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A MULTICRITERIA GROUP DECISION-MAKING SORTING APPROACH FOR EVALUATING BPM MATURITY AND RISK IN PROCESS FACILITIES

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Thesis presented to the Postgraduate Program in Production Engineering at the Universidade Federal de Pernambuco, as a partial requirement for obtaining the title of Doctor in Production Engineering. Area of concentration: Production Management.

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I dedicate this thesis to the memory of my brother Rodrigo, who passed away in 2023, and my father Duarlindo, who departed the following year. Their lives, values, and enduring examples continue to inspire me every day. This achievement is also theirs.

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ABSTRACT

In this thesis, two relevant problems from the literature were analyzed: Risk Analysis in Process Facilities (1) and Business Process Management (BPM) Maturity Evaluation (2). In the context of risk analysis, Multi-criteria Decision Making (MCDM) approaches are widely used. However, previous studies identified opportunities for improvement in both the MCDM methods used (cognitive effort in pairwise comparisons and the risk of misestimating hazards) and the results they produce (difficulty in setting safety measures for ranked hazards or in the transition areas of the risk matrix). In the context of BPM maturity evaluation, although several models have been proposed, issues regarding their practical effectiveness remain unresolved, which includes a clear evaluation procedure and an adjustable structure, with the flexibility to adapt to different organizational contexts. These issues are related to key aspects of BPM maturity assessment and improvement. Both problems were addressed using models constructed from the same Multi-criteria Group Decision Making (MCGDM) method, with adjustments tailored to the specific features of each problem. For the first problem, a hybrid model was developed by combining MCGDM, Strategic Options Development and Analysis (SODA), and Intuitionistic Fuzzy Sets (IFS). This methodology combination addresses all improvement opportunities: SODA with Intuitionistic Fuzzy Cognitive Maps is used in both hazard identification and mitigation stages, while MCGDM with IFS is applied in the hazard classification stage. To address the issues related to problem II, a practical BPM Maturity Model (BPM-MM) and its assessment procedure were proposed. Additionally, a web-based Group Decision Support System was created to facilitate the application of this new BPM-MM. In both cases, real-world applications were conducted, and a comparative analysis of related studies demonstrated the advantages of the proposed approaches. Overall, the MCGDM approach proved beneficial for both problems, primarily due to its flexibility. The proposed model for problem I proved to be effective in addressing the opportunities for improvements from previous studies, showing also benefits such as resource savings, increased focus, objectivity, and a clearer understanding of hazards. In the BPM-MM case, MCGDM with IFS provided a robust, transparent, adaptable, and multidimensional methodology. These models have expanded knowledge in their fields, offering solutions to current challenges, opening new opportunities for exploration, and generating new research questions. When effectively applied by companies, they can also deliver economic, social, and environmental benefits.

Key Words: Multi-criteria Group Decision-Making; Hazard and Operability Study; Business Process Management Maturity Evaluation; Intuitionistic Fuzzy Sets; Web Based Decision Support System.

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF MAIN ACRONYMS AND ABBREVIATIONS

BP	Business Process
BPM	Business Process Management
BPM-MM	Business Process Management Maturity Model
BPO	Business Process Orientation
DSR	Design Science Research
DSS	Decision Support System
HAZOP	Hazard and Operability Study
IFS	Intuitionistic Fuzzy Sets
MCDM	Multi-criteria Decision Making
MCGDM	Multi-criteria Group Decision Making
SODA	Strategic Options Development and Analysis

SUMMARY

Chapter 1 - Introduction

The Multi-criteria Decision-Making (MCDM) approach has steadily expanded in its application and has been instrumental in solving problems across a wide range of research areas. Its growth reflects its versatility and effectiveness in addressing complex issues. This approach has been employed to tackle diverse and complex problems in fields ranging from Business Process Management (BPM) to risk analysis in industrial processes. Dias et al, (2018) emphasize that it offers a clear framework for addressing problems with conflicting goals, while also helping to synthesize input from diverse experts.

In BPM research, these methods have already been applied to various problems, including BPM Maturity Models (BPM-MM) selection (Lima et al., 2017), choosing appropriate modeling languages for BPM (Campos and Almeida, 2016), assigning weights to BPM-MM evaluation criteria (van Looy et al., 2013), and assessing Critical Success Factors in BPM (Bai and Sarkis, 2013).

Many researchers in the field of risk analysis for process facilities often recommend integrating the Multi-Criteria Decision-Making (MCDM) approach with Hazard and Operability (HAZOP) studies — a well-known and widely used risk tool recognized for its effectiveness — to enhance both the efficiency and quality of the analysis. HAZOP involves a facilitator and a team of experts whose role is to identify process deviations, determine their causes and consequences, and propose actions to mitigate the associated risks (Summers, 2003). The core principle of HAZOP is that hazards arise only when the process strays from normal or standard conditions (Khan and Abbasi, 1998). As such, the analysis assesses both hazard and operability issues that might result from the current safety measures in place at process facilities.

Several researchers have utilized MCDM methods (Cheraghi et al., (2019); Aziz et al., (2017); Grassi et al., (2009)) or Fuzzy Sets (Ahn and Chang, 2016) to enhance risk analysis. For instance, Ahn and Chang (2016) applied Fuzzy Set Theory to improve conventional HAZOP by addressing uncertainty and refining the risk matrix. They used fuzzy numbers to represent risks in terms of frequency and consequences of process deviations, creating a risk matrix with 7 regions instead of the traditional 3. Cheraghi et al., (2019) introduced a novel risk ranking system combining fuzzy methods with the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), using 5 risk factors instead of the usual 2 to rank hazards. Similarly, Grassi et al., (2009), though not employing HAZOP, developed a new risk evaluation approach using fuzzy TOPSIS, also based on 5 factors for ranking hazards. Additionally, Aziz et al., (2017) proposed a method known as HAZOP-AHP for hazard prioritization.

Risk analysis in process facilities and BPM maturity level assessment, as well as the definition of strategies of improvement, are clearly not routine decisions. They are critical and strategic, involving significant risks, substantial resources, and the organization's competitive future. These decisions can ultimately determine whether the organization succeeds or fails. The MCDM approach is crucial in addressing the challenges presented by both fields, primarily due to its adaptability, strength, and ability to seamlessly integrate with other methodologies. This versatility and robustness allow it to effectively overcome obstacles in various contexts.

1.1 Motivation of the Proposed Approach: Gaps and Research Needs

Research is driven by the need to address problems, and this thesis is no exception. The motivation is to offer improved solutions and make contribution to both areas of study. This section provides an overview of the key limitations associated with both problems: (1) Risk Analysis in Process Facilities and (2) Business Process Management (BPM) Maturity Evaluation, as identified in the literature.

1.1.1 Research Problem I (Risk Analysis in Process Facilities)

Researchers have identified the limitations of conventional HAZOP (Baybutt, 2015; Grassi et al., 2009). To address some of these limitations, they have combined different methodologies to enhance the application of conventional HAZOP. The focus of this thesis is not on conventional HAZOP itself, but rather on these articles that aim to improve it or others Hazard Identification (HAZID) techniques using other methodologies, including MCDM approach and Fuzzy Set Theory.

The MCDM approach has proven highly effective in risk assessment within industrial processes (Baybutt, 2015; Grassi et al., 2009). Its inherent features, such as addressing various problematics, incorporating multiple criteria and decision makers, and allowing the assignment of different weights to both, make it easily adaptable for use in HAZID techniques, including FMEA (Lolli et al., 2015), FMECA (Melani et al., 2018), and HAZOP (Cheraghi et al., 2019; Aziz et al., 2016).

The application of the MCDM approach and Fuzzy Set Theory in risk analysis is not new. Cheraghi et al. (2019) proposed a ranking of hazards using fuzzy-based methods combined with the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). AHP was also employed to rank hazards in HAZOP (Aziz et al., 2017). Additionally, a risk matrix incorporating Fuzzy Set Theory was proposed to reduce the uncertainty in conventional HAZOP. Ahn and Chang (2016) utilized fuzzy numbers to express risks related to the frequency and consequences of process deviations. Grassi et al. (2009) proposed a new risk evaluation methodology using fuzzy TOPSIS to rank hazards, employing five factors in the process. Although these studies applied an MCDM methodology, all of them, including Ahn and Chang (2016)—which did not adopt an MCDM approach—demonstrate one or more areas requiring further analysis and improvement:

The frequency (F) and consequences (C) of hazards situated in transition zones of the risk matrix (areas between well-defined regions) are not precisely evaluated, making it difficult to devise effective risk mitigation policies. Ranking hazards can hinder the development of improvement strategies, particularly in transition zones. Moreover, this approach can create a false perception of safety due to the difficulty in determining which ranked hazards require mitigation. Except for Grassi et al. (2009) and Ahn and Chang (2016), performing numerous pairwise comparisons for all identified hazards are labor-intensive and increases the likelihood of errors in the analysis. The use of additive MCDM methods, such as AHP, can lead to compensation issues, where some hazards are either undervalued or exaggerated. Although HAZOP relies on a team of experts, none of these studies implemented MCDM techniques to facilitate group decision-making or to aggregate expert judgments. None of the articles evaluated the team's satisfaction with the final results of the HAZOP analysis.

Each of these issues are discussed in detail in section 2.4.1 of chapter 2. In chapter 4, the proposed model is confronted with each of them (section 4.2).

1.1.2 Research Problem II (BPM Maturity Evaluation)

BPM Maturity Models (BPM-MMs) have been developed to help companies evolve their BPM programs, meaning improving end-to-end processes management throughout the entire supply chain. Over the years, many models have been introduced (Pöppelbuß and Röglinger, 2011; Becker et al., 2010) with the main goal of guiding organizations towards best practices to improve their BPM capabilities. However, despite considerable advancements, challenges related to the practical effectiveness of these models remain unresolved (Van Looy et al., 2021), emphasizing the need for further research (Van Looy et al., 2021; Tarhan et al., 2016).

Research has consistently demonstrated that the overall BPM maturity level in organizations is generally low (Froger et al., 2019; Harmon and Wolf, 2016), especially among small and medium-sized enterprises (SMEs) (Harmon and Wolf, 2016). An organization that is process-oriented is usually defined by its capacity to execute high-performance processes and exhibit excellence across all key BPM-related capabilities (Hammer, 2007; Skrinjar and Trkman, 2013).

The literature indicates that significant challenges regarding the practical effectiveness of BPM maturity models (BPM-MMs) remain unresolved (Van Looy et al., 2021; Froger et al., 2019; Tarhan et al., 2016). These challenges primarily relate to the models' practical applicability, particularly in the context of self-assessment. This limitation may explain the relatively low adoption rate of BPM-MMs (Tarhan et al., 2016). SMEs are especially impacted, as the features most relevant to them are among the key areas that require improvement (Britsch et al., 2012). Developing a BPM-MM that effectively overcomes these shortcomings would significantly enhance the success rate of BPM initiatives.

By analyzing the literature, including models’ proposals and BPM-MM related researches in general, it was possible to categorize the issues (gaps) identified into three main aspects: (1) assessment procedure, (2) flexibility and (3) BPM-MM structure. In addition to this categorization, all these issues are directly linked to the guiding statements that drove the research within this specific problem. The first one was the low overall maturity levels reported in Froger et al. (2019) and Harmon and

Wolf (2016), and the second was the limited practical adoption of BPM-MM (Tarhan and Reijers, 2016).

Each of these issues are discussed in detail in section 2.4.2 of chapter 2. In chapter 5, the proposed model is confronted with each of them (section 5.3).

1.2 General and Specific Research Focus

1.2.1 General Focus

In this thesis, it is demonstrated how an Outranking Multi-criteria Group Decision Making (MCGDM) sorting method using Intuitionistic Fuzzy Sets (IFSs) can, either independently or in combination with other methodologies, address distinct yet related problems. To illustrate this, two significant research topics in the literature were examined.

Problem I – Risk analysis in processes facilities with the HAZOP study.

Problem II – Business Process Management Maturity Evaluation.

For problem I, the general objective is to propose an MCDM-based methodology that refines HAZOP analysis, confronting the issues identified in the previous studies. This novel hybrid methodology incorporates Strategic Options Development and Analysis (SODA) and intuitionistic fuzzy cognitive maps to enhance the identification of hazards and the formulation of safety measures. This methodology is designed to place a strong emphasis on expert collaboration, ensuring the necessary support for accurate decision-making. Both the MCDM framework and the SODA approach facilitate group decision-making processes, with SODA serving as an effective mechanism for aggregating and synthesizing expert knowledge.

For Problem II, the general objective is to contribute to the BPM research field by developing a practical BPM maturity model (BPM-MM) along with an assessment procedure to address the identified issues. This model also integrates an MCDM approach with Intuitionistic Fuzzy Sets (IFS) and adopts the framework proposed by vom Brocke et al. (2016), helping companies better understand their BPM contextual factors.

In this proposal, both problems, as outlined in the previous section and further discussed in Chapter 2, present challenges that can be effectively addressed using the MCDM approach, as long as the right method is used. Despite the differences between the problems, the principle for solving them remains the same. In both cases, an MCDM sorting method is required: in HAZOP-based risk analysis, risks must be categorized into different risk levels, while in the BPM Maturity Assessment, companies need to be classified into maturity levels. Since both problems involve uncertainty and subjectivity, combining MCDM with Fuzzy Sets offers the most suitable solution.

1.2.2 Specific Focus

Considering everything discussed in the previous section, the specific objectives are listed below. When achieved collectively, these objectives will contribute to attaining the overall goal involving the construction and application of each of the developed models. Specific goals for MCGDM-based HAZOP:

1. Present a new risk analysis MCGDM model, considering the inherent characteristics and the limitations identified in previous studies.
2. Demonstrate the applicability and benefits of this new model through a real-world application and a comparative analysis.
3. Clearly outline and describe all the steps required to apply the model.

Specific goals for MCGDM-based BPM-MM:

1. Propose a new BPM maturity model combined with the MCGDM approach to address the issues found in previously published models.
2. The maturity model should consist of both the theoretical part (conceptual model) and the practical part (assessment procedure), and both must be presented clearly.
3. Incorporate contextual factors of BPM into the model, using the framework proposed by Van Looy et al. (2016) as a reference.
4. Demonstrate the applicability and benefits of this new model through a real-world application and a comparative analysis.
5. Build a Web-Based GDSS to support companies worldwide in implementing the proposed model.

1.3 Novelty and contribution of the proposed approach

The primary distinguishing feature of this proposal, common to both problems, is the construction of models capable of extracting more accurate information, since an MCGDM approach is applied considering the improvement points of previous studies. The results generated by this information are supposed to be more faithful to the reality of each application. This was achieved due to several factors: (1) the selection of an appropriate multi-criteria group decision-making method, (2) the inclusion of support methodologies, and (3) the ability to handle uncertainty, which reduces the cognitive effort required from specialists and decision makers.

For problem 1, it is proposed and implemented an MCGDM-based HAZOP analysis: a hybrid methodology that integrates an MCDM approach, Strategic Options Development and Analysis (SODA), and Intuitionistic Fuzzy Sets (IFS). This approach leverages the strengths of each methodology by incorporating SODA with Intuitionistic Fuzzy Cognitive Maps and mitigating the inherent uncertainty and subjectivity of HAZOP through an IFS-based MCDM sorting algorithm. For problem 2, an approach was followed that integrates Multi-Criteria Decision-Making (MCDM) with Intuitionistic Fuzzy Sets (IFS). Additionally, a Web-based Group Decision Support System (WB-DSS) was developed to facilitate its implementation within organizations. The model for Problem I is presented in Viegas et al. (2020), and the model for Problem II is found in Viegas and Costa (2023).

In relation to Problem I (Risk Analysis in Process with HAZOP and SODA), the way the HAZOP method using MCGDM was undertaking proved to be more consistent when compared with the improvement opportunities identified in previous studies. Positive aspects were highlighted, with the most frequently noted being resource savings, enhanced focus and objectivity, and a more accurate perception of hazards. Key contributions of the model include:

I. Rather than relying on a ranking system or risk matrix, this new methodology categorizes hazards into predefined categories. This approach enables management to more effectively allocate resources for mitigating risks.
II. The inherent uncertainty and subjectivity of the HAZOP, which are significant issues, were reduced. First, Intuitionistic Fuzzy Numbers were used to conduct the intracriteria evaluation in the Multi-Criteria Decision Making approach and to

define the limiting profiles. Second, conventional cognitive maps were replaced with Intuitionistic Fuzzy Cognitive Maps.

III. SODA was incorporated with intuitionistic fuzzy cognitive maps to more effectively identify the root causes of hazards and address the issues associated with the traditional HAZOP brainstorming technique.

IV. This approach fosters greater team empowerment, leading to increased trust among members and a stronger sense of responsibility for their decisions.

(b) Research Problem II – Business Process Management Maturity Evaluation.

In relating to Problem II, assessing a company's BPM maturity level is challenging due to its complexity, the numerous Critical Success Factors (CSFs) to account for, and the significant uncertainty and subjectivity involved. The MCGDM approach, when combined with Intuitionistic Fuzzy Sets (IFSs), allowed for addressing the inherent subjectivity and uncertainty. Key contributions of the model include:

I. A new BPM maturity framework, built from the identification and joint analysis of the main limitations of the existing models with an evaluation procedure based on MCDM with IFSs.

II. One of the major challenges in BPM-MM research is the restrictions set as prerequisites for transitioning between maturity levels. To the best of our knowledge, this is the first research that aims to objectively define maturity level constraints, referred to here as limiting profiles.

III. The Web-based Decision Support System developed is the first of its kind in the literature addressing this problem and is regarded as equally important as the entire proposed methodology.

In this thesis, the MCGDM approach has demonstrated its importance in addressing the limitations of current studies in both fields of research. It has proven to be a pivotal tool for overcoming the challenges these models face.

1.4 Research Classification and General Steps for Model Development

Classifying a research project before beginning is a crucial step, as it establishes a road map for achieving the desired objectives. Classification can consider various criteria, such as the objectives, nature, methodological approach, and technical procedures.

According to Gil (2002), classification is based on the general objective, which may be exploratory, descriptive, or explanatory. This research is categorized as exploratory, given its intended goal. It seeks to provide greater familiarity with the problem, clarify it, refine ideas, formulate hypotheses, and generate new insights. It also aims to define objectives or discover new perspectives, using survey methods and bibliographic research (Pradanov and Freitas, 2013; Gil, 2002).

Regarding the approach adopted, this research is quantitative. A study is considered quantitative when it assumes that all aspects can be quantified, translating opinions and information into numerical data (Pradanov and Freitas, 2013). Quantitative research typically emphasizes deductive reasoning, logical rules, and measurable attributes (Gerhardt & Silveira, 2009). With regard to its nature, this research is classified as applied, as it focuses on specific contexts and interests, aiming to generate knowledge for practical application to solve particular problems (Gerhardt & Silveira, 2009; Pradanov & Freitas, 2013).

