intelligent tools, to face new market conditions, emergent market and financial adversities. IDEAS consortium presents a multiagent solution, which allows a self-adaptive and flexible behaviour to manufacturing systems. The proposed solution can be seen as a step forward in the development of manufacturing systems. Those have the capability to re-adapt to unexpected disturbances, such as malfunctions or an unpredictable mix of products on the line.

Modularity and Pluggability are characteristics which play an important role in the presented solution. Through these characteristics the system is easily capable to reconfigure itself. It is possible to add, remove and change modules to and from different positions on the physical layout without require any programming effort. With this capacity, the companies can quickly make changes in the production line and take the maximum advantage of new business opportunities. This approach allows also a minimum number of stoppages on the production and consequently reducing the related costs.

The most appropriate case study must consider several aspects:

- The study should be made based on a recent project;
- The case study should contemplate the project with the most developed areas, so the study can be as much complete as possible;
- The access to experts is an important point to the project's choice.

Project IDEAS contemplates all those points, so it is the most appropriate choice.

## 6.2. Experts Evaluation and Risk Assessment Quantitative Model Implementation

Project IDEAS is a source of information regarding the risks of employing and EPS. So the risk factors collected are mostly based on this project experiences. All the experts' panels are defined according to the best possible way to extract the information efficiently. The first experts' panel, from now on referred as $G_1$ is responsible for the risk factors determination. The second group of experts, from now on referred as $G_2$ is responsible for the risk factors evaluation.

The extracted risk factors, defined in Chapter 5, are evaluated by $G_2$ according to the Annex I questionnaire. The risk factors, represented by $R_i \longrightarrow i = \{1, \dots, 38\}$, where I represents the number of risk factors, are evaluated, by an expert, represented by $E_j \longrightarrow j = \{1, \dots, 6\}$, where j represents the number of experts which answered the questionnaire. Table 6.1 presents the evaluation of the six interviewed experts, for all the risk factors.

Table 6.1 – Risk factor measurement by experts

| $R_i$ | *I* | | | | | | *A* | | | | | | *P* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_5$ | $E_6$ | $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_5$ | $E_6$ | $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_5$ | $E_6$ |
| $R_1$ | M | M | H | L | VH | L | M | M | H | M | H | H | H | H | H | L | H | VL |
| $R_2$ | L | L | L | L | VH | M | L | L | H | L | H | M | M | M | L | L | H | L |
| $R_3$ | H | H | H | H | M | H | M | M | H | VL | VH | M | H | L | H | H | H | L |
| $R_4$ | H | M | H | VH | M | M | L | L | H | H | L | M | VH | H | VL | VH | H | L |
| $R_5$ | VH | VH | VH | M | VH | H | VL | VL | VL | L | H | M | L | L | L | L | L | L |
| $R_6$ | VH | VH | VH | VH | M | VH | VL | VL | M | VH | VH | L | | L | M | L | H | L |
| $R_7$ | M | M | H | M | M | M | H | H | H | M | VH | M | H | H | M | M | M | M |
| $R_8$ | VH | VH | M | L | H | M | L | L | H | L | M | M | H | H | H | L | M | L |
| $R_9$ | H | H | VH | M | VH | L | M | VL | M | M | VL | L | M | L | L | M | H | M |
| $R_{10}$ | VH | VH | M | M | M | L | L | L | H | H | M | H | VH | VH | H | H | M | L |
| $R_{11}$ | M | H | H | L | H | M | H | H | M | L | M | H | H | H | H | H | L | L |
| $R_{12}$ | L | VH | L | VH | VH | H | H | M | H | L | VH | H | M | L | VL | L | L | L |
| $R_{13}$ | L | H | M | M | M | M | H | M | VH | VL | M | H | M | M | L | VL | M | L |
| $R_{14}$ | M | M | M | L | H | M | M | M | H | VL | H | H | L | VL | L | L | M | L |
| $R_{15}$ | M | M | L | L | H | L | M | M | H | VL | H | H | L | VL | M | L | M | L |
| $R_{16}$ | VH | VH | H | L | VH | M | L | M | M | VL | M | M | VH | M | H | H | H | M |
| $R_{17}$ | VH | VH | H | VH | VH | H | L | VL | VH | VH | VL | L | VH | H | H | VH | H | H |
| $R_{18}$ | VH | M | M | M | VH | L | L | H | M | L | VL | H | VH | M | H | H | H | L |
| $R_{19}$ | H | VH | H | L | VH | L | M | M | H | VL | VL | H | H | L | VL | L | L | L |
| $R_{20}$ | H | H | M | L | VH | M | M | M | VH | VL | H | H | H | L | L | L | VL | M |
| $R_{21}$ | L | M | M | L | H | L | H | M | H | VL | H | M | H | H | L | M | M | M |
| $R_{22}$ | VH | VH | VH | L | H | H | L | M | H | VL | H | M | VH | VH | L | L | H | M |
| $R_{23}$ | VH | H | H | M | L | H | L | M | M | L | H | M | VH | VH | H | M | H | M |
| $R_{24}$ | VH | H | M | L | L | H | L | M | H | M | H | M | VH | VH | M | M | H | M |
| $R_{25}$ | VH | H | M | VL | L | H | L | M | M | VL | H | M | VH | VH | L | VL | H | M |
| $R_{26}$ | VH | M | VH | M | H | H | L | M | H | L | H | L | VH | M | H | L | H | H |
| $R_{27}$ | H | H | H | M | VH | H | L | H | M | L | M | M | H | H | M | H | L | M |
| $R_{28}$ | H | H | M | M | H | H | L | H | M | M | M | M | H | H | VH | H | L | M |
| $R_{29}$ | H | H | L | M | H | H | L | H | H | M | M | M | H | H | M | H | L | M |
| $R_{30}$ | H | H | M | M | H | H | L | H | H | M | M | M | H | H | H | H | L | M |
| $R_{31}$ | H | M | H | M | VH | H | L | M | H | M | M | L | H | M | H | H | L | H |
| $R_{32}$ | VH | M | H | H | VH | H | H | H | VH | M | VH | M | L | M | M | VL | VL | H |
| $R_{33}$ | VH | VH | VH | VH | VH | VH | H | H | VH | H | VH | M | L | L | VL | VL | L | H |
| $R_{34}$ | H | M | H | L | M | VH | H | VH | VH | L | H | M | VH | H | H | L | H | M |
| $R_{35}$ | H | M | M | H | VH | VL | H | L | L | L | M | M | VH | H | VH | L | M | VL |
| $R_{36}$ | L | L | M | M | M | L | H | M | H | VL | H | M | L | M | M | L | M | M |
| $R_{37}$ | M | M | H | L | M | L | M | M | M | L | M | M | M | L | M | L | L | M |
| $R_{38}$ | H | H | M | M | H | M | H | M | M | L | L | M | L | L | H | L | M | M |

Each column of Table 6.1 presents the experts' $(E_1, \dots, E_6)$ evaluation of the input parameter $(I, A, P)$ to each risk factor $(R_1, \dots, R_{38})$. The evaluation is done in accordance with the categories defined in Chapter 5. The results of risk assessment model implementation from Table 6.1 are represent by:

$$RPN_{ij} = F(I, A, P) \tag{6.1}$$

Where $i$ represents the risk factor identification number and $j$ represents the experts' identification number. The function $F$ represents the Risk Assessment Model implementation, to all risk factors evaluation, using the developed FIS. Table 6.2 summarises the $RPN_{ij}$ generated form the model's application.

