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Amélioration du processus de la conception inventive par l'utilisation de méthodes agiles et d'algorithmes d'apprentissage automatique.

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Improving the inventive design process by using agile methods and machine learning algorithms

Abstract

In recent decades, companies have continually sought approaches that help them reduce the innovation cycle time due to its importance to their success. Among these approaches, the TRIZ method has long proven its value without appearing to the industrial world as inevitable. Design researchers have therefore addressed the limitations of the TRIZ method and have overcome them with new, more systematic, and formalized approaches. Among these, the Inventive Design Method (IDM) has been the subject of several articles and put into practice in the industry. IDM is a framework that has been developed over several years in four phases. This framework is considered an improvement over TRIZ but still suffers from some drawbacks in terms of the time-consuming nature of its implementation. Hence, it is essential to combine IDM with other methodologies to increase its agility.

In this thesis, a Lean-based method, called Inverse Problem Graph (IPG), has been developed to formulate the problem situation during the initial analysis phase of IDM. IPG adds to IDM the characteristics of agile methodologies such as iterative and evolutionary development. Hence, it could significantly increase the agility of this methodology. Nevertheless, the initial version of IPG does not provide the way to prioritize the initial problems. Besides, gathering the required data in the inventive design process through the application of this version needs time and effort. To solve the IPG's drawback in prioritizing the initial problem, we have integrated Analytical Hierarchy Process (AHP) and Failure Mode and Effect Analysis (FMEA) methods into the IPG's process to select the most important initial problem. We have also applied machine learning algorithms and the neural network doc2vec to resolve IPG's drawback in extracting data, including parameters and concepts.

These research works aim to facilitate and accelerate inventive design in companies. The main contributions of these research works are reflected in several aspects. At first, IPG, as a Lean-based method, helps to optimize the problem formulation time by keeping only the essential elements of the study to be collected. As the second contribution, integration of the FMEA and AHP method contributes to formulating the most important contradiction in each iteration of the inventive design process. As the third main contribution, the application of doc2vec and machine learning algorithms can accelerate and facilitate the gathering of essential data in the process.

Key words: Inventive design, TRIZ, Lean theory, Document embedding, Text classification, Similarity computation

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Contents

CHAPTER 1. INTRODUCTION 17

1.1. TRIZ and its drawbacks 17

1.2. Inventive Design Methodology and its drawbacks 17

1.3. Lean and its application to IDM 18

1.4. Thesis contribution 20

1.5. Thesis structure 20

CHAPTER 2. TRIZ AND INVENTIVE DESIGN FRAMEWORKS 23

2.1. Classification of innovative problem approaches 23

2.2. The Theory of Inventive Problem Solving - TRIZ 24

2.3. TRIZ-based frameworks 31

2.4. Conclusion of the chapter 33

CHAPTER 3. PROPOSITION OF INVERSE PROBLEM GRAPH (IPG) BY LEAN INTEGRATION INTO THE INITIAL ANALYSIS PHASE 35

3.1. Introduction 35

3.2. Literature review 36

3.3. Proposed method: Inverse Problem Graph (IPG) 42

3.4. Application of proposed method to Covid-19 case study 47

3.5. Comparison of the IPG method with conventional methods 52

3.6. Conclusion and contribution of the chapter 57

CHAPTER 4. INTEGRATION OF FMEA AND AHP TO PRIORITIZE INITIAL PROBLEMS IN THE INITIAL ANALYSIS PHASE OF INVENTIVE DESIGN 59

4.1. Inverse Problem Graph's drawback in prioritizing the initial problems 59

4.2. Literature review 60

4.3. Proposal method: Integration of (FMEA-AHP) into Inverse Problem Graph62

4.4. Application of the proposal method into "Biomass Power Plant" case study66

4.5. Comparison of the proposal with Network of Problems (NoP) 73

4.6. Conclusion and contribution of the chapter 74

CHAPTER 5. AUTOMATIC EXTRACTION OF ESSENTIAL INFORMATION (PARAMETERS AND CONCEPTS) IN INVENTIVE DESIGN BY APPLYING DOCUMENT EMBEDDING, MACHINE LEARNING, AND SIMILARITY 75

5.1. Introduction 75

5.2. Literature review 76

5.3. Experiment and evaluation 82

5.4. Proposed method: Integration of doc2vec and machine learning algorithms into Inverse Problem Graph 87

5.5. Application of the proposal to Lattice Structure case study 91

5.6. Comparison of the automatic system based on the IPG process and the classical system 103

5.7. Conclusion and contribution of the chapter 106

CHAPTER 6. CONCLUSIONS AND PERSPECTIVES 107

6.1. Summarization of the chapters 107

6.2. Contributions 108

6.3. Limitations 109

6.4. Perspectives 110

REFERENCES 111

ANNEX A 125

ANNEX B 126

RESUME 131

1. Introduction 131

1.2. TRIZ et ses inconvénients 131

1.3. Méthodologie de conception inventive et ses inconvénients 131

1.4. Lean et son application à MCI 132

1.5. Structure de la thèse 132

2. L'état de l'art 132

3. Méthode proposée : Graphe de Problèmes Inverse 133

3.1. Définition du Graphe de Problèmes Inverse (GPI) : 133
3.2. Processus du Graphe de Problèmes Inverse 134
4. Compléments au Graphe de Problèmes Inverse 136
4.1. La priorisation des problèmes initiaux pour l'GPI : 136
4.2. La collecte des données essentielles pour l'GPI 137
5. Contribution de la thèse 142

List of figures

Figure 1.1. The relationship of different parts of Agile Automated System with the chapters 20

Figure 1.2. Agile automated system’s process (Annex B) 22

Figure 2.1. TRIZ approach to solving an inventive problem 24

Figure 2.2. Poly-contradiction template [36] 27

Figure 3.1. A project which applied RCA+ to formulate the problem [36] 38

Figure 3.2. Part of a Cause-Effect Chain Analysis Plus carried out for a project [71] .. 39

Figure 3.3. Problem Graph Application for formulating problems [74] 40

Figure 3.4. Different types of problems and levels in IPG 43

Figure 3.5. LA-IDM with Inverse Problem Graph 44

Figure 3.6. IDM with other discussed methods in the literature review 44

Figure 3.7. Process of Inverse Problem Graph 47

Figure 3.8. Conversion of the problem to partial solution 49

Figure 3.9. Inverse Problem Graph of the case study in the first iteration 49

Figure 3.10. Allocation of the parameters 50

Figure 3.11. Poly-contradiction model of the TRIZ parameters in relation to the assigned parameters of step 7 of the IPG 51

Figure 3.12. Interaction between COVID-19, ACE2, and TMPRSS2 [86] [89] 52

Figure 3.13. Application of the IPG method to the four student projects 55

Figure 3.14. Time-based Comparison of the IPG method and Problem Graph 55

Figure 3.15. Network of Problem and its difference with the Inverse Problem Graph [61] 56

Figure 4.1. The different phases of FMEA-AHP based method (Annex B) 63

Figure 4.2. A three-level hierarchical structure for the objective, criterion, and the initial problems 63

Figure 4.3. The hierarchical structure for the Biomass Power Plant case study 67

Figure 4.4. Graphical representation of the priorities related to the initial problems and criteria 70

Figure 4.5. The identified causes of the initial problem and select the most important cause 71

Figure 4.6. Conversion of the Harmful-Useful problem to the partial solution 72

Figure 4.7. The inverse problem graph related to the selected initial problem.............. 72

Figure 4.8. The allocation of the parameters to the extracted contradiction.................. 73

Figure 4.9. The poly-contradiction of the Biomass Power Plant case study.................. 73

Figure 4.10. Network of Problem and its difference with the proposal [61] 74

Figure 5.1. Different parts and the steps of Agile-Automated Question Answering System (Annex B).. 88

Figure 5.2. A lattice structure.. 92

Figure 5.3. Connection of the causes to the initial problem and selection of the most important cause 96

Figure 5.4. Conversion of the Harmful-Useful problem to the partial solution............. 96

Figure 5.5. Inverse Problem Graph of Lattice Structure.. 98

Figure 5.6. Extraction of the contradiction from the IPG graph 99

Figure 5.7. Comparison of the energy absorption and strength of two structures with a high and low volume fraction [180].. 99

Figure 5.8. Allocation of parameters to the problems and partial solution................. 100

Figure 5.9. Construction of poly-contradiction by applying the parameters 100

Figure 5.10. Different views of our proposed lattice structure 103

Figure 5.11. Comparison of automatic systems in average time to analyze one article106

List of tables

Table 2.1: Different types of relationships between Substance 1 (S1) and Substance 2 (S2) 29

Table 3.1: Information Collected from four different student projects 53

Table 3.2: Collected information from the application of the IPG method to the four student projects 54

Table 3.3: List of problems related to NoP in Figure 3.16, extracted from [61] 56

Table 4.1: The 1-9 scales for pairwise comparison in AHP 64

Table 4.2: Reciprocal matrix for the defined initial problems with respect to the criterion Financial. 68

Table 4.3: Normalized matrix of the initial problems related to the criterion "Financial" 68

Table 4.4: Calculation of the priorities of each initial problem with respect to the first criteria 69

Table 4.5: Pairwise matrix for the initial problems by considering criterion C1 69

Table 4.6: Pairwise matrix for the initial problems by considering criterion C2 69

Table 4.7: Pairwise matrix for the initial problems by considering criterion C3 69

Table 4.8: Pairwise matrix for the defined criteria of the case study 70

Table 4.9: Prioritization of the initial problems with respect to the objective 71

Table 5.1: Accuracy of machine learning algorithms related to the "Cause, Non-cause" data set. 83

Table 5.2: Results related to the application of MLP algorithm to predict the "Cause, Non-cause" labels of ten sentences 83

Table 5.3: Evaluation of machine learning algorithms for the "Positive TRIZ Parameter" group 84

Table 5.4: Evaluation of machine learning algorithms for the "Negative TRIZ Parameter" group 85

Table 5.5: Evaluation of machine learning algorithms for the "Positive Parameter" group 85

Table 5.6: Evaluation of machine learning algorithms for the "Negative Parameter" group 85

Table 5.7: Results related to the application of the machine learning algorithms with the highest accuracy to predict the "Positive and Negative TRIZ Parameters" labels of eight sentences 86

Table 5.8: Results related to the application of the machine learning algorithms with the highest accuracy to predict the "Positive and Negative Parameters" labels of eight sentences 86

Table 5.9: The applied hyper-parameter to train the model 93

Table 5.10: Part of the similar sentences to the first question 94

Table 5.11: The selected cause sentences related to the first question and their extracted parameters 95

Table 5.12: Part of the similar sentences to the second question parameters 97

Table 5.13: The selected causes related to the second question and their extracted parameters 98

Table 5.14: The extracted solution concepts from the concepts database for the formulated contradiction 101

Table 5.15: Analysis of Problem Graph's classical system 104

Table 5.16: Analysis of Inverse Problem Graph's automatic system 105

Chapter 1. Introduction

Reducing the length of the innovation cycle is a crucial issue for the competitiveness of companies [1][2]. With this in mind, they are constantly looking for methodological approaches that help them reduce the time of the innovation process without sacrificing the value of their results. Among these approaches, it is possible to mention the systematic ones such as TRIZ.

1.1. TRIZ and its drawbacks

Genrich Altshuler developed TRIZ or Theory of Inventive Problem Solving. This approach states that any problems encountered by designers in their projects have probably also been dealt with by other designers from other domains [3]. TRIZ could help to reduce the amount of time required to reveal an optimal solution [4]. However, the application of the classical TRIZ method in the R&D department has several limitations. Firstly, it does not provide any methods to formulate the problems in the initial situations. Second, TRIZ does not offer any means to lead its users to select the best solutions among those proposed. As a third limitation, TRIZ does not also provide an accurate way of revealing a contradiction. Finally, there is no complete description of its components and the relationship between them in TRIZ's body of knowledge. To overcome these limitations, researchers have developed numerous frameworks, among which the Inventive Design Methodology (IDM) can be mentioned.

1.2. Inventive Design Methodology and its drawbacks

Inventive Design Methodology (IDM) is a framework that had been developed over several years of research to solve the limitations of TRIZ and to complement its body of knowledge with other theories such as Pugh's theory or graph theory [5]. This framework includes the four following phases: 1) Initial analysis phase, 2) Contradiction formulation phase, 3) Solution concept synthesis phase, and 4) Solution concept selection phase. Nevertheless, one of the criticisms often leveled is that this approach does not have the necessary agility, and it is time-consuming [6] [7] [8]. This is mainly due to the implicit research in each study to construct a complete map of a problem situation by interviewing experts involved in the study and extracting all their knowledge, regardless of how effective it is in solving the problem, to clarify the situation. This stage leads to lots of contradictions that only some of which are used in the final phase to obtain the solution [9]. Therefore, it is necessary to combine IDM with other methodologies that give its process the characteristics of an agile methodology, including the capacity for evolutionary and iterative development, the capability to generate a rapid and flexible response to change, and the capacity of promoting communication and adaptive planning ability [10]. One such methodology is the Lean method.

1.3. Lean and its application to IDM

The origin of the lean theory can be found in the practices of the Toyota Motor Corporation in the 1950s[11]. Nevertheless, its introduction into the world of business was through books such as [12] and [13]. These books focused on the manufacturing aspect of the business. However, their authors emphasized on the implementation of the same principles in other industrial sectors, such as innovation, in order to eliminate non-value-adding activities within a process to achieve excellence [14]. Accordingly, we proposed to apply Lean principles to increase the agility and efficiency of the initial analysis phase of IDM. In this application, the first and second principles helped us to highlight non-value-adding activities within this phase. We were then inspired by the third and the fourth principles to develop Inverse Problem Graph (IPG).

Inverse Problem Graph (IPG) is a Lean-based method to formulate the problem situation in the initial analysis phase of IDM. IPG adds to IDM the characteristics of the agile methodologies [10], which are evolutionary and iterative development, flexible and rapid response to change, promotion of communication, and adaptive planning. Therefore, it could significantly increase the agility of this systematic TRIZ-based approach. However, the initial version of IPG does not provide the way to prioritize the initial problems to begin a project. Furthermore, the collection of essential data by this version requires effort and time and significantly decreases the method's agility. Hence, the initial version needs the following improvements:

1.3.1. FMEA-AHP based method to prioritize the initial problems

To solve the IPG's drawback in prioritizing the initial problems, it is necessary to integrate the failure mode and effects analysis (FMEA) [15] and Analytical Hierarchy Process (AHP) [16] methods into the process of the IPG method to select the most important initial problem. In this integration, FMEA contributes to determining the initial problems at the beginning of the process. Then, AHP helps to prioritize these problems. The result of these integrations is "FMEA-AHP based method to prioritize the initial problems", as shown in Figure 1.1 and 1.2.

1.3.2. Agile Automated – Question Answering System (AA-QAS) to extract the essential data

It is also essential to integrate the neural network doc2vec [17] model and the machine learning text classification algorithms into the Inverse Problem Graph method. This gives the automatic information retrieval capability to the IPG's process to resolve its drawback in extracting the data. The result of these integrations is called "Agile Automated – Question Answering System", as Figure 1.1 and 1.2 show.

The result of this thesis is "Agile Automated System to extract the essential data (TRIZ parameters, contradiction, solution concepts) by considering priorities of the initial problems" that is based on the Inverse Problem Graph process. Figure 1.1 displays the relationship of different parts of this system with the chapter of this thesis. Besides, Figure 1.2 shows this system and its parts in detail.

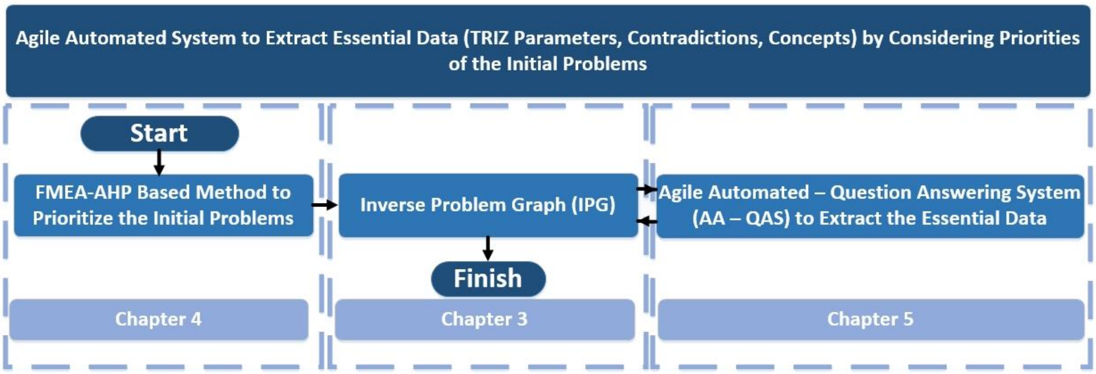


Figure 1.1. The relationship of different parts of Agile Automated System with the chapters

1.4. Thesis contribution

The main contributions of this thesis to the inventive design process is reflected in several aspects. As the first contribution, the application of Lean principles is to optimize the time taken for problem formulation by keeping only the essential elements of the study to be collected. Secondly, integration of the failure mode an effect analysis and analytical hierarchy process is to formulate the most important contradiction in each iteration of initial analysis of inventive design. As the third main contribution, application of the doc2vec model and the machine learning algorithms is to accelerate and facilitate the gathering of essential information to formulate a problem situation in the initial analysis.

1.5. Thesis structure

The rest of the thesis is organized in journal papers format, where each chapter is already a published or submitted paper for a journal. Therefore, in each chapter, you find first a stat of the art about the chapter's problem, then the scientific adding-value and its application case study. We respect in this document the chronological order of our propositions, as follows. Chapter 2 presents a detailed literature review on innovative problems approaches, the Theory of Inventive Problem Solving (TRIZ) and TRIZ-based frameworks. Chapter 3 presents a literature review on the initial analysis methods and Lean theory. Then, it displays the structure of the Inverse Problem Graph

(IPG) method, its steps, and its application to Covid-19 case study. Subsequently, this chapter brings a comparison between IPG and other techniques with the ability to formulate the problems. Chapter 4 presents a description of the FMEA method, its integration to improve TRIZ, and a review of AHP. Subsequently, this chapter shows the result of the integration of FMEA, AHP into the Inverse Problem Graph method, and its application to the Biomass Power Plant case study. Chapter 5 presents a review of several document-embedding techniques, a method for measuring the similarity, and several machine learning algorithms. Then, this chapter displays the structure of the IPG-based automatic system and describes its steps. Besides, it provides a comparison between this automatic system and another automatic technique that helps in the problem formulation.