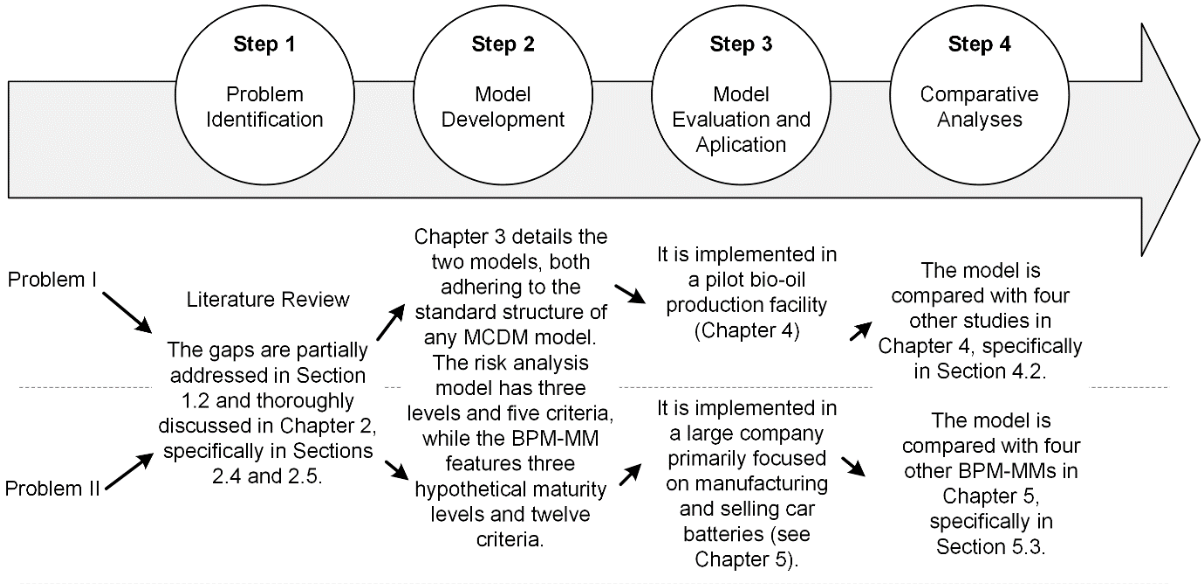
This research employed two main technical procedures: literature review and Design Science Research (DSR). Literature review is a fundamental component of any research (Pradanov and Freitas, 2013). A literature review involves critically analyzing existing research on a topic to identify gaps, trends, and establish a theoretical foundation, contextualizing the study within the current scientific field. DSR is a methodology focused on creating and evaluating artifacts, like models or systems, to solve real-world problems. It emphasizes iterative design, testing, and refinement, aiming for practical utility and theoretical contributions. It bridges practical relevance with academic rigor, advancing knowledge through innovation (Mamoghli et al., 2017). Figure 1 depicts the fundamental steps of Design Science Research (DSR), adapted from Mamoghli et al. (2017). The figure outlines the four steps proposed by Mamoghli et al. (2018), followed by a summary of how each step was implemented for the respective research problems.

1.5 Organization of the thesis

In this initial chapter, the research problems and the main contributions of the proposed methodology are presented. In the rest of this thesis, the following points are addressed:

Chapter 2 – The essential theoretical background necessary to understand the proposal is presented, including Multi-Criteria Group Decision Making (MCGDM) for the sorting problem, Intuitionistic Fuzzy Sets (IFS), Strategic Options Development and Analysis (SODA), challenges of Hazard and Operability Analysis for Process Safety, and challenges of BPM Maturity Assessment and Improvement.

Figure 1 – Steps followed in the Design Science Research methodology



Source: adapted from Mamoghli et al. (2018)

Chapter 3 – The general MCGDM method, from which the models were derived, is presented, along with the specific models for each problem.

Chapter 4 – This chapter is dedicated to research problem I. First, a real application is conducted using a continuous pyrolysis system with a thermal fractionated refrigerating tower for bio-oil production. Then, a discussion of the results and general aspects of the proposal is provided.

Chapter 5 – This chapter is dedicated to research problem II. First, a Web-Based Decision Support System (DSS) developed specifically to assist in the application of the proposed methodology for this problem is presented. Second, a detailed discussion is offered on the improvement points outlined in the proposal, focusing on the three aspects introduced in the thesis introduction.

Chapter 6 – Conclusions are drawn, and future research directions are suggested.

Chapter 2 - Research Background

2.1 MCGDM for the Sorting Problematic

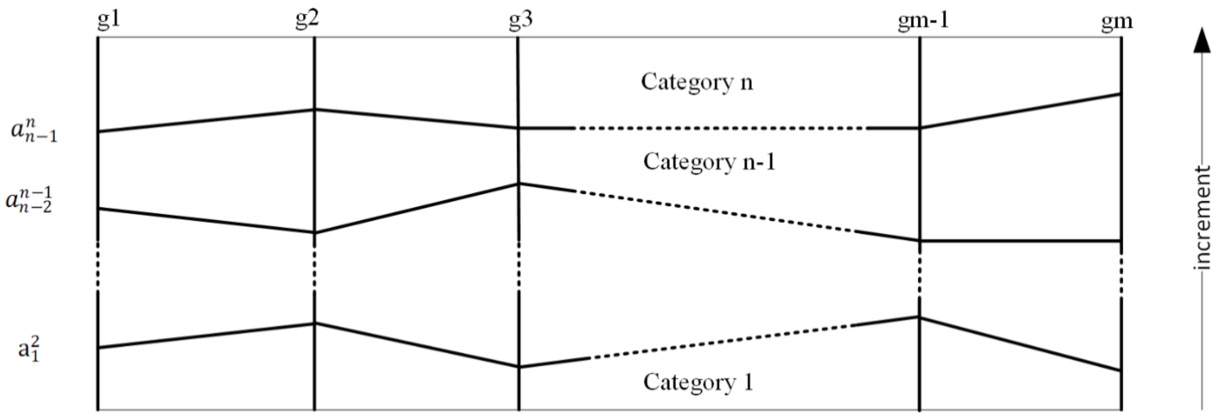
The MCDM approach comprises a set of methods aimed at solving specific problems involving multiple, often conflicting criteria, with characteristics that make them well-suited for this approach (Campos et al., 2015). These methods are divided into three categories: Additive, Outranking, and Interactive Methods (Roy, 1996; Vincke, 1992). The distinction between these categories lies in how each method addresses the problem to support decision-making. In general, a set of **s** alternatives **A** = {a_1, a_2, ..., a_s} should be evaluated according to one of the following main problematics (Roy, 1996): Choice, Ranking and Classification. The choice problematic occurs when the objective is to select from the set of alternatives **A**, a subset of alternatives that presents the best overall performance. In the ranking problematic, alternatives are ranked in descending order of performance. For the classification problem, alternatives must be allocated into different categories (when these categories can be ordered, the problem is known as Sorting, otherwise, it is treated as classification (Zopounidis and Doumpos, 2002). For all three problematic, alternatives are evaluated considering a set of **m** criteria G = {g_1, g_2, ..., g_m} (intracriteria evaluation), a decision maker (DM) or group of **k** decision-makers E = {e_1, e_2, ..., e_k}, in the latter case, Multi-criteria Group Decision Making (MCGDM) must be used. In MCGDM, each DM defines a set of weights for each criteria W_{ij} = {w_{1k}, w_{2k}, ..., w_{mk}} (intercriteria evaluation), for **m** criteria and **k** Decision-makers (DMs).

In this thesis, there is a particular interest in the outranking methods for the sorting problematic, since the alternatives (Hazards/Companies), will be allocated at risk levels. In this case, the set of alternatives A is replaced by the set H = {h_1, h_2, …, h_s}, which represents the hazards, or O = {org_1, org_2, …, org_s}, representing the companies. These Outranking methods use a relation **S** called "Outranking Relation", that means "at least as good as". For example, a hazard $\mathbf{h_1}$ outranks another hazard $\mathbf{h_2}$, or $\mathbf{h_1Sh_2}$, if $\mathbf{h_1}$ is at least as good as $\mathbf{h_2}$. For the sorting problematic, the alternatives are not compared with each other, but with a limiting profile $\mathbf{b_{n-1}^{n}}$ ($(h/org)_x\mathbf{S}b_{n-1}^{n}$). Each category level has two limiting profiles, one upper and one lower for each criterion, except for the first and last level that have just one profile (see Fig. 2.1). The limiting profile represents the minimum and maximum performance required in each criterion for the alternatives to be sorted at a given level.

Thus, exemplifying in the context of risk analysis, a hazard h_i is sorted at a risk level L_l, if, and only if , $h_i\mathbf{S}b^{n}_{n-1}$, i.e. if h_i has performance at least as good as b^{n}_{n-1}, (that represents the lower profile of risk level L_l), in each one of the evaluation criteria g_j, ∀ i = {1, ..., s}, l = {1, ..., n} and j = {1, ..., m}. If a hazard h_i outranks all the lower profiles of one risk level in all criteria, this does not imply their allocation to that level when the problem involves a group of DMs. The same occurs in the specific context for BPM Maturity Evaluation.

In MCGDM, it is also necessary to consider the individual assessment of each decision-maker and their degree of importance, represented by their weights λ_t. This weight should reflect their level of knowledge and skills in the field (Lolli et al., 2015).

Figure 2 - Graphical representation of the limiting profiles at each criterion and risk level in the sorting problematic.



Source: Adapted from Viegas et al., 2020.

Figure 2.1 illustrates a classification problem similar to the one addressed in this thesis: how to classify risks/companies (the alternatives) into the appropriate risk levels/BPM maturity levels (categories). In sorting problems, additional parameters need to be defined, such as "limiting profiles" and the “cut-off level θ.” the cut-off level (θ) is a reference value used for classification (further details on these parameters are provided in chapter 3). Figure 2.1 illustrates these limiting profiles, evaluation criteria, and categories in relation to the problems analyzed in this thesis.

In any MCDM problem, four fundamental steps are followed: (1) intercriteria evaluation, (2) intracriteria evaluation, (3) application of the aggregation procedure, and (4) further analysis. In step (1), the importance of each criterion is established; in step (2), each alternative is assessed against each criterion; in step (3), the data and parameters from the previous steps are used to generate results through the aggregation procedure; and in step (4), additional analysis is conducted to evaluate the quality and robustness of the results.

2.2 Intuitionistic Fuzzy Sets - IFSs

A common challenge in many applications of MCDM methods is the inherent uncertainty and/or subjectivity. To address these issues, many researchers have turned to Fuzzy Set Theory, which includes Intuitionistic Fuzzy Sets (IFS). IFS, developed by Atanassov (1986), are an extension of the Fuzzy Sets (FS) introduced by Zadeh (1965). Unlike FS, which use a single value (degree of membership) to indicate how much an element belongs to a given set, IFS use two values: the degree of membership and the degree of non-membership, known as Intuitionistic Fuzzy Values (IFVs). This dual approach provides a more nuanced way of capturing uncertainty, making it particularly useful in complex decision-making environments, such as evaluating risk or maturity in process.

For a crisp set A, an element x could only receive two types of classification: $x \in A$ or $x \notin A$. In fuzzy sets, by (Zadeh, 1965), each element y gets a degree of membership $\boldsymbol{\mu} \in \mathbf{[0\ 1]}$.

The adherence of an element y to a fuzzy set B is measured by its degree of membership, which is increased as μ approaches 1. Thus, an element y with values of $\boldsymbol{\mu}_B$ between 0 and 1 partially belongs to B, while $\boldsymbol{\mu}_B = 0 \rightarrow y \notin B$ and $\boldsymbol{\mu}_B = 1 \rightarrow y \in B$. The Intuitionist fuzzy sets were introduced by (Atanassov, 1986) for cases involving non-membership **v**. Basically, an IFS A in X can be defined as:

$A = [\{x, \mu_A(x), \nu_A(x)\} / x \in X]$

Where the functions $\mu_A: X \rightarrow [0,1]$ and $\nu_A: X \rightarrow [0,1]$ correspond to the degree of membership and non-membership of the element $x \in X$ respectively, and of $x \in X$, $0 \leq \mu_A(x) + \nu_A(x) \leq 1$.

The values of **μ** and **v** are used to represent the degree of membership and non-membership to which the hazard $\mathbf{h_x}$ meets or does not meet, in that order, each of the criteria used. These values, called Intuitionistic Fuzzy Values (IFV), are used on two occasions within the proposed methodology: intracriteria evaluation and for the definition of the profiles $\mathbf{b}_{\mathbf{n-1}}^{\mathbf{n}}$. These two occasions require greater cognitive effort from the DMs due to the high degree of uncertainty and subjectivity involved, therefore the use of IFS helps to lessen the inaccuracy of responses. In our evaluation framework, the IFVs are utilized in the intra-criteria evaluation (step 1) and to establish the limiting profiles.

2.3 Strategic Options Development and Analysis - SODA

SODA is a problem-structuring method that facilitates understanding complex issues and supports decision making. It focuses on the expert and the cognitive processes involved in decision making, relying on cognitive mapping as a central element. Cognitive maps generate extensive information about the problem and help establish meaningful dialogue with experts (Ackermann and Eden, 2004a). In this thesis, traditional cognitive maps were replaced by Intuitionistic Fuzzy Cognitive Maps to better illustrate the relationships among deviations, causes, consequences, and actions within HAZOP. Table 1 presents the types of arcs used and their corresponding IFV classes. SODA treats team members individually and acknowledges their differing perspectives on the problem. Its effectiveness is reflected in the experts' level of engagement, which is essential, as the approach is grounded in the subjectivity inherent in decision-making processes (Ackermann and Eden, 2004b).

2.4 DSR Step 1 (Literature review)

In this section, a comprehensive literature review, aligned with the initial phase of the DSR methodology, was conducted to identify the main challenges associated with the two problems guiding this study. Subsection 2.4.1 presents the primary challenges associated with HAZOP studies and risk analysis involving multi-criteria models. Subsection 2.4.2 provides a detailed discussion of the limitations inherent to BPM-MM.

2.4.1 Challenges of Hazard and Operability Analysis for Process Safety

HAZOP operates on the core idea that hazards arise solely when a process deviates from its normal or standard conditions (Khan and Abbasi, 1998). This methodology assesses the likelihood of hazards and operational issues stemming from the current safety measures implemented in process facilities. Over time, HAZOP has expanded into diverse research domains. Applications include risk assessment for radioactive waste storage tanks (Zou et al., 2018), maintenance strategies for coal-fired power plants, and subsea petroleum production systems (Melani et al., 2018; Moreno-Trejo et al., 2013). Additionally, it has been applied to a sour crude-oil processing plant (Marhavilas et al., 2019), as part of a literature review (Lim et al., 2018), and even to identify risks within waste pickers' cooperatives (Fattor and Vieira, 2019). These examples highlight HAZOP's wide-ranging versatility, proving its relevance beyond the oil and gas industry.

HAZOP primarily involves a facilitator and a team of experts tasked with identifying process deviations, analyzing their causes and consequences, and recommending actions to mitigate associated risks (Summers, 2003). Its key benefits, as noted by Trujillo et al. (2018), include:

1. A rigorous, structured, systematic, and comprehensive approach.
2. Broad applicability to chemical process industries and manufacturing operations.
3. The facilitation of knowledge sharing, serving as a training opportunity for HAZOP team members.
4. Prevention of accidents and reduction of potential damage.

The HAZOP risk analysis process comprises two distinct stages:

1. Hazard identification, achieved by correlating deviations with causes and consequences.
2. Prioritization of hazard likelihood, often performed using a Multi-Criteria Decision Method (MCDM).

Despite its widespread adoption, the conventional HAZOP methodology has notable limitations. As highlighted by Guo and Kang (2015), it lacks the capability to deliver quantitative assessments or explicitly illustrate how faults propagate within a plant's processes. This shortfall arises from its failure to address the root causes of faults or identify specific equipment failure elements, often leading to ineffective decision-making. Furthermore, it relies solely on two factors—frequency and severity—and assumes these factors carry equal weight. Another drawback is its dependence on crisp and precise data, which are often imprecise and challenging to obtain or estimate (Guo and Kang, 2015).

The reliance on a qualitative approach in HAZOP introduces uncertainty and subjectivity, often cited as major drawbacks (Cheraghi et al., 2019; Ahn and Chang, 2016; Fuentes-Bargues et al., 2016). Baybutt (2015) provides a holistic critique of HAZOP, emphasizing several weaknesses, particularly those concerning the expert team, the identification of deviations, and the role of initiating events. Grassi et al. (2009) point out issues with the traditional formula R = P · M, commonly used after hazard identification in HAZOP. This formula calculates the risk level (R) by multiplying the probability (P) of occurrence by the magnitude (M) of the hazard. The authors highlight several limitations associated with this practice.

Several studies have aimed to address these challenges. Baybutt (2015), for instance, not only identifies weaknesses in HAZOP but also suggests potential solutions. To tackle issues such as inexperienced experts and the time-consuming nature of the method, some researchers have proposed the development of Automatic HAZOP systems (Rodríguez and la Mata, 2012; Rossing et al., 2010). Regarding uncertainty and subjectivity, both factors must be reduced to enhance the accuracy of risk analysis results. Various studies have attempted to resolve these issues through the application of fuzzy sets, with notable contributions from Ahn and Chang (2016), Fuentes-Bargues et al. (2016), and Cheraghi et al. (2019).

Ahn and Chang (2016) assert that fuzzy set theory is not only widely employed to address uncertainty but also proves highly effective in risk analysis. This is because it allows for the modeling of linguistic variables related to causes, phenomena, and impacts, thereby facilitating scientific decision-making. In Traditional HAZOP, risks are often overestimated, leading to heightened costs and complexity (Ahn and Chang, 2016). By contrast, fuzzy-based HAZOP significantly reduces the likelihood of these issues (Ahn and Chang, 2016).

Many researchers frequently explore the addition of complementary techniques to HAZOP to enhance its efficiency and quality. For instance, some studies have employed MCDM methods (Cheraghi et al., 2019; Grassi et al., 2009; Aziz et al., 2016) or Fuzzy Sets (Ahn and Chang, 2016). To mitigate the effects of uncertainty in conventional HAZOP and improve the risk matrix, researchers have applied Fuzzy Set Theory. For example, Ahn and Chang (2016) used fuzzy numbers to represent risks associated with the frequency and consequences of process deviations, developing a risk matrix with 7 regions instead of the traditional 3.

Additional enhancements to HAZOP include methods for risk ranking. One study proposed a system using fuzzy-based methods combined with the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Cheraghi et al., 2019). This approach incorporated five risk factors, expanding on the traditional two, for hazard classification. Grassi et al. (2009), although not directly applying HAZOP, introduced a risk evaluation methodology using fuzzy TOPSIS, also relying on five factors for hazard ranking. To further refine HAZOP's applicability, Aziz et al. (2016) developed HAZOP-AHP, designed specifically to prioritize hazards effectively. Although well-established, through the analysis of related articles, potential opportunities for improvement were identified, which are summarized in Table 1. These improvement opportunities served as the guiding framework for constructing the model related to Problem I of this thesis.

Table 1 - Gaps identified for problem I during the literature review

Gaps analyzed for Problem I	Description
Opportunities with the results obtained	
The transition region of the risk matrix (I)	For hazards that lie on the boundary between two distinct regions of a risk matrix, it is challenging to determine the most appropriate mitigation policy based on severity or frequency.
Problem with ranked hazards (II)	In the case where hazards are ranked, it is difficult to establish, within the ranking, to what extent these hazards should or should not receive a certain type of attention.
Opportunities with the MCDM method	
Methods with pair wise comparations (III)	Performing pairwise comparisons between different hazards can be very exhausting and lead to analysis errors due to the cognitive effort required.
Additive MCDM method (IV)	Using an additive MCDM method may lead to hazards being overestimated or underestimated, due to the trade-off problem between assessment criteria.
Methods for individual decision (V)	Since risk analysis involves a group of experts, an MCDM method for group decision making seems to be more suitable, due to the various features it can provide.
Evaluation of the satisfaction level (VI)	Assessing the satisfaction level of each team member, as well as that of the group as a whole, provides valuable insight into the results achieved.