Table 6.2 – Risk level of employing an EPS per expert

| $R_i$ | $RPN_{ij}$ | | | | | |
|---|---|---|---|---|---|---|
| | $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_5$ | $E_6$ |
| $R_1$ | 6,19 | 6,19 | 6,19 | 3,81 | 6,19 | 3,81 |
| $R_2$ | 3,81 | 3,81 | 3,81 | 3,81 | 6,19 | 5,00 |
| $R_3$ | 6,19 | 6,19 | 6,19 | 7,50 | 5,00 | 6,19 |
| $R_4$ | 7,44 | 6,19 | 3,81 | 7,44 | 6,19 | 5,00 |
| $R_5$ | 7,44 | 7,44 | 7,44 | 5,00 | 5,00 | 6,19 |
| $R_6$ | 7,50 | 7,44 | 7,44 | 5,00 | 5,00 | 7,44 |
| $R_7$ | 5,00 | 5,00 | 5,00 | 5,00 | 5,00 | 5,00 |
| $R_8$ | 7,50 | 7,50 | 5,00 | 3,81 | 6,19 | 5,00 |
| $R_9$ | 6,19 | 6,19 | 7,44 | 5,00 | 7,50 | 3,81 |
| $R_{10}$ | 7,50 | 7,50 | 5,00 | 5,00 | 5,00 | 3,81 |
| $R_{11}$ | 5,00 | 6,19 | 6,19 | 5,00 | 6,19 | 3,81 |
| $R_{12}$ | 3,81 | 7,44 | 3,81 | 7,44 | 5,00 | 3,81 |
| $R_{13}$ | 3,81 | 6,19 | 3,81 | 5,00 | 5,00 | 3,81 |
| $R_{14}$ | 5,00 | 5,00 | 3,81 | 3,81 | 5,00 | 3,81 |
| $R_{15}$ | 5,00 | 5,00 | 3,81 | 3,81 | 5,00 | 3,81 |
| $R_{16}$ | 7,50 | 7,44 | 6,19 | 6,19 | 7,44 | 5,00 |
| $R_{17}$ | 7,50 | 7,50 | 6,19 | 7,50 | 7,50 | 6,19 |
| $R_{18}$ | 7,50 | 5,00 | 6,19 | 6,19 | 7,50 | 3,81 |
| $R_{19}$ | 6,19 | 7,44 | 3,81 | 3,81 | 7,44 | 3,81 |
| $R_{20}$ | 6,19 | 6,19 | 3,81 | 3,81 | 5,00 | 5,00 |
| $R_{21}$ | 3,81 | 6,19 | 3,81 | 5,00 | 5,00 | 3,81 |
| $R_{22}$ | 7,50 | 7,50 | 5,00 | 3,81 | 6,19 | 6,19 |
| $R_{23}$ | 7,50 | 7,44 | 6,19 | 5,00 | 3,81 | 6,19 |
| $R_{24}$ | 7,50 | 7,44 | 5,00 | 3,81 | 3,81 | 6,19 |
| $R_{25}$ | 7,50 | 7,44 | 5,00 | 0,49 | 3,81 | 6,19 |
| $R_{26}$ | 7,50 | 5,00 | 6,19 | 5,00 | 6,19 | 6,19 |
| $R_{27}$ | 6,19 | 6,19 | 6,19 | 6,19 | 7,44 | 6,19 |
| $R_{28}$ | 6,19 | 6,19 | 7,44 | 6,19 | 6,19 | 6,19 |
| $R_{29}$ | 6,19 | 6,19 | 3,81 | 6,19 | 6,19 | 6,19 |
| $R_{30}$ | 6,19 | 6,19 | 5,00 | 6,19 | 6,19 | 6,19 |
| $R_{31}$ | 6,19 | 5,00 | 6,19 | 6,19 | 7,44 | 6,19 |
| $R_{32}$ | 5,00 | 5,00 | 5,00 | 5,00 | 5,00 | 6,19 |
| $R_{33}$ | 5,00 | 5,00 | 5,00 | 5,00 | 5,00 | 7,44 |
| $R_{34}$ | 6,19 | 5,00 | 6,19 | 3,81 | 5,00 | 7,44 |
| $R_{35}$ | 6,19 | 6,19 | 7,50 | 6,19 | 7,44 | 0,49 |
| $R_{36}$ | 3,81 | 3,81 | 5,00 | 5,00 | 5,00 | 3,81 |
| $R_{37}$ | 5,00 | 5,00 | 6,19 | 3,81 | 5,00 | 3,81 |
| $R_{38}$ | 3,81 | 6,19 | 6,19 | 5,00 | 6,19 | 5,00 |

The values generated from the model's application belong to the interval $[0{,}00\,;10{,}00]$ (this scale is the same used to define the risk fussy set). Table 6.2 presents the $RPN_{ij}$, where $i$ represents the number of the risk factor, and $j$ the expert's number, concerning each risk factors per expert. So this model is designed to analyse individual experts' evaluation. The use of a second model, an auxiliary model, is required to define the risk level for each risk factors. The used approach, of analysing the experts' evaluation separately, allows two complementary analysis of the consensus level between them. So, to analyse the experts' consensus level it is necessary to aggregate de $RPN_{ij}$. The data aggregation is in accordance with the proposal presented in Chapter 5. To determine $\bar{X}_{RPN_{ij}}$ and $S_{RPN_{ij}}$ values, to each risk factor, presented in Table 6.3, the equations 5.2 and 5.3 were used, from the Conceptual Model Chapter.

Table 6.3 – List of the aggregated risks levels with the respective $\bar{X}_{RPN_{ij}}$ and $S_{RPN_{ij}}$

| $R_i$ | $\bar{X}_{RPN_{ij}}$ | $S_{RPN_{ij}}$ | $R_i$ | $\bar{X}_{RPN_{ij}}$ | $S_{RPN_{ij}}$ |
|---|---|---|---|---|---|
| $R_1$ | 5,40 | 1,23 | $R_{20}$ | 5,00 | 1,07 |
| $R_2$ | 4,40 | 1,00 | $R_{21}$ | 4,60 | 0,97 |
| $R_3$ | 6,21 | 0,79 | $R_{22}$ | 6,03 | 1,44 |
| $R_4$ | 6,01 | 1,42 | $R_{23}$ | 6,02 | 1,43 |
| $R_5$ | 6,42 | 1,20 | $R_{24}$ | 5,62 | 1,68 |
| $R_6$ | 6,64 | 1,27 | $R_{25}$ | 5,07 | 2,66 |
| $R_7$ | 5,00 | 0,00 | $R_{26}$ | 6,01 | 0,93 |
| $R_8$ | 5,83 | 1,49 | $R_{27}$ | 6,40 | 0,51 |
| $R_9$ | 6,02 | 1,43 | $R_{28}$ | 6,40 | 0,51 |
| $R_{10}$ | 5,63 | 1,52 | $R_{29}$ | 5,79 | 0,97 |
| $R_{11}$ | 5,40 | 0,97 | $R_{30}$ | 5,99 | 0,49 |
| $R_{12}$ | 5,22 | 1,78 | $R_{31}$ | 6,20 | 0,77 |
| $R_{13}$ | 4,60 | 0,97 | $R_{32}$ | 5,20 | 0,49 |
| $R_{14}$ | 4,40 | 0,65 | $R_{33}$ | 5,41 | 1,00 |
| $R_{15}$ | 4,40 | 0,65 | $R_{34}$ | 5,61 | 1,27 |
| $R_{16}$ | 6,63 | 1,01 | $R_{35}$ | 5,67 | 2,61 |
| $R_{17}$ | 7,06 | 0,68 | $R_{36}$ | 4,40 | 0,65 |
| $R_{18}$ | 6,03 | 1,44 | $R_{37}$ | 4,80 | 0,90 |
| $R_{19}$ | 5,42 | 1,82 | $R_{38}$ | 5,40 | 0,97 |

The Table 6.4 values are the base for the consensus-based model.

## 6.3. Consensus-based Model – Application

This auxiliary model is created with the goal of ranking the risks, based on a list generated by the risk assessment model. This model presents the risk level which are used to ranks them from the most important risk factors, those are a priority to find a solution, to the less urgent risks. Table 6.4 presents the ranked list of risks, according to the consensus-based model.