The end of this thesis reports the conclusion and suggestions for future work

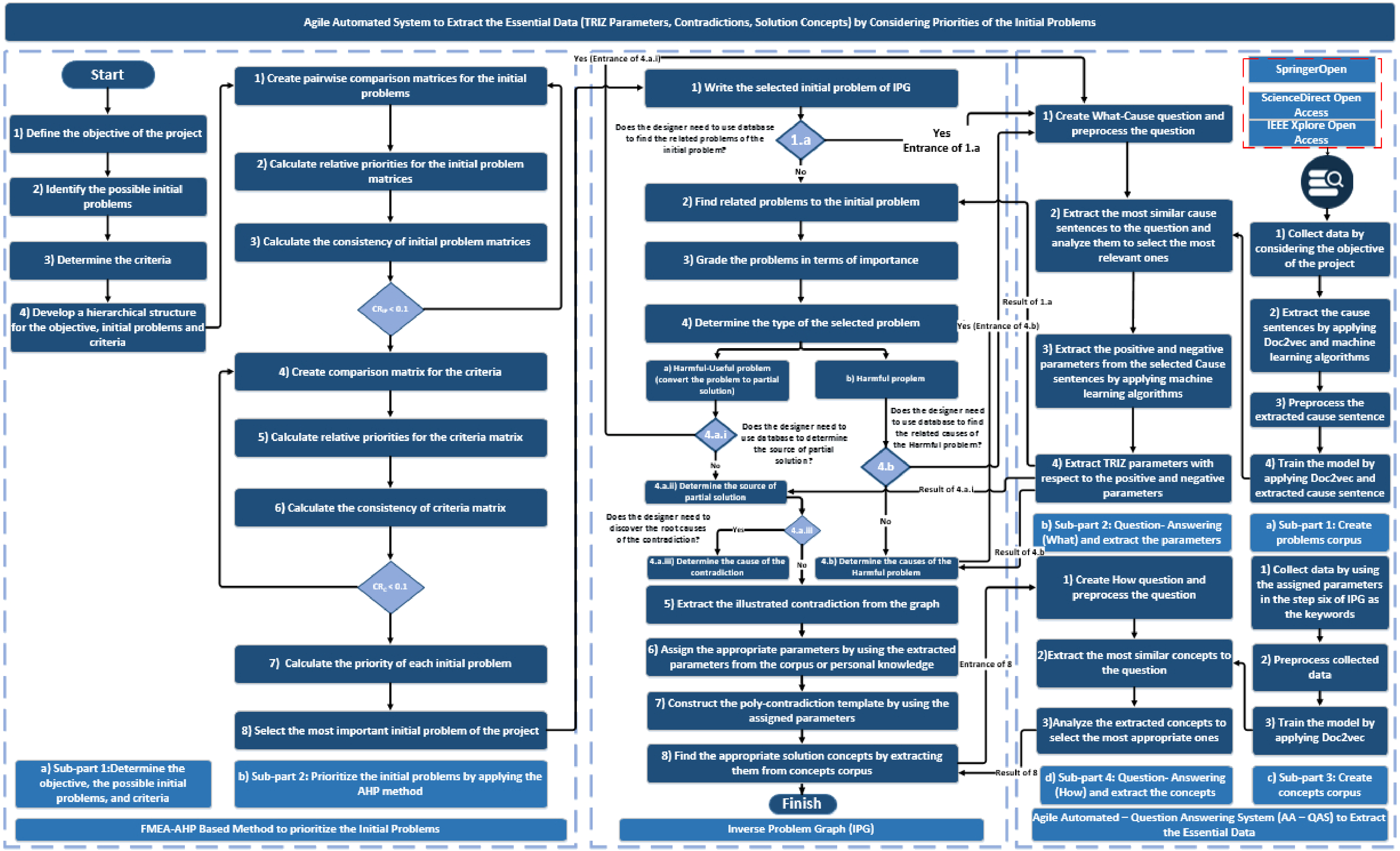


Figure 1.2. Agile automated system's process (Annex B)

Chapter 2. TRIZ and inventive design frameworks

This chapter includes a literature review about TRIZ and TRIZ-based frameworks. At first, we present a review of different types of innovative problem approaches. Then, in the TRIZ part, we provide an introduction of TRIZ and the notions of TRIZ such as technical and physical contradiction. Further, we introduced TRIZ's tools, including analytical tools and knowledge-based tools. In the third part, we present a review of the existing TRIZ-based frameworks, including xTRIZ, OTSM-TRIZ, and IDM frameworks.

2.1. Classification of innovative problem approaches

The innovative problem-solving approaches can be classified into two groups [4]:

1) Experimental approaches,

2) Systematic approaches.

Experimental approaches: This group consists of those approaches that use brainstorming or trial-and-error methods to attack a problem [4]. These approaches do not provide specific rules to develop an innovative solution. Furthermore, innovations by using them rely on the participators' inspiration [18]. They could not also consider all possible solutions for the best selection. Additionally, they are highly dependent on chance [4].

Systematic approaches: This group relates to those approaches that use systematic methods to develop new ideas helping to solve innovative problems [19]. The existing methods in this group permit selection of optimal solution by providing comprehensive coverage of solution space. Besides, their ability to perform a systematic analysis can increase the speed of access to an optimal solution [4]. The systematic approaches of innovation can be classified to TRIZ-based and Non-TRIZ based approaches.

Non-TRIZ based approaches relate to those methods that use tools other than TRIZ to develop an innovative solution.

TRIZ based approaches include those methods that somehow use TRIZ to develop innovative solutions [4]. These approaches can help to identify the problems in a shorter time. As a result, the speed of achieving innovative solutions is increased. Furthermore, these kinds of methods can help to generate more ideas [20].

Our work focuses on these kinds of approaches.

2.2. The Theory of Inventive Problem Solving - TRIZ

2.2.1. Introduction of TRIZ

Genrich Altshuller began to develop the Theory of Inventive Problem Solving (TRIZ) as a systematic methodology to create innovations since 1946 [21] [22]. After analyzing 400,000, Altshuller extracted basic patterns which governed the process of generating new ideas and creating innovations [20]. TRIZ says that any problem that designers encounter may have already resolved by other designers [23]. The fundamental idea of TRIZ is to provide the means to facilitate access to a wide range of solutions proposed by former inventors [24]. This theory provides tools and techniques that contribute the designers to develop a new idea without numerous trials and errors [25].To solve the problem within TRIZ, the problem-solver should transform the real problem into a conceptual one. Then, it is the time of searching the abstract solutions, helping to diverge thinking and generate practical solutions [23]. Figure 2.1 displays the TRIZ approach to solving a problem.

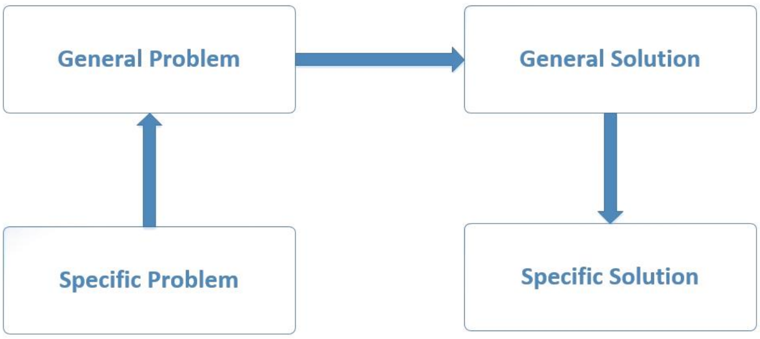


Figure 2.1. TRIZ approach to solving an inventive problem

According to the results of Altshuller's studies, there are five levels of invention, which are as the following:

- The first level refers to those solutions that create small modifications in a technical system [26]. These kinds of solutions use available methods within a trade relevant to that system [27]. This level includes 30 % of the total [28].
- The second level contains the solutions that help to resolve technical contradictions in an existing system [27]. These solutions use the knowledge

from various fields within an industry relevant to the system [26]. This level includes 45 % of the total [28].

- The third level refers to the solutions that contribute to solving the physical contradictions within a system [27].These types of solutions need knowledge from other industries [28]. The creative design solutions appear in this level, containing 20 % of the total[29].
- The fourth level includes the interdisciplinary solutions that use knowledge from different fields of science [26] [27]. This level contains 4 % of the total [29].
- The fifth level includes innovative solutions that are not previously discovered [26]. These solutions are less than 1 % of the total [28].

The result of Altshuller's research showed that a large number of patents belong to levels 1 and 2. TRIZ contribute the designers to develop an inventive solutions at level 3 & 4 [27].

2.2.2. Notions of TRIZ

2.2.2.1. Contradiction

Contradictions: are inventive problems resulting from the conflict of desired characteristics within a system[20]. Improvement of the system requires the identification and resolution of hidden contradictions within the system [30]. The most effective solutions are obtained by solving the technical problems containing a contradiction [27]. To uncover the contradictions, it is necessary to think paradoxically, which makes the problem evident [21]. Because the resolution of the contradictions is challenging, most people avoid these kinds of problems [23]. TRIZ aims to propose solutions to remove contradictions within a system [28]. There are three types of contradictions [31].

Administrative contradiction: this kind of contradiction describes a willingness to improve a system without showing the direction of the resolution. An administrative contradiction should be transformed into a technical contradiction. This transformation could contribute to reducing the ambiguity of a problematic situation [30].

Technical contradiction: this kind of contradiction shows itself when the improvement of certain characteristics of a system leads to the deterioration of others in the same system [28]. For instance, the bigger engine could improve the speed of a car, but it could also worsen its weights [20]. To facilitate resolving the technical contradictions, TRIZ proposes to apply the matrix of contradictions. This matrix includes 39 features, most frequently used in the design process, and inventive principles [25]. The technical contradictions could occur in the following situation [30]:

- The Creation of a useful function in a subsystem could create a harmful function in another subsystem.
- The removal of the harmful function in one subsystem deteriorates useful function in another subsystem.
- Increase the positive effect of a useful function or decrease the negative effect of a harmful function could lead to an unacceptable complexity of other subsystems.

Physical contradiction: this contradiction arises when one element of the system should have two opposite values at the same time [20]. For example, an umbrella should be small for the convenience of the users, and at the same time, it should be big to protect them [20]. To resolve the physical contradictions, it is possible to employ the separation principles [25]. These principles are as the following: 1) separation of the opposite desired values in time; 2) Separation of the opposite desired values in space; 3) Separation upon condition; 4) Separation within a whole and its parts [32]. Physical contradictions happen in the following situation:

- An Increase in the positive effect of a useful function in a subsystem could intensify the negative effect of a harmful function in the same subsystem[30].
- Reduction of the negative effect of a harmful function could reduce the positive effect of a useful function in the same system [30].

According to TRIZ, contradiction comprises the following components [33] [34] [35]: 1) Element, 2) Parameters, and 3) Values. In the following, we describe each component.

Elements: They are the constituents of the system [34] [35]. From a syntactical viewpoint, elements could be expressed by applying nouns, names, or groups of names [33]. The nature of an element could be constantly changed based on the description which is given by it [33]. For example, " the hammer pushes the nail" can become "the anvil drives the nail" when expressed by another expert [34].

Parameters: These qualify elements by giving them a specificity, reflecting an explicit knowledge of the observed field [35]. It is possible to use adverbs, names, or complements to object to express the parameters. The form of their expression is different when represented by various experts [33]. There are two categories of parameters [31]:

- **Action parameter:** The parameter that designers have the capacity of modifying its states, is called the action parameter. Indeed, this kind of parameter has a negative effect on another parameter when its value is (-V), and it has a positive effect on another parameter when its value tends to the opposite direction (V) [34] [31]. For instance, the designer can decide to increase or decrease the weight of the hammer's head. In this case, weight is an action parameter [34].
- **Evaluation parameter:** the parameter that can evaluate positive and negative aspects of the designer's choice [31]. The consequence of designing a hammer with a heavy head is to facilitate the driving of the nail. In this case, the facility of driving is an evaluation parameter [35]. The evaluation parameter has a single logical direction, whereas the action parameter possesses two logical directions [33].

Values: They are the adjectives applied to describe a parameter[34]. The weight of the hammer's head should be high; in this case, high is a value that describes the weight.

Poly-contradiction: The relation between all the contradictions arising from the encounter between the parameters should be shown. For this purpose, it is possible to apply the poly-contradiction template, which is a table in which the Action Parameter (AP) is placed on the top of the table. In the following, all the related Evaluation Parameters(EP) are successively listed under the AP. Figure 2.2 shows a poly contradiction template [36].

	Action Parameter	
	Va	$\overline{\mathbf{Va}}$
Evaluation Parameter (EP1)	☺	☹
Evaluation Parameter (EP2)	☹	☺

Figure 2.2. Poly-contradiction template [36]

2.2.3. TRIZ's tools

TRIZ methodology includes several tools and techniques that are classified as the following [25]:

1. Analytical tools for problem analysis
2. Knowledge base tools for system changing

2.2.3.1. Analytical-based tools

Analytical tools such as functional analysis and Su-field analysis contribute to formulating a problem [20]. Below there is a description of each tool.

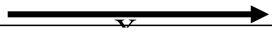
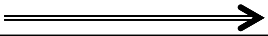
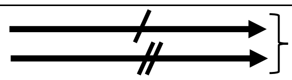
Function analysis: TRIZ Function Analysis map all the components of the system to draw out the problems arising from system functions [37]. Function is the motivation for the existence of a system [38] [39]. The function is the result of the action between a subject and an object in the system [40]. The subject (tool) produces the action, and the object receives that action [39].

The action is any influence that modifies the object [23]. Actions are described by applying the verbs [39]. TRIZ classifies the actions as the following [39] [40]:

- Useful actions: the actions that make the required modification to the value of object property [41]. These actions are divided into the following groups [41]:
- Adequate useful action: The action can make the desired modifications to the object [38].
- Insufficient action: they are the actions that have useful effects, but they are inadequate [38]. These actions need increment [39].
- Absent useful actions: the actions that needs introduction [39].
- Excessive useful actions: the actions that are excessive [23].
- Harmful actions: the actions that cause undesired modification on the object property [38]. These kinds of actions requires elimination [39].

Su-field analysis: The Su-Field (substance-field) analysis is a TRIZ analytical tool to represent a graphical model of problems related to a technological system [42]. A complete Substance-Field analysis model includes three components : a field, named F, and two substances, named S1 and S2 [43]. A substance is any object within a system, which could be qualified as a tool if it produces an action or could be characterized as a product if it receives the action, produced by tool [44]. Field is defined as an energy, being essential for the interaction between two substances [45]. The model can be shown by a triangle, having the substances in its corners and fields as interactions between substances. There are nine types of relationships between S1 and S2 , as shown in the Table 2.1 [43]:

Table 2.1: Different types of relationships between Substance 1 (S1) and Substance 2 (S2)

N°	**Relationship**	**Symbol**
1	Inaction	
2	Deficiency action	
3	Harmful action	
4	Break of connection	
5	Transformation	
6	Interaction	
7	Various Actions	
8	Normal	
9	Directed Action	

2.2.3.2. Knowledge-based tools

Knowledge-based tools provide information to transform the systems. In this group, it is possible to mention the tools such as the inventive principles, 76 standard solutions and effects [20].

Inventive principles: After analyzing 40000 patents in various fields such as chemistry, mechanics, electrical engineering, the early TRIZ community had derived 40 ways, which help to solve the contradictions, and named them the 40 inventive principles [46]. The inventive principles are general solutions to perform an action in a system [47]. Application of these principles to a problem allow the designers to create numerous innovative and uncommon ideas [46].

The problem-solvers can apply the contradiction matrix to connect to the inventive principles. Furthermore, they are able to use their personal intuition to find the best fitting principle [21]. The contradiction matrix is one of the effective tools of TRIZ, which was developed by Altshuller in the process of research about the patents [48]. The matrix consists of 39 columns and rows [21]. The horizontal rows contain the technical parameters to be improved, while the vertical columns represents the technical parameters that can be degraded as a result of improving the parameters [49]. The intersection of the improved and degraded parameters contains the numbers that guide the designers to the inventive principles [50].

The process of applying the contradiction matrix includes three steps: 1) Step 1: In the first step, the desired parameter should be translated into one of technical parameters existing in the rows. 2) Step 2: In the second step, the harmful feature is transformed into one of the parameters of the vertical columns. 3) Step 3: the designers extract one or several inventive principles from the intersection of the parameters to solve the technical contradiction [21] [28].

76 standard solutions: G. Altshuller and his associates developed the 76 Standard Solutions between 1975 and 1985 to solve inventive problems based on the laws of evolution of technological Systems [25] [51]. The standards are grouped into 5 classes and 18 groups according to their objectives [52] [53]:

- Class 1consists of 13 standard solutions that help to improve the system with no or little modification.
- Class 2 includes 23 standard solutions that contribute to improving the system through its modification.
- Class 3 contains 6 standard solutions that help the system transition.
- Class 4 includes 17 standards solutions applied in the measurement and detection in the technical.
- Class 5 consists of 17 standard solutions used as strategies for improvement and simplification.

The standards are usually employed as a step of ARIZ [54]. The application of them requires the identification of the components and the construction of the Su-Field model, helping to identify the class and the specific solution [50].

2.2.4. TRIZ's advantages and drawbacks

TRIZ has ability to discover the possible solutions to the identified problems, while other applied methods to problem solving, such as mind mapping, brainstorming, could only help to uncover a problem, and its related causes [20]. Moreover, TRIZ could contribute to reducing the amount of time to reveal an optimal solution and launch a new product [4]. However, there are several limitations involved in applying classical TRIZ in the R & D departments [55]. The first is that it does not provide any way to formulate the problems in the initial situations. Second, there is no means in TRIZ to lead its users to select the best solutions among the proposed ones. As the third limitation, TRIZ does not also provide an accurate way to reveal a contradiction. Finally, there is not a complete description of its components and the relations between them in TRIZ's body of knowledge. To overcome these limitations, researchers have developed numerous frameworks such as Inventive Design Methodology (IDM).

2.3. TRIZ-based frameworks

After introduction of TRIZ, various frameworks have been developed to solve its drawbacks. Among them, it is possible to mention xTRIZ, OTSM-TRIZ and Inventive Design Methodology (IDM). Here, we briefly describe each framework and their related process.

2.3.1. xTRIZ

"xTRIZ" was developed in seven stages to support a problem solving process with TRIZ for Management and Business. These stages are as the following [56]:

1. Collection of the information: At the first stage, the information about the problem is collected. Furthermore, constraints, limitations, and major targets, used as criteria to evaluate new ideas generated in stage 5 of the process, are identified [57].
2. Decomposition of the problem: The second stage of xTRIZ process relates to the decomposition of the problem by applying the RCA+ [56].
3. Identification of the contradiction: The thirds stage of the process relates to identify the contradictions that can help the designers to achieve the expected results [56].
4. Creation of a list of available resources: In the fourth stage, a list of the available resources within the contradictions' context is created. The creation of this list should be performed by considering classical TRIZ procedures [57].
5. Generation of inventive solutions: In the fifth step, the TRIZ methods such as contradiction matrix and inventive principles are used to generate new inventive solutions and eliminate the contradictions [57].
6. Creation of a tree of generated solutions: The sixth stage concerns about creating a tree of generated solutions [56].

7. Evaluation of the solutions: The seventh stage relates to the evaluation of the solutions by applying Multi-Criteria Decision Matrix. The purpose of this stage is to identify the best solutions [36].

2.3.2. OTSM-TRIZ

OTSM-TRIZ is the Russian acronym for Genral Theory of Powerful Thinking that introduces new procedure to describe complex problems, which is called Problem Flow Network (PFN) [58]. The objective of OTSM-TRIZ is to manage interdisciplinary and complex problem [59] [60]. OTSM includes two main phases [61]: 1) Construction of Networks, 2) Proposition of solution.

1. Construction of Networks phase: The first phase consists on developing several networks by applying OTSM's technologies. These networks are as the following: 1) Network of Problems, 2) Contradiction Network, and 3) Parameter Network [62].
2. In the second phase, the process proposes to apply the tools such inventive standards, inventive principles developing by classical TRIZ to solve the problems [61].

2.3.3. Inventive Design Methodology (IDM)

Inventive Design Methodology (IDM) is a framework, which has been developed within several years of research to solve limitations of TRIZ and to complete its body of knowledge with other theories such as Pugh's theory or graph theory [5]. This framework includes the following four phases [63]:

1. Initial Analysis phase: In this phase, in the beginning, the designers should gather all the relevant knowledge, coming from internal documents and patent, tacit know-how of experts, and other related documents to the subject. Then, the accumulated knowledge should be transformed into a graphical model to facilitate decision-making [5]. For this purpose, it is possible to apply problem Graph.
2. Contradictions Formulation phase: In the second phase, the designers could apply several methods such as poly-contradiction template to formulate the contradictions, which are technical and physical issues in a system [55]. These issues are considered as bottlenecks in the development of the system [5].

Subsequently, the extracted contradictions are used as an input point to apply TRIZ techniques and methods.

3. Solution Concept Synthesis phase: The designer applies different TRIZ tools to solve physical and technical contradictions in the third phase [64] [65].
4. Solution Concept Selection phase: In the last phase, the experts should weigh the concepts in order to measure the impact of each concept. To this end, they could apply an evaluation grid to select the most relevant concept [5].