Source: This research.

2.4.2 Challenges of BPM Maturity Assessment and Improvement

This section presents the main challenges identified in the literature related to BPM-MMs. To enhance the discussion, these challenges have been categorized into three key aspects of BPM-MMs: (1) their maturity evaluation mechanism (clarity, availability, and accuracy), (2) their flexibility (compliance), and (3) their structure (path to maturity). These drawbacks are directly tied to their practical application and the efforts of companies striving for improvement. And they significantly contribute to the low overall maturity levels reported by Froger et al. (2019) and Harmon and Wolf (2016), as well as the limited practical adoption of these models highlighted by Tarhan and Reijers (2016).

The structure of a BPM maturity model (BPM-MM) significantly influences its application and overall effectiveness. Since organizations can adopt various strategies to achieve their goals, these models should feature a non-linear structure (Van Looy et al., 2021; Froger et al., 2019). Additionally, the structure must be multidimensional, encompassing all critical dimensions necessary for a comprehensive evaluation of companies (Van Looy et al., 2021; Froger et al., 2009; Malinova and Mendling, 2018; Fisher, 2004). Currently, the structures of most models are based on the Capability Maturity Model (CMM), which may no longer be suitable for modern organizational needs (Szelagowski and Berniak-Wozny, 2022). These challenges highlight the need to rethink the evaluation approach and adapt the model's structure. Thus, the structure must not only be non-linear and multidimensional but also adjustable to meet evolving demands.

The primary areas requiring improvement, consistently emphasized in the literature, relate to the assessment procedures used to evaluate a company's BPM maturity level. Researchers advocate that BPM maturity models (BPM-MMs) should offer enhanced user support, particularly to address uncertainties, thereby providing a transparent and ready-to-use tool (Röglinger et al., 2012; Britsch et al., 2012). These models must explicitly define critical aspects, such as who should implement the model and how it should be applied (Pöppelbuß and Röglinger, 2011). Additionally, the prescriptive features—intended to guide organizations in improving their BPM capabilities—require further exploration (Tarhan et al., 2016; Röglinger et al., 2012; Pöppelbuß and Röglinger, 2011). Lastly, a clear distinction should be established between the BPM maturity model itself and its maturity assessment procedure (Tarhan et al., 2016).

In the broader context of maturity evaluation, multiple procedures are used to aggregate information and determine the maturity level. Among these, the most widely applied method is discrete comparison (Santos-Neto and Costa, 2019). This approach establishes the maturity level by comparing the best practices implemented by the evaluated company with those specified by the maturity model for corresponding levels. However, this method inherently entails greater uncertainty and subjectivity, demanding Decision Makers (DMs) with substantial expertise and experience to ensure a thorough and accurate evaluation.

Another notable issue lies in the fact that these models generally define a set of requirements for each maturity level, addressing every assessment element (OMG, 2008; Hammer, 2007). As a result, a company must fulfill the current level's requirements to advance to the next. However, achieving all these requirements simultaneously is nearly impossible. In practice, companies often display varying stages of maturity, with different assessed elements residing at different levels (Van Looy et al., 2021). BPM maturity models (BPM-MMs) should adopt a more objective approach to account for the restrictions or prerequisites necessary for achieving each maturity level (Froger et al., 2019). At present, there is no clear guideline regarding the degree to which a company must address each restriction to progress to the next maturity level.

Another significant issue gaining attention in recent years is the importance of considering context. For these models to be effectively applied, they must demonstrate flexibility and adapt to diverse organizational realities (vom Brocke et al., 2016; Röglinger et al., 2012; Britsch et al., 2012). At present, these models define maturity in a static manner, assuming uniform efforts across different companies and contexts. This has sparked criticism of the one-size-fits-all approach, as highlighted by vom Brocke et al. (2016) and Van Looy et al. (2021).

The BPM initiative is primarily designed to enhance processes and achieve improved overall results. However, current models fail to address the need for adopting varied strategies. Additionally, organizations may implement BPM initiatives to fulfill specific objectives, requiring the BPM maturity model (BPM-MM) to be adapted to the unique context of each organization (Castro et al., 2020; Froger et al., 2019; Trkman, 2010; Röglinger et al., 2012). The importance of organizational context as a critical success factor for BPM initiatives has been increasingly acknowledged, drawing significant attention from academia in recent years (Ongena and Ravesteyn, 2019; vom Brocke et al., 2016). Today, it is widely recognized as indispensable for ensuring the success of such initiatives (vom Brocke et al., 2016). All aspects discussed are summarized in Table 2.

Table 2 – Gaps identified for problem II during the literature review

Gaps analyzed for Problem II	Description
Aspect 1 (Assessment Procedure)	
Availability and transparency	It refers to the availability of an assessment tool and its transparency (clarity).
Prescriptive characteristics	Ability to provide some type of recommendation or suggestion for improvement based on the assessment that was carried out.
Distinction among assessment tool and the BPM-MM	Provide a theoretical model and its assessment tool separately.
Nature of restrictions between maturity levels	The way the company is evaluated on each criterion and how it is determined when to move up a level.
Aspect 2 (Flexibility/compliance)	It is important that models are able to capture the specific needs of each company during evaluation.
Aspect 3 (Structure – path to maturity)	
Non-linear	It allows companies to follow different strategic paths to reach the desired level of maturity.
Multidimensional	To allow a holistic assessment of the company, considering all important aspects, models must allow for different nuances of assessment.
Adjustable	A feature introduced in this research to address the recent need for greater compliance with contextual factors.

Source: This research.

Chapter 3 - The MCGDM method and its derived models

In this chapter, it is presented the Multi-criteria Group Decision Making (MCGDM) method used to build the specific models for each problem (section 3.1). It is important to highlight that the set of equations presented in section 3.1 correspond only to the aggregation algorithm; the other steps related to a common application of any MCGDM method, such as those discussed in section 2.1, are presented separately for each of the models. Additionally, the construction of each model is thoroughly detailed in Sections 3.2 and 3.3, in accordance with the second stage of our DSR methodology (model development).

Considering the characteristics of both models, as described in introduction and in Chapter 2, the method proposed by Shen et al. (2016) was selected for constructing the sorting models. The choice of this method considered aspects outlined in Section 1.2 of the introductory chapter, which excluded methods for individual decision-making, additive methods, methods based on pairwise comparisons between alternatives, and those used for other problematics than sorting. The box below presents the overall notation used in this method.

- The set of alternatives, represented by $A = \{a_1, \ldots, a_s\}$
- The set of criteria, represented by $G = \{g_1, g_2, \ldots, g_m\}$
- The set of weights of the criteria, represented by $W = \{w_1, \ldots, w_z\}$
- The set of Decision Makers, represented by $E = \{E_1, E_2, \ldots, E_k\}$
- The set of weights of the experts, represented by $\lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_k\}$
- The categories, represented by $L = \{L_1, L_2, \ldots, L_n\}$
- The set of limiting profiles, representing by $B = \{b_1^2, b_2^3, \ldots, b_{n-1}^n\}$

3.1 The MCGDM method

Both problems require a multi-criteria group decision-making (MCGDM) method with similar characteristics. For this research, the method proposed by Shen et al. (2016) was selected, which involves an aggregating algorithm consisting of five basic steps:

Step 1 – The scoring function and degree of hesitation.

Both are determined using Eq. (1) and Eq. (2) respectively, where **μ(x)** and **ν(x)** are the degrees of membership and non-membership determined in the **intracriteria evaluation** and to deffing the **limiting profiles** (See section 2.2).

$$S(\mathrm{x}) = \mu(\mathrm{x}) - \nu(\mathrm{x}) \qquad \text{(Eq. 1)}$$

$$\pi(\mathrm{x}) = 1 - \mu(\mathrm{x}) - \nu(\mathrm{x}) \qquad \text{(Eq. 2)}$$

Step 2 – The concordance test with the support function.

For this, two thresholds are used: indifference **q** and preference **p** ($0 \leq q_j \leq p_j \leq 2$). The function expresses the degree to which criterion **j** supports the assertion that $\mathbf{a_i}$ outranks $\mathbf{b^n_{n-1}}$. Where $\mathbf{S_{ij}}$ and $\mathbf{S^n_{(n-1)j}}$ are the scoring functions calculated according to Eq. (1), in criterion **j**, for $\mathbf{a_i}$ and $\mathbf{b^n_{n-1}}$, respectively.

$$\psi_j(a_i, b^n_{n-1}) = \begin{cases} 1, & if \quad S_{ij} + q_j > S^n_{(n-1)j}, \\ 0, & if \quad S_{ij} + p_j < S^n_{(n-1)j}, \\ \dfrac{p_j - (S^n_{(n-1)j} - S_{ij})}{p_j - q_j}, & Otherwise. \end{cases} \qquad \text{(Eq. 3)}$$

Step 3 – The non-discordance teste with the risk function.

The non-discordance test must be performed with the risk function, in which two thresholds are used: indifference **u** and veto **v** ($0 \leq u_j \leq v_j \leq 1$). The function is defined according to Eq. (4) and indicates the degree of risk to which criterion **j** disagrees with the statement that $\mathbf{a_i}$ outranks $\mathbf{b^n_{n-1}}$. Where $\boldsymbol{\pi_{ij}}$ and $\boldsymbol{\pi^n_{(n-1)j}}$ are the degrees of hesitation calculated according to Eq. (2), in criterion **j**, for $\mathbf{a_i}$ and $\mathbf{b^n_{n-1}}$, respectively.

$$\tau_j(a_i, b^n_{n-1}) = \begin{cases} 1, & if \quad \pi_{ij} - u_j < \pi^n_{(n-1)j}, \\ 0, & if \quad \pi_{ij} - v_j > \pi^n_{(n-1)j}, \\ \dfrac{v_j - (\pi_{ij} - \pi^n_{(n-1)j})}{v_j - u_j}, & Otherwise. \end{cases} \qquad \text{(Eq. 4)}$$

Step 4 – The intuitionistic fuzzy credibility index.

It indicates the degree of credibility of the statement that **a**$_i$ outranks $\mathbf{b_{n-1}^{n}}$. Where **w**$_j$ is the weight for criterion **j**, **w**$_j$ ∈ [0,1] e $\sum_{j=1}^{n} w_j = 1$. With this equation, an individual result is obtained for each decision maker/expert and the next step is to aggregate the results of the individual decision to determine the group index.

$$\rho(a_i, b_{n-1}^{n}) = \sum_{j=1}^{n} w_j \ (\psi_j(a_i, b_{n-1}^{n}) \times \tau_j(a_i, b_{n-1}^{n}) \qquad \text{(Eq. 5)}$$

Step 5 – The group intuitionistic fuzzy credibility index.

This index calculetad with Eq. (6) represents the degree of credibility for the assertion that the alternative **a**$_i$ outranks $\mathbf{b_{n-1}^{n}}$. Where $\lambda_{(l)}$ ∈ [0,1] (l = 1, 2, ..., y) are the decision makers weights and $\sum_{l=1}^{y} \lambda_{(l)} = 1$.

$$\rho_G(a_i, b_{n-1}^{n}) = \sum_{l=1}^{y} \lambda_{(l)}\rho_{(l)}(a_i, b_{n-1}^{n}) = \sum_{l=1}^{y}\sum_{j=1}^{n} \lambda_{(l)} w_j \ (\psi_j(a_i, b_{n-1}^{n}) \times \tau_j(a_i, b_{n-1}^{n})) \qquad \text{(Eq. 6)}$$

The method of Shen et al., (2016) require some parameters. The weights of the criteria (w_j) and of the experts ($\lambda_{(l)}$), the thresholds q, p, u and v (**q** and **u** for indifference, **p** for preference, and **v** for veto), the cut-off level θ, and the limiting profiles of the categories $\mathbf{b_{n-1}^{n}}$. The cut-off level is a predefined value that serves as a reference for outranking the profiles. In other words, for an alternative to be assigned to a specific category, its credibility degree (Eq. (6)), must be greater than or equal to θ $(\rho_G(a_i, b_{n-1}^{n}) \geq \theta, \forall \mathbf{b_{n-1}^{n}}, \text{and } \theta \in [0.5, 1]$.

The limiting profiles should be determined using IFV as following: For the value of **μ**, each expert should define the minimum value that a hypothetical alternative must reach to advance to the next category. For the value of **υ**, each expert should set the maximum value that a hypothetical alternative must not exceed to progress to the next category.

This method also enables the determination of the group's satisfaction level with the results obtained, utilizing three equations (Eq. (7), Eq. (8), and Eq. (9)):

$$\varphi_{(E)} = \frac{\sum_{i=1}^{m} \phi_{(E)}\,(a_i)}{m} \qquad \text{(Eq. 7)}$$

Where,

$$\phi_{(E)}(a_i) = \begin{cases} 1, & if\ u_{(E)}(a_i) = U(a_i) \\ 0, & otherwise \end{cases} \quad \text{(Eq. 8)}$$

Where $u_{(E)}(a_i)$ represents the alternative **a$_j$** sorting result of the each DM, **U(a$_i$)** is its group sorting result, and **m** represents the number of alternatives.

$$\varphi_G = \sum_{l=1}^{y} \lambda_{(E)}.\varphi_{(E)} = \sum_{l=1}^{y}\sum_{i=1}^{m} \frac{\lambda_{(E)}.\varphi_{(E)}(a_i)}{m} \quad \text{(Eq. 9)}$$

Individual satisfaction is determined using Eq. (7), while Eq. (9) is used for the grup satisfaction. The degree of satisfaction ranges from 0 to 1, with values closer to 1 indicating a higher level of satisfaction ($\varphi_G \in [0,1]$).

In the rest of this chapter, we present the models developed to address each problem. Since the aggregation algorithm is the same as described in the previous section, the following sections will focus on the specific characteristics of the problems, including evaluation conditions, criteria, and sorting categories. The equations are presented again without the detailed explanations previously provided, serving only to facilitate understanding with the new notations introduced for each problem.

3.2 Derived model for risk analysis

In this subsection, the corresponding model to the first problem is presented (DSR Step 3). This model was constructed to support risk analysis in process in diverse types do industries, and not limited to gas and oil industries (Viegas et al., 2020). In risk assessment, one of the most important steps is the task of prioritizing risks, and this proposal can also be adapted for this purpose into risk evaluation in workplaces., extending even more its applicability. All the characteristics of this problem is presented, including evaluations conditions, notations, criteria and risk levels.

The following notation was adopted:

- The set of hazards, represented by H = {h_1, …, h_s}
- The set of criteria, represented by G = {g_1, g_2, …, g_m}
- The set of weights of the criteria, represented by W = {w_1, …, w_z}
- The set of experts, represented by E = {E_1, E_2, …, E_k}

- The set of weights of the experts, represented by λ = {λ_1, λ_2, …, λ_k}
- The risk levels, represented by L = {L_1, L_2, …, L_n}
- The set of limiting profiles, representing by B = $\{b_1^2, b_2^3, \ldots, b_{n-1}^n\}$

Next are presented the basic steps of the derived model with the specific notation for this problem. The only difference between these equations and those presented at the beginning of the chapter is the value of **a**, which has been replaced by **h**, representing the risks. The equations are repeated here for the sake of clarity.

$$S(x) = \mu(x) - \nu(x) \tag{1}$$

$$\pi(x) = 1 - \mu(x) - \nu(x) \tag{2}$$

$$\psi_j(\boldsymbol{h}_i, b_{n-1}^n) = \begin{cases} 1, & if \quad S_{ij} + q_j > S_{(n-1)j}^n, \\ 0, & if \quad S_{ij} + p_j < S_{(n-1)j}^n, \\ \dfrac{p_j - (S_{(n-1)j}^n - S_{ij})}{p_j - q_j}, & Otherwise. \end{cases} \tag{3}$$

$$\tau_j(\boldsymbol{h}_i, b_{n-1}^n) = \begin{cases} 1, & if \quad \pi_{ij} - u_j < \pi_{(n-1)j}^n, \\ 0, & if \quad \pi_{ij} - v_j > \pi_{(n-1)j}^n, \\ \dfrac{v_j - (\pi_{ij} - \pi_{(n-1)j}^n)}{v_j - u_j}, & Otherwise. \end{cases} \tag{4}$$

$$\rho(\boldsymbol{h}_i, b_{n-1}^n) = \sum_{j=1}^{n} w_j \left(\psi_j(\boldsymbol{h}_i, b_{n-1}^n) \times \tau_j(\boldsymbol{h}_i, b_{n-1}^n)\right) \tag{5}$$

$$\rho_G(\boldsymbol{h}_i, b_{n-1}^n) = \sum_{l=1}^{y} \lambda_{(l)} \rho_{(l)}(\boldsymbol{h}_i, b_{n-1}^n) = \sum_{l=1}^{y} \sum_{j=1}^{n} \lambda_{(l)} w_j \left(\psi_j(\boldsymbol{h}_i, b_{n-1}^n) \times \tau_j(\boldsymbol{h}_i, b_{n-1}^n)\right) \tag{6}$$

3.2.1 Evaluation criteria

To evaluate each hazard identified and sort them in the appropriated risk level, we considered seven criteria proposed by Grassi et al., (2009) and Cheraghi et al., (2019), which are:

- Consequence: refers to the severity of the hazard, measured by factors such as the possibility of business interruption, damage and injuries.

- Occurrence/Frequency: measures the frequency with which the hazard may occur or the possibility of its occurring. In accordance with current safety measures, some hazards being more recurrent than others for specific reasons.
- Undetectability: Undetectability assesses the level of difficulty of the imminent hazard being detected before it occurs.

In addition, sensitivity to:

- Non-execution of maintenance
- Non-use of personal protective equipment (PPE):
- The effectiveness of maintenance
- Failure of safety measures.

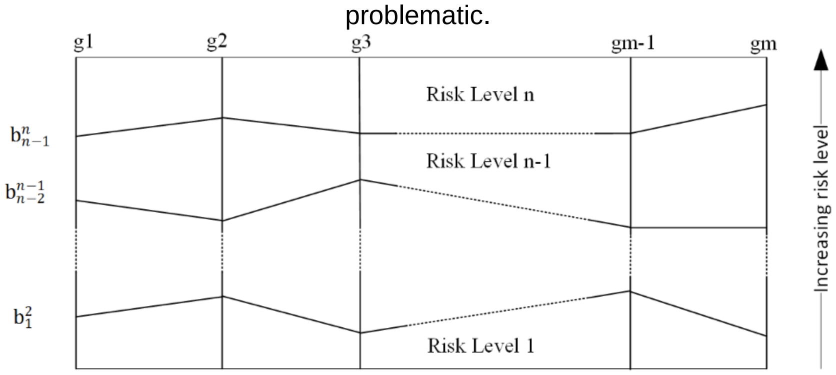
These last four criteria measure the sensitivity of the hazard, i.e. how much it can be affected by lack of maintenance (4), non-use of PPE (5), lack of effective maintenance (6) or safety measures (7), all applied to the analyzed node. Further details in Grassi et al., (2009) and Cheraghi et al., (2019).