Table 6.4 – Risk level generated from the consensus-based model implementation

| $R_i$ | Risk Level $\bar{X}_{RPN_{ij}}$ | $R_i$ | Risk Level $\bar{X}_{RPN_{ij}}$ |
|---|---|---|---|
| $R_1$ | 6,424 | $R_{20}$ | 5,000 |
| $R_2$ | 3,478 | $R_{21}$ | 3,576 |
| $R_3$ | 6,824 | $R_{22}$ | 6,740 |
| $R_4$ | 6,728 | $R_{23}$ | 6,734 |
| $R_5$ | 6,926 | $R_{24}$ | 6,540 |
| $R_6$ | 7,033 | $R_{25}$ | 5,985 |
| $R_7$ | 5,000 | $R_{26}$ | 6,728 |
| $R_8$ | 6,643 | $R_{27}$ | 6,914 |
| $R_9$ | 6,734 | $R_{28}$ | 6,914 |
| $R_{10}$ | 6,546 | $R_{29}$ | 6,619 |
| $R_{11}$ | 6,424 | $R_{30}$ | 6,717 |
| $R_{12}$ | 6,331 | $R_{31}$ | 6,817 |
| $R_{13}$ | 3,576 | $R_{32}$ | 6,312 |
| $R_{14}$ | 3,478 | $R_{33}$ | 6,430 |
| $R_{15}$ | 3,478 | $R_{34}$ | 6,527 |

| $R_i$ | Risk Level $\overline{X}_{RPN_{ij}}$ | $R_i$ | Risk Level $\overline{X}_{RPN_{ij}}$ |
|---|---|---|---|
| $R_{16}$ | 7,028 | $R_{35}$ | 6,561 |
| $R_{17}$ | 7,604 | $R_{36}$ | 3,478 |
| $R_{18}$ | 6,740 | $R_{37}$ | 3,688 |
| $R_{19}$ | 6,437 | $R_{38}$ | 6,424 |

This model aims to rank the risks according the level of consensus between the experts, presented by $S_{RPN_{ij}}$ and in accordance with the risk level presented by the $\overline{X}_{RPN_{ij}}$.

## 6.4. Results' Analysis

The Results' Analysis chapter is divided in two complementary but different analysis. The first is an intermediate analysis whose purpose is to measure the risk assessment model results. The second analysis consists on an interpretation of results from the implementation of both models. In accordance with the defined proposed methodology a first analysis is done. The purpose of the analysis of the aggregated results from the risk assessment model is to identify the consensus level of the six experts for the Vulnerable Areas and for the Risk Classification.

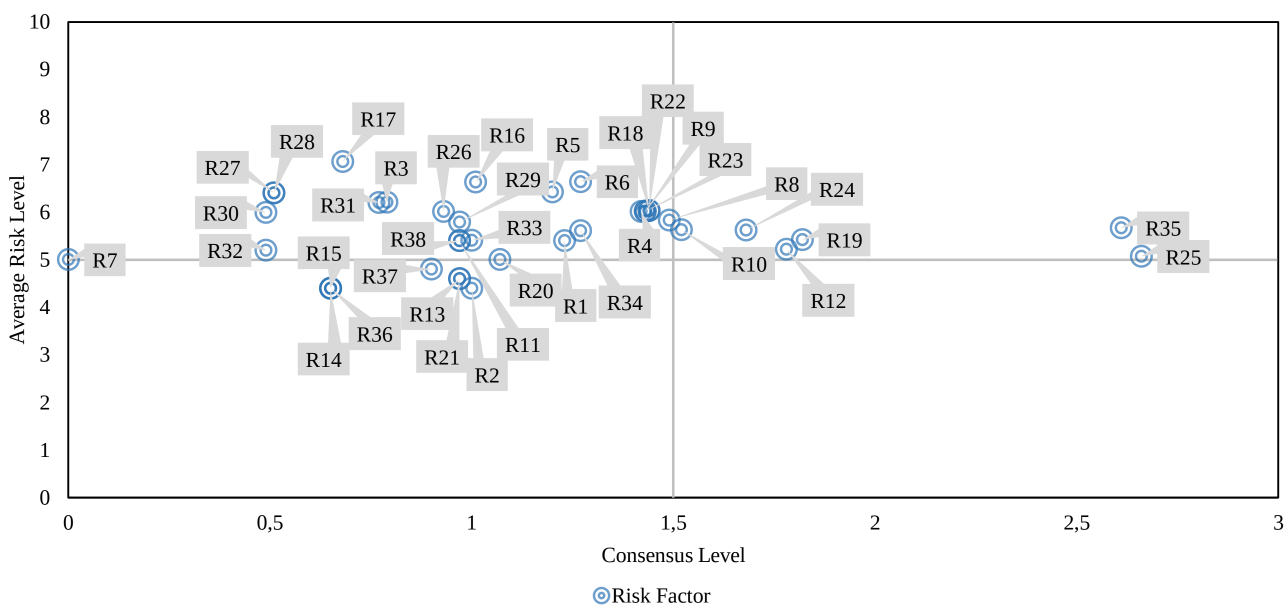



Figure 6.1 – Relation between the average risk and the consensus level

Figure 6.1 presents a graphical representation of the average risk level and consensus level. The risk level is higher as higher is the value presented on it axis. The horizontal line presented in the graphic, defines the middle level of the risk factor average, so in between 0 and 5 the risk is considered low, in between 5 and 10 the risk is considered high. Similarly to the risk average, the consensus level is higher as lower is the value presented on it axis. The vertical line is the middle level of the consensus level, so between 0 and 1,5 the experts' consensus is considered high, between 1,5 and 3 the level in considered low.

Figure 6.1 presents two risk factors, $R_{25}$: Inadequate integration with the existing simulation tools, and $R_{35}$: Entry and exit order of products cannot be assured, are the risks that presents the less consensus among experts, although there are some other risk factors that present also a high level of uncertainty.

This discrepancies on the experts' evaluation may be related with two factors, the first factor is the fact that all experts have different know-how regarding the development and implementation of an EPS, the second factor may be associated to how expert responded to the questionnaire, adopting a more conservative or more optimistic view over this challenges.

On the other hand $R_7$: Inadequate quantity of controllers is the risk where all experts agree in terms of the evolution of all parameters $(I, A, P)$ (Figure 6.1). This is the only risk factor where is some consensus on the evaluation because this is the most discussed subject of the EPS paradigm.

It is also possible to visualise that the majority of the risk factors' are located on the first charts' quadrant. This information represents a high risk level to the employment of an EPS. This information is analysed this way since the first quadrant is where the experts' consensus level is high and the risk level is also high.

This is a complementary analysis, being the most accurate results given by the consensus-based model. Table 6.5 presents the order of solving the risk factors.

Table 6.5 – Risk factors ranking based on the consensus-based model

| ***Ranking*** $\bar{X}_{RPN_{ij}}$ | $R_i$ | ***Ranking*** $\bar{X}_{RPN_{ij}}$ | $R_i$ |
|---|---|---|---|
| 1 | $R_{17}$ | 20 | $R_{24}$ |
| 2 | $R_6$ | 21 | $R_{34}$ |
| 3 | $R_{16}$ | 22 | $R_{19}$ |
| 4 | $R_5$ | 23 | $R_{33}$ |
| 5 | $R_{27}$ | 24 | $R_1$ |
| 6 | $R_{28}$ | 25 | $R_{11}$ |
| 7 | $R_3$ | 26 | $R_{38}$ |
| 8 | $R_{31}$ | 27 | $R_{12}$ |
| 9 | $R_{18}$ | 28 | $R_{32}$ |
| 10 | $R_{22}$ | 29 | $R_{25}$ |
| 11 | $R_{23}$ | 30 | $R_7$ |
| 12 | $R_9$ | 31 | $R_{20}$ |
| 13 | $R_{26}$ | 32 | $R_{37}$ |
| 14 | $R_4$ | 33 | $R_{13}$ |
| 15 | $R_{30}$ | 34 | $R_{21}$ |
| 16 | $R_8$ | 35 | $R_2$ |
| 17 | $R_{29}$ | 36 | $R_{14}$ |
| 18 | $R_{35}$ | 37 | $R_{15}$ |
| 19 | $R_{10}$ | 38 | $R_{36}$ |

According to the application of this auxiliary model the three most demanding risks that should be solved are $R_{17}$: Inertia to start the paradigm's transition, $R_6$: Shutdown of all PS (related with power cuts), and $R_{16}$: Unspecialised system's integrators, by this order. On the other side are the less urgent risk that need a solution $R_{14}$: Unperformed maintenance, in the PL, $R_{15}$: Insufficient maintenance performed in the PL and $R_{36}$: Increases human error in implementation (Table 6.5). Figure 6.2 presents the risks percentage, according to each vulnerable area, present in the first half of the ranks.