The TRIZ-based frameworks are considered an improvement over TRIZ but still suffers from some drawbacks in terms of the time-consuming nature of their implementation. In this thesis, we focused on the Inventive Design Method process by trying to both identify its areas of inefficiencies while attempting to preserve the quality of its deliverables.

2.4. Conclusion of the chapter

In this chapter, we firstly presented an overview of different types of the innovative approaches. Subsequently, an introduction of TRIZ, TRIZ's notions including physical and technical contradiction, and the TRIZ's tools were presented. At the end of this chapter, we reviewed several TRIZ-based frameworks including xTRIZ, OTSM-TRIZ and IDM. In the next chapter, we will introduce a Lean-based method to formulate a problem situation in the initial analysis phase of inventive design.

Chapter 3. Proposition of Inverse Problem Graph (IPG) by Lean integration into the initial analysis phase

3.1. Introduction

In recent decades, many companies have been competing on improving innovation cycle time because of its importance to their success [1][2]. There are many examples in today's competitive world that highlight the importance of time in innovation, including the recent emergence of the coronavirus case, called COVID-19, whose rapid international and national spread caused a global health emergency [66]. Indeed, in this case, pharmaceutical companies show that they do not have an adequate speed to respond to the world's urgent need. These types of companies could overcome this drawback by adopting TRIZ-based systematic approaches such as Inventive Design Methodology (IDM).

3.1.1. IDM's Drawbacks

IDM is a framework that had been developed to solve the limitations of TRIZ and to complement its body of knowledge with other theories such as Pugh's theory or graph theory [5]. Nevertheless, one of the criticisms often leveled is that this approach does not have the needed agility and is time-consuming [6] [7] [8]. This is mainly due to the implicit step in each study to construct a complete map of a problem situation by interviewing experts involved in the study and extracting all their knowledge, regardless of how effective it is for the overall process. This stage leads to lots of contradictions that only some of which are used in the final phase to obtain the solution [9]. Therefore, it was necessary to combine IDM with other methodologies that transfer its agility to IDM to constitute a hybrid methodology, featuring the good capacities for iterative development and the capability to generate a rapid and flexible response to change [10]. Obviously, the Lean method came into play in our approach.

3.1.2. Lean theory and its integration to solve IDM's drawbacks

The origin of the lean theory can be found in the practices of the Toyota Motor Corporation in the 1950s[11]. Nevertheless, its introduction into the world of business was through books such as [12] and [13]. These books focused on the manufacturing aspect of the business. However, their authors emphasized on the implementation of the same principles in other industrial sectors, such as innovation, in order to eliminate non-value-adding activities within a process to achieve excellence [14]. Hence, we proposed to apply Lean principles to IDM. To do so, we first applied the first and second principles to highlight non-value-adding activities within the initial analysis phase of IDM. We were inspired by the third and the fourth principles of Lean, which suggest identifying possible solutions to create a flow and a pull stream of information between the stages of the process, to develop our proposal to formulate the problem situation.

3.1.3. Objective and contribution

The proposal of this chapter aims to increase the agility and efficiency of the initial analysis phase of Inventive Design Methodology. The main contribution of this proposal is to optimize the problem formulation time by keeping only the essential elements of the study to be collected through the application of Lean principles.

3.1.4. Chapter structure

The rest of the chapter is organized as follows. In Section 2, we present the relevant literature review. Subsequently, Section 3 displays the structure of the proposed method and its steps. In Section 4, a case study is presented in which the proposed method is applied to introduce a new way of observing the COVID-19 situation in order to formulate the related problems and to suggest relevant candidates of solutions, proposed by other medical specialists, by applying TRIZ tools. In Section 5, we make a comparison between our method and other techniques with the ability to formulate the problems. Then, Section 6 presents the discussion, and reports the conclusion of the chapter.

3.2. Literature review

3.2.1. Initial Situation Analysis methods

As we mentioned previously, initial analysis is a phase that involves gathering all the group's knowledge to construct a map of the problem by applying a variety of methods. In the state-of-the-art, we identified two groups: 1) Cause-searching-based methods, and 2) Effect-searching-based methods.

3.2.1.1. First group: Cause-searching-based methods

The existing methods in the first group are applied to identify the causes related to the selected problem in a system. These methods are attached to the following sub-groups: 1) Non-illustrator of contradictions. 2) Illustrator of contradictions.

The first sub-group comprises the methods such as Cause-Effect Chain Analysis and Ishikawa [67] [68]. These methods cannot reveal the contradictions. For this reason, the designers, particularly those looking for innovative solutions, require the methods in the second sub-group.

The second sub-group is related to those methods with the ability to represent the contradictions. These include Root Conflict Analysis Plus and Cause-Effect Chain Analysis Plus, described in below. In inventive design, we need to overcome the contradiction in a complex problem. Hence, we focus on this category.

Root Conflict Analysis Plus (RCA+) could eliminate the difficulties of extracting contradictions [69]. Its process begins with the vague statement of a problem, located on top of the diagram. RCA+ uses several rules to parse this vague statement [70]. Unlike classical RCA, the designers do not use the why-question, which could also show the objectives, to identify the causes. Instead, they apply the question "What is the cause?", showing the object, its feature, the physical parameter related to an object, and the action which is responsible for producing the problem [69]. The resulting cause, in response to the "what" question, could have a negative effect, and so on. If the identified cause leads to a positive effect, along with its negative effect, it is known as a contradiction in the RCA+ diagram. Once the identified cause has only a negative effect, the chain of the cause will be explored downward until appearing a contradiction [69]. A cause could be written as a sentence, presenting the condition of a parameter of a system, a description of a function, and a radical change of system [69]. In the structure of RCA+, we can find four types of causes: 1) A cause with a negative effect, which should be eliminated. 2) A cause with a positive effect, which does not need to be changed. 3) A cause with a positive-negative effect, which shows the contradiction in the system. 4) An unchangeable cause [69] [70]. After completing the first chain, the designers continue the process for other problems with a negative effect in the diagram until discovering all potential causes. A designer stops the development of a chain of causes in the following situations: 1) an unchangeable cause, which could not be changed for the reason like laws of nature, weather conditions, local and international policies, legal obligations. 2) A cause with a positive and negative effect, showing the contradiction. 3) A cause beyond control [69] [70]. Figure 3.1 shows an RCA+ related to a project. The RCA+, showing the contradictions, could play an important role in presenting a problematic situation. This method could also provide direct input for the contradiction resolution techniques in the next phases of inventive design [69] [68]. Nevertheless, a designer should create all chains of causes in the initial analysis phase, without paying attention to their utility in the solution stage. Additionally, this method does not merge the solution directions into its main structure. This is why a method such as Cause-Effect Chain Analysis Plus has been suggested.

Lee et al. introduced the Cause-Effect Chain Analysis Plus (CECA+) method. This method has a development trend quite similar to RCA+ [71]. Figure 3.2 shows part of a CECA+ diagram. Although this method could demonstrate the contradictions, it ignores the waste of time in formulating useless chains of causes. Furthermore, this method could not show solutions that could partially solve the problems. The reviewed methods in the second group could solve the last drawback by adding partial solutions to their structures.

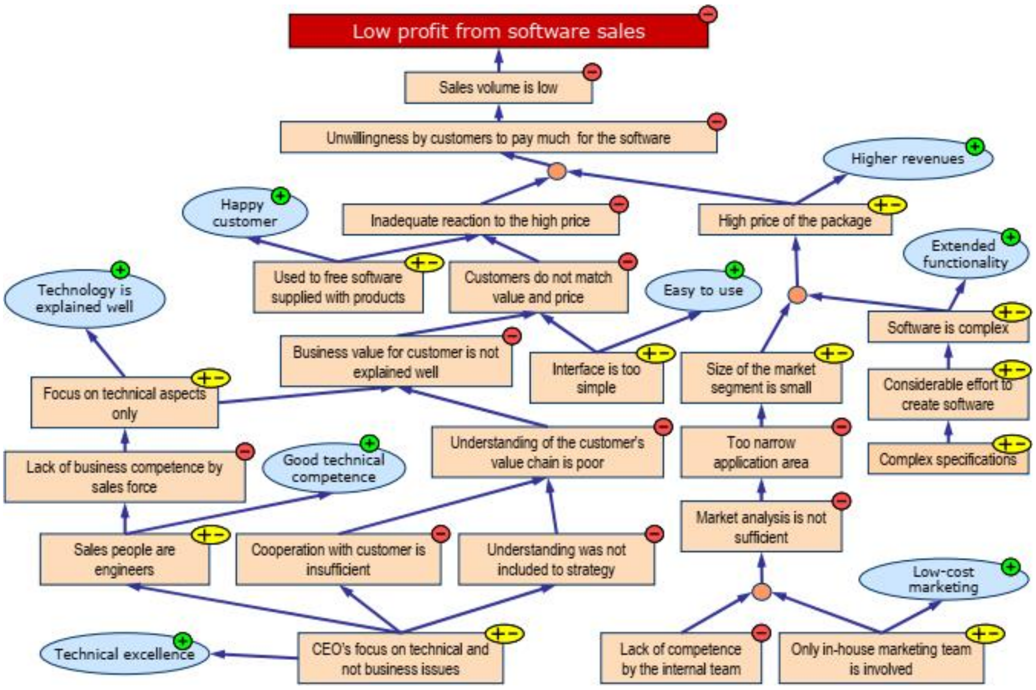


Figure 3.1. A project which applied RCA+ to formulate the problem [36]

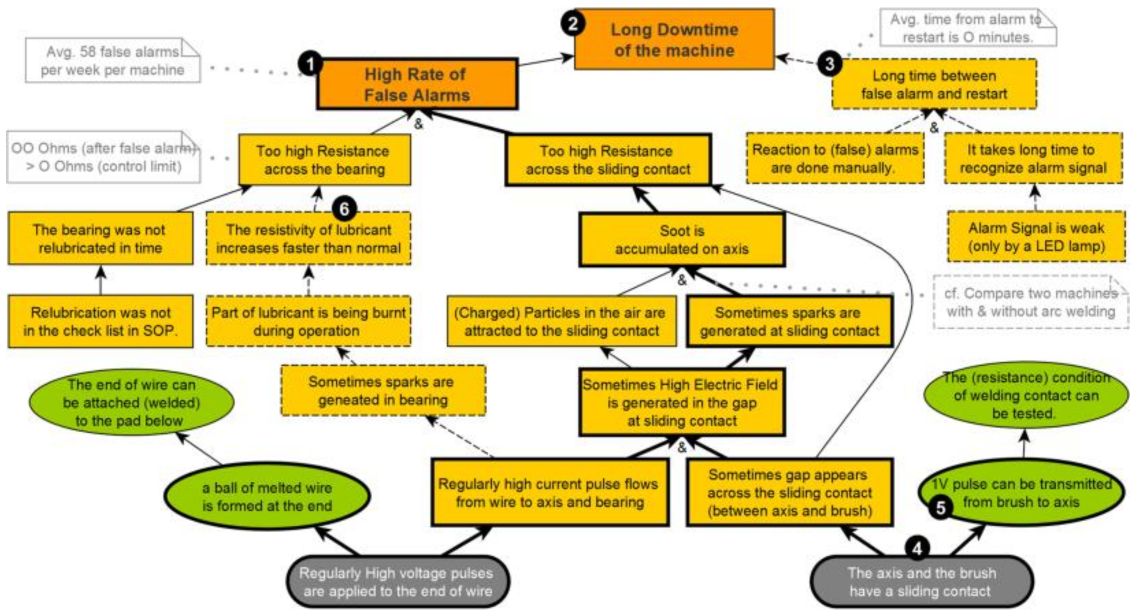


Figure 3.2. Part of a Cause-Effect Chain Analysis Plus carried out for a project [71]

3.2.1.2. Second group: Effect-searching-based methods

The second group is related to those techniques and methods used to investigate the effects of initial problems. In this group, we could find the Network of Problems (NoP) and Problem Graph.

NoP has been developed in the OTSM-TRIZ framework theory to help designers to break down an overall problem into a set of sub-problems, which are easier to solve [72] [73]. A NoP organizes related knowledge to the problem situation and could help to solve a contradiction [72]. However, its original version did not provide a clear definition of the nodes, which constitute its main structure [72]. Additionally, due to the method guide, designers should start projects with a complex problem, being overly general, which causes an excessive expansion of the network of problems and designer's confusion. For solving some of the drawbacks related to NoP, researchers proposed other methods, one of which is the problem graph method.

The problem graph method has been introduced in the framework of Inventive Design Methodology [74]. This method demonstrates a connection between a large set of problems and partial solutions, resulting from a problem situation. According to the definitions presented for the components of the problem graph structure, a problem is a sentence that describes an obstacle, barricading the achievement of objectives [74]

[63]. A set of interrelated problems, sufficient to describe the main problem situation, is defined as the problem space [7]. Considering the same definition provided for the structure, a partial solution explains the knowledge of the members of the design team about a patent or upon their experiences [74] [63]. A set of partial solutions related to problem space forms partial solution space [7]. As shown in Figure 3.3, a problem graph can graphically represent a problematic situation. Furthermore, it presents a formal definition of its main components, constructs its structure. However, to create a problem graph, it is necessary to dedicate a lot of time collecting information at the beginning regardless of its usability at the end of the project.

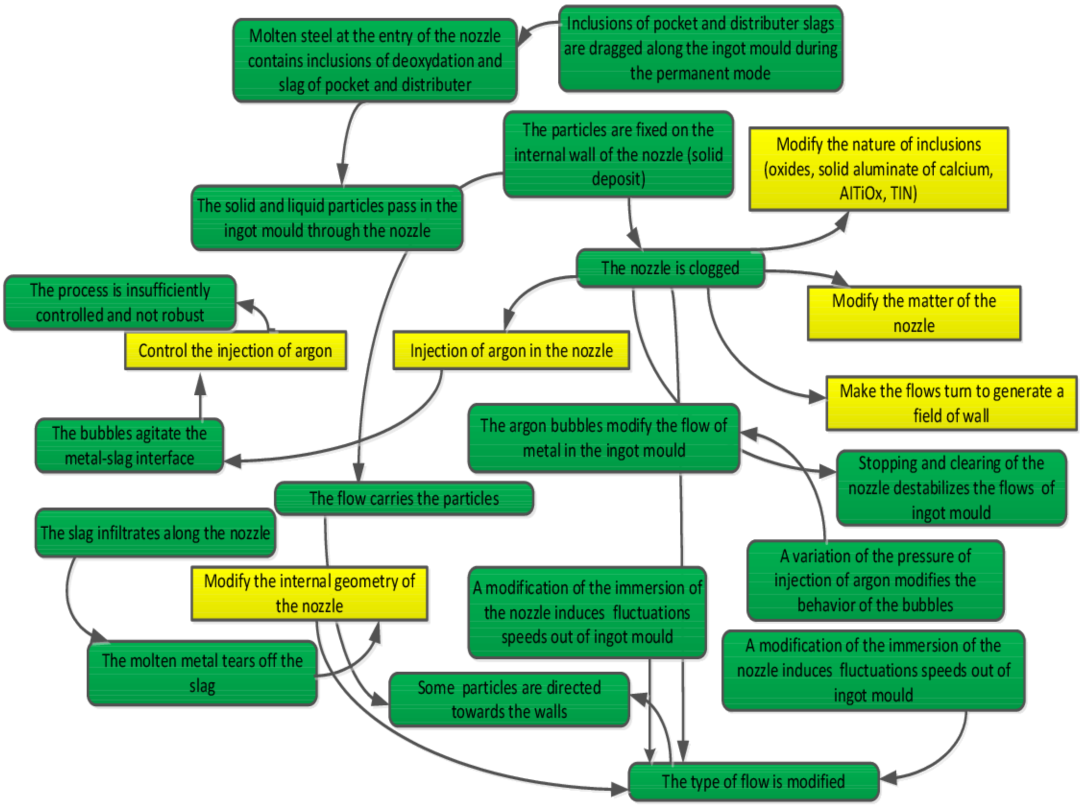


Figure 3.3. Problem Graph Application for formulating problems [74]

As we have seen, most of the analyzed methods in the literature review do not take into account the time spent gathering the group's knowledge, which is sometimes useless to map a problem situation. As a result, it was necessary to apply complementary approaches such as Lean to improve the agility and performance of the method.

3.2.2. Lean theory

Lean theory was introduced into the business world through the books [12] and [13]. The authors of these books emphasized that Lean principles could be implemented not only in the manufacturing aspect of the business but also in different industrial sectors to eliminate various types of waste within these sectors [11]. This theory has classified seven forms of waste as follows: 1) Generating more than required. 2) Products or information that could not meet the expectation. 3) Unnecessary raw material, work in process, finished stock storage, and delay of products or information. 4) Unnecessary process steps. 5) Movement of information and products with no added value. 6) Waiting time for information, people, or products. 7) Poor workplace structure , causing a loss of items [75] [76]. Lean proposes a set of principles and techniques to continuously remove different waste during the process to increase its efficiency and agility. Nevertheless, to eliminate waste and deliver improvement beyond the boundaries of manufacturing, it is necessary to understand five Lean principles. These principles are as follows [77]:

1) Value definition: it implies that it is necessary to get rid of activities that use resources but cannot create value.

2) Value-stream specification: it is essential to highlight non-value added activities within a process.

3) Making a value-stream flow: the process should be optimized in order to obtain a flow of information and raw material.

4) Producing while taking requirements into consideration: it is essential to produce by considering the requirements.

5) Monitoring for waste products regularly: Waste removal must be constant.

3.2.2.1. Application of the Lean principles into IDM

In this chapter, the Lean principles, particularly the third and the fourth one, encouraged us to develop a method for the initial analysis phase that gives the characteristics of agile methodologies, such as iterative and evolutionary development, to IDM. For this purpose, we firstly applied the first and second principles to highlight the Value Added, Non-Value Added activities related to the phases of the IDM framework. This application showed that designers should collect and analyze all the data and partial solutions without paying attention to their use in the solution step. In the contradiction formulation phase, we also considered the same problem that designers formulate, all the contradictions that are sometimes useless. Our analysis also demonstrates that designers use only some of the collected problems, partial solutions, and the formulated contradictions in the solution phase.

The third and fourth principle of Lean suggests to optimize the process by creating a flow and a pull stream of information between the phases of the process. Accordingly, we considered that it is essential to start the process of inventive design from a problem that could connect the designers to the most appropriate solution. Hence, we realized that if the designers formulated the problems from the lower-level of a problem situation instead of the upper-level, they could avoid collecting many useless problems and partial solutions. Accordingly, by integrating the best features of the methods with the ability to illustrate the contradictions, we suggested a new method, which extends the chains of problems and partial solutions in the opposite direction of the analyzed methods. In the next section, we will introduce this method.

3.3. Proposed method: Inverse Problem Graph (IPG)

3.3.1. Notions of the IPG Components

The Inverse Problems Graph (IPG) includes the following types of entities, shown graphically in Figure 3.4:

1. Problem: In IPG, a problem is a sentence that represents a barrier, preventing the fulfillment of what has to be done [78]. The construction of this sentence could be as such:

    - Subject + Verb + additional information, describing the situation.

We proposed five types of problems for the structure of IPG, as Figure 3.4 illustrates:

a. Initial problem: It is a problem at the first level of the graph. This problem is defined according to the objective of the project.
b. Harmful problem: It is a problem that has a harmful effect on the system, removed from the system by eliminating the contradiction [71] [79]. This problem causes the initial problem or another harmful problem. In the event of such a problem, it is essential to pursue the chain of causes to reach a harmful-useful problem.
c. Harmful-Useful problem: This is a problem that is both harmful and useful to the system. If a problem contains such ambiguous aspects, both seemingly beneficial and harmful for the system, this signifies that the problem should be reformulated as a Partial solution to become the center of a contradiction[71] [79].

d. Source of a partial solution: It is a problem that causes the partial solution. This problem is located at the end of the contradiction.

e. Out-of-capacity problem: There are some problems that are harmful, but the designer does not have the ability to eliminate them.