3.2.2 Risk Levels (Categories)

For this study, we adopted three risk levels as the categories to sort the hazards, which are the same as those suggested by Ahn & Chang (2016), they are:

- Negligible: means that no additional safety measures are required.
- ALARP (As-low-as Reasonably Practicable): indicates that risks are supported with new safety measures.
- Unacceptable: the risk requires modifications to be made to the project.

Figure 3 - Graphical representation of the limiting profiles at each criterion and risk level in the sorting problematic.



Source: Adapted from Viegas et al., (2020)

3.3 Derived model for maturity analysis

In this subsection, the corresponding model to the second problem, published by Viegas and Costa (2023), is presented (DSR Step 3).

Important sets:

Set of CSFs, represented by F (f_1, f_2, …, f_m);

Set of CSFs Weights, represented by W (w_1, w_2, …, w_z);

Set of DMs, represented by D (d_1, d_2, …, d_k);

Set of DMs Weights, represented by λ (λ_1, λ_2, …, λ_k);

Set of BPM Maturity Levels, represented by L (l_1, l_2, …, l_n)

Set of Limiting Profiles (restrictions), represented by B (b_1, b_2, …, b_{n-1})

The fundamental procedures of the adapted model are outlined below, now incorporating notation tailored specifically to this application. For improved clarity, the equations are restated in this section. The sole modification compared to those introduced earlier in the chapter is the substitution of the parameter **a** with **org**, which denotes the organization being evaluated.

$$S(\mathrm{x}) = \mu(\mathrm{x}) - \nu(\mathrm{x}) \tag{1}$$

$$\pi(\mathrm{x}) = 1 - \mu(\mathrm{x}) - \nu(\mathrm{x}) \tag{2}$$

$$\psi_j(\boldsymbol{org}_i, b_{n-1}^n) = \begin{cases} 1, & if \quad S_{ij} + q_j > S_{(n-1)j}^n, \\ 0, & if \quad S_{ij} + p_j < S_{(n-1)j}^n, \\ \dfrac{p_j - (S_{(n-1)j}^n - S_{ij})}{p_j - q_j}, & Otherwise. \end{cases} \tag{3}$$

$$\tau_j(\boldsymbol{org}_i, b_{n-1}^n) = \begin{cases} 1, & if \quad \pi_{ij} - u_j < \pi_{(n-1)j}^n, \\ 0, & if \quad \pi_{ij} - v_j > \pi_{(n-1)j}^n, \\ \dfrac{v_j - (\pi_{ij} - \pi_{(n-1)j}^n)}{v_j - u_j}, & Otherwise. \end{cases} \tag{4}$$

$$\rho(\boldsymbol{org}_i, b_{n-1}^n) = \sum_{j=1}^{n} w_j \left(\psi_j(\boldsymbol{org}_i, b_{n-1}^n) \times \tau_j(\boldsymbol{org}_i, b_{n-1}^n)\right) \tag{5}$$

$$\rho_G(\boldsymbol{org}_i, b_{n-1}^n) = \sum_{l=1}^{y} \lambda_{(l)} \rho_{(l)}(\boldsymbol{org}_i, b_{n-1}^n) = \sum_{l=1}^{y} \sum_{j=1}^{n} \lambda_{(l)} w_j \left(\psi_j(\boldsymbol{org}_i, b_{n-1}^n) \times \tau_j(\boldsymbol{org}_i, b_{n-1}^n)\right) \quad (6)$$

3.3.1 Evaluation criteria

Various terminologies have been adopted in the literature to describe the key components that influence the success of BPM initiatives. These include "Capabilities" (Hammer, 2007), "Core Elements" (Rosemann and von Brocke, 2015), and "Process Areas" (OMG, 2008). However, they are most commonly referred to as Critical Success Factors (CSFs), which are widely recognized as the primary determinants of successful BPM implementation (Buh et al., 2015; Bai and Sarkis, 2013; Trkman, 2010). These CSFs, or their conceptual equivalents, form the basis of BPM assessment frameworks, serving as essential indicators for evaluating BPM effectiveness.

To develop a comprehensive model, a thorough search was conducted across leading academic databases—Emerald, Web of Science, Scopus, SpringerLink, and ScienceDirect—to identify all relevant CSFs in the context of BPM. The analysis proceeded in three distinct phases: first, identifying relevant publications; second, classifying the extracted CSFs; and third, performing a detailed examination of each CSF. During the classification phase, similar CSFs were grouped under broader conceptual categories to reflect overarching success dimensions. The detailed analysis phase focused on aspects such as how each CSF was assessed, validated, and the specific contexts in which they were applied. This process ultimately yielded 11 validated CSFs along with 39 associated Best Practices and Capabilities, which are summarized in Appendix A alongside their respective sources. All identified CSFs had previously undergone empirical validation in earlier research. These include: (1) Strategic Alignment, (2) Top Management Support, (3) BPM Governance, (4) People, (5) Information Technology, (6) BPM Methods, (7) BPM Culture, (8) Continuous Improvement, (9) Performance Measurement, (10) Project Management, and (11) Communication.

3.3.2 BPM Maturity Levels (Categories)

The framework adopts a maturity continuum ranging from zero to one, where higher values indicate more advanced levels of BPM maturity. Each CSF is evaluated along this same scale, allowing a granular assessment of organizational performance. As illustrated on the right-hand side of Figure 4, the framework defines three illustrative maturity levels to help organizations situate themselves within this continuum.

The first level represents an initial stage, typically occupied by organizations just beginning to implement BPM initiatives. The second level reflects a transitional stage—companies at this level have met the minimum performance thresholds across all CSFs but have not yet achieved full excellence. The third and highest level refers to mature organizations that demonstrate strong or complete mastery of all CSFs. These organizations also exhibit a commitment to continuous improvement and innovation and often serve as benchmarks for others.

It is important to note that these maturity levels are not fixed stages but serve only as reference points. Since organizations continuously strive to reach higher levels of maturity, the model emphasizes progression along the continuum rather than discrete categorizations. The visual representation in Figure 4 exemplifies how the CSF requirements are distributed along this scale.

3.3.3 The conceptual maturity model

Within the proposed framework, CSFs are visually represented as vertical columns along its base (Figure 4), emphasizing their foundational role in assessing and guiding BPM initiative advancement. Each CSF aligns with the maturity continuum, which spans from zero to one—higher values correspond to more advanced stages of BPM maturity.

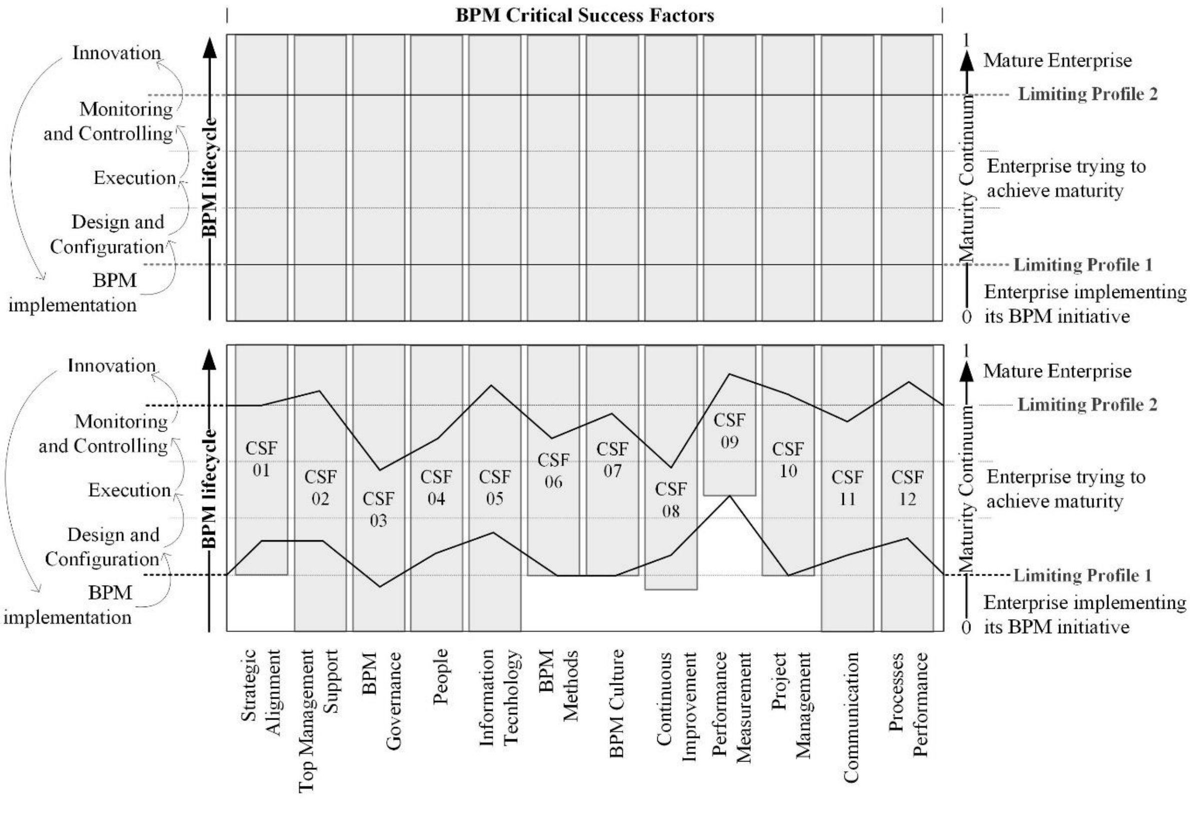
To help organizations understand their position along this continuum, the framework defines three illustrative maturity levels. The initial level encompasses organizations in the early stages of BPM implementation. The intermediate level refers to those that have satisfied the minimum requirements for all CSFs but have yet to reach full maturity. The highest level is reserved for organizations of excellence—those that consistently perform well across all CSFs, engage in continuous innovation, and often serve as benchmarks for industry peers.

Importantly, these maturity levels are not rigid classifications but serve as reference points for positioning within a continuous progression. Figure 4 illustrates how each CSF maps onto this continuum.

Beyond static assessment, the framework emphasizes dynamic, ongoing improvement throughout the BPM lifecycle. This lifecycle, consisting of five stages as shown in Figure 4, supports incremental enhancement of BPM initiatives over time. While most CSFs must be addressed from the outset, others—such as CSFs 1, 6, 7, 8, 9, and 10—become more prominent in later stages, as depicted in Figure 3.

To operationalize each CSF, specific best practices (BPs) and capabilities were identified. Establishing these BPs and capabilities across the lifecycle enables organizations to strengthen their BPM initiatives and make measurable progress toward strategic objectives.

Figure 4 - BPM maturity framework with an illustrative representation of each CSF requirement.



Source: Adapted from Viegas and Costa, 2023.

3.3.4 Evaluations steps

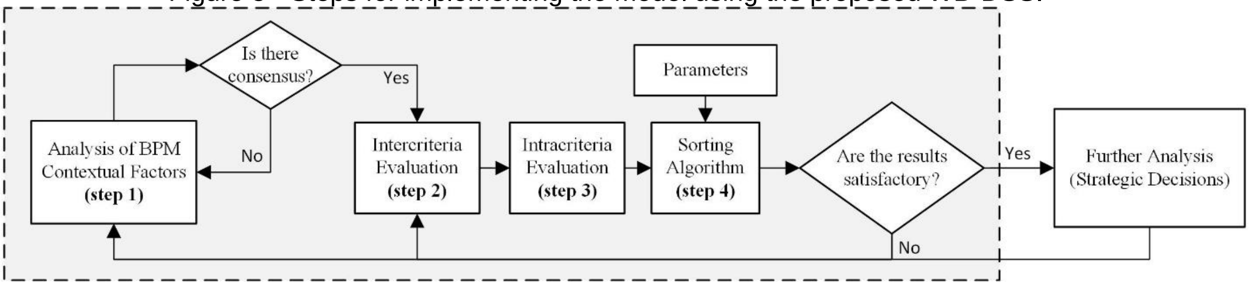
The proposed maturity assessment model consists of four sequential steps, as illustrated in Figure 5. While the final three steps align closely with the standard procedures found in MCGDM methods, the initial step distinguishes this model from conventional approaches.

Before advancing to the remaining stages, organizations must conduct a contextual analysis to identify factors that influence the success of their BPM initiatives. For this purpose, the framework developed by vom Brocke et al. (2016) is recommended, as it facilitates a deeper understanding of the organizational environment and highlights the most influential BPM factors.

To support the implementation of this model, a Web-based Group Decision Support System (WB-DSS) was developed. This system operationalizes the framework and enables collaborative evaluation across the assessment process. Further technical and functional details of the WB-DSS can be found in Chapter 5.

The subsequent three steps in the model conform to established MCGDM methodologies, ensuring consistency with widely accepted decision-making practices.

Figure 5 - Steps for implementing the model using the proposed WB-DSS.



Source: Adapted from Viegas and Costa, 2023.

Following the initial contextual assessment, the second step in the model focuses on intercriteria evaluation, which determines the relative importance of each assessment criterion—in this case, the BPM CSFs. This stage is critical, as it significantly influences the final results and introduces inherent uncertainty. To reduce the cognitive load on DMs, they are only asked to rank the CSFs according to their strategic relevance. Based on these rankings, the WB-GDSS computes the corresponding weights through a dedicated algorithm.

In contrast to this simplified input process, the following step requires a more granular evaluation from each DM. Here, organizations are assessed individually against each CSF using Intuitionistic Fuzzy Values (IFVs), as described in Section 2.2. For each CSF, the DM assigns a pair of values (μ, ν), where μ represents the degree to which the company satisfies the CSF, and v indicates the degree of non-satisfaction, subject to the constraint $0 \leq \mu + v \leq 1$.

The final step—Step 4—consists of the aggregation process. In this phase, the data derived from the parameter configuration, intracriteria assessments, and intercriteria rankings are consolidated into a single outcome: the Group Intuitionistic Fuzzy Credibility Index, which quantifies the organization's BPM maturity level. The mathematical formulations used in this step are consistent with those introduced in Section 3.1, as the entire model was constructed based on the methodology outlined there.

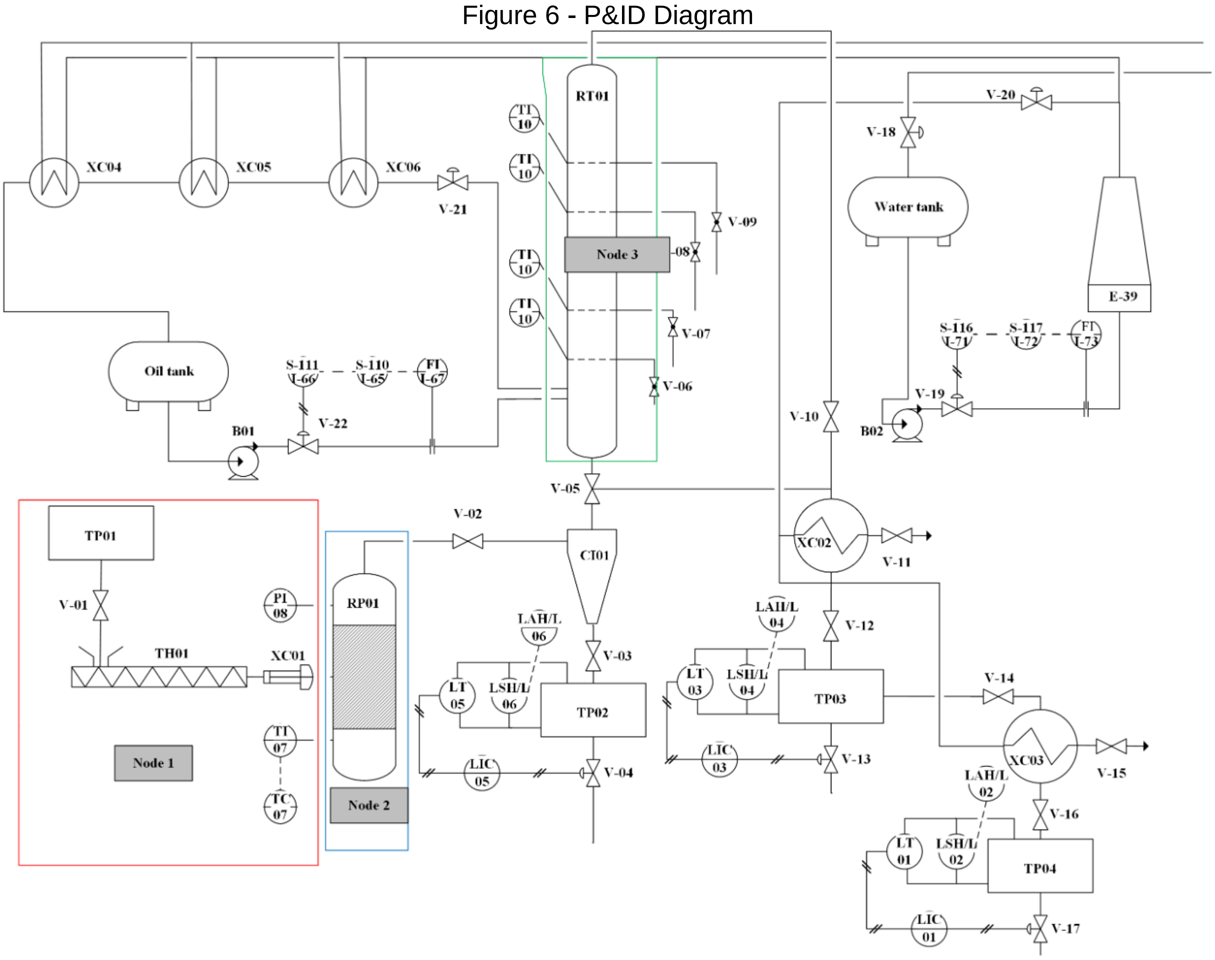
Chapter 4 - Research Problem I (Process Risk Analysis)

In this chapter, we present a real-world application of the proposed methodology, corresponding to the fourth and final stage of our DSR methodology (model evaluation and application), and analyze the results (Section 4.1). Subsequently, we conduct a comparative analysis with the main related models already published, corresponding to the second phase of our DSR methodology (comparative analysis), and discuss the contributions and advances of the methodology to the research field (Section 4.2).

4.1 A real application

The case study focuses on a continuous pyrolysis unit featuring a thermally fractionated cooling tower, engineered for the production of bio-oil. This pilot-scale system is installed at the Technology Center of the Federal University of Piauí, located in Brazil. The process and instrumentation diagram (P&ID) is illustrated in Figure 6, which identifies the specific nodes selected for analysis in this investigation.

Figure 6 - P&ID Diagram



Source: Adapted from Viegas et al., 2020.

The bio-oil production process in this specific unit is structured as follows: the biomass sample is initially deposited into a feed tank (TP01), which is connected to a variable-speed helical conveyor (TH01). At the end of this conveyor, the biomass passes through a bitubular heat exchanger (XC01) (Node 1). From there, it is transferred to the pyrolysis reactor (RP01) (Node 2), where the biomass undergoes thermal decomposition, resulting in the breakdown of molecular chains and the generation of hydrocarbon gases. Pyrolysis also produces a substantial amount of particulate matter (tar and char), which is removed via a cyclone separator (CL01). The resulting gases are then directed toward two distinct condensation systems.