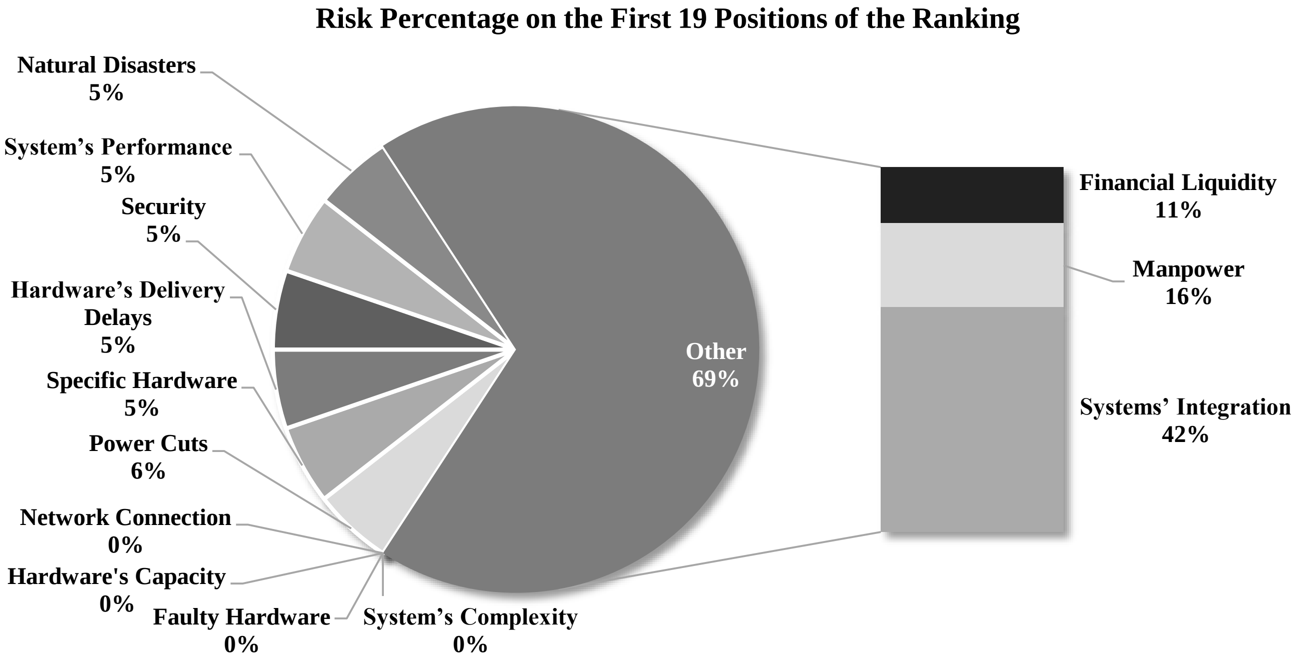



Figure 6.2 – Risk percentage, associated with the vulnerable areas, on the first 19 positions of the ranking

In order to present a more complete analysis of the results, Figure 6.3 presents the risk factors' number to each vulnerable area (conceptual model 1).

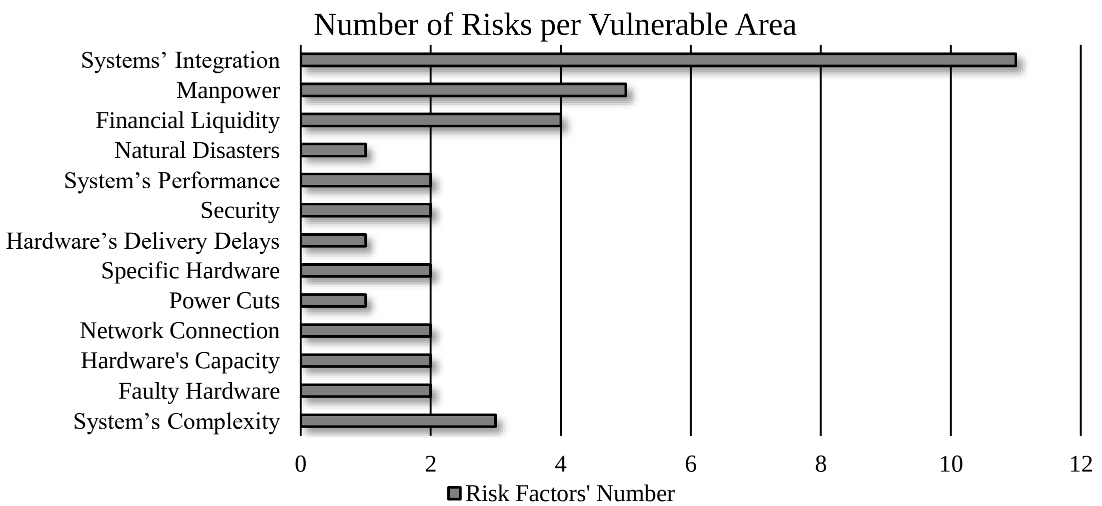



Figure 6.3 – Number of risk factors for each Vulnerable Area

Analysing both Figure 6.2 and Figure 6.3 simultaneously, it is possible to claim that the Human class is the most vulnerable one. This class presents the largest percentage of risk factor with highest RPN values and also have the highest percentage of risk factors, 45% of the variables' total. This class has also the largest variability in terms of the experts' consensus. As mentioned before this is a conservative and superficial analysis, since all the factors associated to this analysis are not being considered. Figure 6.2 presents the risks percentage, according to each vulnerable area, presented on the first half of the ranks.

According to Figure 6.2, on the first half of the defined ranking the Network Connection, the Hardware's Capacity, the Faulty Hardware and the Systems' Complexity areas with 0% of risk present on the first half of the ranking. The Natural Disasters, the System's Performance, the Security, the Hardware's Delivery Delays, the Specific Hardware and the Powers Cuts areas represent 31% of the 19 first position of the ranking. Finally 69 % of the risks are represented by the Financial Liquidity, the Manpower and the Systems' Integration areas.

The Financial Liquidity area is represented by 11% of risks, which corresponds to 50% of this area. The Manpower area has 16% of the 19 positions of the rank, and it corresponds to 60%of this area. The largest percentage is associated with the Systems' Integration area with 42% of the 19 first position of this ranking, and it corresponds to a 73% of the total of risk factors from this area.

The same analysis is done to the risk classification. Figure 6.4 presents the risks percentage, according to each risk classification, present in the first half of the ranks.