We adopt the partial solution proposed by [78]: A phrase that expresses the knowledge of the members of the design team about a registered patent or their experience. The structure of this phrase could be as follows:

- Infinitive + additional information describing the situation

We also use the parameters or notions proposed in [33]: the classification of the existing parameters in IPG's structure is as follows:

f. Evaluation parameters: These are the parameters that give the designers the capacity to evaluate their design choice. In IPG, a problem gives rise to evaluation parameters.

g. Action parameters: They are parameters whose nature lies in the capacity of state modification. Each partial solution in IPG could result in this kind of parameters.

Level: The level specifies the location of the problem and partial solution in the IPG hierarchy, by considering that the direction of movement in the graph is from left to right or from initial problem to right. As Figure 3.4 shows, there are three types of levels as these include:

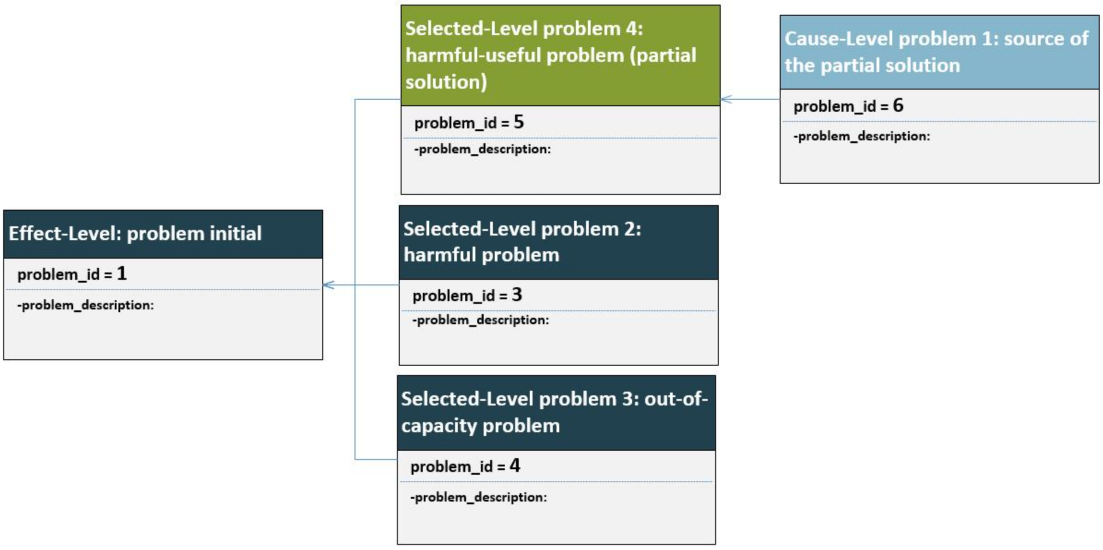


Figure 3.4. Different types of problems and levels in IPG

a. Effect-Level: The level that is before the selected level in the graph.

b. Cause-Level: The level that is after the selected level in the graph.

c. Selected-Level: The current level of problem analysis.

Iteration: The number of entries in the IPG, to choose a contradiction, is called iteration. In Figures 3.5 and 3.6, you can see the Lean-Agile IDM framework (LA-IDM) with IPG (Figure 3.5) and the Inventive Design Methodology (IDM) with other discussed methods in the literature review (Figure 3.6).

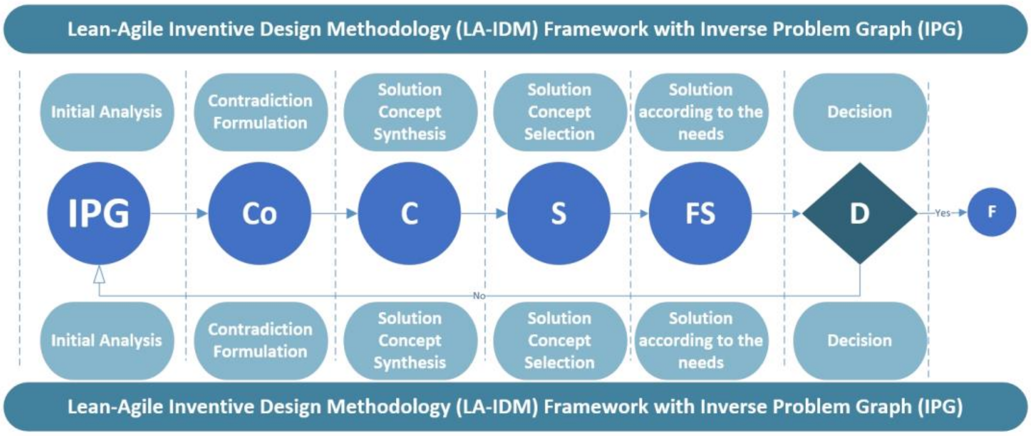


Figure 3.5. LA-IDM with Inverse Problem Graph

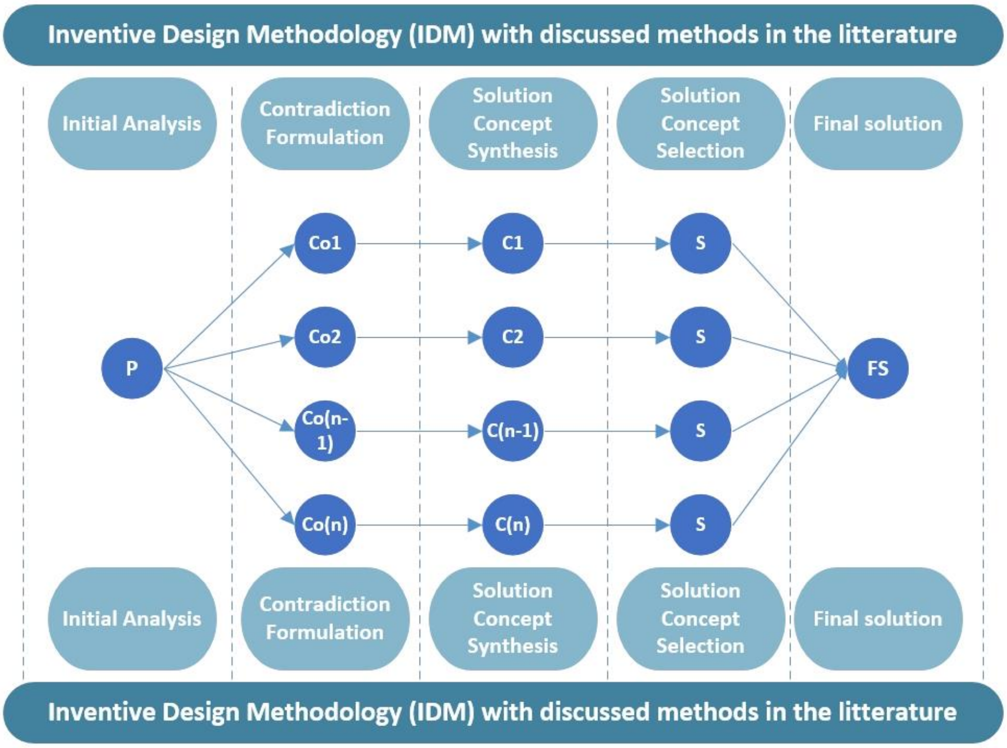


Figure 3.6. IDM with other discussed methods in the literature review

The Lean theory and its integration into the IDM framework led us to add this notion to IPG's structure, and we proposed a new framework for inventive design, called Lean

Agile Inventive Design Framework. In the following, we introduce the steps of IPG, which belong to the first phase of the LA-IDM framework.

3.3.2. Inverse Problem Graph (IPG)

Our proposed method consists of three phases. In the first phase, the Inverse Problem Graph method helps to perform initial analysis of the problem situation. The second phase refers to the formulation of the contradiction by applying the given parameters of step 7 of the IPG. The applied tool in this phase is called poly-contradiction template [55]. In the third phase, designers apply TRIZ methods such as contradictions matrix and inventive principles to solve the formulated contradiction. In this paper, we will focus only on the first phase (Phase 1), which consists of 7 steps in the IPG, as Figure 3.7 shows. These steps are as follows:

Step1: Define the aim of the project: This step is related to the determination of fulfilling the objective of the project. What a designer wants today, respecting actual constraints.

Step 2: Define the initial problem of the IPG: The designers define the initial problem by considering the objective of the project.

Step 3: Find related problems to the initial problem: In the third step, the designers determine the problems, which cause the initial problem. In order to determine them, designers could simply ask the question, "What problems in the Cause-Level cause the initial problem?".

Step 4: Grade problems in terms of importance: The designers should verify the degree of importance of each problem, by asking “What is the problem at the borderline of the company’s activities?” Additionally, they should check its profit for the company, by asking “Which problem can bring the most profit, while minimizing costs?” In each iteration, the designers should accept the most important problem by considering the answer to the questions.

Step 5: Determine the type of the selected problem: The designers determine the type of the chosen problem in the previous step by considering the notions existing in the structure of the IPG.

(a) If the selected problem was a Harmful-Useful problem, (i) it is essential to convert the Harmful-Useful problem to a partial solution. (ii) Subsequently, the designers should answer the question: “What problems in the Cause-Level cause this partial solution?" to identify the source of partial solution (causes of partial solution). (iii) In the following, if the designers need to discover the root causes of the contradiction, they could apply the following question: "What problems at the Cause-Level lead to the source of partial solution?"

(b) If the selected problem was a Harmful problem, (i) it is essential to determine the related causes of Harmful problems by answering the question: "What problems at the Cause-Level lead to this Harmful problem?". (ii) After identifying the potential causes, the designers should go back to step 4 of the process to grade them.

Step 6: Extract the illustrated contradiction of the selected problem from the graph: In this step of the IPG, the designers have to extract the illustrated contradiction of the selected problem from the IPG graph. We should remember that, in each iteration, the designers could select just one contradiction to receive a flow of information.

Step 7: Assign the appropriate parameters: Finally, the designers should respectively assign the evaluation and action parameters to the problems and partial solution, forming the structure of the extracted contradiction.

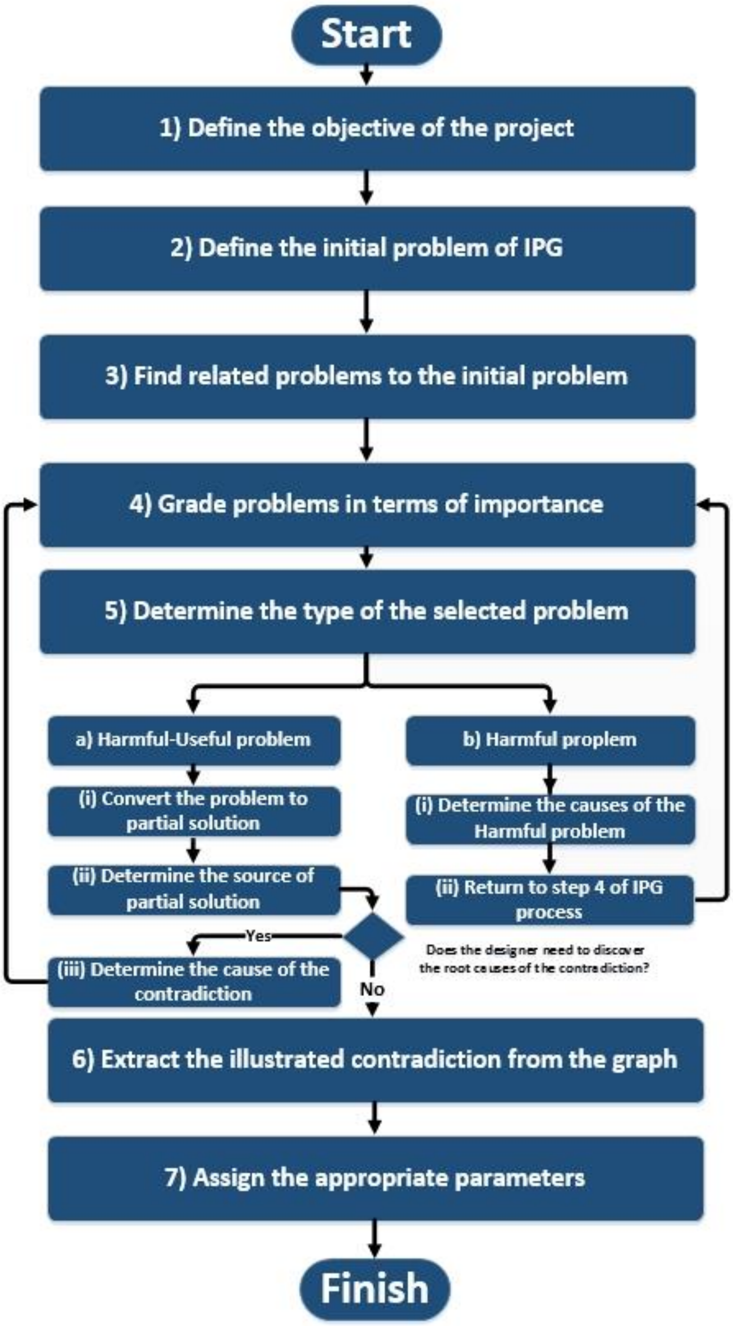


Figure 3.7. Process of Inverse Problem Graph

3.4. Application of proposed method to Covid-19 case study

In this section, in order to illustrate the operation of the proposed approach in a pedagogic way, we decided to rely on a current international situation, that of COVID-19, of which we are not experts, but whose elements allowing the characterization are eminently multidisciplinary and whose sources abound in the literature review. Prior to the confirmation of this topic, as a case study, there was a discussion among the members of our laboratory, concerning the fact that this case is a medical case, and whether we should apply our proposed method to such topic. The reason for this argument is related to the needs of patients, infected with the new 2019 coronavirus, to medical and health specialists for their treatment.

As a result, we can know about this virus and its case as an industrial topic, although this industry needs medical professionals to determine the potential causes and to discover the appropriate solutions. It was also suggested that we propose our solution, which was not satisfactory for a case study in this paper. Our objective in writing this paper was to show IPG's capabilities in formulating a problem situation. That is why we chose COVID-19 as our case study.

The “COVID-19” virus, whose rapid spread is causing a global health emergency, was first detected in December 2019 [66]. The COVID-19 case study aims to identify the causes that make the virus the enemy of humanity in a short period of time, and to propose the solutions suggested by other health specialists. For this purpose, we applied IPG to formulate the contradictions and to solve them by implementing TRIZ methods. In what follows, we explain this application for this case study.

The first phase of the proposal was related to the initial analysis of the problem and the creation of its Inverse Problem Graph (IPG). This phase includes the following steps:

Step1: We defined “To propose some treatments for COVID-19 virus” as the objective of the project, considering that this virus has increased patient mortality worldwide [80].

Step2: We need to determine the initial problem based on the objectives. Hence, we have defined “COVID-19 has fatal consequences on humans” as the initial problem.

Step3: We determined all the Harmful and Harmful-Useful problems associated to the initial problem by asking the question: “What problems in the Cause-Level cause the initial problem?” As a result, we found the following problems and causes through the research that we conducted in the articles on this topic. Firstly, “COVID-19 damages the human heart due to the high expression of ACE2 in this organ” [81]. Secondly, it mentions the problem “COVID-19 damages the neurons in the brain” [82]. And thirdly, it was the problem “COVID-19 causes lung injury” [83]. Figure 3.9 shows these problems.

Step4: We need to grade the problems found and select one of them, which was the most important. Therefore, the problem “COVID-19 damages the human heart due to the high expression of ACE2 in this organ" was selected, showed in the red dotted rectangle in Figure 3.9, because, according to [84], cardiac injury is a prominent feature of COVID-19, which occurs in 20 % - 30 % of hospitalized patients and leads to 40 % of deaths .

Step5: We need to determine the type of problem selected. Based on the notions presented for the IPG structure, we have concluded that the selected problem is a Harmful problem. Hence, it was necessary to find the causes of this Harmful problem at the Cause-Level of the diagram. Considering the research on the subject COVID-19, we obtained the following problem: "The patients use drugs for cardiovascular diseases, which increase ACE2, to treat heart diseases" [85], which is a Harmful-Useful problem. Consequently, we converted it to the partial solution "To use cardiovascular drugs, which increase the levels of ACE2, to treat heart diseases", as Figure 3.8 shows. Then, the source of the partial solution was determined as follows: "Patients suffer from heart disease". Figure 3.9 shows the IPG in the first iteration of our case study.

Figure 3.8. Conversion of the problem to partial solution

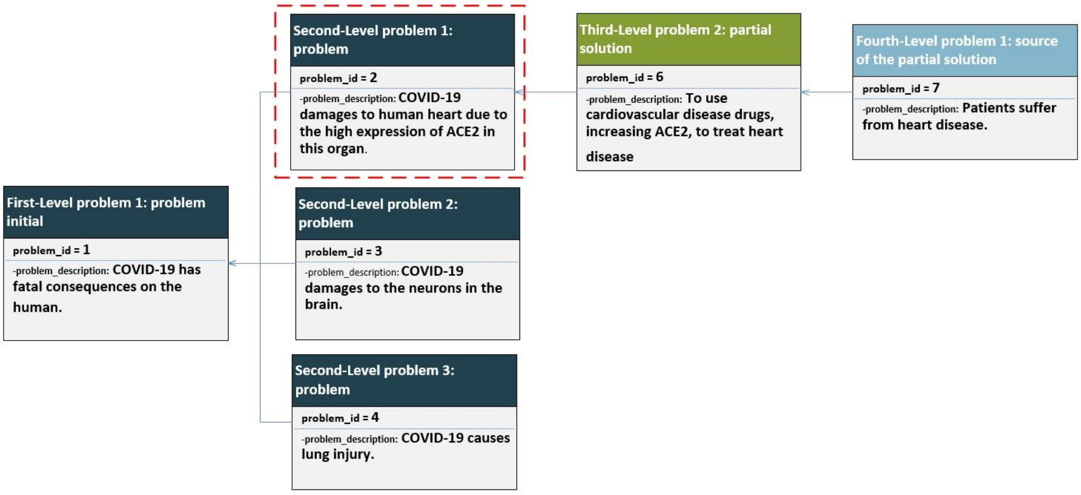


Figure 3.9. Inverse Problem Graph of the case study in the first iteration

Step 6: The illustrated contradiction of the most important problem in the diagram was extracted, as Figure 3.10 shows. The figure shows a contradiction between the ability of the heart to perform its intended function and the vulnerability of this organ to the harmful effect of the COVID-19 virus due to the level of ACE2. This means that the efforts to improve heart function by using drugs for cardiovascular diseases could increase its permeability to the virus.

Step 7: We assigned the appropriate parameters to the problems and partial solution of the prior step. Figure 3.10 illustrates this assessment. The first parameter "Easy access of the virus to the heart cells (Vulnerability of heart to the harmful effect of the virus)" was an evaluation parameter, extracting from the problem "COVID-19 damages the human heart due to the high level of ACE2 in this organ" because COVID-19 hurts the body. Furthermore, we selected "The ability of heart to perform its intended function" as our second assessment parameter because heart diseases have an impact on the intended function of this organ of the body. These parameters were translated to TRIZ parameters in the next phase of the process of constructing the table of contradictions and in the third phase as an input for using the contradiction matrix and extracting inventive principles.