In the first path, the vapors are sent to a set of shell-and-tube heat exchangers (XC02, XC03), cooled by water from a cooling tower. Due to the high temperatures, this system is expected to condense only hydrocarbons with high molecular weights. In the second path, the vapors are directed to a thermodynamic equilibrium separation tower (TR01) (Node 3), which contains helically coiled tubes internally cooled by thermal oil. This oil, with a high boiling point (approximately 550 °C), does not evaporate within the system. Once heated, it circulates through a shell-and-tube heat exchanger array where it is cooled and subsequently recirculated. This pilot unit is located at the Technology Center of the Federal University of Piauí, Brazil.

4.1.1 Prerequisites

The HAZOP analysis was conducted by the same team that performed the conventional study on this facility in 2016. Comprised of four members, including a designated Facilitator, the group was well-acquainted with the operational details of the plant and demonstrated solid expertise in the traditional HAZOP methodology. Notably, the Facilitator also possessed specialized knowledge in Multi-Criteria Decision Making (MCDM), Intuitionistic Fuzzy Sets (IFS), and Strategic Options Development and Analysis (SODA) techniques. For this implementation, three evaluation criteria were utilized: Consequence, Frequency, and Undetectability. While the first two criteria were assessed using five-level rating scales, Undetectability was measured on a three-level scale, as shown in Tables 3, 4, and 5. In each instance, qualitative descriptions drawn from the original data sources were translated into Intuitionistic Fuzzy Values (IFVs), following approaches similar to those proposed by Grassi et al. (2009) and Cheraghi et al. (2019).

Table 3 - Category profiles for the consequence criterion

Consequence	Intuitionistic Fuzzy Values
Negligible	If (μ < 15 and v > 0.60)
Marginal	If (0.15 ≤ μ < 0.40 and 0.40 < v ≤ 0.60)
Moderate	If (0.40 ≤ μ < 0.65 and 0.15 < v ≤ 0.40)
Critical	If (0.65 ≤ μ < 0.85 and 0.10 < v ≤ 0.15)
Catastrophic	If (μ ≥ 0.85 and v ≤ 0.10)

Source: Adapted from Viegas et al., 2020.

Table 4 - Category profiles for the frequency criterion

Frequency	Intuitionistic Fuzzy Values
Improbable	If (μ < 15 and v > 0.60)
Remote	If (0.15 ≤ μ < 0.40 and 0.40 < v ≤ 0.60)
Occasional	If (0.40 ≤ μ < 0.65 and 0.15 < v ≤ 0.40)
Probable	If (0.65 ≤ μ < 0.85 and 0.10 < v ≤ 0.15)
Frequent	If (μ ≥ 0.85 and v ≤ 0.10)

Source: Adapted from Viegas et al., 2020.

Table 5 - Category profiles for the undetectability criterion

Undetectability	Intuitionistic Fuzzy Values
Low	If (μ < 0.40 and v > 0.60)
Medium	If (0.40 ≤ μ < 0.80 and 0.15 < v ≤ 0.60)
High	If (μ ≥ 0.80 and v ≤ 0.15)

Source: Adapted from Viegas et al., 2020.

Table 6 - Weights of criteria and experts (Intercriteria Evaluation)

Criteria	Expert 1	Expert 2	Expert 3
	0.35	0.35	0.3
g_1	0.50	0.60	0.50
g_2	0.30	0.20	0.25
g_3	0.20	0.20	0.25

Source: This research.

Table 7 - Limiting profiles of the categories in each criterion defined by the three experts

	Criteria	Profiles	
		$\boldsymbol{b_1^2}$	$\boldsymbol{b_2^3}$
	g_1	0.30; 0.10	0.75; 0.25
Expert 1	g_2	0.20; 0.20	0.80; 0.2
	g_3	0.30; 0.20	0.85; 0.10
	g_1	0.40; 0.20	0.85; 0.15
Expert 2	g_2	0.30; 0.20	0.75; 0.25
	g_3	0.40; 0.20	0.75; 0.20
	g_1	0.25; 0.25	0.65; 0.20
Expert 3	g_2	0.40; 0.30	0.80; 0.15
	g_3	0.30; 0.25	0.70; 0.20

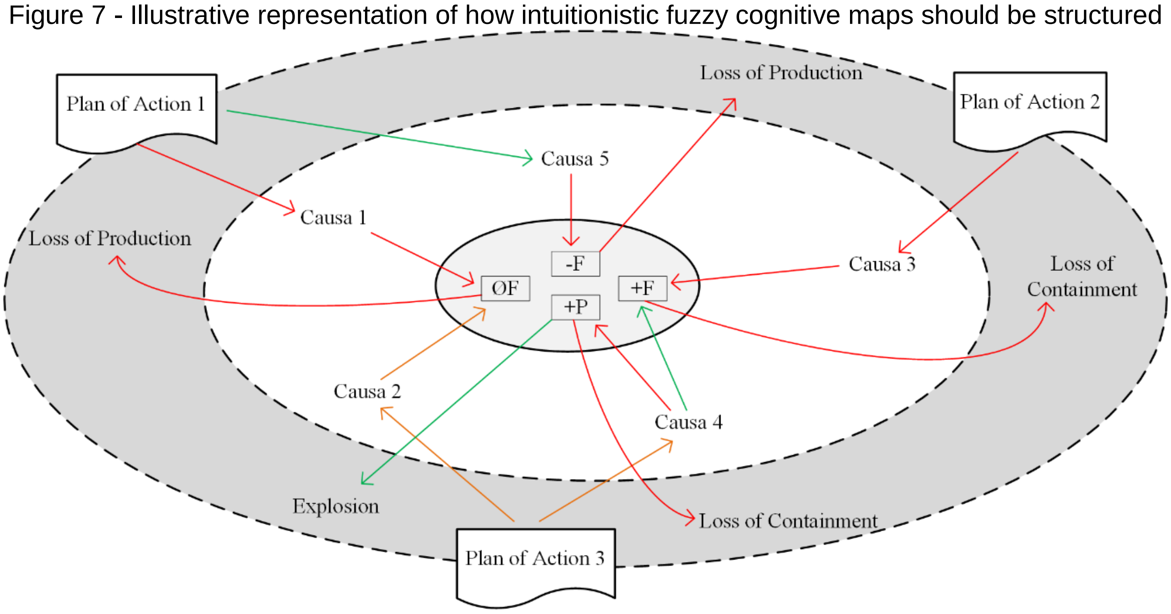
Source: This research.

Prior to initiating the analysis, the necessary parameters were established. The Facilitator defined the threshold values as follows: q = 0.1, p = 0.2, u = 0.2, and v = 0.5, with a cut-off value θ set at 0.6. Table 6 provides the weighting assigned to each expert, along with the individual weights they allocated to each evaluation criterion. The limiting profiles used to distinguish between the predefined risk levels are presented in Table 7. A comprehensive description of the methodological procedures applied to Problem I is available in Appendix B.

4.1.2 Step 1 – Hazard Identification

Hazard identification was conducted using the SODA methodology, with traditional cognitive maps being replaced by Intuitionistic Fuzzy Cognitive Maps, as illustrated in Figure 7. The approach was implemented in two phases. In the initial phase, each expert independently developed a cognitive map for every node under analysis. During the second phase, these individual maps were consolidated through a structured brainstorming session. A detailed explanation of the mapping procedure, including the rationale behind its construction, can be found in Appendix C. The final integrated map for each node served as the basis for hazard identification. As a result of this process, 40 hazards were identified across the three nodes examined. Table 8 summarizes the findings from this initial step, including the corresponding deviations and their associated consequences for each identified hazard.

Figure 7 - Illustrative representation of how intuitionistic fuzzy cognitive maps should be structured



Source: This research.

Table 8 - Hazards identified in HAZOP 1 (Hazard Identification)

	Node 1 - Feeding System		Node 2 - Pyrolysis reactor		Node 3 - Fractionation tower	
Deviation	Consequence	Hazard	Consequence	Hazard	Consequence	Hazard
ØF	No production	h_1	No production	h_{12}	No production	h_{25}
-F	Loss of production	h_2	Loss of production	h_{13}	Loss of production	h_{26}
+F	Explosion More production Loss of containment Loss of production	h_3 h_4 h_5 h_6	More production Explosion	h_{14} h_{15}	Loss of production More production	h_{27} h_{28}
-T	More production	h_7	Loss of production	h_{16}	Loss of production	h_{29}
+T	Explosion Loss of production Loss of containment	h_8 h_9 h_{10}	More production Explosion Loss of production	h_{17} h_{18} h_{19}	Explosion More production Loss of containment Faulty products	h_{30} h_{31} h_{32} h_{33}
ØP			No production	h_{20}	Loss of production	h_{34}
-P			Loss of production	h_{21}	Loss of production Faulty products	h_{35} h_{36}
+P	Loss of containment	h_{11}	Explosion More production Loss of containment	h_{22} h_{23} h_{24}	More production More production Loss of containment Faulty products	h_{37} h_{38} h_{39} h_{40}

Source: This research.

4.1.3 Step 2 – Hazard Classification

The subsequent phase entails the classification of the previously identified hazards, employing the classification algorithm embedded within the proposed model. This process integrates the outputs of both the intracriteria and intercriteria evaluations, in conjunction with the model's defined parameters. Comprehensive procedures for conducting these evaluations can be found in Appendix D, while

Appendix F outlines the method used to establish the limiting profiles for each risk level according to individual criteria.

Using the data from the intracriteria evaluation (refer to application steps in Appendix B) and the corresponding parameters, the sorting algorithm was executed following the sequence defined in Section 3.2, specifically Equations (1) through (6). Table 9 presents the calculated group intuitionistic fuzzy credibility indices for each of the 40 hazards, based on Equation (6). The detailed results of the intracriteria assessments by each expert, across all criteria and hazards, are provided in Appendix E.

The classification mechanism utilizes the symbols S and S^{-1}, representing outranking and non-outranking relationships, respectively—where S applies when $\rho_G(h_i, b_{n-1}^n) \geq \theta$, and S^{-1} otherwise.

As indicated in Table 9, no hazard was assigned to the highest risk level (Risk Level 3, unacceptable). Only three hazards, constituting 7.5% of the total, fell within Risk Level 2 (ALARP), suggesting the need for further review of current safety strategies. The remaining hazards were categorized as Risk Level 1 (negligible). These findings reinforce the advantage of employing a classification approach over traditional ranking methods, as it provides clearer prioritization of critical hazards. Moreover, this enhances resource allocation efficiency and reduces unnecessary expenditure.

4.1.4 Step 3 – Hazard Mitigation

Step 3 of the proposed methodology, which concerns hazard mitigation, is not addressed in this thesis, as it falls outside the scope of this study. However, after obtaining the initial results, some important considerations should be made to improve the reliability of the outcomes. Before proceeding to Step 2, it is recommended that the team conduct a robustness analysis to identify which parameters of the model are most sensitive to the results. These parameters should then be further investigated to ensure the consistency and validity of the findings.

It is also essential to assess the team's level of satisfaction with the outcomes. If satisfaction falls below the defined threshold, adjustments must be made to reach an acceptable level. Low satisfaction may indicate that one or more participants either overestimated or underestimated their responses, potentially compromising the accuracy and credibility of the final results.

4.2 Evaluation and Interpretation of Findings

It is essential to highlight the flexibility of the proposed model, which offers several advantages: (1) criteria can receive distinct weights according to each Decision Maker's (DM's) perspective; (2) different importance levels can be assigned to each DM; (3) a reduced set of criteria can be selected to better suit the characteristics of each organization, plant, or node; and (4) only the most experienced DMs can be included in the process. These features enable the model to be adapted to the organization's specific context and the diverse expertise of its members. Additionally, the approach grants participants greater autonomy in the decision-making process, which contributes to a stronger sense of engagement and responsibility.

Table 9 - Group intuitionistic fuzzy credibility indices

Hazard	b_1^2	b_2^3	Hazard	b_1^2	b_2^3
h_1	0.075 → S^{-1}	0.000 → S^{-1}	h_{21}	0.000 → S^{-1}	0.000 → S^{-1}
h_2	0.250 → S^{-1}	0.000 → S^{-1}	h_{22}	0.535 → S^{-1}	0.535 → S^{-1}
h_3	0.535 → S^{-1}	0.535 → S^{-1}	h_{23}	0.385 → S^{-1}	0.000 → S^{-1}
h_4	0.408 → S^{-1}	0.000 → S^{-1}	h_{24}	0.560 → S^{-1}	0.535 → S^{-1}
h_5	0.535 → S^{-1}	0.385 → S^{-1}	h_{25}	0.083 → S^{-1}	0.000 → S^{-1}
h_6	0.035 → S^{-1}	0.000 → S^{-1}	h_{26}	0.135 → S^{-1}	0.000 → S^{-1}
h_7	0.035 → S^{-1}	0.000 → S^{-1}	h_{27}	0.035 → S^{-1}	0.000 → S^{-1}
H_8	0.535 → S^{-1}	0.535 → S^{-1}	h_{28}	0.058 → S^{-1}	0.000 → S^{-1}
H_9	0.075 → S^{-1}	0.000 → S^{-1}	h_{29}	0.105 → S^{-1}	0.000 → S^{-1}
H_{10}	0.610 → S	0.535 → S^{-1}	h_{30}	0.710 → S	0.535 → S^{-1}
H_{11}	0.635 → S	0.560 → S^{-1}	h_{31}	0.150 → S^{-1}	0.000 → S^{-1}
h_{12}	0.000 → S^{-1}	0.000 → S^{-1}	h_{32}	0.535 → S^{-1}	0.535 → S^{-1}
h_{13}	0.175 → S^{-1}	0.000 → S^{-1}	h_{33}	0.325 → S^{-1}	0.175 → S^{-1}
h_{14}	0.385 → S^{-1}	0.000 → S^{-1}	h_{34}	0.028 → S^{-1}	0.000 → S^{-1}
h_{15}	0.535 → S^{-1}	0.535 → S^{-1}	h_{35}	0.150 → S^{-1}	0.000 → S^{-1}
h_{16}	0.215 → S^{-1}	0.000 → S^{-1}	h_{36}	0.373 → S^{-1}	0.175 → S^{-1}
h_{17}	0.448 → S^{-1}	0.000 → S^{-1}	h_{37}	0.385 → S^{-1}	0.385 → S^{-1}
h_{18}	0.535 → S^{-1}	0.535 → S^{-1}	h_{38}	0.000 → S^{-1}	0.000 → S^{-1}
h_{19}	0.538 → S^{-1}	0.535 → S^{-1}	h_{39}	0.535 → S^{-1}	0.535 → S^{-1}
h_{20}	0.000 → S^{-1}	0.000 → S^{-1}	h_{40}	0.325 → S^{-1}	0.175 → S^{-1}

Source: This research.

As mentioned earlier, prior studies highlight gaps regarding potential improvements, with the main goal of this work being the development of a new methodology that addresses these gaps. In addition, efforts were made to tackle several critical issues of traditional HAZOP. Table 11 compares the proposed approach to previous studies, while Table 1 identifies key areas for improvement, especially in hazard prioritization. As shown throughout this thesis, the proposed method resolves all six limitations identified. Table 10 presents the comparative analysis results, where previous models are evaluated against the proposed methodology in terms of each of these improvement areas.

Table 10 - Improvement Opportunities met by the proposed method and related studies

Aspects to be improved	Ahn and Chang (2016)	Cheraghi *et al., (2019)*	Grassi *et al., (2009)*	Aziz *et al., (2017)*	This Proposal
I	x	v	v	v	v
II	v	x	x	x	v
III	v	x	v	x	v
IV	v	v	v	x	v
V	x	x	x	x	v
VI	x	x	x	x	v

Source: Adapted from Viegas et al., 2020.

The hazard prioritization phase employed a Multi-Criteria Decision-Making (MCDM) approach through a sorting algorithm. Hazards identified during the initial HAZOP analysis were assigned to distinct risk categories according to a defined set of criteria and evaluations provided by a panel of experts, as presented in Tables 9 and 10. A key strength of the proposed model lies in its adaptability, offering multiple configuration options: (1) individual criteria weights can be assigned based on each decision maker’s (DM) viewpoint; (2) decision makers themselves can be assigned differentiated weights; (3) the set of criteria may be selectively reduced to reflect the specific context of a given organization, facility, or process node; and (4) only those DMs with the highest levels of expertise and experience may be selected to participate. These features enable the model to be tailored to the unique needs and characteristics of each organization, while also encouraging active engagement and a heightened sense of accountability among participants.

Several limitations of the traditional HAZOP methodology, particularly its inability to investigate the root causes of hazards, have been highlighted by Baybutt (2015). Notably, none of the reviewed studies have proposed improvements to address this gap. In response, this work incorporated the SODA methodology, which utilizes cognitive maps to trace causal relationships, including root causes and sub-causes. This enhancement enables a deeper understanding of each hazard's origin and facilitates iterative improvement, as these maps can be preserved and expanded upon as new insights emerge.

Furthermore, Baybutt (2015) also noted a weakness of group brainstorming: individuals often generate more innovative ideas when working independently and are typically more reflective in solitude. To overcome this, the proposed methodology integrates individual cognitive maps using the SODA framework, thereby improving the overall quality of the brainstorming process. Additionally, the group decision-making structure inherent to SODA promotes more effective knowledge aggregation by synthesizing individual perspectives.

Another critical issue found in earlier works—such as those by Grassi et al. (2009) and Cheraghi et al. (2019)—concerns the oversimplification involved in using only two equally weighted criteria for prioritization. Wu et al. (2012) offers a more robust solution by permitting variable weights for both criteria and experts. This flexibility is essential to accommodate the diverse backgrounds and knowledge levels among the evaluators, directly addressing the concerns raised in prior studies.

Lastly, the inherent uncertainty and subjectivity involved in hazard assessments—often due to incomplete or outdated data—can undermine the reliability of deterministic models, as emphasized by Grassi et al. (2009) and Ahn and Chang (2016). Consequently, this thesis advocates for the application of fuzzy logic principles to model such uncertainties more effectively. The additional use of flexible weighting mechanisms further contributes to the robustness and credibility of the prioritization outcomes, ensuring a more dependable framework for decision-making in hazard analysis.