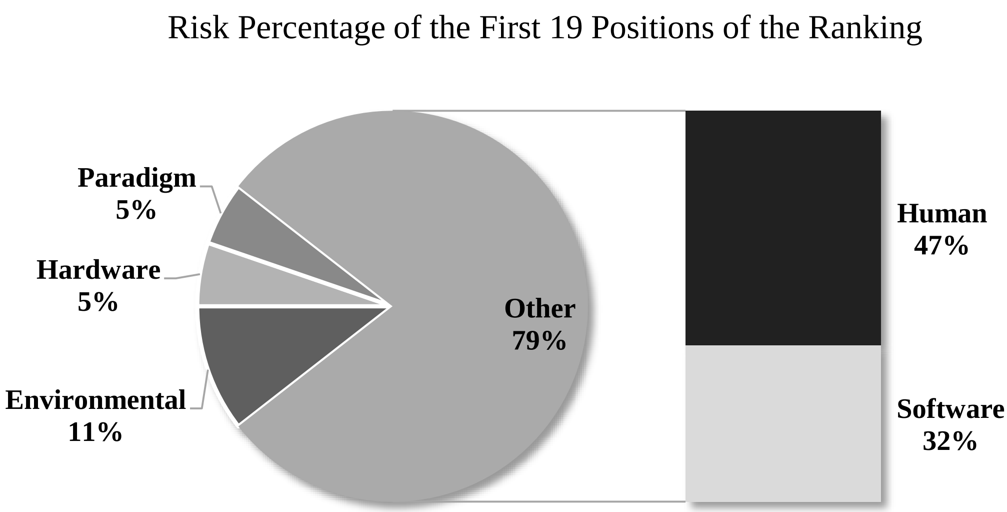



Figure 6.4 – Risk percentage, associated with the risk classification, on the first 19 positions of the ranking

In order to present a more complete analysis of the results, Figure 6.5 presents the risk factors' number to each risk classification (conceptual model 2).

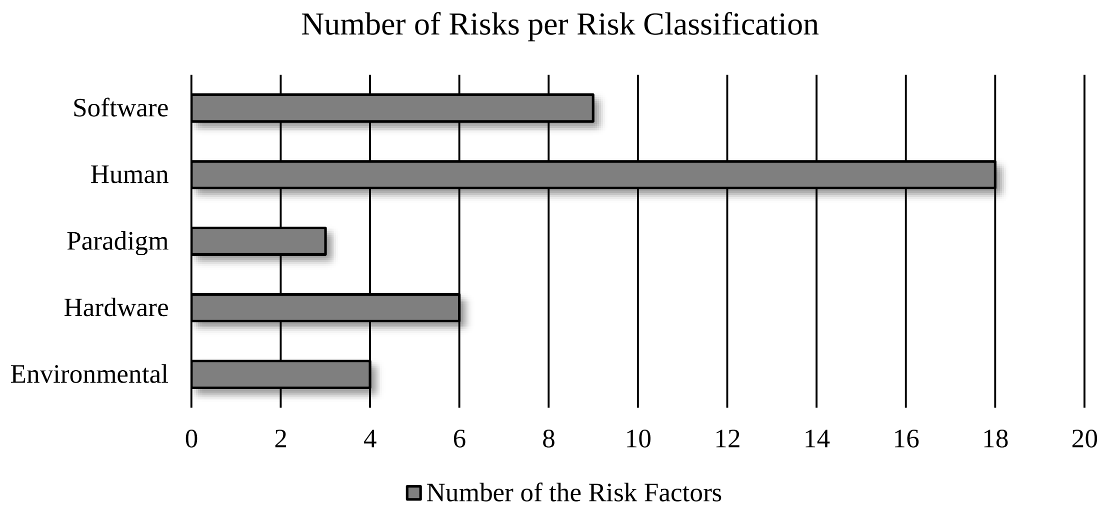



Figure 6.5 – Number of risk factors related with to each Risk Classification

On the first half of the defined ranking the classes Paradigm, Hardware and Environmental represent 21% from the total positions number, and 79% of the places are related with the Human and the Software classes. The Software class is represented with 32% of risk, and it corresponds to a total 67% of risks associated to this class. With the largest percentage of the risks is the Human class, with 47% of the first 19 positions, and it represents a total of 56% of this class.

# 7

# Discussion and Further Work

## 7.1. Discussion

The Evolvable Production System is a new trend in agile manufacturing systems with the goal of help companies achieving their targets, in an operational level. This emergent paradigm aims to offer a new competitive advantage to companies which operate in an unstable and unpredictable market. Although there are some proofs of the applicability of the EPS paradigm, it still need some improvements in several areas.

New technologies need some time to be improved, to develop a stable and marketable version. For companies, in general, changing from traditional technology to the new fashioned technology is a hard decision. To survive in an uncertain environment and deal with radical changes in the business, there is no conservative option. It's always important to recognise the challenges and threats, classify them and try to find relevant solutions to tackle the risks. This could help to minimise the probability of failure for implementing new technology.

This dissertation presents an overview on the main characteristics of this paradigm and also on the main challenges of employing it. There are several important characteristics of EPSs. Evolvable Production Systems make usage of the recent evolution on the available IT and controllers. This evolution brings, through the researches and develops, the possibility of create intelligence on the resource level, the lowest level on the Shop Floor. The EPS uses entities, running on each device, to guarantee a very fine granularity. This approach brings cost effective modular approach allowing the possibility to plug and unplug devices in runtime without stoppages and programming effort to the system.

A fully distributed approach creates another challenges, not verified in the usual centralised approaches. This necessity obliges an assurance in terms of a cooperation and collaboration between resources without a highest level entity. The capacity to analyse and cooperate with other resources offers the ability to emerge new capabilities and bring constant evolution to the system, according to resources availability on the systems and the current context. In start, the Evolvable Production Systems are self-organised systems capable to adapt and adjust to disturbances and changes.

Although all these characteristics are major advantages of this paradigm in relation with others, it is necessary to study the potential risks in order to improve the final work. This dissertation objective is the identification of the potential threats of employing an EPS. The objective is also to design a methodology that allows the risks evaluation. Regarding this two points, a methodology is developed, in three parts. First, is developed a method to identify and classify the risks. Then a conceptual model is developed, to evaluate the threat that does risks may represent to companies. Finally, the risks are ranked.

In order to evaluate the risk factors presented on the conceptual model, three key parameters are used. The impact of that threat (I), the ability that a company has of reacting (A) and finally the probability that it has to occur (P). The parameters I and P are the most commonly used on the risk assessment area, although the use of the third one, A, is really important on this analysis, because companies only can adopt this emergent technology if they have the ability to overcome the risks.

To determine the risk level to the risk factors is defined the Risk Assessment Model which uses the three defined parameters to generate a RPN through the use of a FIS. The generated values $(RPN_{ij})$, are firstly aggregated and then analysed. This approach has an advantage, if there are more evaluations done by new experts, it is possible to apply the model without being necessary to start from the zero point, so this is a versatile model.

The aggregation method is based on a simple sample average $\left(\bar{X}_{RPN_i}\right)$ and a sample standard deviation $\left(S_{RPN_i}\right)$. In this method all experts have the same weight, so no experts is considered to have more knowledge about this emergent paradigm than other. Although this assumption might be the most "politically correct", it not demonstrate the reality. The experts' majority is still working with this new technology, although two of the experts worked on this methodology only for the projects period. So, the information provided by this two experts is more limited because they did not follow it development. The other four experts are in the academic world, and work on EPSs' development so they have a different perspective of this subject.

Based on the data aggregation it is possible to identify the risk factors where experts are not unanimous. Risk factors $R_{25}$: Inadequate integration with the existing simulation tools, and $R_{35}$: Entry and exit order of products cannot be assured, are those which have the less consensus among experts. On the other side, risk factor $R_7$: Inadequate quantity of controllers, is the one where all experts have consensus. Although those three cases are the most visible ones, it is possible to verify that are several risk factors where experts do not agree. Another interesting characteristic of this first analysis it the possibility to verify that the majority of the risk factors' average is distributed in a short range, mostly in between 5 and 7. This may happens due to two interrelated situation. First the used aggregation method, a simple average, which may cause this event. Second, the answers may be really different, so with the adopted method the middle value tends to be similar to all risk factors. Although this second reason may by dismiss since the risk factors majority are placed under the medium consensus level, which means that the experts are almost unanimous on the risk factors' evaluation

After the data aggregation the, Consensus-based Model is applied. This model establishes the final risk factors' level based on the two previous inputs, the $\bar{X}_{RPN_i}$ and the $S_{RPN_i}$. This model provides the risk level based on the risk factor evaluation and on the experts level of consensus. The results of this model are influenced by an important factor, although one of the experts is currently in the business world, the presented perspective may be influence by the academic vision, since the available contacts were done during the development of the master thesis. The rest of the experts are also related directly the academic world.