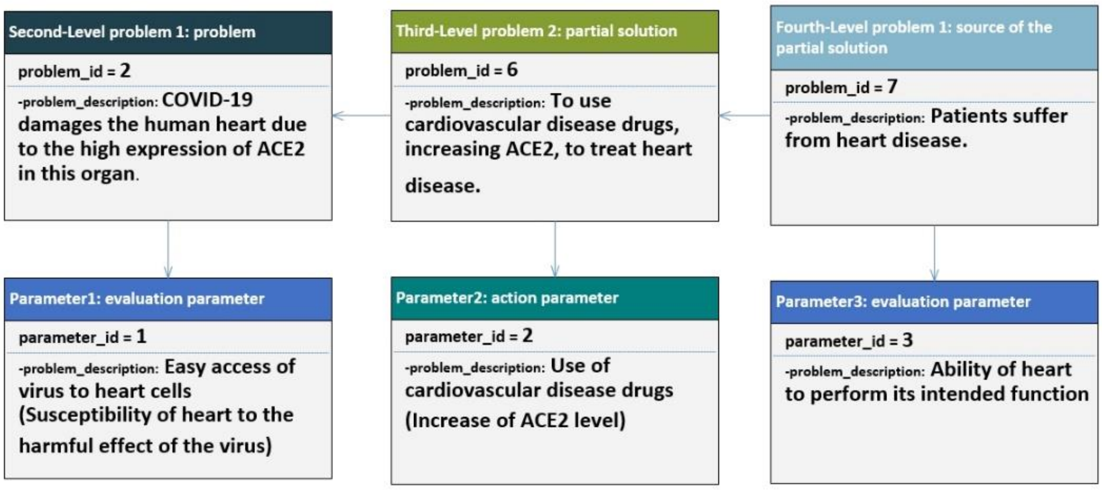


Figure 3.10. Allocation of the parameters

In the second phase of the inventive design, we firstly translated the assigned parameters from step 7 of IPG to the TRIZ parameters. The first evaluation parameter "Easy access of the virus to the heart cells (Vulnerability of the heart to the harmful effect of the virus)" was translated to "External harm affects the heart". Furthermore, we translated the second evaluation parameter "The ability of the heart to perform its intended function" into "Reliability of the heart". Subsequently, we applied the TRIZ parameters to construct the poly-contradiction model. As shown in Figure 3.11, the relationship between the parameters of the model, when using drugs against diseases, we encounter a contradiction between two parameters, "Reliability of the heart" and

“External harm affects the heart”. This means that the consumption of heart medicines, which increase the ACE2 level in the heart, could improve the reliability of the heart. However, it could increase the harmful effects of the virus on this organ of the body.

	Use of cardiovascular disease drugs (Increase in ACE2 level)	
	Yes	**No**
Reliability of the heart	☺	☹
External harm affects the heart	☹	☺
TRIZ definition of the applied parameters		
Reliability: A system’s ability to perform its intended functions in a predictable manner		
External harm affects the system: Vulnerability of a system to external harmful effects		

Figure 3.11. Poly-contradiction model of the TRIZ parameters in relation to the assigned parameters of step 7 of the IPG

Phase 3 consists of listing the inventive principles by applying the TRIZ’s contradictions matrix and selecting one of them, which is closest to our problem. The list below shows the inventive principles obtained from the intersection of the parameters in the matrix.

1. Principle 27: Cheap short-lived objects
   a. Replace an expensive object with a multiple of inexpensive objects
2. Principle 35: Parameter changes
   a. Change an object’s physical state
   b. Change the concentration or consistency
   c. Change the degree of flexibility
   d. Change the temperature
   e. Change the pressure
   f. Change other parameters
3. Principle 2: Taking out
   a. Extract or isolate from the object a part or one of its disturbing properties
   b. Extract or isolate only the property or the useful part
4. Principle 40: Composite materials
   a. Change from uniform to multiple materials where each material is tuned to a particular functional requirement.

According to the existing research on the COVID-19 virus, the virus requires cellular receptors (ACE2) and host cell proteases (TMPRSS2) to enter the cell, as Figure 3.12 illustrates [86] [66] [87]. Unlike the cellular receptor (ACE2), the host cell protease (TMPRSS2) is not necessary for the patients. Instead, it helps the virus to access the cell. The host cell protease (TMPRSS2) is therefore disruptive to the cell and body. According to principle 2, if a part of an object has disturbing properties, designers could isolate it. Therefore, isolation of the host cell protease (TMPRSS2) could be a good treatment against the COVID-19 virus. This solution has previously been suggested before in [86] by using Camostat mesylate, which is an inhibitor of TMPRSS2 [88].

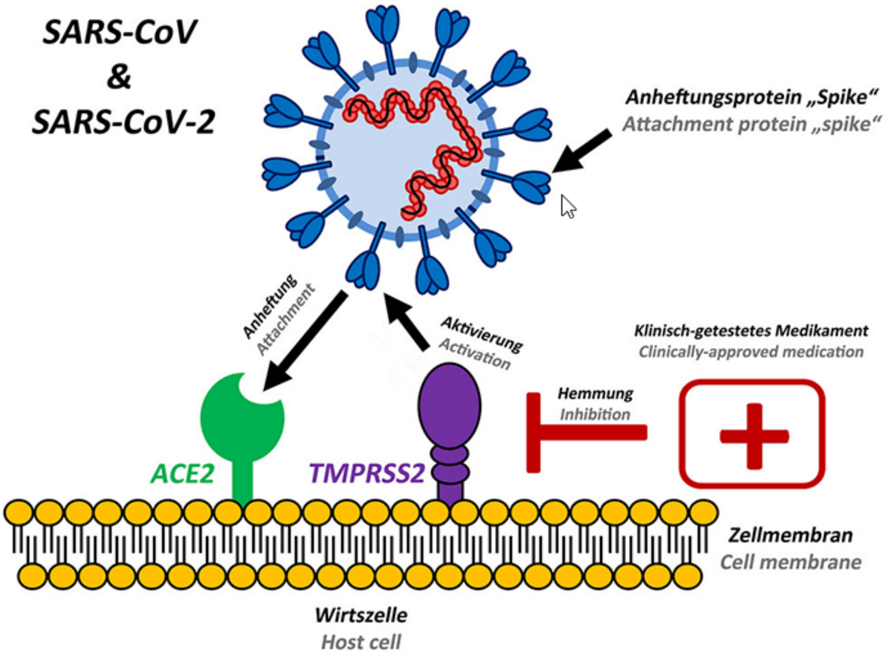


Figure 3.12. Interaction between COVID-19, ACE2, and TMPRSS2 [86] [89]

3.5. Comparison of the IPG method with conventional methods

3.5.1. Comparison in terms of time

In this section, we first present a quantitative comparison between the Inverse Problem Graph and the Problem Graph methods to show their time differences in the initial analysis and contradiction formulation. This comparison is based on the application of both methods to four projects. In this application, there were two groups of students. To analyze the Problem Graph capability, we asked one of the groups to apply this method. Then, we collected information such as the number of constructed elements and the total time allocated to these constructions. Table 3.1 shows this collected information. As shown in the table, the students constructed sixteen problems in the Luggage project. Considering that each of these problems took 30 minutes to construct, we obtained 480 minutes as the total time to construct the problems in this project. Similarly, we calculated the total time to construct the remaining elements in the first project to obtain the total time spent in the initial analysis and contradiction formulation phases, which was 1140 minutes ($480\ min + 360\ \mathrm{min} +\ 300\ min = 1140\ min$). Table 3.1 also demonstrates the total time of these phases in the other three projects. Moreover, the table shows the average time (1235 minutes) to perform the initial analysis and contradiction formulation by applying the Problem Graph.

Table 3.1: Information Collected from four different student projects

Essential time for the initial analysis and contradiction formulation phases (Problem Graph)				
Project	**Element to construct**	**Construction Time**	**Number of elements in the project**	**Total time**
Luggage	Problem (including general problem)	30 min	16	480 min
	Partial solution	30 min	12	360 min
	Contradiction	20 min	15	300 min
	Total time for the initial analysis and contradiction formulation phases			1140 min
Hammer	Problem (including general problem)	30 min	28	840 min
	Partial solution	30 min	9	270 min
	Contradiction	20 min	4	80 min
	Total time for the initial analysis and contradiction formulation phases			1190 min
Keyboard	Problem (including general problem)	30 min	19	570 min
	Partial solution	30 min	17	510 min
	Contradiction	20 min	23	460 min
	Total time for the initial analysis and contradiction formulation phases			1540 min
Desk lamp	Problem (including general problem)	30 min	11	330 min
	Partial solution	30 min	10	300 min
	Contradiction	20 min	22	440 min
	Total time for the initial analysis and contradiction formulation phases			1070 min
Average time for the initial analysis and contradiction formulation phases				**1235 min**

Table 3.2 shows the information on the capability of the IPG method in formulating the problem situations. To construct this table, we asked the other group to apply our proposal to the same projects mentioned in Table 3.1. Figure 3.13 demonstrates the Inverse Problem Graphs related to each project. As Table 3.2 illustrates, we first calculated the total construction time for each element in four different projects. Then, we obtained the time spent on the initial analysis and the contradiction formulation phases in each project. Table 3.2 also displays the average time, which was 162.5 minutes, to complete these phases using the IPG method.

Table 3.2: Collected information from the application of the IPG method to the four student projects

Essential time for the initial analysis and contradiction formulation phases (Inverse Problem Graph)				
Project	**Element to construct**	**Construct time**	**Number of elements in the project**	**Total time**
Luggage	Problem (including initial problem)	30 min	3	90 min
	Partial solution	30 min	1	30 min
	Contradiction	20 min	1	20 min
	Total time for the initial analysis and contradiction formulation phases			140 min
Hammer	Problem (including initial problem)	30 min	4	120 min
	Partial solution	30 min	1	30 min
	Contradiction	20 min	1	20 min
	Total time for the initial analysis and contradiction formulation phases			170 min
Keyboard	Problem (including initial problem)	30 min	4	120 min
	Partial solution	30 min	1	30 min
	Contradiction	20 min	1	20 min
	Total time for the initial analysis and contradiction formulation phases			170 min
Desk lamp	Problem (including initial problem)	30 min	4	120 min
	Partial solution	30 min	1	30 min
	Contradiction	20 min	1	20 min
	Total time for the initial analysis and contradiction formulation phases			170 min
Average time for the initial analysis and contradiction formulation phases				**162.5 min**

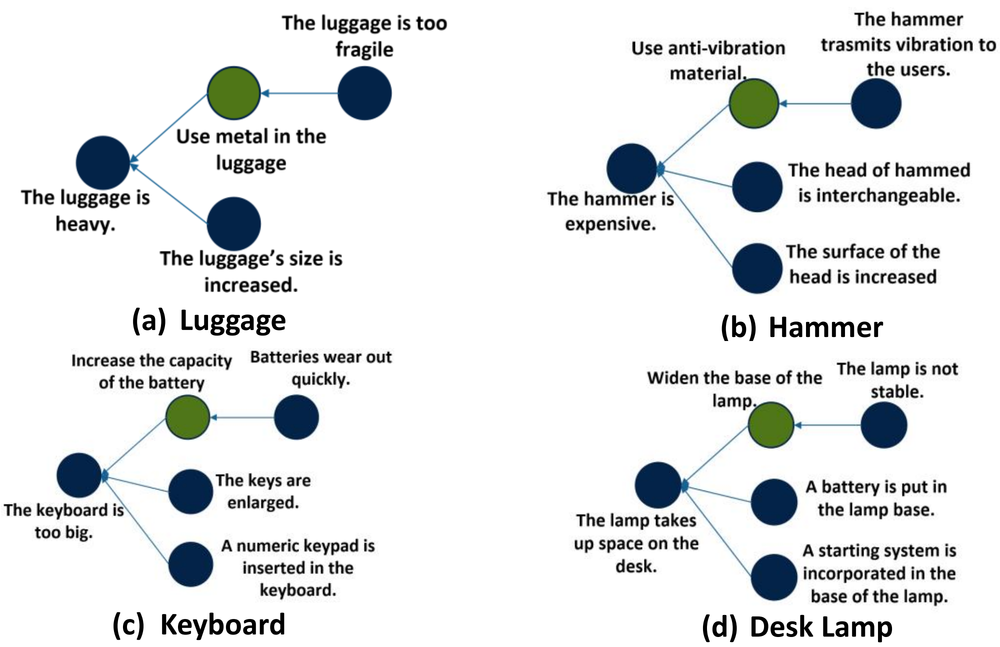


Figure 3.13. Application of the IPG method to the four student projects

Figure 3.14 shows a comparison between the integrated IPG method and Problem Graph in terms of the total time spent in the initial analysis and contradiction formulation phases of the four projects. Furthermore, the figure shows the average time spent in these phases using our proposal and the classical method.

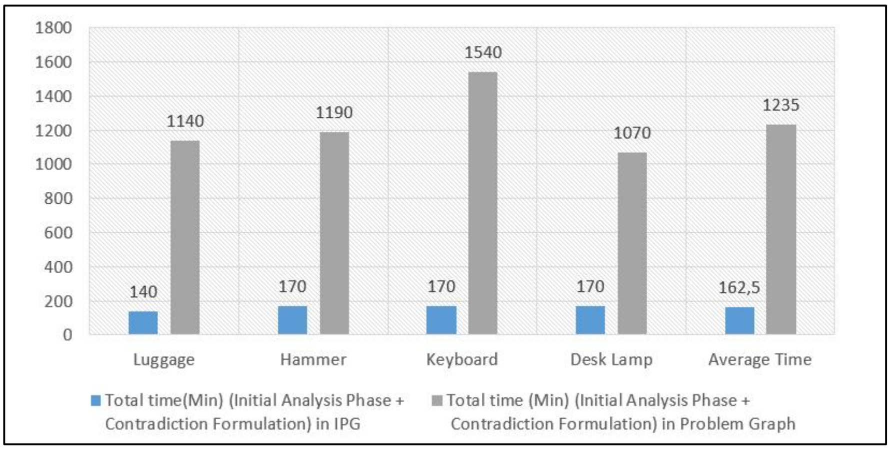


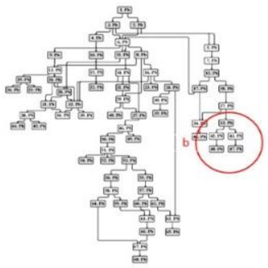
Figure 3.14. Time-based Comparison of the IPG method and Problem Graph

3.5.2. Comparison in terms of complexity

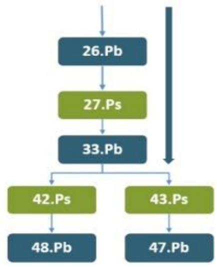
In order for the readers of this article to be more aware of the differences in terms of complexity, we also compare our proposal with the NoP method. To perform this comparison, we extracted the information from [61], as shown in Figure 3.15 and Table 3.3, in which the authors applied NoP to the 'Biomass Power Plant' case study. Indeed, Table 3.3 and Figure 3.15 (a) & (b) show that the designers have to collect all problems and partial solutions to arrive at a problem at the lower level of a problem situation by applying NoP. For instance, as shown in the table, the designers collected about sixty problems and partial solutions to illustrate contradictions related to problem sixty-eight. Likewise, for the contradiction related to problem forty-eight, they collected about forty problems. From the Inverse Problem Graph, this shortcoming was addressed by providing the possibility of starting directly from a lower level of a problem situation, as illustrated in Figure 3.15 (c). Figure 3.15 (d) shows the number of constructed elements, including problems and partial solutions, by applying the IPG and NoP methods.

Table 3.3: List of problems related to NoP in Figure 3.16, extracted from [61]

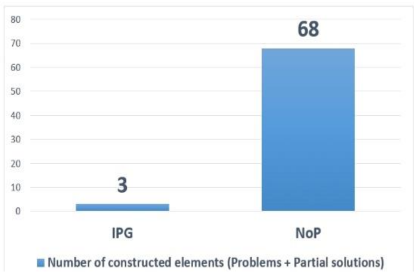
Pb or PS ref.	Description of Problem (Pb) or Partial Solution (PS)	Pb or PS ref.	Description of Problem (Pb) or Partial Solution (PS)
1.Pb	Biomass power plant should be improved.	**33.Pb**	In order to accumulate more heat, the bed material should stay longer in the combustion chamber.
…	…	**…**	…
5.Ps	Produces clean biogas.	**42.Pb**	Decrease speed of movement of the bed material in the combustion chamber.
…	…	**…**	…
8.Pb	How can one eliminate tar vapour from the biogas?	**48.Pb**	At a low speed, the bed material will not go through the combustion chamber and transport the heat energy to a gasification chamber.
…	…	**68.Pb**	High temperature, high speed of flue gases destroy the post combustion chamber at the turn point.



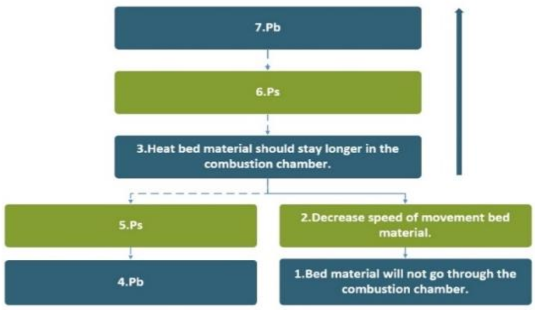
(a) NoP of the biomass power plant



(b) One of the developed chains of biomass power Plant



(d) Number of constructed elements by applying IPG and NoP



(c) IPG and the direction of the movement to find the causes of the initial problem

Figure 3.15. Network of Problem and its difference with the Inverse Problem Graph [61]

3.6. Conclusion and contribution of the chapter

In this chapter, we developed a Lean-based method to formulate a problem situation during the initial analysis phase of systematic innovation processes such as IDM. To develop this method, we first analyzed existing methods that assist designers in the formulation of problems upstream of innovation projects. Among the elements analyzed, we identified that there is one point there all share: they do not consider the time spent collecting information as well as its consequences for the productivity of the company. Accordingly, we integrated the related features of the analyzed methods, and applied Lean principles to develop a new method, called the Inverse Problem Graph. In what followed, we used the COVID-19 topic to demonstrate the ability of the IPG to formulate contradictions and suggested the solutions, proposed by other health specialists. Finally, we compared our proposal with other reviewed methods in the literature review to highlight its characteristics.

Chapter 4. Integration of FMEA and AHP to prioritize initial problems in the initial analysis phase of inventive design

4.1. Inverse Problem Graph's drawback in prioritizing the initial problems

In the previous chapter, we proposed Inverse Problem Graph (IPG) to formulate a complex problem. IPG could help to improve the agility of the inventive design process. However, it cannot show the way to prioritize the initial problems to start a project. Hence, to select the most important initial problem, it is necessary to integrate the Inverse Problem Graph method with the approaches such as the Failure Mode and Effect Analysis (FMEA) and Analytic Hierarchy Process (AHP) methods.

4.1.1. Integration of FMEA and AHP into the Inverse Problem Graph to prioritize the initial problems

FMEA is an engineering technique widely applied to improve a system by identifying and eliminating potential failures [15]. The original version of this technique uses the Risk Priority Number (RPN) method to prioritize the identified failures [90]. However, the RPN method has been criticized in the literature due to some drawbacks [91]. Therefore, many authors proposed to integrate the FMEA approach with alternative methods such as Analytical Hierarchy Process (AHP) [16]. AHP is a mathematical method to prioritize a given set of alternatives by considering the decision criteria [92]. Since AHP's introduction, this method has been applied to many types of decision problems, such as the justification of new manufacturing technology or the evaluation of strategic alternatives [93]. This chapter aims is to integrate the FMEA, AHP methods into the Inverse Problem Graph process. In this integration, FMEA helps to identify the initial problems, and AHP contributes to prioritize them.

4.1.2. Contribution

The main contribution of the chapter is to introduce a methodology to formulate the most important contradiction in each iteration of initial analysis of inventive design.

4.1.3. Chapter structure

The remainder of the paper is organized as follows. In Section 2, we present a review of the FMEA method and its integration to improve TRIZ, and a description of the AHP method. Then, Section 3 shows the structure of the proposal and its application in the Biomass Power Plant case study. In Section 4, we present a comparison between our proposal and the classical method. Subsequently, Section 5 reports the conclusion of the chapter.

4.2. Literature review

4.2.1. FMEA method and its integration to improve TRIZ-based process

Failure Mode and Effect Analysis (FMEA) is a methodology widely applied to identify, prioritize critical failures in a system [94]. FMEA was first developed by the National Aeronautics and Space Administration (NASA) in 1960 [91]. Since its introduction, FMEA has been applied in various fields such as chemical, aerospace, automobile, marine, nuclear industries [15].