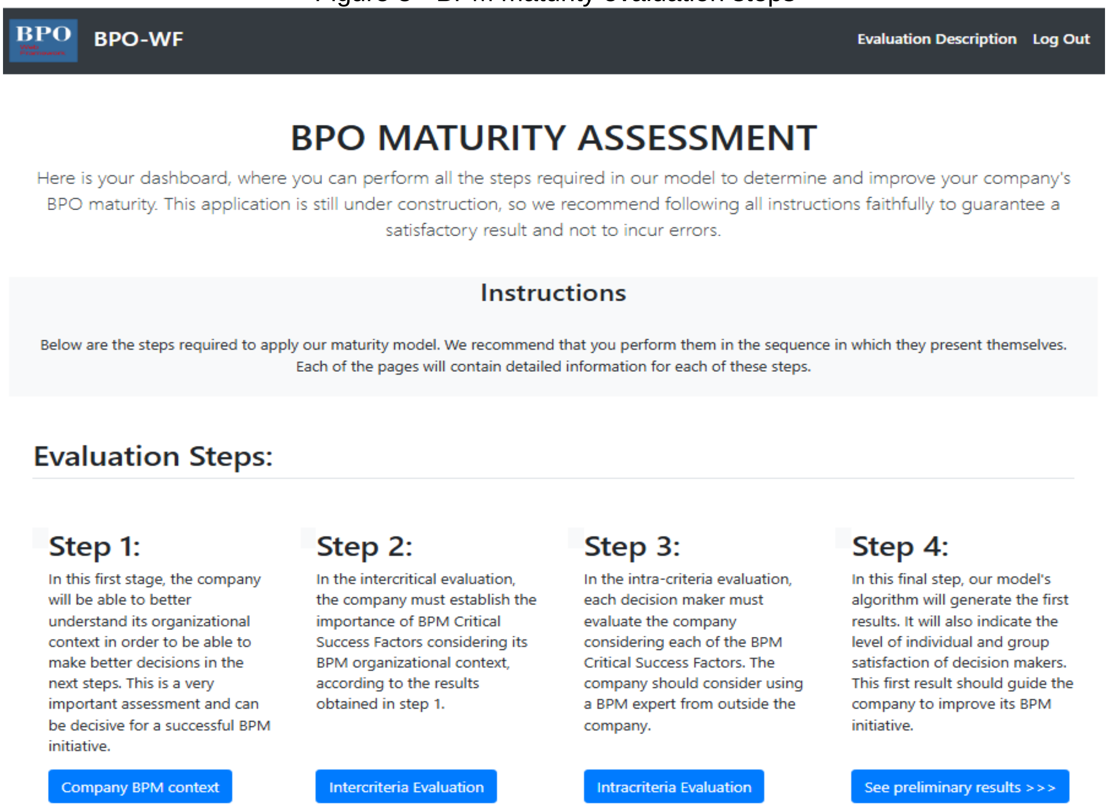
Chapter 5 - Research Problem II (BPM Maturity Evaluation)

In this chapter, we present a real application of the proposed methodology using a Web-Based Decision Support System (WB-DSS), specifically designed to facilitate the application of the proposed model. This application represents the fourth and final stage of our DSR methodology. The WB-DSS and the company under evaluation are described, detailing the steps and results. Finally, we discuss the contributions of this work, including a comparative analysis of key related models, aligned with the fourth phase of the DSR methodology.

5.1 The Web-based Decision Support System (WB-DSS)

The Figure 8 presents the evaluation steps that take place within the WB-DSS. These steps were presented in Chapter 3 (section 3.3). In this figure, the dashboard is shown, where all decision makers involved in the evaluation are required to perform each step. All information and instructions required are presented. Except for the first step, all the others are typically found in MCGDM methods.

Figure 8 - BPM maturity evaluation steps



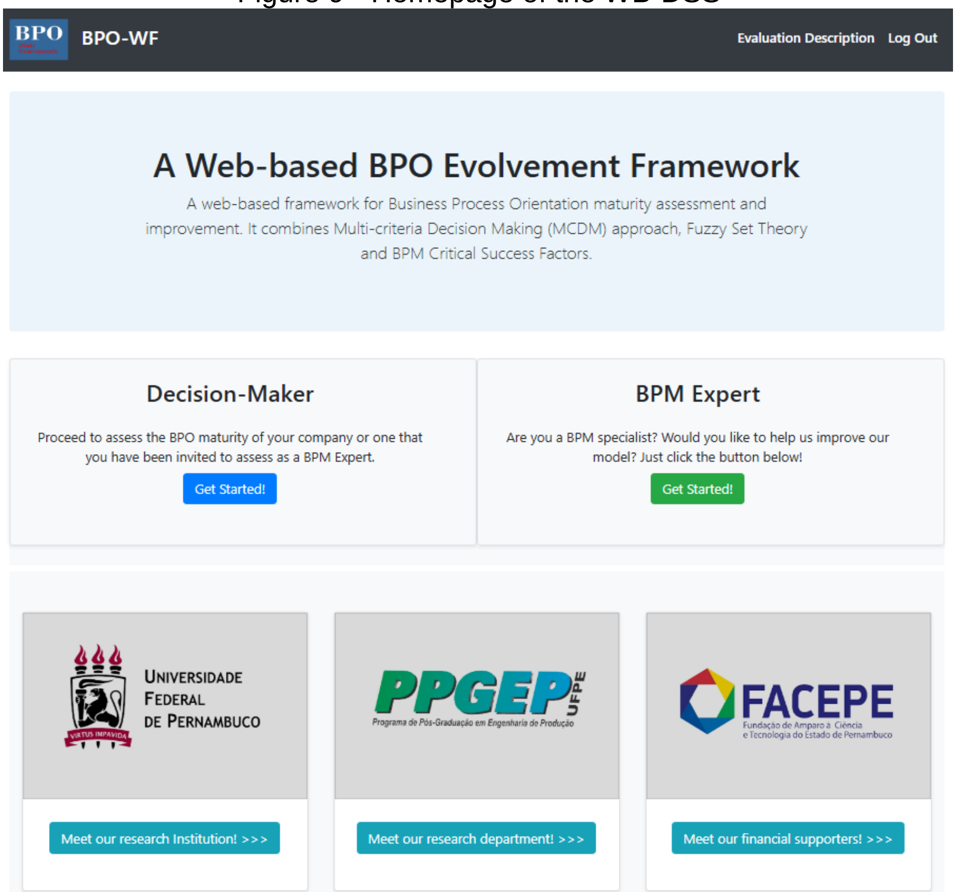
Source: This research.

For the application of the model, there are four steps described in Figure 8. Steps 1 and 2 (Analysis of Contextual Factors in BPM and Intercriteria Assessment) must be carried with all the members of the team responsible for the assessment, i.e., they must be gathered virtually at the same time. In these first two steps, only one of the members must fill out the forms. In step 3 (Intercriteria Assessment), each of the DMs must answer the questionnaire separately. Step 4 corresponds to the aggregation algorithm, where all the data is used in equations 1 to 6 presented in chapter 3 (section 3.3). All these calculations are performed by the system, for which it is sufficient for any of the members to enter the code defined for the company in the initial step. At the end, a report is presented with the final result of the application.

5.1.1 Users' roles and responsibilities

Users of this system have two different profiles, the BPM experts and DMs; in the latter case, they represent companies (See Figure 9). When invited by a company, the expert may also take on the role of a DM. In this case, they are referred to as an "external DM."

Figure 9 - Homepage of the WB-DSS



Source: This research.

As BPM experts, they are responsible for defining key parameters of the system. As this is a GDSS based on a MCGDM method, it is necessary to define some parameters (for the method by Shen et al. (2016), which was chosen, it is necessary to define the criteria, thresholds, and cutting level). Particularly, they have to determine the BPM CSF, limiting profiles, and Best Practices and capabilities related to these CSFs. Once logged into the system, any user can access this functionality; however, before these data provided are implemented in the system, they go through process guarantee the quality of the answers. First, the veracity of the personal information provided is verified. Once it has being confirmed, the next step is to verify that the user is a BPM expert. Details about the user are analyzed, including: 1 – BPM certification, such as those provided by the Association of Business Process Management Professionals International, or ABPMP International; 2 – publication of articles or books in scientific journals; and (3) – practical experience proven by the institution in which the user works. Finally, the responses from these users are analyzed.

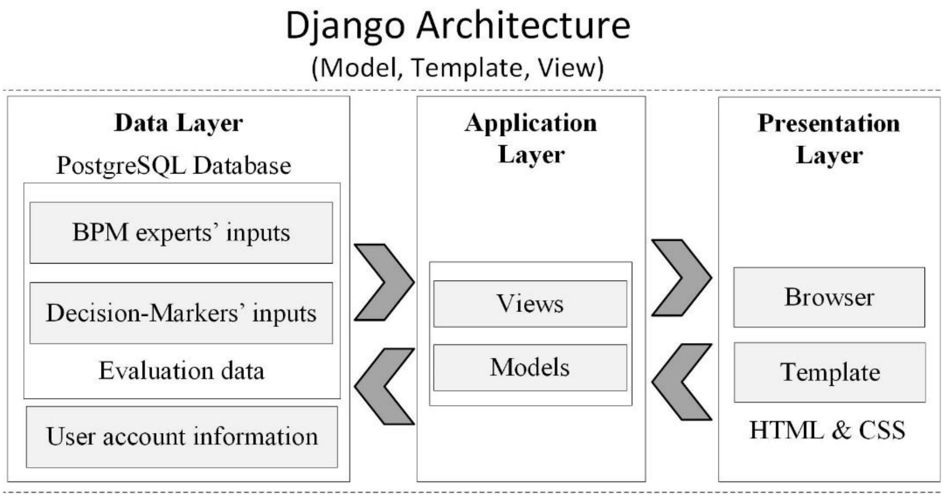
The responsibility of DMs is solely toward their own companies. They must guarantee the highest possible level of authenticity in their answers so that the best of the system is used to provide a result that is as consistent as possible with the reality of the company. It is recommended that individuals with the most extensive knowledge, whether in BPM or company processes, be selected for this type of decision. This person should be qualified based not on the hierarchical level it occupies, but on their ability to provide detailed and relevant information.

The other tasks are performed automatically by the system according to the set of aggregation equations of the MCGDM method adopted.

5.1.2 Software architecture

The template component is used to present the application's interface to the user. It corresponds to the web page, which will be viewed by the user enable them to interact with the system. This component was built entirely with HTML 5, CSS and with Bootstrap framework. The component View represents the application logic, where the main functions that will be used to collect the data, manipulate it and generate the results are defined. This component mutually interacts with the database through the Model component and with the users in the Template component. In the Model component, all data and data types that will be stored in the database and used in the system application are determined. These data correspond to the parameters defined by the BPM specialists, user data, inputs from the companies' evaluations (data generated in each of the stages and results), and data used in the evaluation. For this application, the PostgreSQL database was used.

Figure 10 - The software architecture



Source: This research.

5.2 A real application

5.2.1 Prerequisites

Prior to the application of the model, it was necessary to define certain parameters of the multi-criteria decision-making (MCDM) framework—namely, the limiting profiles and threshold values. The limiting profiles were established by a panel of nine Business Process Management (BPM) experts certified by the Association of Business Process Management Professionals International (ABPMP International), comprising six from Brazil, two from the United States, and one from France. These experts employed Interval-Valued Fuzzy Sets (IFVs) to define the profiles. Specifically, for each critical success factor (CSF), the experts were required to assign four IFVs: membership (μ) and non-membership (υ) degrees for the first limiting profile (b1), and likewise for the second limiting profile (b2). These values were determined based on the expected performance levels of the CSFs across different maturity stages, as judged by the experts according to their professional experience and domain knowledge. The aggregated results, derived by averaging the individual responses, are presented in Table 11. For this particular application, the following thresholds were adopted: q = 0.1, p = 0.2, u = 0.2, and v = 0.5. Additionally, the cut-off level θ was set at 0.65.

The initial step in applying the framework involves establishing the relative importance of each critical success factor (CSF), a process referred to as intercriteria evaluation. Given the total of 12 CSFs, assigning weights directly could lead to inconsistencies. To address this, decision-makers were first instructed to rank the CSFs in descending order of importance. Based on these rankings, a score was assigned to each CSF using the Borda count method (Nurmi, 1983). Subsequently, the Ranking Ordered Centroid (ROC) method was employed to derive the final weights. The ROC method consists of a series of equations that calculate the weight of each criterion according to its position in the ordered ranking (Edwards and Barron, 1994). Following the intercriteria evaluation, the framework proceeded with step 2, the intracriteria evaluation, and step 3, the aggregation algorithm, as detailed in Section 3.2.

Table 11 - Limiting profiles with IFV

CSFs	b_1		b_2	
	μ	ʋ	μ	ʋ
F_1	0,38	0,62	0,91	0,09
F_2	0,44	0,56	0,91	0,09
F_3	0,34	0,66	0,82	0,18
F_4	0,34	0,66	0,78	0,22
F_5	0,32	0,68	0,78	0,22
F_6	0,37	0,63	0,82	0,18
F_7	0,35	0,65	0,83	0,17
F_8	0,34	0,66	0,80	0,20
F_9	0,32	0,68	0,85	0,15
F_{10}	0,33	0,67	0,81	0,19
F_{11}	0,41	0,59	0,87	0,13
F_{12}	0,32	0,68	0,84	0,16

Source: This research.

5.2.2 Organizational context for model applying

To enhance and validate the proposed model, it was implemented in a large Brazilian company specializing in the manufacturing and distribution of car batteries. The evaluation was conducted at one of its operational units responsible for product storage and distribution. The assessment covered all processes within the selected unit and involved four internal decision-makers (DMs). All DMs held undergraduate degrees, with three possessing postgraduate qualifications, including master's degrees, specialized training, and professional certifications such as Six Sigma Green Belt. In terms of organizational roles, one participant held a managerial position, while the others served as coordinators. The average professional experience among the DMs was 4.75 years.

At the outset, the evaluation of the organization's BPM contextual factors revealed that the company seeks to improve both process effectiveness and efficiency as part of its commitment to operational excellence. The company holds ISO 9001:2015 certification, which, as noted by Froger et al. (2019), reflects a mature process management system. It is also certified under ISO 14001, ISO/TS 16949, ISO 20400, and possesses a Duns & Bradstreet D-U-N-S® Number (D&B 2008). Given this context, the application of traditional BPM tools is deemed appropriate.

5.2.3 Preliminary results and further analysis

Tables 12 and 13 present the preliminary findings of the assessment. Table IV displays both individual and group credibility indices in relation to the two limiting profiles. As shown, all profiles were outranked, with the exception of profile b2 for Decision-Maker 1 (DM1), for whom the credibility index was 0.603—below the defined cut-off threshold θ (0.65). Table 12 summarizes the maturity level classifications at both the individual and group levels. According to DM1, the organizational unit is currently positioned at maturity level 2. In contrast, the remaining decision-makers and the group as a whole assessed the unit at level 3, which is the highest level in the framework. The calculated group satisfaction degree was 0.75, indicating a lack of full agreement among the DMs. In such cases, it is advisable to apply the group consensus adaptive search and adjustment method to refine the collective evaluation (see Shen et al., 2016). The subsequent phase involves conducting a deeper analysis to better comprehend the current maturity level and to inform future improvement initiatives. While this analysis lies beyond the scope of the present thesis, it is strongly recommended to begin with a sensitivity analysis. This will help identify which critical success factors (CSFs) require greater attention. Once the priority CSFs have been determined, an internal investigation should be conducted to pinpoint the specific units, sectors, or processes that are contributing to either underperformance or strong results in those CSFs. The outputs from the intracriteria evaluation and the contextual BPM factors may provide valuable support for this analysis.

The results of the application demonstrated, to a certain extent, that the company's current situation is accurately represented by the model. Given that the primary objective of these evaluations is to determine whether the organization has sustained operational excellence, the findings support the conclusion that this goal has been achieved. Moving forward, the company is now equipped with knowledge regarding which critical success factors (CSFs) most significantly contribute to this outcome. This insight enables the development of more targeted and effective improvement strategies.

Table 12 - Individual and group credibility indexes

Limiting Profiles	DM_1	DM_2	DM_3	DM_4	Group
b_1	1.000 S	1.000 S	1.000 S	1.000 S	1.000 S
b_2	0.603 S^{-1}	0.871 S	0.867 S	1.000 S	0.835 S

Source: This research.

Table 13 - Individual and group final classifications

	DM_1	DM_2	DM_3	DM_4	Group
Company Unit	2	3	3	3	3

Source: This research.

5.3 Evaluation and Interpretation of Findings

The maturity evaluation mechanism presented in this study includes a fully documented set of questions and procedures that detail all necessary steps. Furthermore, it provides two forms of prescriptive guidance: one derived from contextual factor analysis, and another generated by the aggregation algorithm, which explicitly identifies the CSFs requiring prioritization.

In this thesis, the conditions required to transition between maturity levels are referred to as “limiting profiles,” which were objectively defined using Intuitionistic Fuzzy Values (IFVs). According to Froger et al. (2019), such restrictions warrant deeper investigation, and to the best of our knowledge, this is the first study to employ IFVs to define maturity level boundaries within a BPM maturity model. IFVs also help reduce the inherent uncertainty commonly associated with such assessments.

The model offers flexibility by allowing companies to assign weights to decision-makers (DMs), who may, in turn, attribute different weights to CSFs based on their experience and expertise. This feature improves alignment with organizational priorities, as the weighting reflects both strategic goals and corporate culture. Moreover, the entire assessment process is grounded in Intuitionistic Fuzzy Sets (IFSs), enabling DMs and BPM experts to express their views on complex, subjective matters. Combined with the organizational context framework of vom Brocke et al. (2016), this allows for a deeper understanding of the company’s BPM environment.

Structurally, the model adopts a non-linear, multidimensional design, enabling companies to tailor strategies according to their specific objectives. It supports application at different organizational levels—process, unit, company, or value chain—and prioritizes ease of interpretation through a single-plane visualization format (see Fig. 4). Despite its complexity, the layout remains user-friendly and can be adjusted to exclude CSFs deemed nonessential to the company's strategy.

When compared with existing models (Table 14), the advantages of the MCDM-based approach become clear. Among the three aspects examined in this study, only Hammer’s BPM-MM addresses the evaluation process (aspect I), but it falls short on issues 3 and 4. While it partially addresses issue 2 by specifying performance criteria at each level, it lacks broader contextual integration. No existing model fully addresses contextual factors, a topic still gaining traction. Although most models feature multidimensional structures, only Froger et al. (2019) and the present model incorporate non-linear design. Furthermore, this model offers enhanced adaptability by allowing for flexible structural adjustments (see Section 5.1.3).

Tabel 14 - BPM-MM Comparative analysis (Adapted from Viegas and Costa, 2023)

	Aspects to be improved		
	Maturity evaluation mechanism	**Flexibility/Compliance**	**The structure (path to maturity)**
Hammer (2007)	Partially addresses	Out of scope	Multidimensional
OMG (2008)	Not addresses	Out of scope	Multidimensional
Rosemann and de Bruin (2015)	Not addresses	Out of scope	Multidimensional and non-linear
Froger et al., (2019)	Not addresses	Out of scope	Multidimensional and non-linear
This Proposal	Addresses all issues	Supports	Multidimensional, non-linear and adjustable

Source: This research.

Chapter 6 - Conclusions and Future remarks

The driving force behind any research is the pursuit of solutions to problems, with the goal of improving the lives of individuals, enhancing the performance of companies, benefiting nations, and contributing to the well-being of the planet. This research addresses two strategic issues that are critical for companies of any size, whether small, medium, or large, anywhere in the world: (1) Assessing and mitigating risks in their processes, and (2) Evaluating and enhancing their BPM maturity level.

To conduct a risk analysis, it is need to have both technical and managerial skills. While most studies focus on technical aspects, this approach incorporates key managerial strategies. Using cognitive maps with SODA improved traditional brainstorming and empowered the team, enhancing trust and responsibility. The new MCDM approach also addresses issues related to inexperience or differing expert opinions. As HAZOP relies on group decision-making, these methods were integrated to foster sound judgment. Practically, future users must be familiar with the methodologies, and this thesis provides guidance and a framework. A real-world application using a continuous pyrolysis system demonstrates the methodology's flexibility. Methodologically, this approach sharpens focus while expanding HAZOP's scope, contributing to the reduction of safety problems in industrial processes.