Analysing the consensus-based model results, it is possible to conclude that from the three first places two are related with Manpower vulnerable area to the Human class. The risk factors of those three first places of the ranking are the $R_{17}$: Inertia to start the paradigm's transition, the $R_6$: Shutdown of all PS (related with power cuts), and the $R_{16}$: Unspecialised system's integrators. Table 6.5 presents the full rank. Based on that ranking, there are several conclusions that may be considered.

Considering half of the risk factors, 19, mentioned on Table 6.5, which are the effective ones, there are some conclusion that be done.

The most vulnerable areas, according to the experts' evaluation, representing a total of 69%, are the Systems' Integration, the Manpower and the Financial Liquidity, with 42%, 16% and 11%, respectively, of those 19 risk factors. The Systems' Integration area have 73% of the risk present in those 19 positions, the Manpower have 60% and the Financial Liquidity area have 50% of it associated risk factors on those positions. The remaining areas are represented by the residual 31% with representative percentages no higher than 5%, or even 0% (Figure 6.2).

From the risk classification point of view, the most threaten classes are the Human and the Software, represented by 79% of the first 19 positions. The Human class represents 47% of the total, the Software represents 32%. The percentage of the Human class risk factors present on those positions correspond to 56%. The Software class have 67% of its risk factors on those 19 position.

Analysing all values as a unit, it is possible verify that the Human area is seen by experts as the most susceptible to potential failures. The risk related to this area can be reduced through formation of new experts on this new technology. Another improvement is to create more awareness around companies and make them to understand that this new technology is being developed to make production easier to businesses from emergent and/or unstable markets. It is important also to inform more the companies about the potentialities of this emergent technology, but also present studies, similar to the present one, to make companies confident that the progress is being thoughtfully done.

To overcome the Inertia challenge there are some adaptations to this emergent paradigm that are being developed. Project PRIME is the most recent developed technology that uses EPS to deploy components in real time. The PRIME's architecture has particularity, it work with different standard technology (A. D. Rocha, Barata, Di Orio, Santos, & Barata, 2015). This can be seen as a first approach to the implementation of this emergent paradigm on the shop floor.

## 7.2. Further Work

The present model should be also applied to project PRIME in order to do the same analysis done to project IDEAS. This would increase the risk factors knowledge base of this risk assessment methodology.

This is the first risk assessment work developed around EPS, so there are some improvements that can be implemented. The first improvement involves the risk factors gathering, during a projects' implementation. Using this method, it is possible identify more risk factors. This method allows the possibility of having an easier access to experts' answers on the evaluation process. It is difficult to have access to the experts' information during the risk factors detection process, due to several factors, distance, time zone and mostly the experts' priorities, their jobs, personal life and others. So, using this approach, to detect all the presented risk factors, all experts do not need to take their free time to identify the potential threats.

Another important point is also the diversification of the experts. All the evaluation presented on this dissertation are done by academic experts. So, to enlarge the risk factors knowledge base, it is important to have experts with other backgrounds, e.g. from the manufacturing business, presenting different/new types of risks and evaluating them.

An additional advancement is the model's definition improvement. The evaluation of the risk factors is defined based on the presumption that all risk factors are independent from each other. In reality this is not true, because in fact there are several risk that may potentiate the emergence of other(s). Or on the other way, one risk factor may inhibit the occurrence of some other risks. So to detect this interdependencies it is important to adopt a method which correlates all the risk factors.

Lastly, the most important part is the development and implementation of a risk management method. Although most of the risk were already detected by experts, some of them were discovered with the present study. So, it is important to define a strategy to solve, analyse control the evolution of those risk and emergence of new ones.

# Bibliography

Akillioglu, H., & Onori, M. (2011). Evolvable production systems and impacts on production planning. In *Proceedings - 2011 IEEE International Symposium on Assembly and Manufacturing, ISAM 2011*. http://doi.org/10.1109/ISAM.2011.5942328

Antzoulatos, N., Castro, E., Scrimieri, D., & Ratchev, S. (2014). A multi-agent architecture for plug and produce on an industrial assembly platform. *Production Engineering*, *8*(6), 773–781. http://doi.org/10.1007/s11740-014-0571-x

Aven, T. (2010). On how to define, understand and describe risk. *Reliability Engineering & System Safety*, *95*(6), 623–631.

Babiceanu, R., & Chen, F. (2006). Development and applications of holonic manufacturing systems: a survey. *Journal of Intelligent Manufacturing*, *17*, 111–131. http://doi.org/10.1007/s10845-005-5516-y

Bitaraf, S. (2011). *Risk Assessment and Decision Support*. Retrieved from http://publications.lib.chalmers.se/records/fulltext/146565.pdf

Boyce, C., & Neale, P. (2006). CONDUCTING IN-DEPTH INTERVIEWS: A Guide for Designing and Conducting In-Depth Interviews for Evaluation Input. Retrieved from http://www2.pathfinder.org/site/DocServer/m_e_tool_series_indepth_interviews.pdf

Chang, K.-H., & Cheng, C.-H. (2010). A risk assessment methodology using intuitionistic fuzzy set in FMEA. *International Journal of Systems Science*, *41*(12), 1457–1471.

Chapman, C., & Ward, S. (1996). Project risk management: processes, techniques and insights.

Commission, E. (2013). *Factories of the Future - Multi-annual roadmap for contractual PPP under Horizon 2020*.

Creswell, J. W. (2013). *RESEARCH DESIGN Qualitative, Quantitative. and Mixed Methods Approaches*. (C. D. Laughton, V. Novak, D. E. Axelsen, & A. J. Sobczak, Eds.) (Second). SAGE Publications.

De Wolf, T., & Holvoet, T. (2005). Emergence versus self-organisation: Different concepts but promising when combined. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* (Vol. 3464 LNAI, pp. 1–15). http://doi.org/10.1007/11494676_1

El Maraghy, H. A. (2006). Flexible and reconfigurable manufacturing systems paradigms. In *Flexible Services and Manufacturing Journal* (Vol. 17, pp. 261–276). http://doi.org/10.1007/s10696-006-9028-7

Elkins, D. A., Huang, N., & Alden, J. M. (2004). Agile manufacturing systems in the automotive industry. *International Journal of Production Economics*, *91*, 201–214. http://doi.org/10.1016/j.ijpe.2003.07.006

Frei, R., Barata, J., & Onori, M. (2007). Evolvable production systems context and implications. In *IEEE International Symposium on Industrial Electronics* (Vol. 00, pp. 3233–3238).