Several authors proposed to integrate FMEA and TRIZ. Among these integrations, Russo et al. [95] developed a tool by combining FMEA, TRIZ function analysis, and AFD. This combination helped to identify the possible failure modes of the carne through several questions. Besides, Regazzoni et al. integrated FMEA with the tools such as TRIZ functions analysis and Su-Fields models. In this integration, TRIZ function analysis firstly contributes to identifying the primary functions of the technical system. Then, all the potential failure modes are identified by applying FMEA. In the end, the substance-field model and TRIZ standard solutions help to search for the solutions. This integration aimed to reduce failure occurrence by increasing the capability of anticipating problems and technical solutions [96]. Moreover, Mzougui et al. proposed to integrate the advantages of the TRIZ Anticipatory Failure Determination (AFD) method into FMEA. The objective of this integration was to improve the process of identification of failures [97]. Besides, Spreafico et al. proposed to empower the FMEA through the integration of function analysis, Film Maker, perturbed functional analysis, and subversion analysis [98]. But closest to our research, Hakim et al. proposed to apply FMEA to prioritize the output contradictions of Network of Problem (NoP) [99]. This application can reduce the number of contradictions to solve in the following phases of inventive design. Furthermore, it can help the designers to concentrate on the problems with a higher degree of importance. However, this proposal cannot help to decrease the number of formulated contradictions in the initial analysis phase of inventive design.

The traditional FMEA approach prioritizes the failures utilizing the Risk Priority Number (RPN), which is calculated by multiplying the scores of risk factors, namely, detection (D), severity (S), and occurrence (O) as Equation 1. Shows [100].

$$RPN = S \times O \times D \tag{1}$$

The classical RPN formula is straightforward and very simple to understand [101]. However, the RPN considers only three factors to prioritize the failures, which may neglect other important factors such as time, cost, urgency, etc. [97]. Besides, it does not take into consideration the possible weights for the importance of its risk factors [16]. To overcome the mentioned limitations, several studies in the literature have developed various models [16]. The analytic hierarchy process (AHP) is one of these models.

4.2.2. Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is an approach that was developed to support multi-criteria decision-making [102]. Satty introduced this approach to determine a ranking of the choices when all the decision criteria are considered [103]. The process of the AHP method consists of the following steps [104]:

(1) In the first step of the AHP process, a hierarchical structure is established [105]. To do so, AHP decomposes a complex decision problem into a hierarchy of interrelated decision alternatives and criteria [104]. This hierarchy includes at least three levels: the decision alternatives at the bottom, the criteria in the middle of the structure, and the objective located at the top-level [102].
(2) The second step is to construct the pairwise comparison matrix to indicate the importance of criteria and alternatives [106]. The construction of this matrix is performed according to a numerical rating including nine rank scales, as Table 1 shows [104].
(3) In the third step, the pairwise matrices should be normalized to calculate the priority weight of alternatives and criteria [106].

(4) The fourth step of AHP is defined to check the consistency of the pairwise matrices output[104]. To do so, the consistency index (CI) is firstly determined by applying the following equation [106]:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

Where λ_{max} is the principal Eigenvalue, and n is the number of compared elements in the comparison matrix.

Then, the consistency ratio (CR) is obtained as the ratio of the CI and the random index (RI), as equation 3 shows [105]. This ratio is used to check the consistency of the comparison matrix.

$$CR = \frac{CI}{RI} \quad (3)$$

The acceptable value of this ratio must be less than 0.1. Otherwise, the construction matrix process and its evaluation has to be repeated [107].

AHP can consider a large number of qualitative and quantitative criteria to prioritize the failure modes [103]. Furthermore, it has ability to address the relative importance of the risk factors [90]. For these reasons, we choose it to prioritize the initial problem.

4.3. Proposal method: Integration of (FMEA-AHP) into Inverse Problem Graph

This proposed methodology consists of three phases for constructing the most important contradiction in the first iteration of inverse problem graph. Figure 4.1 illustrates these phases. These phases were developed by inspiring from the main process of the FMEA method. As at the beginning of the FMEA process, it is necessary to identify the potential failure modes, we proposed to determine the initial problems instead of the failure modes in the first phase of our proposal. In this phase, we should also determine the objective and criteria of the project. According to the FMEA process, RPN is used to prioritize the identified failure modes. By considering the drawbacks related to RPN, mentioned in the literature review, we proposed to use AHP to prioritize the initial problems in the second phase. The FMEA process also requests to identify the causes of the failure mode, but without introducing a specific tool to perform this identification. In our proposal, we apply the Inverse Problem Graph (IPG) to identify the causes and the contradictions in the third phase.

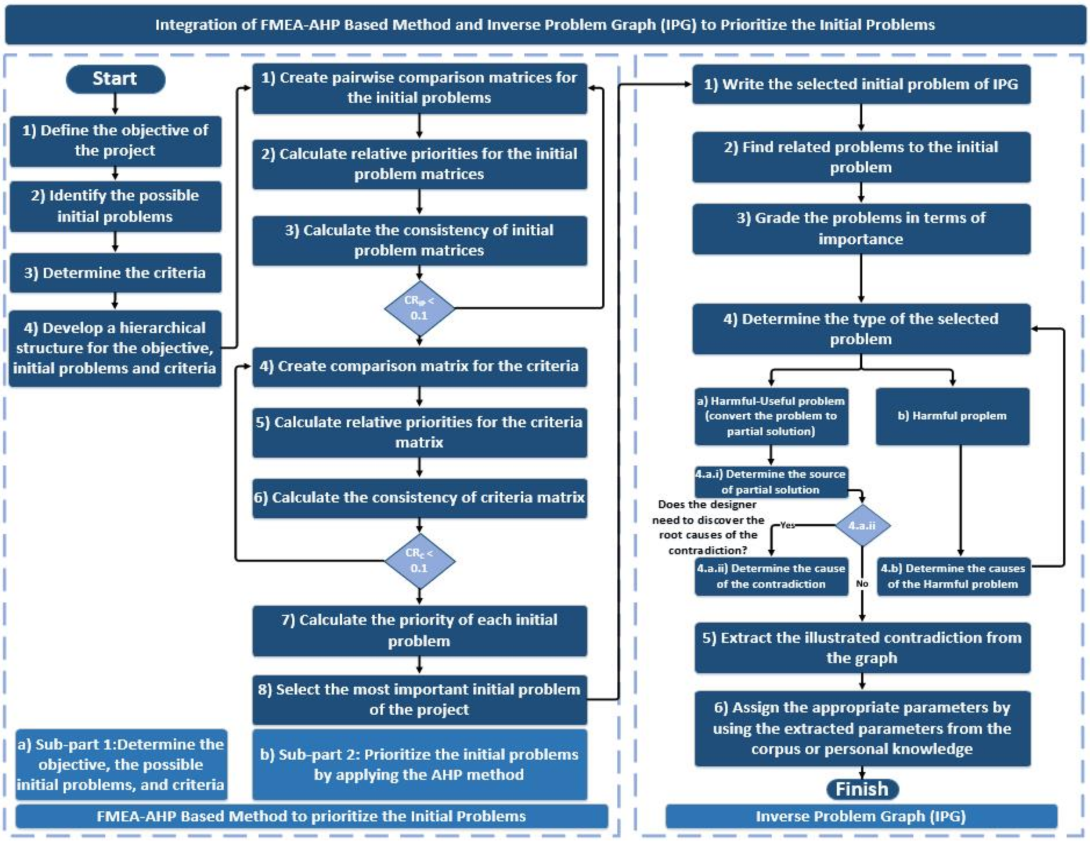


Figure 4.1. The different phases of FMEA-AHP based method (Annex B)

In the first phase, FMEA is used to determine the initial problems and the criteria used to evaluate them. This phase begins with the definition of the objective of the project. Then, the initial problems are identified as the failure modes in FMEA. Subsequently, the criteria are determined as the risk factors of the FMEA method. The previous step allows to develop a hierarchical structure at the end of this phase, as shown in Figure 4.2.

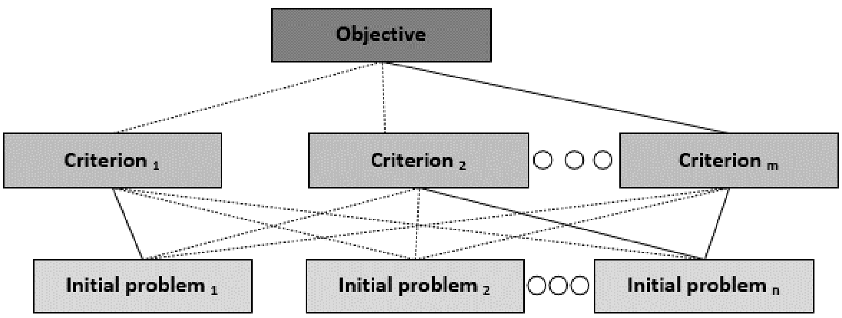


Figure 4.2. A three-level hierarchical structure for the objective, criterion, and the initial problems

The second phase is defined to prioritize the initial problems by applying the AHP method. This phase consists of the following steps:

Step 1: Create pairwise comparison matrices for the initial problems: The first step of this phase relates to creating the pairwise comparison matrices of the initial problems by considering all criteria. In this step, it is possible to use a numerical rating including nine rank scales, as Table 4.1 shows. Let A represents (n x n) pairwise contradictions matrix related to the initial problems.

Table 4.1: The 1-9 scales for pairwise comparison in AHP

Importance intensity	Definition
1	Equal importance
3	Moderate importance of one over another
5	Strong importance of one over another
7	Very strong importance of one over another
9	Extreme importance of one over another
2,4,6,8	Intermediate values
Reciprocals	Reciprocals for inverse comparison

$$A = (a_{ij})_{nxn} = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} = \frac{1}{a_{12}} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} = \frac{1}{a_{1n}} & a_{n2} = \frac{1}{a_{2n}} & \dots & 1 \end{bmatrix} \qquad (4)$$

Step 2: Calculate relative priorities for the initial problem matrices: In this step, the priorities related to each initial problem in the matrices should be calculated. For this purpose, each set of column values is summed. Subsequently, each value of the matrices is divided by the sum of its column. Finally, the average of row values is calculated to obtain the priorities of the matrices.

Step 3: Calculate the consistency of initial problem matrices: In the third step, it is necessary to check the consistency of the pairwise matrices related to the initial problems. This step includes the following sub steps:

Sub-step 1: Calculate the principal Eigen value (λ_{max}): In this sub-step, the principal Eigen value should be calculated.

Sub-step 2: Calculate the consistency index (CI_{IP}): In this sub-step, the consistency index is determined through the following equation:

$$CI_{IP} = \frac{\lambda_{max} - n}{n - 1} \qquad (5)$$

Sub-step 3: Calculate the consistency ratio(CR_{IP}): In the final sub-step of step 3, the consistency ratio is calculated as the ratio of CI_{IP} and the random index (RI), as the following equation shows:

$$CR_{IP} = \frac{CI_{IP}}{RI} \qquad (6)$$

If the consistency ratio is less than the threshold of 0.1, the pairwise comparison matrix has an acceptable consistency; otherwise, the process of constructing the matrix should be repeated.

Step 4: Create comparison matrix for the criteria: This step relates to creating the comparison matrix for the determined criteria in the first phase with respect to the objective of the project. Let B represents m x m pairwise contradiction matrix related to the criteria.

$$B = \left(b_{ij}\right)_{mxm} = \begin{bmatrix} 1 & b_{12} & \dots & b_{1m} \\ b_{21} = \frac{1}{b_{12}} & 1 & \dots & b_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ b_{m1} = \frac{1}{b_{1m}} & b_{m2} = \frac{1}{b_{2m}} & \dots & 1 \end{bmatrix} \qquad (7)$$

Step 5: Calculate relative priorities for the criteria matrix: In this step, the priorities related to each criterion in the matrix should be calculated.

Step 6: Calculate the consistency of criteria matrix: In the sixth step, it is necessary to check the consistency of the pairwise matrix related to the criteria. This step consists of the following sub steps:

Sub-step 1: Calculate the principal Eigen value (λ_{max}): In this sub-step, the principal Eigen value should be calculated.

Sub-step 2: Calculate the consistency index (CI_C): In this sub-step, the consistency index is determined through the following equation:

$$CI_C = \frac{\lambda_{max} - n}{n - 1} \qquad (8)$$

Sub-step 3: Calculate the consistency ratio (CR_C): In the final sub-step of step 3, the consistency ratio is calculated as the ratio of CI_C and the random index (RI), as the following equation shows:

$$CR_C = \frac{CI_C}{RI} \qquad (9)$$

If the consistency ratio is less than the threshold of 0.1, the pairwise comparison matrix has an acceptable consistency; otherwise, the process of constructing the matrix should be repeated.

Step 7: Calculate the priority of each initial problem: In this step, the priorities of the initial problems with respect to the objective of the project should be calculated.

Step 8: Select the most important initial problem of the project: In the last step of the second, the most important initial problem by considering the calculated priorities should be selected.

After prioritizing the initial problems, it is time to identify the contradictions in the third phase through the application of IPG. As explain in the Chapter 3, at the beginning of this phase, it is time to write the selected initial problem on the graph. Then, all the problems related to the selected initial problem are determined. For this purpose, it is necessary to question "What in the selected level causes the initial problem?". In the third step, the problems are ranked to select the most important one among determined ones. The fourth step of this phase relates to determining the type of the chosen problem. If the problem was a Harmful-Useful one, it is necessary to convert it to a partial solution and identify its related causes. Otherwise, its chain should be continued to obtain a Harmful-Useful problem. Subsequently, the contradiction of the most important problem should be extracted in the fifth step of the phase. Finally, the appropriate parameters are allocated to the problems and partial solutions of the extracted contradiction.

4.4. Application of the proposal method into "Biomass Power Plant" case study

In this section, we applied the proposed method "FMEA-AHP based method" to the

Biomass Power Plant case study to evaluate its applicability. It is worth noticing that this subject has been extracted from [62] to illustrate the application of the proposal. Renewable energy sources have quickly become a high priority for many countries due to their lack of environmental impact [108]. Biomass is one of the principal renewable resources that can provide clean energy to improve energy security, the economy, and the environment [109]. The source of biomass is organic materials comprised of wood wastes, agriculture residue, crops, and animal wastes [110]. There are many ways to convert the chemical energy stored in these organic materials into beneficial energy forms [111]. Among these ways, it is possible to mention biomass power plant that converts biomass renewable energy to electricity [112]. In this case study, we formulate the contradiction related to the biomass power plant by considering the priority of initial problems. For this purpose, we first prioritize the initial problems through the first and second phases of the proposal. We then apply Inverse Problem Graph as the last phase of the proposed method to construct the contradiction. In the following, we explain the application of our proposal to this case study.

In the first phase of the process, the designer should define the objective at the beginning of the project. In our case study, the "Improvement of Biomass Power Plant" was selected as the objective. Then, we determined "IP_1: Constant supply of powder increases the costs of power plant.", "IP_2: The efficiency of power plant has been reduced.", and "IP_3: Cleaning operation is expensive." as the three existing initial problems in this case study. In the following, we determined "C_1: Financial", "C_2: Strategic", and "C_3: Urgency" as three criteria of the "Biomass Power Plant" case study. In the end of this phase, the hierarchical structure of the objective, initial problems, and criteria was developed in the first step of the second phase. As Figure 4.3 shows, there are three levels in this structure to prioritize the initial problems. The determined objective of the project is in the first level. The criteria and the initial problems are located respectively on the second and third levels of hierarchy.

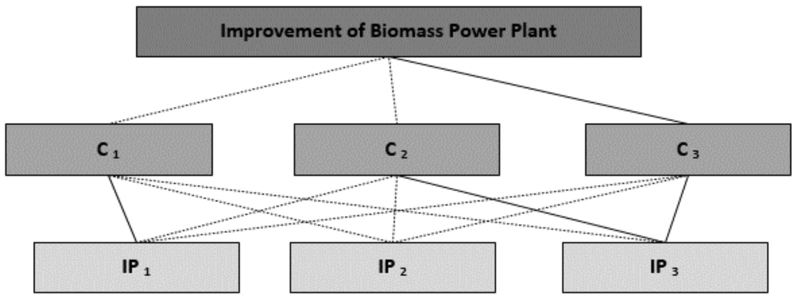


Figure 4.3. The hierarchical structure for the Biomass Power Plant case study

After forming the hierarchical structure of the biomass power plant, the initial problems were prioritized by considering the criteria through the steps of the second phase. To do so, we firstly constructed the pairwise matrices according to the criteria of the project. Then, the priority related to each initial problem based on the criterion of its matrix was calculated. In the following, we checked the consistency of the pairwise matrices. For instance, as shown in Table 4.2, we firstly created pairwise matrix (reciprocal matrix) for the defined initial problems with respect to the criterion "C1: Financial". To construct this matrix, we applied the scale given in Table 4.1.

Table 4.2: Reciprocal matrix for the defined initial problems with respect to the criterion Financial.

C 1: Financial	IP1: Constant supply of powder increases the costs of power plant.	IP 2: The efficiency of power plant has been reduced.	IP 3: Cleaning operation is expensive.
IP1: Constant supply of powder increases the costs of power plant.	1	$\frac{1}{3}$	5
IP 2: The efficiency of power plant has been reduced.	3	1	7
IP 3: Cleaning operation is expensive.	$\frac{1}{5}$	$\frac{1}{7}$	1

Once the pairwise matrix of the initial problems based on the financial criterion was created, we converted the fractional values to the decimal values. Then, we normalized the matrix. To this end, we divided each element of the matrix by the sum of its column. Table 4.3 displays the normalized matrix of the initial problems related to the first criterion.

Table 4.3: Normalized matrix of the initial problems related to the criterion "Financial"

C 1: Financial	IP1: Constant supply of powder increases the costs of power plant.	IP 2: The efficiency of power plant has been reduced.	IP 3: Cleaning operation is expensive.
IP1: Constant supply of powder increases the costs of power plant.	0.238	0.224	0.384
IP 2: The efficiency of power plant has been reduced.	0.714	0.680	0.538
IP 3: Cleaning operation is expensive.	0.047	0.095	0.076

After constructing the normalized matrix, we calculated the average value of the all the elements existing in each row of the matrix, as Table 4.4 illustrates.

Table 4.4: Calculation of the priorities of each initial problem with respect to the first criteria

C 1: Financial	IP1: Constant supply of powder increases the costs of power plant.	IP 2: The efficiency of power plant has been reduced.	IP 3: Cleaning operation is expensive.	Priorities
IP1: Constant supply of powder increases the costs of power plant.	0.238	0.224	0.384	0.282
IP 2: The efficiency of power plant has been reduced.	0.714	0.680	0.538	0.643
IP 3: Cleaning operation is expensive.	0.047	0.095	0.076	0.073

Subsequently, we needed to calculate the consistency of the matrix to check if the calculated values are correct or not. To do so, we calculated the principal Eigen value (λ_{max}=3.11) related to the created matrix. Then, the Consistency Index ($CI_{IP} = \frac{\lambda_{max}-3}{3-1} = 0.055$) was obtained. Finally, we calculated the Consistency Ratio ($CR_{IP} = \frac{CI_{IP}}{RI} = 0.095$) of the matrix, which was less than 0.1. Hence, we accepted the created pairwise matrix. Table 4.5 shows the final matrix of the initial problems related to the first criterion.

Table 4.5: Pairwise matrix for the initial problems by considering criterion C1

C 1	IP1	IP 2	IP 3	Priority
IP 1	0.238	0.224	0.384	0.282
IP 2	0.714	0.680	0.538	0.643
IP 3	0.047	0.095	0.076	0.073
Consistency	**λmax= 3.11, CI = 0.055, CR = 0.095 < 0.1 (Acceptable)**			

Likewise, we constructed the pairwise matrices of the initial problems related to the other defined criteria of the “Biomass Power Plant” case study. Table 4.6 and 4.7 show these matrices.