The results also include a practical BPM-MM and its assessment procedure to help companies determine and improve their BPM initiatives, through the combination of a new MCDM model with IFSs. This proposal demonstrated that the MCDM approach is effective in addressing the challenges of BPM-MMs highlighted and analyzed in this research. Specifically, this framework is robust, transparent, and easy to apply. Its non-linear, multidimensional, and dynamic structure facilitates the achievement of desired maturity and improvements. Thus, it can be stated that all issues for this problem have been partially or fully addressed.

From a theoretical perspective, this proposal paves the way for future studies, offering new tools that elevate the maturity assessment field, both in BPM and beyond. These tools, closely tied to the MCDM component, include Web-based DSS, Neuroscience in decision-making, AI, and cognitive maps. Practically, companies can now quantitatively assess their BPM maturity level. Software can analyze evaluation data, offering insights for improvement. Sensitivity analysis provides critical information for immediate action, and results can be reanalyzed until consensus is reached. Combined with IFSs, this method better reflects company realities. Even with inexperienced participants, common in SMEs, the assessments become more reliable by weighting inputs, boosting confidence and motivation among participants.

The developed models offer some economic, social, and environmental advantages. In terms of industrial protection (Problem I), efforts must not be mitigated. Every company presents some level of risk, whether to workers, shareholders, or the community, and these risks must be addressed with the necessary rigor. Although our model is not limited to chemical industries such as refineries and oil platforms, these industries stand out for their high-risk levels. Economically, our model helps companies better manage resources allocated to protection by effectively prioritizing risks. Accidents in chemical industries can generate billionaire losses, and the proper use of the model, combined with other tools, contributes to preventing them, from minor incidents to catastrophic events. Socially, the model promotes the physical and emotional well-being of all stakeholders. Companies that adopt our methodology not only ensure their own safety but also care for their employees' health and safety, strengthening a collective sense of responsibility. Environmentally, when applied effectively together with other security measures, it improves process control, reducing pollution, waste, and accidents such as leaks and explosions, which can cause severe harm to human, animals, and plant life.

When it comes to a maturity model for BPM, any company aiming to remain competitive must understand its processes and the importance of managing them, especially amid rapid changes in the business landscape. A successful BPM initiative forms the foundation for digital transformation, generating significant economic benefits by optimizing workflows, reducing costs, and enabling the integration of advanced technologies like process automation and artificial intelligence. These tools not only streamline tasks and improve operational efficiency but also transform data into actionable insights. For small and medium-sized enterprises, the advantages are even more pronounced: better allocation of limited resources, reduced operational costs, and increased efficiency with minimal investment. Given the high costs often associated with BPM implementation through specialized consulting firms, our solution provides an alternative, especially in Brazil, where small and medium-sized enterprises account for a substantial share of the gross domestic product.

Beyond economic gains, the social and environmental benefits of BPM adoption are equally impactful. Socially, BPM fosters workplace safety, reduces stress, and enhances employee satisfaction by clarifying and streamlining processes, creating a healthier and more productive organizational environment. This is particularly beneficial for small and medium-sized enterprises, which can reinvest in training and better working conditions, positively affecting local communities. Environmentally, BPM helps large companies minimize their significant waste and resource usage while enabling small and medium-sized enterprises to adopt sustainable practices efficiently. Overall, BPM reduces waste, lowers natural resource consumption, and controls emissions through continuous process optimization and monitoring, supporting both operational efficiency and environmental stewardship.

It is essential to highlight the importance of using the DSR methodology in this thesis. Its robust structure, with well-defined stages and iterative refinements, was crucial for the completion of this work. As expected, the application of DSR resulted in three important solutions. The first is a model for managing and evaluating risks in industrial processes, combining a theoretical foundation with a practical framework for companies, published by Viegas et al. (2020). The second is a maturity model for business process management, also with theoretical and practical approaches, published by Viegas and Costa (2023). The third is a web-based system that allows companies to assess their current BPM maturity level and plan improvements for implementation (Available online soon). In all cases, a rigorous literature review enabled the development of these solutions to address, to a large extent, the gaps identified in previously published models, and this is due to the application of the DSR methodology.

This research is not devoid of limitations. In both problems, one of the primary challenges lies in the definition of the model parameters. This task is complex and must be carried out by a team of specialists. In the context of risk assessment, the HAZOP team itself may define the parameters, as this type of assessment typically relies solely on experts. However, in the case of evaluating the maturity level in BPM, this does not apply. Since the organization itself can perform the evaluation, even without BPM specialists, the ideal scenario would be for the model to provide predefined parameters. Nonetheless, securing the participation of such experts to contribute to the study has proven to be a labor-intensive task.

Although the IFSs assist in addressing issues related to uncertainty and subjectivity, the cognitive effort required to provide responses may pose a challenge. This aspect was not explored in the present study, but it may serve as a potential avenue for future research, where alternative input methods that demand less cognitive effort from experts could be considered.

With regard to Problem I, although the selection of the methodologies integrated with HAZOP has proven effective, numerous other combinations remain available for exploration. In the case of Problem II, the application of the MCDM approach may constitute a limiting factor in the practical implementation of the model, as it introduces an additional layer of complexity, despite the favorable outcomes. Even with the development of the web-based system, it remains essential for organizations to grasp certain key concepts to ensure the effective application of the model.

It is expected that future studies will enhance and automate these proposals to simplify their application. A Decision Support System (DSS) for risk analysis (model 1) will also greatly assist future implementations. Additionally, incorporating problem structuring tools like SODA and Value-Focused Thinking (VFT), integrated with IFS and FS, in risk analysis, will significantly improve the quality of these studies. Future research in BPM-MM should explore Critical Success Factors (CSFs) more thoroughly, especially to adapt them for company digitalization. In this thesis, CSFs, along with related Best Practices (BPs) and Capabilities, were identified, but a more in-depth analysis is required for BPM initiatives to succeed. Key areas to explore include linking BPs to each CSF, examining the interdependence of CSFs, BPs, and capabilities, and defining BPs for each maturity level, all of which will strengthen this proposal (see Mamoghli et al., 2017; Buh et al., 2015; Bai and Sarkis, 2013). Given the fast-paced developments in the field, the DSR methodology outlined in this thesis may not represent the most current approach. Recent contributions by Gauss et al. (2024a) and Gauss et al. (2024b) have advanced the understanding of DSR, and it is recommended that future DSR applications incorporate and analyze these works for a more up-to-date perspective.

Both models have successfully advanced the frontier of knowledge in their respective research fields, offering solutions to existing problems, opening new avenues for exploration, and generating new questions to be addressed.

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Appendix A (part 1) – CSFs and Related Best Practices and Capabilities

	Sources of CSFs and Related Best Practices and Capabilities																													
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD
Strategic Alignment (F1)	x	x	x	x	x	x	x		x		x					x	x			x					x			x		
Align goals and targets to strategic planning		x		x						x	x		x	x				x	x		x	x	x			x	x			
Alignment of process to organizational goals									x		x																			
Clear definition of organizational strategy and corporate mission																												x		
Top Management Support (F2)	x	x	x	x	x					x	x		x	x		x	x	x	x	x	x	x	x	x	x	x	x	x		
Executive support throughout the implementation stages										x	x		x		x						x	x								
Managers actively participating with the BPM Office										x	x		x		x						x	x								
Sponsorship from High level management																												x		
BPM Governance (F3)		x	x				x		x		x																	x		
Proper representation of organization																												x		
Clear and defined responsibilities				x						x	x		x					x	x		x	x	x			x				
Controlling excessive bureaucracy										x				x	x				x			x							x	x
BPM Office and a BPM project champion					x				x																					
Clearly defined process owners				x			x				x																	x		
People (F4)	x	x	x	x		x	x	x	x		x																			
Process and Technical skills					x																									
Understanding the BPM concept			x				x				x																			
Level of employee’s specialization				x																										
Information Technology (F5)	x			x		x	x	x	x		x					x	x			x					x			x		
Level of IT investments				x							x																			
Technology support											x																			
Clear definition of supporting technologies																												x		
Align IT and Business (information sharing domain)		x			x						x		x									x		x		x				
Standardization and Automation of processes																									x			x		
Tools to support process																												x		

visualization																														
Data management infrastructure					x																									
BPM methods (F6)		x	x			x	x		x		x																	x		
Proper documentation of procedures and policies																												x		
Tools to link process design to process execution																												x		
BPM culture (F7)	x	x	x			x	x		x		x	x				x	x			x					x					
BPM Collaborative environment				x												x	x			x					x					
Investing in human capital				x						x	x		x	x	x			x	x		x	x	x	x		x			x	x
Training and empowerment of employees				x							x		x	x	x			x	x		x	x	x	x		x		x	x	x
Adequate level of employee buy-in and Personnel commitment											x																	x		
Capable and motivated employees										x	x																			
Use of techniques to getting engagement and accountability																												x		
BPM education																												x		
Control resistance to change		x		x	x					x	x			x					x			x	x	x						x
Implementation of proposed changes				x																										
Continuous Improvement (F8)		x	x	x			x		x		x																			
Use of a continuous improvement system				x																										
Performance Measurement (F9)		x	x	x		x					x						x			x					x					
Continuous measurement and monitoring		x		x						x	x		x	x				x	x		x	x	x				x			
Project Management (F10)	x	x	x		x	x			x	x	x		x	x	x	x	x		x	x	x	x	x	x	x	x				
Clearly defined objectives											x																			
Purpose and plan of BPM project											x																			
Defined roles and responsibilities											x																			
Structured and systematic documents methodology										x																				
Communication (F11)	x	x	x	x	x	x	x				x																			
Effective communication between business and IT				x																										

Appendix A (part 2) – Sources of CSFs and Related Best Practices and Capabilities

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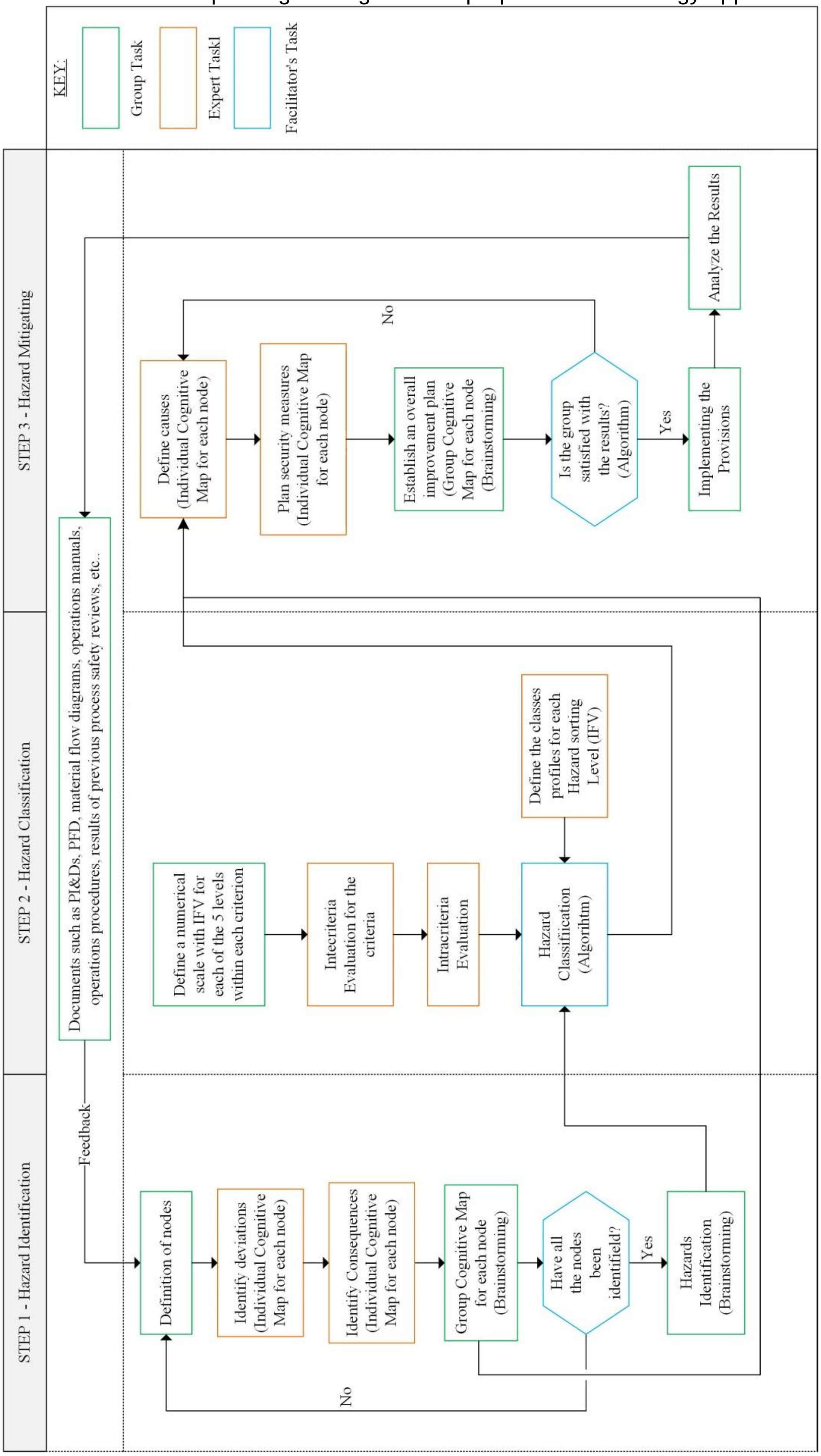
Appendix B - Framework encompassing all stages of the proposed methodology applied to Problem I.

Figura 11 - Framework encompassing all stages of the proposed methodology applied to Problem I.



Appendix C – Procedure for Step 1 of the Methodology Application to Problem 1 (Hazard Identification)

EXPERT X

Document for the Application of the MCDM-Based HAZOP Methodology in the Fast Pyrolysis Pilot Unit

STEP 1

Step 1 consists of analyzing each node of the pyrolysis plant to identify potential hazards. The nodes considered in this study are marked in the diagram presented in Figure 6, using the colors red, orange, and green.

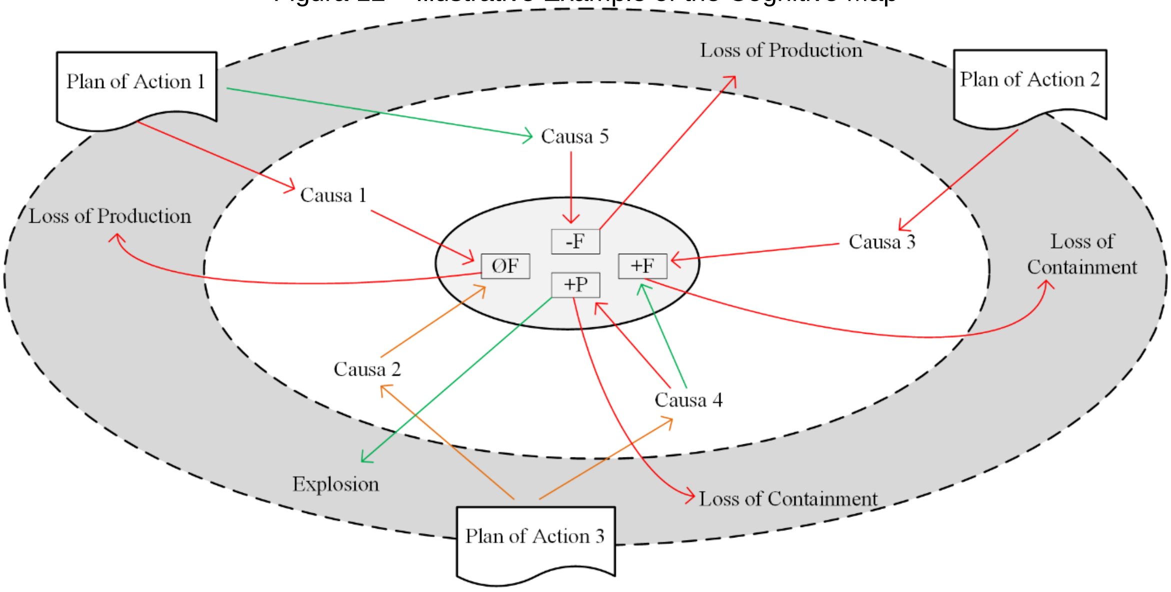
For each node, the specialists shall:

1. Identify possible deviations from the design intentions. Example: Pressure deviations (High Pressure); Temperature deviations (Low Temperature); Flow deviations (Low Flow).
2. Identify potential consequences that these deviations may cause. Example: Explosion; Leaks; Toxic injury; Flammable injury; Flammable or toxic damage.
3. Develop a cognitive map for each node, following the example shown in Fig. 1. The map can be created manually or using software tools such as VIZIO or Decision Explorer. The arcs connecting causes and consequences must be constructed according to the data presented in Table 15, which correspond to intuitionistic fuzzy numbers (IFNs). The values of μ and v in the table represent, respectively, the degrees of membership and non-membership. For instance, consider the arc linking the deviation +F to the consequence *Loss of Containment* in Fig. 12. In this example, the arc is drawn in red because, according to the specialist who constructed it, this deviation may lead to this consequence with a membership degree of $\mu \geq 0.80$ and a non-membership degree of $v \leq 0.10$. The greater the value of μ and the lower the value of v, the stronger the relationship between the deviation and the consequence. A red arc represents the strongest relationship, while a green arc represents the weakest one (see μ and v values in Table 12). If you choose to manually construct the cognitive map, the following symbols may be used for subsequent analysis: **R** for a red arc, **O** for an orange arc, and **G** for a green arc. The symbol should be placed at the midpoint of the arc connecting a deviation to a consequence. The map presented in Fig. 12 is merely

illustrative and should be used as a reference for constructing your own. **Important:** At this stage, only deviations and consequences should be defined.

4. After constructing the maps, develop new relationships between deviations and consequences, and attempt to identify possible interrelations among them and with the existing ones.
5. Upon completion, respond to the email with the three generated maps (one for each node) attached.

Figura 12 – Illustrative Example of the Cognitive Map



Souce: This research.

Legend: F – Flow; T – Temperature; P – Pressure; L – Level; Ø – None; - Less; + More

Table 15 - Reference Arcs for the Construction of Cognitive Maps

Arc	IFN
(red line)	If ($\mu \geq 0.80$ and $v \leq 0.10$)
(orange line)	If ($0.60 \leq \mu < 0.80$ and $0.10 < v \leq 0.20$)
(green line)	If ($\mu < 0.60$ and $v > 0.20$)

Appendix D - Step for hazard assessment (Intracriteria Evaluation)

Expert

Document for the Implementation of the MCDM-Based HAZOP Methodology in the Fast Pyrolysis Pilot Unit.

Note 1 – Use no more than two decimal places for all responses in this document.

To support overall understanding, the following sets are defined:

The set of hazards, represented by H = {H1,…, H40};

The set of criteria, represented by G = {g1, g2, g3};

The set of weights of these criteria, represented by W = {w1, w2, w3};

The risk levels, represented by L = {L1, L2, L3};

The set of profiles of these categories, represented by B = {b_1^2, b_2^3};

Step 2

<u>Step 2 is divided into Substeps 2.1 and 2.2:</u>

Substep 2.1 consists of the evaluation of the hazards identified in Step 1, which are listed in Table 17. (The table categorizes the hazards by node and type of deviation.) The assessment of these 40 hazards will be based on three criteria: Consequence (g_1), Frequency (g_2), and Non-detectability (g_3).