Frei, R., Ribeiro, L., Barata, J., & Semere, D. (2007). Evolvable Assembly Systems: Towards User Friendly Manufacturing. In *Assembly and Manufacturing, 2007. ISAM '07. IEEE International Symposium on* (pp. 288–293). http://doi.org/10.1109/ISAM.2007.4288487

Galan, R., Racero, J., Eguia, I., & Garcia, J. (2007). A systematic approach for product families formation in Reconfigurable Manufacturing Systems. *Robotics and ComputerIntegrated Manufacturing*, *23*(5), 489–502. http://doi.org/10.1016/j.rcim.2006.06.001

Goldstein, J. (1999). *Emergence as a Construct: History and Issues*. *Emergence* (Vol. 1). http://doi.org/10.1207/s15327000em0101_4

Gou, L. G. L., Luh, P. B., & Kyoya, Y. (1997). Holonic manufacturing scheduling: architecture, cooperation mechanism, and implementation. In *Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics*. http://doi.org/10.1109/AIM.1997.652897

Gunasekaran, A. (1998). Agile manufacturing: Enablers and an implementation framework. *International Journal of Production Research*, *36*, 1223–1247. http://doi.org/10.1080/002075498193291

Gunasekaran, A. (1999). Design and implementation of agile manufacturing systems. *International Journal of Production Economics*, *62*, 1–6. http://doi.org/10.1016/S0925-5273(98)00216-3

Guyonnet, D., Bourgine, B., Dubois, D., Fargier, H., Co‸me, B., & Chilès, J.-P. (2003). Hybrid Approach for Addressing Uncertainty in Risk Assessments. *Journal of Environmental Engineering*, *129*(1), 68–78. http://doi.org/10.1061/(ASCE)0733-9372(2003)129:1(68)

Herrmann, C., Schmidt, C., Kurle, D., Blume, S., & Thiede, S. (2014). Sustainability in Manufacturing and Factories of the Future. *International Journal of Precision Engineering and Manufacturing-Green Technology*, *1*(4), 283–292.

Holton, G. A. (2004). Defining risk. *Financial Analysts Journal*, *60*(6), 19–25.

Jager, R. (1995). *Fuzzy Logic in Control*. Delft University of Technology, Delft, The Netherlands. Retrieved from http://www.ohio.edu/people/starzykj/network/Class/ee690/Machine Self-organization and Learning/Reasearch Papers/Fuzzy Logic Jager Professorship.pdf

Kales, P. (1998). *Reliability: for technology, engineering, and management*. Pearson College Division.

Kaplan, S., Garrick, B. J., Kaplin, S., & Garrick, G. J. (1981). On the quantitative definition of risk. *Risk Analysis*, *1*(1), 11–27. http://doi.org/10.1111/j.1539-6924.1981.tb01350.x

Khanmohammadi, S., Rezaie, K., Jassbi, J., & Tadayon, S. (2012). A model of the failure detection based on fuzzy inference system for the control center of a power system. *Appl. Math. Sci*, *6*(36), 1747–1758.

Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G., & Van Brussel, H. (1999). Reconfigurable Manufacturing Systems. In *CIRP Annals - Manufacturing Technology* (Vol. 48, pp. 527–540). http://doi.org/10.1016/S0007-8506(07)63232-6

Kristensen, V., Aven, T., & Ford, D. (2006). A new perspective on Renn and Klinke's approach to risk evaluation and management. *Reliability Engineering & System Safety*, *91*(4), 421–432.

Leitão, P. (2009). Agent-based distributed manufacturing control: A state-of-the-art survey. *Engineering Applications of Artificial Intelligence*, *22*(7), 979–991.

Leitão, P., Barbosa, J., & Trentesaux, D. (2012). Bio-inspired multi-agent systems for reconfigurable manufacturing systems. In *Engineering Applications of Artificial Intelligence* (Vol. 25, pp. 934–944). http://doi.org/10.1016/j.engappai.2011.09.025

Leitão, P., & Restivo, F. (2006). ADACOR: A holonic architecture for agile and adaptive manufacturing control. *Computers in Industry*, *57*(2), 121–130. http://doi.org/10.1016/j.compind.2005.05.005

Lucena, C. I. M. de. (2012). Aplicação de técnicas de controlo óptimo difuso em ambientes distribuídos.

Maffei, A., Akillioglu, H., & Flores, L. (2013). Characterization of costs and strategies for automation in evolvable production systems. In *Proceedings - 2013 IEEE International Conference on Systems, Man, and Cybernetics, SMC 2013* (pp. 4866–4871). http://doi.org/10.1109/SMC.2013.828

Maffei, A., Neves, P., & Onori, M. (2013). Identification of the value proposition of an evolvable production system. In *2013 9th International Symposium on Mechatronics and Its Applications, ISMA 2013*. http://doi.org/10.1109/ISMA.2013.6547366

Markowski, A. S., & Mannan, M. S. (2008). Fuzzy risk matrix. *Journal of Hazardous Materials*, *159*(1), 152–157. http://doi.org/10.1016/j.jhazmat.2008.03.055

Mehrabi, M. G., Ulsoy, A. G., & Koren, Y. (2000). Reconfigurable manufacturing systems and their enabling technologies. *International Journal of Manufacturing Technology and Management*, *1*, 114. http://doi.org/10.1504/IJMTM.2000.001330

National Research Council. (1983). *Risk Assessment in the Federal Government: Managing the Process*. National Academy Press.

National Research Council. (2002). *Cybersecurity Today and Tomorrow: Pay Now or Pay Later*. Retrieved from http://citadel-information.com/wp-content/uploads/2012/08/cybersecurity-today-and-tomorrow-pay-now-or-pay-later-national-research-council-2002.pdf

Neves, P., & Barata, J. (2009). Evolvable production systems. *2009 IEEE International Symposium on Assembly and Manufacturing*. http://doi.org/10.1109/ISAM.2009.5376907

Nunes, I. L. (2010). Handling Human-Centered Systems Uncertainty Using Fuzzy Logics–A. *The Ergonomics Open Journal*, *3*, 38–48.

Oliveira, J. (2003). *Coalition based approach for shop floor agility – A multiagent approach*. Retrieved from http://run.unl.pt/handle/10362/2483

Onori, M., Alsterman, H., & Barata, J. (2005). An architecture development approach for evolvable assembly systems. *(ISATP 2005). The 6th IEEE International Symposium on Assembly and Task Planning: From Nano to Macro Assembly and Manufacturing, 2005.* http://doi.org/10.1109/ISATP.2005.1511444

Onori, M., Barata, J., & Frei, R. (2006). Evolvable Assembly Systems Basic Principles. In *Information Technology For Balanced Manufacturing Systems SE - 34* (Vol. 220, pp. 317–328). Springer US. http://doi.org/10.1007/978-0-387-36594-7_34

Pereira, Z. L., & Requeijo, J. G. (2008). *Qualidade: Planeamento e controlo estatístico de processos*. *Fundamentos do Desenho de Experiências, 1a edição, Prefácio, Caparica*.

PMI. (2009). *Practice Standard for Project Risk Management*. *Practice Standard for Project Risk Management* (4th Editio).

Ribeiro, L., & Barata, J. (2011). Re-thinking diagnosis for future automation systems: An analysis of current diagnostic practices and their applicability in emerging IT based production paradigms. *Computers in Industry*. http://doi.org/10.1016/j.compind.2011.03.001

Ribeiro, L., Barata, J., Cândido, G., & Onori, M. (2010). Evolvable Production Systems: An Integrated View on Recent Developments. In G. Huang, K. L. Mak, & P. Maropoulos (Eds.), *Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology SE - 65* (Vol. 66, pp. 841–854). Springer Berlin Heidelberg. http://doi.org/10.1007/978-3-642-10430-5_65

Ribeiro, L., Barata, J., Onori, M., Hanisch, C., Hoos, J., & Rosa, R. (2011). Self-organization in automation-the IDEAS pre-demonstrator. *IECON 2011-37th …*, 2752–2757. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6119747

Ribeiro, L., Barata, J., & Pimentao, J. (2011). Where evolvable production systems meet complexity science. In *Proceedings - 2011 IEEE International Symposium on Assembly and Manufacturing, ISAM 2011*. http://doi.org/10.1109/ISAM.2011.5942351

Rocha, A. (2013). *An agent based architecture for material handling systems*. Faculdade de Ciências e Tecnologia.

Rocha, A. D., Barata, D., Di Orio, G., Santos, T., & Barata, J. (2015). PRIME as a Generic Agent Based Framework to Support Pluggability and Reconfigurability Using Different Technologies. In *Technological Innovation for Cloud-Based Engineering Systems* (pp. 101–110). Springer.