Table 4.6: Pairwise matrix for the initial problems by considering criterion C2

C 2	IP1	IP 2	IP 3	Priority
IP 1	0.19	0.183	0.285	0.219
IP 2	0.761	0.734	0.642	0.713
IP 3	0.047	0.081	0.071	0.066
Consistency	**λmax= 3.06, CI = 0.03, CR = 0.053 < 0.1 (Acceptable)**			

Table 4.7: Pairwise matrix for the initial problems by considering criterion C3

C 3	IP1	IP 2	IP 3	Priority
IP 1	0.157	0.272	0.148	0.192
IP 2	0.052	0.090	0.106	0.080
IP 3	0.789	0.636	0.744	0.721
Consistency	**λmax= 3.11, CI = 0.055, CR = 0.095 < 0.1 (Acceptable)**			

After constructing the pairwise matrix of the initial problems, it was also essential to evaluate criteria of the project by forming their related matrix. Hence, we firstly assigned weights to the criteria by applying the scale given in Table 4.1. Then, we calculated the relative priorities and the consistency of the matrix. Table 4.8 shows the pairwise matrix related to the criteria.

Table 4.8: Pairwise matrix for the defined criteria of the case study

Criteria	C 1	C 2	C 3	Priority
C 1	0.652	0.692	0.555	0.633
C 2	0.217	0.230	0.333	0.260
C 3	0.130	0.076	0.111	0.106
Consistency	**λmax= 3.06, CI = 0.034, CR = 0.059 < 0.1 (Acceptable)**			

At the end of the second phase of the process, the overall priority of each initial problem with respect the objective of the project was computed. To do so, we summed the products of the criterion priority times the priority of its initial problem. For example, the overall priority of the first initial problem was calculated: $((0.282 \times 0.633) + (0.219 \times 0.26) + (0.192 \times 0.106)) = 0.255$. Figure 4.4 shows a graphical representation of the criteria and initial problems priorities. Further, Table 4.9 demonstrates the overall priorities relate to the initial problems of the case study with respect to the objective of the project. Accordingly, we selected "IP_2: The efficiency of power plant has been reduced." as the most important initial problem.

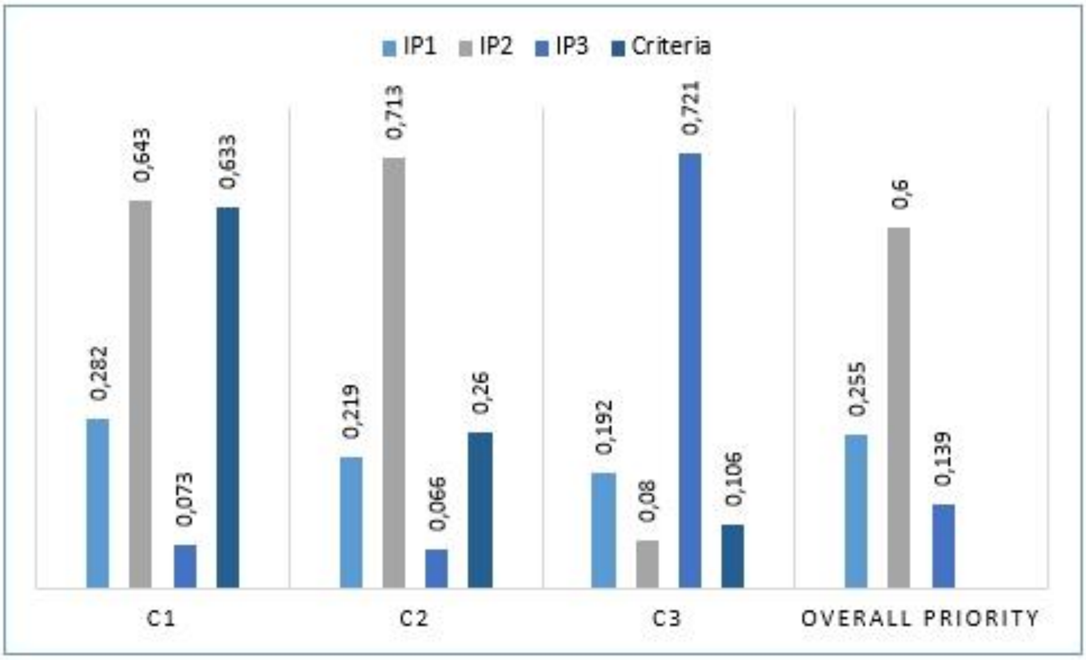


Figure 4.4. Graphical representation of the priorities related to the initial problems and criteria

Table 4.9: Prioritization of the initial problems with respect to the objective

Initial problems	C 1	C 2	C 3	Overall priority	Priority
IP1	0.178	0.056	0.020	0.255	2
IP 2	0.407	0.185	0.008	0.600	1
IP 3	0.046	0.017	0.076	0.139	3

In the third phase, we determined the causes of the selected initial problem by applying Inverse Problem Graph. Accordingly, we identified "Heat exchanger is used" and "Biogas is burnt" as causes that reduce the efficiency of the power plant. Figure 4.5 shows these causes.Then, we graded the identified causes, and as shown in the figure, we selected the "Heat exchager is used" as the most important cause that has an impact on the initial problem.

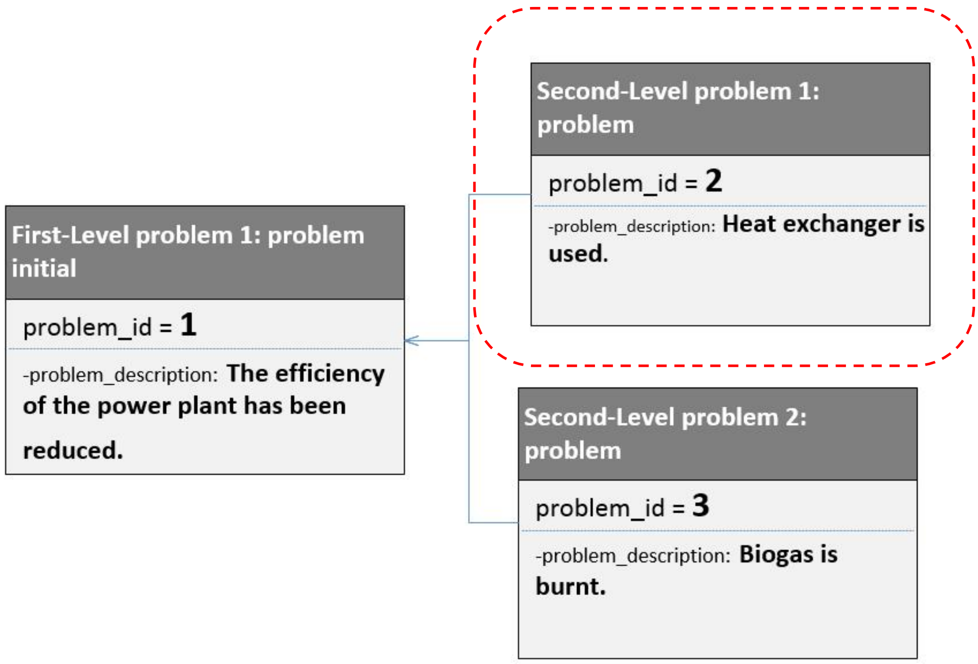


Figure 4.5. The identified causes of the initial problem and select the most important cause

In what follows, we determined the type of the selected cause, which was a Harmful-Useful problem. Therefore, we converted it to the partial solution "To use heat exchanger". This means that we converted its structure to the structure of the partial solution, as Figure 4.6 shows.

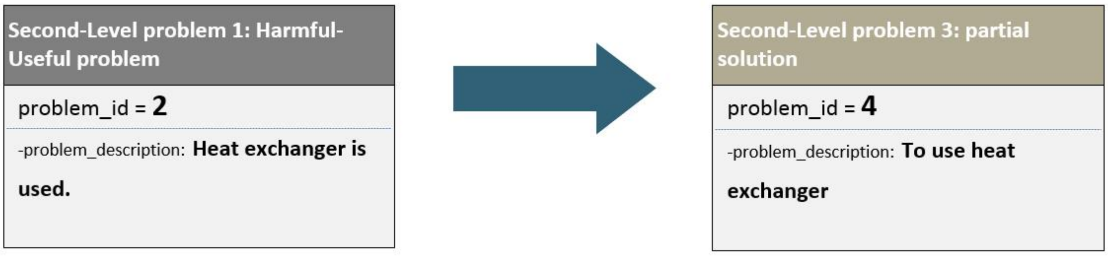


Figure 4.6. Conversion of the Harmful-Useful problem to the partial solution

Subsequently, we identified the problem "Biogas should be cooled" as the cause of the partial solution. Then, we constructed the Inverse Problem Graph of the first iteration, as Figure 4.7 shows.

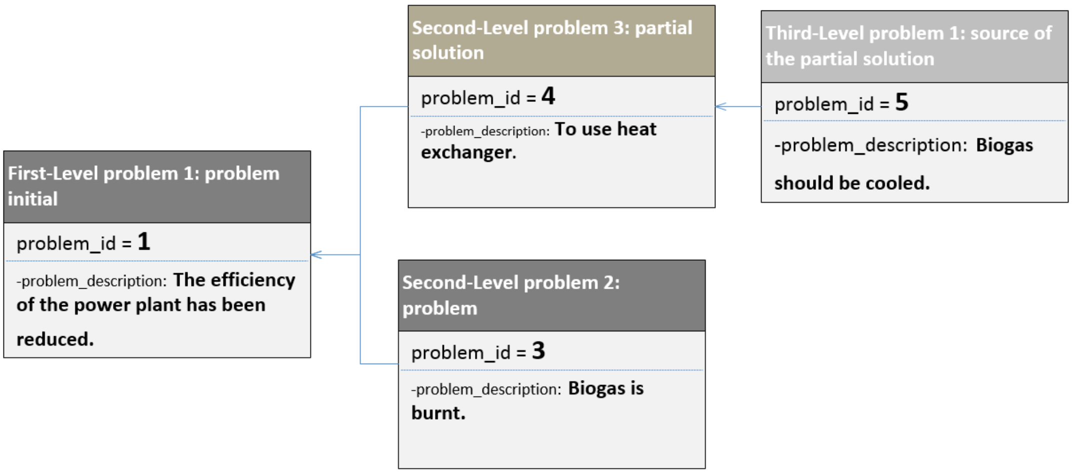


Figure 4.7. The inverse problem graph related to the selected initial problem

In the following, we extracted the illustrated contradiction from the graph, as shown in Figure 4.8. In this figure, there is a contradiction between cooling of the biogas and the efficiency of the power plant. This means that to cool the biogas in the system, it is essential to apply heat exchanger. This application results in reducing the efficiency of the power plant.

Subsequently, we should allocate the parameters to the problems and partial solution of the extracted contradiction. As shown in Figure 4.8, we assigned "Efficiency of power plant" as the evaluation parameter to the problem "The efficiency of power plant has been reduced". The second evaluation parameter "Cooling the biogas" was allocated to the cause of the partial solution, which is "Biogas should be cooled". We assigned also "Presence of heat exchanger" as an action parameter to the partial solution.

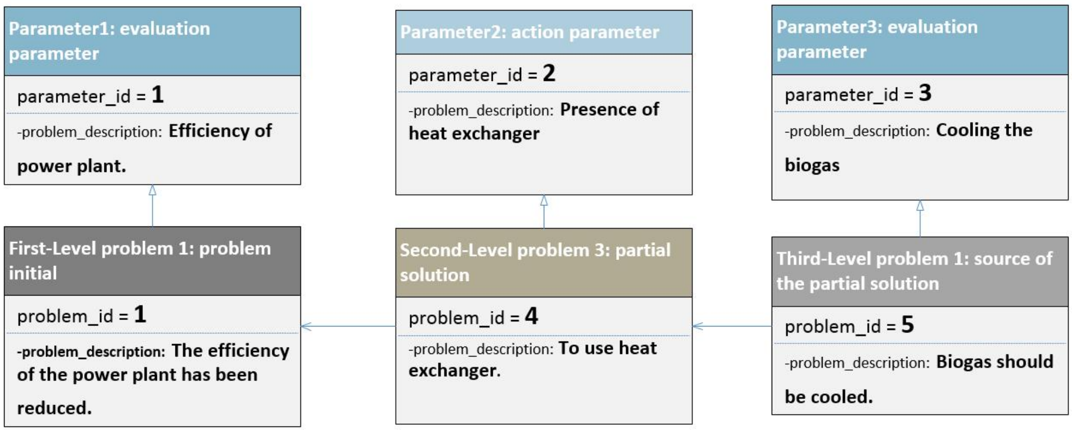


Figure 4.8. The allocation of the parameters to the extracted contradiction

Finally, the TRIZ parameters were interpreted from the allocated parameters in the previous step of the process. We applied these parameters to construct the poly-contradiction template of the case study, as Figure 4.9 illustrates.

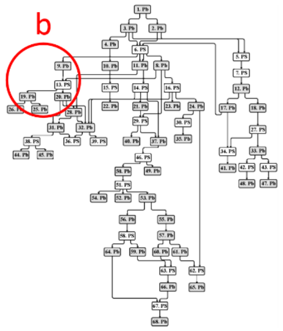
	Presence of heat exchanger	
	No	**Yes**
Productivity of the system (efficiency of power plant)	☺	☹
Temperature (cooling the biogas)	☹	☺
Temperature: The thermal condition of the object or system.		
Productivity: The output per unit time, or the cost per unit output.		

Figure 4.9. The poly-contradiction of the Biomass Power Plant case study

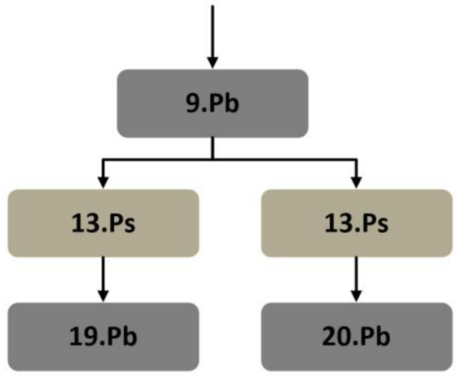
The TRIZ parameters are used in the next phases as inputs to extract the inventive principles from TRIZ contradiction matrix. We used then the principles to develop our inventive solutions.

4.5. Comparison of the proposal with Network of Problems (NoP)

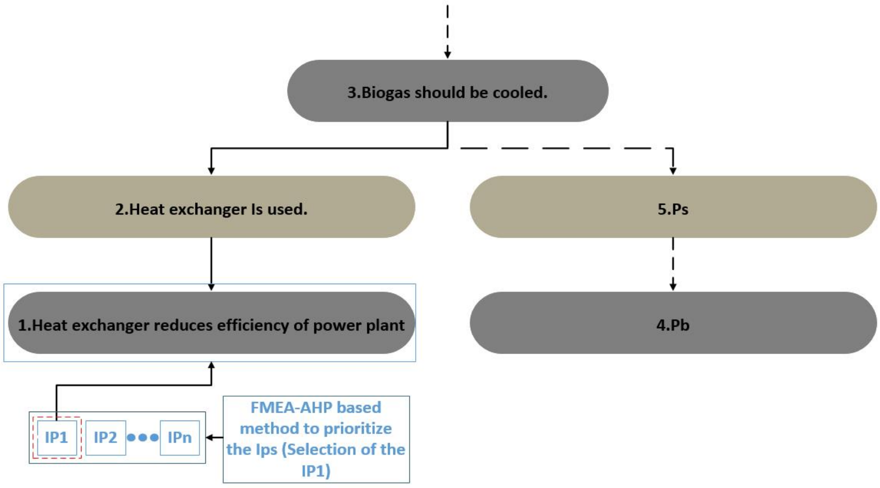
In order for the readers of this research work to be more aware of the differences of our proposal and the classical method (NoP), we compared them in this section. To perform this comparison, we used the collected information from [62], as shown in Table 7 & Figure 4.10 (a) & (b). The figures and table display that designers formulated all the problems and partial solutions related to the "Biomass Power Plant" subject without considering their priorities. As illustrated in Figure 4.10 (c), this drawback has been solved in the IPG method by integrating the FMEA-AHP based method, providing the possibility to prioritize the initial problems.



(a) NoP related to the biomass power plant



(b) One of the constructed chains in NoP of biomass power plant



(c) Integration of IPG and FMEA-AHP based method

Figure 4.10. Network of Problem and its difference with the proposal [61]

4.6. Conclusion and contribution of the chapter

In this study, we proposed a method to integrate FMEA and AHP into Inverse Problem Graph to prioritize the initial problems in the initial analysis phase of inventive design. To develop our proposal, we analyzed firstly the studies in the literature about the failure mode and effect method to highlight its shortcomings and advantages. Accordingly, we reviewed several articles on the Analytical Hierarchy Process. Finally, we proposed a combination of FMEA, AHP methods to prioritize the initial problems in the Inverse Problem Graph method. We then tested the ability of the proposal by its application in the Biomass Power Plant case study. The analysis of this practical application demonstrated the usability and usefulness of our proposal.

Chapter 5. Automatic extraction of essential information (parameters and concepts) in inventive design by applying document embedding, machine learning, and similarity

5.1. Introduction

5.1.1. Inverse Problem Graph and its drawback in gathering essential data

In Chapter 3 of this thesis, we introduced the Inverse Problem Graph (IPG) method to formulate a problem situation during the initial analysis phase of Inventive Design Methodology (IDM). IPG adds to IDM the characteristics of the agile methodologies [10], which are an evolutionary and iterative development, flexible and rapid response to change, enhancement of communication, and adaptive planning. Consequently, it could significantly increase the agility of this systematic TRIZ-based approach. Nevertheless, the gathering of essential data (parameters and solution concepts) within the IDM framework is still done manually. Therefore, we experiment the integration of an automatic information retrieval technique, such as the neural network doc2vec model and machine learning algorithms, into the process to increase its performance.

5.1.2. Inverse Problem Graph and its drawback in collection of the essential data

Doc2vec model is proposed by Le et al. in [17] (paragraph vectors) as a document embedding method in 2014. This model is applicable in text classification and document similarity calculation [113]. Text classification is known as the task of classifying a given text into a set of pre-defined classes [114]. To perform this, it is possible to apply machine learning algorithms [115]. The main goal of this chapter is to integrate the doc2vec model and machine learning algorithms into the inventive design process to extract the essential data such as the parameters and solution concepts.

5.1.3. Contribution

The main contribution of this chapter is to propose a method that facilitates and accelerates the gathering of essential and pertinent data, including parameters and solution concepts, in the inventive design process.

5.1.4. Chapter structure

The remaining part of the chapter is organized as follows. In Section 2, we present the literature relating to the IDM framework, a review of several document-embedding techniques, a method for measuring the similarity, and a description of several machine learning text classification algorithms. Then, we evaluate several machine learning algorithms in Section 3. Section 4 displays the structure of the proposed method and describes the steps of this proposal. In Section 5, a case study is presented in which the proposal is used to formulate the inventive problems related to the lattice structures and extract the solution concepts. In Section 6, we make a comparison between our proposal and another automatic technique applied in IDM. In the last section, we report the conclusion of the chapter.

5.2. Literature review

5.2.1. Automatic extraction methods related to the first phase of IDM

Generally, it is possible to divide the automatic extraction methods, applied in the initial phase of IDM, into two main groups:

- Automatic methods to extract information from patents
- Automatic methods to extract information from scientific papers

5.2.1.1. Automatic methods to extract information from patents

Patent documents are an important repository of technical knowledge used to gain competitive advantages [116]. Nevertheless, the analysis of the patents requires a lot of human effort as they are lengthy and rich in technical terminology [117]. Moreover, manual extraction of desired innovative patents existing in a database is a time-consuming process [118]. For this reason, automatic systems for assisting engineers to access the knowledge contained in patents are in high demand. To extract relevant patent information and analyze it, researchers have proposed several patent analysis tools [117]. However, in this paper, we only discuss those that are related to the initial phase of the Inventive Design Framework.

One of the approaches, which automatically extracts the IDM concepts, such as partial solutions, problems, and parameters, to create a problem graph in the initial analysis phase of IDM, was developed by Souili et al. [74]. However, this approach inherits most of the drawbacks related to the problem graph method. One of these drawbacks is that it extracts all the problems and partial solutions from their desired patents without considering the needs of designers. Therefore, it is necessary to analyze those problems and partial solutions one by one and select among them the most appropriate one to create a problem graph. This process, once more, is time-consuming and requires a lot of human effort.