Consequence refers to the damage that a hazard may cause if it occurs. Frequency refers to the likelihood or possibility of occurrence—some hazards may be more likely to occur than others. Non-detectability refers to the difficulty in detecting the imminent hazard. You, as a specialist, must evaluate each of the 40 hazards with respect to each of the three criteria. The evaluation will be conducted using intuitionistic fuzzy sets, through the determination of intuitionistic fuzzy numbers (IFNs) μ and v, which represent the degrees of membership and non-membership, respectively.

The greater the consequence, the higher the value that should be assigned to μ. Conversely, if the hazard does not involve serious consequences, a lower value of μ should be assigned. The same logic applies to the criteria of Frequency and Non-detectability. Similarly, the greater the consequence, the lower the value that should be assigned to v. Conversely, if the hazard does not involve serious consequences, a higher value of v should be assigned. This reasoning also applies to the criteria of Frequency and Non-detectability. The relationship between μ and v is as follows: the sum of these values for each hazard must not exceed 1 ($\mu + v \leq 1$), and they are not complementary—that is, they do not necessarily sum to 1. Additionally, the evaluation (0.5; 0.5), meaning 0.5 for μ and 0.5 for v, is not valid.

Important: The responses for Substep 2.1 must be entered directly into Table 2. Below is an example illustrating how to perform the evaluation:

Illustrative Example: The responses must be entered as shown in Table 16 below. In this illustrative case, for the Consequence criterion (g_1), hazard H1 received the evaluation (0.80; 0.13). The value 0.80 refers to μ, and 0.13 to v ($\mu + v = 0.93 \leq 1$). This high value of μ and low value of v indicate that hazard H1 has serious consequences. However, it is not very frequent, as shown by its evaluation under the Frequency criterion (g_2), (0.25; 0.60), where μ is low and v is high.

For the Non-detectability criterion (g_3), the μ and v values of 0.85 and 0.10, respectively, suggest that the hazard is difficult to detect before it occurs.

Table 16 - (For illustrative purposes only)

Hazards	**Expert**		
	g_1	g_2	g_3
H1	(0.80; 0.11)	(0.25; 0.60)	(0.85; 0.10)
H2			

Source: This research.

Important: To assist you in evaluating and completing Table 18, refer to Tables 20, 21, and 22. These tables should be used for reference only—the μ and v values contained in them must not be copied literally. You may assign the μ and v values based on the criterion scales and the corresponding ranges defined in the tables. The μ and v values must comply with the intervals established in the tables 20, 21 and 22.

In the example above, hazard H1 would be classified, for instance, as having Critical Consequence, Remote Frequency, and High Non-detectability.

Substep 2.2 concerns the definition of the model parameters.

These parameters refer to the weights of the three criteria, $W = \{w_1, w_2, w_3\}$, and to the profiles of the risk levels, $B = \{b_1^2, b_2^3\}$. The weights of the three criteria must be entered in Table 19, and their sum must equal 1 ($w_1 + w_2 + w_3 = 1$).

You, as a specialist, must define the relative importance of each criterion. For example, you may assign a weight of 0.4 to g_1, 0.3 to g_2, and 0.3 to g_3. In this case, the Consequence criterion would be considered the most important, while Frequency and Non-detectability would be regarded as equally important. This example is for illustrative purposes only; the weights should be determined based on your expertise and experience in the field.

Important: Both this document and the other one must be sent via email once completed.

Table 17 – Hazards Identified by the experts

	Node 1 - Feeding System		Node 2 - Pyrolysis reactor		Node 3 - Fractionation tower	
Deviation	Consequence	Hazard	Consequence	Hazard	Consequence	Hazard
ØF	No production	h_1	No production	h_{12}	No production	h_{25}
-F	Loss of production	h_2	Loss of production	h_{13}	Loss of production	h_{26}
+F	Explosion More production Loss of containment Loss of production	h_3 h_4 h_5 h_6	More production Explosion	h_{14} h_{15}	Loss of production More production	h_{27} h_{28}
-T	More production	h_7	Loss of production	h_{16}	Loss of production	h_{29}
+T	Explosion Loss of production Loss of containment	h_8 h_9 h_{10}	More production Explosion Loss of production	h_{17} h_{18} h_{19}	Explosion More production Loss of containment Faulty products	h_{30} h_{31} h_{32} h_{33}
ØP			No production	h_{20}	Loss of production	h_{34}
-P			Loss of production	h_{21}	Loss of production Faulty products	h_{35} h_{36}
+P	Loss of containment	h_{11}	Explosion More production Loss of containment	h_{22} h_{23} h_{24}	More production More production Loss of containment Faulty products	h_{37} h_{38} h_{39} h_{40}

Source: This research. Note: The symbols H_i represent the hazards.

Table 18 - Intuitive fuzzy decision matrix (Intracriteria Evaluation)

Hazards	**Expert**		
	g_1	g_2	g_3
H1			
H2			
H2			
⋮			
H37			
H38			
H39			
H40			

Source: This research.

Table 19 – Weights of criteria

	Expert Answer
g_1	
g_2	
g_3	

Source: This research.

Table 20 – Profiles of the classes for the Consequence criterion.

Consequence	**IFN**
Negligible	If ($\mu < 15$ and $v > 0.60$)
Marginal	If ($0.15 \leq \mu < 0.40$ and $0.40 < v \leq 0.60$)
Moderate	If ($0.40 \leq \mu < 0.65$ and $0.15 < v \leq 0.40$)
Critical	If ($0.65 \leq \mu < 0.85$ and $0.10 < v \leq 0.15$)
Catastrophic	If ($\mu \geq 0.85$ and $v \leq 0.10$)

Source: This research.

Table 21 – Profiles of the classes for the Frequency criterion.

Frequency	**IFN**
Improbable	If ($\mu < 15$ and $v > 0.60$)
Remote	If ($0.15 \leq \mu < 0.40$ and $0.40 < v \leq 0.60$)
Occasional	If ($0.40 \leq \mu < 0.65$ and $0.15 < v \leq 0.40$)
Probable	If ($0.65 \leq \mu < 0.85$ and $0.10 < v \leq 0.15$)
Frequent	If ($\mu \geq 0.85$ and $v \leq 0.10$)

Source: This research.

Table 22 – Profiles of the classes for the Non-detectability criterion.

Undetectability	**IFN**
Low	If ($\mu < 0.40$ and $v > 0.60$)
Medium	If ($0.40 \leq \mu < 0.80$ and $0.15 < v \leq 0.60$)
High	If ($\mu \geq 0.80$ and $v \leq 0.15$)

Source: This research.

Appendix E – Intuitive fuzzy decision matrix (Intracriteria Evaluation)

Table 23 - Intuitive fuzzy decision matrix (Results of the Intracriteria Evaluation)

Hazards	Expert 1			Expert 2			Expert 3		
	g_1	g_2	g_3	g_1	g_2	g_3	g_1	g_2	g_3
h_1	0.10; 0.70	0.40; 0.60	0.15; 0.80	0.20; 0.80	0.30; 0.50	0.20; 0.70	0.35; 0.50	0.55; 0.30	0.20; 0.75
h_2	0.20; 0.50	0.50; 0.15	0.30; 0.60	0.20; 0.50	0.50; 0.20	0.20; 0.60	0.25; 0.60	0.60; 0.25	0.35; 0.65
h_3	0.85; 0.10	0.15; 0.60	0.30; 0.60	0.85; 0.10	0.17; 0.60	0.20; 0.60	0.82; 0.15	0.12; 0.85	0.30; 0.65
h_4	0.50; 0.40	0.40; 0.55	0.30; 0.60	0.60; 0.40	0.50; 0.60	0.20; 0.66	0.20; 0.60	0.25; 0.60	0.30; 0.65
h_5	0.85; 0.10	0.15; 0.60	0.30; 0.60	0.85; 0.15	0.15; 0.40	0.10; 0.65	0.65; 0.30	0.18; 0.60	0.30; 0.65
h_6	0.10; 0.70	0.40; 0.50	0.3; 0.60	0.13; 0.80	0.30; 0.60	0.30; 0.65	0.15; 0.60	0.25; 0.50	0.30; 0.65
h_7	0.50; 0.60	0.15; 0.50	0.15; 0.80	0.60; 0.65	0.15; 0.55	0.20; 0.80	0.15; 0.60	0.20; 0.60	0.25; 0.70
h_8	0.85; 0.10	0.15; 0.60	0.15; 0.85	0.85; 0.10	0.15; 0.50	0.35; 0.75	0.84; 0.15	0.15; 0.60	0.20; 0.75
h_9	0.10; 0.80	0.15; 0.60	0.15; 0.85	0.15; 0.80	0.15; 0.50	0.15; 0.85	0.15; 0.60	0.55; 0.17	0.20; 0.75
h_{10}	0.80; 0.10	0.20; 0.50	0.10; 0.80	0.80; 0.10	0.30; 0.55	0.10; 0.80	0.78; 0.15	0.35; 0.32	0.20; 0.75
h_{11}	0.80; 0.10	0.15; 0.50	0.10; 0.85	0.80; 0.12	0.15; 0.45	0.20; 0.75	0.85; 0.09	0.30; 0.40	0.70; 0.25
h_{12}	0.10; 0.70	0.15; 0.60	0.10; 0.80	0.12; 0.65	0.15; 0.60	0.20; 0.75	0.35; 0.55	0.35; 0.60	0.38; 0.61
h_{13}	0.20; 0.50	0.50; 0.15	0.15; 0.85	0.33; 0.50	0.50; 0.15	0.35; 0.75	0.25; 0.60	0.35; 0.60	0.40; 0.55
h_{14}	0.50; 0.40	0.30; 0.65	0.10; 0.81	0.64; 0.40	0.35; 0.60	0.15; 0.82	0.20; 0.60	0.20;0.60	0.35; 0.65
h_{15}	0.70; 0.10	0.10; 0.65	0.10; 0.75	0.85; 0.10	0.20; 0.65	0.15; 0.70	0.88; 0.09	0.16; 0.60	0.35; 0.65
h_{16}	0.20; 0.50	0.50; 0.15	0.10; 0.75	0.25; 0.55	0.50; 0.15	0.30; 0.70	0.18; 0.56	0.37; 0.45	0.20; 0.76
h_{17}	0.50; 0.40	0.30; 0.65	0.10; 0.80	0.57; 0.43	0.40; 0.60	0.10; 0.80	0.15; 0.60	0.37;0.42	0.16; 0.84
h_{18}	0.80; 0.10	0.15; 0.60	0.30; 0.65	0.84; 0.10	0.20; 0.55	0.30; 0.65	0.86; 0.09	0.10; 0.85	0.16; 0.84
h_{19}	0.80; 0.10	0.15; 0.50	0.10; 0.85	0.75; 0.12	0.25; 0.50	0.15; 0.75	0.80; 0.15	0.35; 0.48	0.45; 0.55
h_{20}	0.10; 0.80	0.10; 0.65	0.10; 0.80	0.12; 0.70	0.10; 0.65	0.20; 0.70	0.15; 0.55	0.12; 0.76	0.35; 0.65
h_{21}	0.10; 0.85	0.10; 0.65	0.10; 0.85	0.12; 0.80	0.13; 0.75	0.12; 0.75	0.18; 0.55	0.15; 0.60	0.25; 0.75
h_{22}	0.80; 0.10	0.15; 0.60	0.15; 0.85	0.82; 0.12	0.16; 0.60	0.25; 0.85	0.92; 0.08	0.25; 0.45	0.20; 0.72
h_{23}	0.50; 0.40	0.40; 0.55	0.30; 0.60	0.50; 0.37	0.15; 0.55	0.35; 0.50	0.25; 0.50	0.25; 0.45	0.20; 0.72
h_{24}	0.80; 0.10	0.15; 0.50	0.15; 0.50	0.85; 0.10	0.18; 0.50	0.25; 0.50	0.86; 0.12	0.45; 0.55	0.20; 0.72
h_{25}	0.10; 0.80	0.40; 0.50	0.15; 0.85	0.12; 0.70	0.35; 0.50	0.20; 0.80	0.18; 0.60	0.38; 0.45	0.35; 0.66
h_{26}	0.10; 0.60	0.40; 0.50	0.20; 0.80	0.10; 0.80	0.30; 0.50	0.30; 0.75	0.15; 0.60	0.42; 0.38	0.45; 0.50
h_{27}	0.10; 0.60	0.40; 0.50	0.15; 0.65	0.15; 0.60	0.15; 0.50	0.30; 0.75	0.15; 0.60	0.35; 0.58	0.35; 0.70
h_{28}	0.50; 0.60	0.40; 0.50	0.20; 0.65	0.50; 0.60	0.40; 0.50	0.30; 0.65	0.10; 0.75	0.30; 0.60	0.35; 0.70
h_{29}	0.10; 0.80	0.40; 0.50	0.15; 0.70	0.13; 0.82	0.65; 0.50	0.20; 0.75	0.15; 0.60	0.30; 0.58	0.25; 0.60
h_{30}	0.85; 0.10	0.40; 0.40	0.10; 0.80	0.84; 0.11	0.40; 0.40	0.15; 0.75	0.78; 0.15	0.12; 0.78	0.25; 0.60

h_{31}	0.20; 0.55	0.15; 0.50	0.20; 0.65	0.10; 0.55	0.15; 0.50	0.15; 0.75	0.45; 0.40	0.25; 0.60	0.25; 0.60
h_{32}	0.80; 0.10	0.15; 0.60	0.40; 0.50	0.84; 0.10	0.15; 0.50	0.35; 0.50	0.80; 0.15	0.15; 0.60	0.25; 0.60
h_{33}	0.20; 0.40	0.70; 0.15	0.40; 0.50	0.30; 0.40	0.75; 0.15	0.40; 0.50	0.45; 0.20	0.30; 0.50	0.25; 0.60
h_{34}	0.10; 0.55	0.15; 0.60	0.30; 0.62	0.13; 0.55	0.15; 0.60	0.20; 0.64	0.40: 0.45	0.25; 0.55	0.42; 0.50
h_{35}	0.10; 0.60	0.15; 0.60	0.30; 0.61	0.10; 0.70	0.15; 0.60	0.25; 0.65	0.40; 0.30	0.20; 0.60	0.40; 0.55
h_{36}	0.20; 0.40	0.70; 0.15	0.40; 0.50	0.14; 0.40	0.68; 0.15	0.35; 0.50	0.40; 0.32	0.35; 0.42	0.40; 0.55
h_{37}	0.80; 0.10	0.15; 0.60	0.40; 0.62	0.76; 0.10	0.14; 0.60	0.40; 0.62	0.16; 0.60	0.25; 0.60	0.25; 0.60
h_{38}	0.12; 0.50	0.15; 0.60	0.30; 0.62	0.12; 0.50	0.15; 0.60	0.30; 0.62	0.25; 0.48	0.33; 0.60	0.25; 0.60
h_{39}	0.85; 0.10	0.15; 0.55	0.38; 0.62	0.75; 0.10	0.17; 0.50	0.30; 0.65	0.80; 0.15	0.30; 0.45	0.25; 0.60
h_{40}	0.20; 0.40	0.70; 0.15	0.40; 0.50	0.14; 0.40	0.80; 0.15	0.35; 0.50	0.40; 0.32	0.30; 0.55	0.25; 0.60

Source: This research.

Appendix F - Procedure used to define the limiting profiles of categories for each criterion/CSFs

Figura 13 – Procedure used to define the limiting profiles of risk levels for each criterion

OBJECTIVE – DEFINITION OF RISK LEVEL PROFILES

The objective of this tool is to define the profiles corresponding to the risk levels of the model under development. The model comprises three risk levels, ordered as follows: Level 1 – Negligible < Level 2 – ALARP < Level 3 – Unacceptable. The profiles are threshold values that determine the transition from one risk level to another. Since there are three risk levels, two profiles must be defined: profile *b1*, which lies between levels 1 and 2, and profile *b2*, which separates levels 2 and 3, as illustrated in the adjacent figure. ALARP represents the risk level at which hazards are tolerated through the implementation of additional safety measures, without requiring major modifications to the plant design.

Level 3 - Unacceptable
perfil **b2**
Level 2 - ALARP
perfil **b1**
Level 1 - Negligible

The profiles will be defined using Intuitionistic Fuzzy Sets. You will conduct the evaluation by assigning values of u and v for each criterion within each profile. Below, the definitions of u and v are provided, along with the procedure to be followed for the construction of the profiles.

During the assessment of a hazard, its degree of membership and non-membership with respect to each criterion will be evaluated. The membership degree u indicates the extent to which the hazard satisfies the criterion, whereas the non-membership degree v reflects the extent to which the same hazard fails to satisfy the same criterion. However, in this context, you are not required to evaluate any specific hazard, as was done in the previous document. Instead, you are to define the profiles of the risk levels through the specification of u and v values. The procedure is as follows: For the value of u, you must specify the minimum threshold that a hypothetical hazard must reach in order to transition to the next risk level. For example, if you assign a value of 0.4 to b1 for criterion Y, it implies that for this hypothetical hazard—when evaluated using this model—to move to Risk Level 2 with respect to criterion Y, it must attain at least 0.4. For the value of v, you must specify the maximum threshold that a hypothetical hazard must not exceed in order to transition to the next risk level. For example, if you assign a value of 0.15 to b1 for criterion Y, it means that for the hazard to advance to Risk Level 2 with respect to criterion Y, its non-membership value must not exceed 0.15.

Important:

The sum of u and v for each profile must not exceed 1 ($u + v \leq 1$). However, it is not mandatory that their sum equals exactly 1; this condition may or may not occur.

Ilustrative Example

Criterion		Answer u	Answer v	Soma	
Criterion X	**b2**	0,75	0,15	0,9	Ok!
	b1	0,45	0,22	0,67	Ok!

In the illustrative example above, for criterion X, a u value of 0.45 in profile b1 represents the minimum requirement for a hazard, when evaluated under that criterion, to transition from Risk Level 1 to Level 2. However, a u value of 0.75 in profile b2 implies a higher threshold, making it more difficult for the hazard to move from Level 2 to Level 3—thus reflecting a stricter evaluation. The opposite logic applies to the v value: a higher v denotes lower rigor in the requirement. Different criteria may demand different levels of stringency, and it is the responsibility of you, the specialist, to determine the appropriate values based on your expert judgment.

Important Considerations:

A high u value in profile b1, for example, indicates greater stringency. This means that for a hazard to transition from Level 1 to Level 2, it must substantially satisfy the corresponding criterion (Note: satisfying the criterion in this context does not imply a positive outcome). Therefore, the closer u is to 1, the more stringent the requirement. Conversely, a high v value indicates lower stringency regarding the hazard with respect to that criterion, in any profile.

It is common for u values to increase from b1 to b2, as illustrated in the adjacent example. However, this is not a strict rule. You are expected to assess the criteria individually and define the values of u and v based on your informed judgment.

PLEASE PROVIDE THE VALUES BELOW FOR EACH CRITERION WITH THEIR RESPECTIVE PROFILES (USE TWO DECIMAL PLACES)

Criterion		You Answer u	You Answer v	Soma	
Consequence	**b2**			0	Ok!
	b1			0	Ok!

Criterion		You Answer u	You Answer v	Soma	
Frequency	**b2**			0	Ok!
	b1			0	Ok!

Criterion		You Answer u	You Answer v	Soma	
Undetectability	**b2**			0	Ok!
	b1			0	Ok!

Source: This research.