Setchi, R. M., & Lagos, N. (2004). Reconfigurability and Reconfigurable Manufacturing Systems - State-of-the-art Review. In *Industrial Informatics, 2004. INDIN '04. 2004 2nd IEEE International Conference on* (pp. 529–535). http://doi.org/10.1109/INDIN.2004.1417401

Stamatis, D. H. (2003). *Failure mode and effect analysis: FMEA from theory to execution*. ASQ Quality Press.

Stoneburner, G., Goguen, A., & Feringa, A. (2002). Risk management guide for information technology systems. *Nist Special Publication*, *800*(30), 800–830.

Sutton, I. (2014). *Process risk and reliability management: operational integrity management*. Gulf Professional Publishing.

Tharumarajah, A. (1996). Comparison of the bionic, fractal and holonic manufacturing system concepts. *International Journal of Computer Integrated Manufacturing*, *9*(3), 217–226. http://doi.org/10.1080/095119296131670

Ueda, K. (1992). *A Concept for Bionic Manufacturing Systems Based on DNA-type Information. PROgraming LAnguages for MAnufacTuring*.

Van Brussel, H., Wyns, J., Valckenaers, P., Bongaerts, L., & Peeters, P. (1998). Reference architecture for holonic manufacturing systems: PROSA. *Computers in Industry*, *37*, 255–

274. http://doi.org/10.1016/S0166-3615(98)00102-X

Vrba, P., Tichý, P., Mařík, V., Hall, K. H., Staron, R. J., Maturana, F. P., & Kadera, P. (2011). Rockwell automation's holonic and multiagent control systems compendium. In *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews* (Vol. 41, pp. 14–30). http://doi.org/10.1109/TSMCC.2010.2055852

Wawrzyniak, D. (2006). Information security risk assessment model for risk management. In *Trust and Privacy in Digital Business* (pp. 21–30). Springer.

Willows, R., Reynard, N., Meadowcroft, I., & Connell, R. (2003). *Climate adaptation: Risk, uncertainty and decision-making. UKCIP Technical Report*. UK Climate Impacts Programme.

Young, T. L. (2013). *Successful project management* (Vol. 52). Kogan Page Publishers.

Zadeh, L. A. (1965). Fuzzy Sets. *Information and Control*, *8*, 338–353. Retrieved from http://www-bisc.cs.berkeley.edu/Zadeh-1965.pdf

Zadeh, L. A. (1973). Outline of a New Approach to the Analysis of Complex Systems and Decision Processes. *IEEE Transactions on Systems, Man, and Cybernetics*, *SMC-3*. http://doi.org/10.1109/TSMC.1973.5408575

Zimmerman, R. (1998). Historical and Future Perspectives on Risk Perception and Communication. In D. of Edited by Beijing Normal University, Society for Risk Analysis-Japan Section & E. S.-N. N. S. F. of China (Eds.), *Risk Research and Management in Asian Perspective: Proceedings of the First China-Japan Conference on Risk Assessment and Management* (pp. 481 – 487). Beijing, China: International Academic Publishers, 1998.

Zimmerman, R., & Bier, V. M. (2010). Risk assessment for extreme events.

# Annex I

## Questionnaire

Dear Sir/Madam

This questionnaire has the purpose of evaluate the risks detected on the employment of an Evolvable Production System on the real factory environment. The main goal of this work is to detect the risks of implementation of this paradigm in order to avoid failures by using FMEA technique (Failure Mode and Effects Analysis) as a powerful tool for forecasting and analysing risks, to be prepared for tackling possible ones.

In Table I.4 are listed several risks which should be evaluated according to three parameters, 'Impact of the Threat', 'Ability to React' and 'Probability to Occur'. In each column the evaluation should be set according to Table I.1, Table I.2 and Table I.3. In regard to the 'Impact of the Threat' column, the scale should represent the impact that on company will face while an EPS is implemented. In respect to the 'Ability to React' column, the scale represent the ability of a company to react to any challenge, during the implementation ant the use on as EPS.

Finally, the last evaluated parameter is 'Probability to Occur'. The evaluation of the column is similar to the previews parameters. For this case the scale represents the amount of times on risk will appear during the employment of this new paradigm.

Table I.1 – Scale of the risk evaluation regarding the impact of the threat

| Scale | Description |
|---|---|
| Very Low (**VL**) | The impact of the threat is almost inexistent |
| Low (**L**) | The impact of the threat is non-significant |
| Moderate (**M**) | The impact of the threat is moderately significant |
| High (**H**) | The impact of the threat is considerably significant |
| Very High (**VH**) | The impact of the threat compromises the EPS's success |

Table I.2 – Scale of the risk evaluation regarding the ability to react

| Scale | Description |
|---|---|
| Very Low (**VL**) | The ability to react is almost inexistent |
| Low (**L**) | The ability to react is low |
| Moderate (**M**) | The ability to react is medium |
| High (**H**) | The ability to react is significant |
| Very High (**VH**) | The ability to react is good enough to address the problem |

Table I.3 – Scale of the risk evaluation regarding the probability to occur

| Scale | Description |
|---|---|
| Very Low (**VL**) | The probability to occur is almost inexistent |
| Low (**L**) | The probability to occur is non-significant |
| Moderate (**M**) | The probability to occur is moderately significant |
| High (**H**) | The probability to occur is considerably significant |
| Very High (**VH**) | The probability to occur compromises the EPS's success |

Please answer the questionnaire having as an example of an implemented EPS, project IDEAS.

To clarify any question, please email it to m.parreira@campus.fct.un.pt.

Thank you for your cooperation.

Best regards,

Mafalda Parreira

Table I.4 – List of the potential failures and the respective evaluation

| Vulnerability | Failure | Impact of the Threat | Ability to React | Probability to Occur |
|---|---|---|---|---|
| Financial Liquidity | Insufficient financial resources to remodel the production line | | | |
| | Insufficient financial resources to build a new production line | | | |
| | Inaccurate choice of hardware | | | |
| | Inadequate facilities | | | |
| Natural Disasters | Incapability to produce | | | |
| Power Cuts | Shutdown of all production system | | | |
| Specific Hardware | Inadequate quantity of controllers | | | |
| | Inadequate capacity of the controllers | | | |
| Hardware's Delivery Delays | Delay in the delivery of the hardware | | | |
| Security | Information leakage | | | |
| | Data inconsistency | | | |
| Faulty Hardware | Shut down of the entire system | | | |
| | Decrease of the entire system's performance | | | |
| Manpower | Unperformed maintenance in the production line | | | |
| | Insufficient maintenance performed in the production line | | | |
| | Unspecialised system's integrators | | | |
| | Inertia to start the paradigm's shift | | | |
| | Inadequate design of the production line | | | |
| Hardware Capacity | Failure of the entire production line | | | |
| | Decrease of the entire system's performance | | | |
| Systems' Integration | Human error | | | |
| | Inadequate integration with the existing control systems | | | |
| | Inadequate integration with the existing statistical analysis tools | | | |
| | Inadequate integration with the existing visualisation tools | | | |
| | Inadequate integration with the existing simulation tools | | | |
| | Inadequate integration between EPS and managerial subsystem | | | |
| | Incompatibility with the existing control systems | | | |
| | Incompatibility with the existing statistical analysis tools | | | |
| | Incompatibility with the existing visualisation tools | | | |
| | Incompatibility with the existing simulation tools | | | |
| | Incompatibility between EPS and managerial subsystem | | | |
| Network Connection | Inefficient connection between agents, entities | | | |
| | Inexistent connection between agents, entities | | | |
| System's Performance | Optimal performance is not guaranteed | | | |
| | Entry and exit order of products cannot be assured | | | |
| System's Complexity | Increases human error in implementation | | | |
| | Overload controllers | | | |
| | Unpredictable behaviour of the system | | | |