Accordingly, in [119], the authors proposed to use claims hierarchical structure and its structural information to reduce noise and improve the final output of the IDM-related information extraction tool. This proposal could only contribute to removing the repeated information from the extraction, whereas drawback results from the extraction according to the designer's needs remain in the tool. Another shortcoming that can be mentioned here concerns the inability to extract information from scientific papers.

5.2.1.2. Automatic extraction from scientific papers

Scientific papers contain potential information that their extraction could improve the quality of human life [120]. The volume of such documents in various fields is immense and constantly increasing [121]. This makes the process of studying and analyzing their content difficult and time-consuming for researchers [122]. For this reason, the need for automated systems in various scientific fields that can assist researchers in extracting this amount of data from the papers is growing.

One such field is innovation and inventive design. Consequently, Nédey et al. proposed a tool within the IDM framework to extract partial solutions, problems, and parameters from scientific news articles and scientific papers by improving the IDM patent extraction methodology [123]. However, this proposal, like its original method, extracts data beyond the designer's needs, making their analysis quite laborious, and cumbersome.

As we have seen, all the methods developed under the Inventive Design Methodology framework ignore the principal demand of designers to extract the information. This makes analyzing their results difficult and time-consuming, especially when the number of selected documents increases. This drawback mainly results from the development of IDM extraction tools based on the existing methods to formulate the problems applied in the initial analysis phase of IDM. For this reason, we apply document-embedding techniques and machine learning algorithms to the Inverse Problem Graph method. In the next section, we compare several document-embedding techniques, and we select the most suitable of them to apply to our proposal.

5.2.2. Document embedding techniques

5.2.2.1. Bag of words

The Bag of Words is a model that represents a document as a vector [124]. BOW is a simple method for assigning a document to a fixed-length vector [124]. However, the model can only calculate the number of occurrences of each word in the text. Furthermore, it ignores grammar, the order, and the meaning of the existing words in a document [125][126]. Moreover, due to the lack of integration of the linguistic meanings and semantic, the extracted information from documents is not understandable [25]. Besides, by applying BOW, increasing the number of documents results in sparse and high-dimensional representation. As a result, the model cannot effectively represent the proximity between the documents [127].

5.2.2.2. Word2vec

Word2vec is a shallow word embedding technique for creating distributional vectors, which has been proposed by Mikolov et al. [128]. This technique includes two different model architectures to create a word embedding representation [6]. These models include: 1) Continuous bag-of-words (CBOW), and 2) Skip-gram model. Word2vec allows the calculation of the semantic similarity between two words and to derive similar words semantically [129]. Nevertheless, although the word order in a text contains valuable information, this method loses this order [130]. Therefore, to overcome this drawback of word2vec, the researchers proposed a paragraph vector or doc2vec.

5.2.2.3. Doc2vec

Doc2vec is an unsupervised method for learning variable-length text, which has been proposed by Le et al [131]. Indeed, this method is an extension of word2vec that can express a sentence, paragraph, or document as a vector [132]. This extended method is applicable to document similarity calculation and document classification [113]. There are two architecture models in doc2vec: Distributed Bag of Words (PV-DBOW) and

Distributed Memory (PV-DM) [17].Doc2vec method applies to texts of different lengths, ranging from sentences to large documents [17]. Besides, this method gives the possibility to exploit the semantic information existing in a text. It can also receive higher precision term vectors by extracting the word order information in the text [130]. After obtaining the term vectors of two documents, the similarity of the terms corresponds to the correlation between their vectors. This similarity can be calculated by a method such as Cosine Similarity [133].

5.2.3. *Cosine similarity*

Cosine similarity is a method to measure the similarity between two vectors (two documents) by calculating the cosine of the angle between them [134]. Given two document vectors D & D', the cosine similarity between these vectors is calculated by the following formula [135]:

$$similarity_{D,D'} = \cos(\theta) = \frac{D \cdot D'}{\|D\|\|D'\|} = \frac{\sum_{i=1}^{n} D_i D'_i}{\sqrt{\sum_{i=1}^{n} D_i^2}\sqrt{\sum_{i=1}^{n} D'^2_i}}$$

Where θ is the angle between D and D' in the n-dimensional space, and Di and D'i are the ith components of the documents D and D' respectively. This method does not take into account the document length; as a result, it could identically treat the input data with the same elements but different lengths [136]. Furthermore, it is a popular method for finding similar documents to a given text. As a result, we integrated it into our method. To extract the type of each sentence and its related parameters, we also need the machine learning text classification algorithms. In the next section, we reviewed some of these algorithms.

5.2.4. *Text classification and machine learning algorithms*

Text classification is defined as the task of classifying a given document into a set of pre-defined classes according to the extracted features [114]. To automate text classification, there are two main types of machine learning algorithms as the following [115]:

Unsupervised learning: This group refers the machine learning algorithms that learn the underlying features from available data without providing any prelabeled training samples [137].

Supervised learning: This group includes those machine learning algorithms that learn from data samples and their associated training labels [138]. Here, we focus only on the existing algorithms in this group because our proposal uses the provided prelabeled samples to build the model. In the following, we describe some of these algorithms.

5.2.4.1. *Logistic regression*

David Cox developed the logistic regression model in 1958 [115]. Logistic regression (LR) is a supervised machine learning classification technique based on the probabilistic statistics of the data [139]. Logistic regression is classified as the following [140]:1) Binominal or binary logistic model, where the observed outcome can only take two possible types [141]. This model is applied when the dependent variable is dichotomous and the independent variables are of any type [140]. 2) Multinomial logistic regression model, where the target variable can have three or more possible types [142]. This model is employed when the dependent variable consists of more than two unordered or nominal classes [143]. Logistic regression performs well to predict categorical outputs [144].

5.2.4.2. *Multilayer perceptron*

The Multilayer Perceptron (MLP) was proposed by Rosenblatt in 1958 [145]. MLP is a feed-forward neural network that maps input data to the outputs [146]. MLP is constructed of multiple layers consisting of an input layer, an output layer, and one or more hidden layers between its input and output layers [147]. Each layer of MLP includes its nodes, which are fully connected to the nodes existing in the next layer [148]. The connections between nodes are represented through the weights [149]. In MLP, the input layer receives an external activation vector including the values {X1, X2,…, Xn} [150]. Then, the layer transfers the values via weighted connections to the nodes of the first hidden layer [151]. Subsequently, the hidden layer computes their activations and distributes them to the nodes in the succeeding layer [150]. MLP is applied in the various business and industrial domains to classify and predict problems [149].

5.2.4.3. *Random forest*

Random forest (RF) is an ensemble learning classification algorithm using bagging to build multiple decision trees [152]. This algorithm is called Random because it selects random (n) features to obtain the best split point while creating decision trees [152]. Random Forest develops several decision trees at training time [153]. To do so, each tree is constructed with a different bootstrap sample extracted from the training subset. The trees are developed to their maximum size without any pruning procedure [154]. Subsequently, the algorithm uses a random selection of the subset of features to split each node in a tree [153]. To classify new input data, the new observation is given to all classification trees in the Random Forest [152]. Then, each tree votes for one class, and the algorithm predicts the class label with the maximum number of votes for that input data [154]. Random forest is efficient in handling large datasets and feature sets [155]. Besides, it does not overfit on large datasets [153]. Additionally, it is one of the most accurate algorithms [156]. The algorithm has also a significant performance improvement compared with the single tree classifier [157].

5.2.4.4. K-Nearest Neighbour classifier

The K-Nearest Neighbor (KNN) was introduced by Cover and Hart in 1968 [158]. KNN is a conventional non-parametric machine learning algorithm applied for supervised learning tasks [159] [160]. This algorithm classifies the objects based on the nearest training samples in the feature space [161]. KNN is a lazy or instance-based learner because it only approximates the function locally, and all computation is delayed until classification [162]. To classify a test sample represented by some feature vectors, the KNN algorithm computes all the distances between the samples in the training data set and the test sample. The distance with the smallest value shows the sample in the training set that is nearest to the set sample [159]. Accordingly, the algorithm can assign the test sample to a class by considering the K training samples that are the closest neighbors to the test sample [160]. The k-nearest neighbor classification algorithm is easy to implement [163]. Besides, it works well even in handling multi-class documents [144]. However, KNN demands more time to categorize texts when there is a large number of training samples [163].

5.2.4.5. Support vector machine (SVM)

The support vector machine (SVM) was introduced by Vapnik [164]. SVM is a supervised learning algorithm that is based on Structural Risk Minimization (SRM) principle in the statistical learning theory [165]. SRM means maximizing the margin between various classes [166]. SVM constructs a hyperplane or multiple hyperplanes to separate different classes by applying a set of data vectors with known class labels acquired by a-priori knowledge [167] [168]. The principle of the support vector machine is to find the optimal classification hyperplane between data of classes in a sample space [169]. SVM is applicable on both non-linear and linear data classification tasks [167]. In the linear classification task, SVM applies linear separating hyperplane to divide the training data into two classes [166]. In the non-linear classification cases, the support vector machine maps the data onto a high dimensional feature space by applying a kernel function such as Gaussian radial basis, polynomial or linear function. In the following, the hyperplane separates the training data [165]. SVM is applied to a wide variety of classification problems, including not linearly separable and high dimensional problems [170]. This algorithm has usually the highest classification precision. Nevertheless, SVM requires more computation time [171].

5.3. Experiment and evaluation

In this section, we evaluate the accuracy of the reviewed machine learning algorithms for the “Cause, Non-cause” and “Parameters” data sets. Furthermore, we test the ability of the algorithms with the highest precision to predict the labels of several sentences.

For the first evaluation, we used our “Cause, Non-cause” data set. This data set consists of 2800 sentences, 2 labels (61.60 % Cause and 38.40% Non-cause). We perform a train-test split using the 80-20 rule where 80 % of data is used for training, and the remaining 20% is used for testing. The reviewed machine learning algorithms in the literature were trained using the training data and tested on the test set for their accuracies. For accuracy evaluation, we consider F1, recall, and precision to evaluate the overall accuracy of the machine learning algorithms. Here, precision is the percentage of the predicted sentences for a given label that are classified correctly [155]. Recall (R) is the percentage of the sentences for a given label that are classified correctly [172]. F1-Score is the weighted average of Recall and Precision [173]. Table 5.1 displays the accuracy of each machine learning algorithm related to the “Cause, Non-cause” data set.

Table 5.1: Accuracy of machine learning algorithms related to the "Cause, Non-cause" data set.

Algorithms	F1 scores	Precision scores	Recall scores
Logistic regression	84.37 %	84.95 %	84.64 %
Random forest	82.65 %	82.89 %	82.85 %
K nearest neighbor	85.28 %	85.31 %	85.35 %
Support vector machine	83.75 %	83.96 %	83.92 %
MLP	85.69 %	85.68 %	85.71 %

We apply MLP as the algorithm with the highest precision to predict the labels of 10 new sentences for the "Cause, Non-cause" data set. Table 5.2 shows the result of this application. As the table shows, there is just one error in these predictions. The algorithm predicted non-cause for the sentence N° 4, while its label should be "Cause".

Table 5.2: Results related to the application of MLP algorithm to predict the "Cause, Non-cause" labels of ten sentences

N°	Texts	Cause, Non-cause labels
1	raise the storage pressure can increase the hydrogen density but will also remarkably increase the energy consumption for compression	Cause
2	the compressive strength of CA mortar decreases with higher temperature.	Cause
3	The small increase of the cutting speed value from 30 to 35 m/min leads to an increase of temperature	Cause
4	Loss of energy in PDE due to the viscosity of the fuel is an important factor.	Non-cause
5	the diameter of the lead core is mm and the width of the rubber layer is mm	Non-cause
6	Pump scheduling [M1] can be used to control the speed of pumps.	Cause
7	the coordination of the energy storage system with the generating units can improve the energy efficiency of the system,	Cause
8	content of the absorber in the shell of the hollow sphere the volume density of the hollow sphere and the bulk density of the composite	Non-cause
9	Biodiesel can reduce carbon dioxide () emissions.	Cause
10	The thermal stability of cofibrils increased with the increase of the C4S content.	Cause

Parameters data set is used for the second evaluation of machine learning algorithms. This data set consists of 3607 sentences and 4 following groups of parameters: 1) The "Positive TRIZ Parameters" group includes 40 labels (39 TRIZ parameters labels + nan label), 2) The "Negative TRIZ Parameters" group consists of 40 labels (39 TRIZ parameters + nan label), 3) The "Positive Parameters" group has 78 labels, and 4) The group "Negative Parameter" includes 51 labels. To evaluate the reviewed machine learning algorithms by the parameters data set, we first selected 8 highest labels in each group of the parameters as the following:

1) "Positive TRIZ Parameters" group (469 sentences, Parameters: 15.77 % Strength, 14.07 % Object-generated harmful factors, 13.21 % Temperature, 12.36 % Use of energy by stationary object, 11.72 % Loss of energy, 11.30 % Speed, 10.87 % Quantity of substance, 10.66 % nan (There is not positive TRIZ parameter in the sentence), …).
2) "Negative TRIZ Parameter" group (410 sentences, Parameters: 13.90 % Strength, 13.41 % Loss of energy, 12.92 % Temperature, 12.68 % Loss of substance, 12.43 % Reliability, 11.95 % Use of energy by stationary object, 11.46 % Object-generated harmful factors, 11.21 % nan (There is not negative TRIZ parameter in the sentence),…).
3) "Positive Parameters" group (327 sentences, Parameters: 13.76 % Weight, 13.45 % Energy consumption, 13.14 % Energy efficiency, 12.84 % Thermal conductivity, 12.53 % CO_2 emission, 11.92 % Density, 11.62 % Thermal stability, 10.70 %, nan (There is not a positive parameter in the sentence) , …).
4) "Negative Parameters" group (230 sentences, Parameters: 7.80 % Energy consumption, 7.80 % Temperature, 7.80 % Loss of energy, 7.56 % Compressive strength, 7.56 % Weight, 5.85 % Energy dissipation, 5.85 % Material loss, 5.85 % nan (There is not a negative parameter in the sentence),…).

Then, we perform a train-test split using the 80-20 rule, where 80 % of data is used for training, and the remaining 20% is used for testing. In what followed, the reviewed machine learning algorithms in the literature were trained using the training data and tested on the test set for their accuracies. Tables 5.3, 5.4, 5.5, and 5.6 show the accuracy for each machine learning algorithm related to the parameter dataset.

Table 5.3: Evaluation of machine learning algorithms for the "Positive TRIZ Parameter" group

Algorithms	F1 scores	Precision scores	Recall scores
Logistic regression	83.35 %	85.24 %	83.67 %
Random forest	78.57 %	81.42 %	79.59 %
K nearest neighbor	91.81 %	**92.12 %**	91.83 %
Support vector machine	80.50 %	85.84 %	81.63 %
MLP	78.62 %	81.79 %	79.59 %

Table 5.4: Evaluation of machine learning algorithms for the "Negative TRIZ Parameter" group

Algorithms	F1 scores	Precision scores	Recall scores
Logistic regression	80.60 %	84.09 %	80 %
Random forest	87.83 %	**89.77 %**	88 %
K nearest neighbor	84.66 %	88 %	84 %
Support vector machine	84.27 %	86.66 %	84 %
MLP	80.66 %	83.42 %	80 %

Table 5.5: Evaluation of machine learning algorithms for the "Positive Parameter" group

Algorithms	F1 scores	Precision scores	Recall scores
Logistic regression	86.36 %	87.09 %	87.10 %
Random forest	81.38 %	83.22 %	80.64 %
K nearest neighbor	76.64 %	81.52 %	77.41 %
Support vector machine	83.93 %	86.45 %	83.87 %
MLP	87.52 %	**88.38 %**	87.09 %

Table 5.6: Evaluation of machine learning algorithms for the "Negative Parameter" group

Algorithms	F1 scores	Precision scores	Recall scores
Logistic regression	82.96 %	87.77 %	83.33 %
Random forest	74.14 %	78.88 %	75 %
K nearest neighbor	74.24 %	85.71 %	75 %
Support vector machine	83.33 %	88.88 %	83.33 %
MLP	91.75 %	**93.33 %**	91.66 %

We applied the algorithms with the highest precision to predict the labels related to four groups of the parameter data set for 8 sentences. Tables 5.7 & 5.8 illustrate the result of these predictions. As shown in the tables, the algorithm correctly predicted the parameters for most of the sentences. For instance, the algorithm predicted "Density" as "Positive Parameters" for the first sentence "raise the storage pressure can increase the hydrogen density but will also remarkably increase the energy consumption for compression", as there is in this sentence. The algorithm also correctly predicted "Quantity of substance" as "Positive TRIZ Parameters" for the first sentence, relating to the positive parameter "Density". As the tables display, there is just one error for the "Positive Parameters" group in Table 5.8. Our used machine learning algorithm predicted "nan" for the sentence N°7, while its label should be "Co2 emission". Here, we should mention that the system can also show the contradiction in one sentence. For example, as shown in the tables, the system extracted positive and negative parameters for the first sentence. This illustrates the existing contradiction in one sentence. It means that the improvement of one parameter deteriorates the other parameter.

Table 5.7: Results related to the application of the machine learning algorithms with the highest accuracy to predict the "Positive and Negative TRIZ Parameters" labels of eight sentences

N°	Texts	Positive TRIZ Parameters	Negative TRIZ Parameters
1	raise the storage pressure can increase the hydrogen density but will also remarkably increase the energy consumption for compression	Quantity of substance	Use of energy by stationary object
2	the compressive strength of CA mortar decreases with higher temperature.	nan	Strength
3	The small increase of the cutting speed value from 30 to 35 m/min leads to an increase of temperature	nan	Temperature
4	Loss of energy in PDE due to the viscosity of the fuel is an important factor.	nan	Loss of Energy
5	Pump scheduling [M1] can be used to control the speed of pumps.	Speed	nan
6	the coordination of the energy storage system with the generating units can improve the energy efficiency of the system,	Loss of Energy	nan
7	Biodiesel can reduce carbon dioxide () emissions.	Object-generated harmful factors	nan
8	The thermal stability of cofibrils increased with the increase of the C4S content.	Temperature	nan

Table 5.8: Results related to the application of the machine learning algorithms with the highest accuracy to predict the "Positive and Negative Parameters" labels of eight sentences

N°	Texts	Positive Parameters	Negative Parameters
1	raise the storage pressure can increase the hydrogen density but will also remarkably increase the energy consumption for compression	Density	Energy consumption
2	the compressive strength of CA mortar decreases with higher temperature.	nan	Compressive strength
3	The small increase of the cutting speed value from 30 to 35 m/min leads to an increase of temperature	nan	Temperature
4	Loss of energy in PDE due to the viscosity of the fuel is an important factor.	nan	Loss of energy
5	Pump scheduling [M1] can be used to control the speed of pumps.	Speed	nan
6	the coordination of the energy storage system with the generating units can improve the energy efficiency of the system,	Energy efficiency	nan
7	Biodiesel can reduce carbon dioxide () emissions.	nan	nan
8	The thermal stability of cofibrils increased with the increase of the C4S content.	Thermal stability	nan

5.4. Proposed method: Integration of doc2vec and machine learning algorithms into Inverse Problem Graph

In this section, we integrated doc2ec and machine learning algorithms into the Inverse Problem Graph (IPG) method to reduce time and widen the scope of explored data when extracting information from existing database. This helped us to introduce an extended method for the Initial Analysis and Solution Concepts phases of the inventive design process. This method consists of two main parts: A) Inverse Problem Graph (IPG), and B) Agile Automated-Question Answering System (AA–QAS), which includes the creation of corpora sub-parts and the question-answering sub-parts. Figure 5.1. shows the different parts of this proposal. Below, we explain these parts in detail:

5.4.1. Part 1: Inverse Problem Graph (IPG):

We improved the IPG method by adding the sub-steps 1.a, 4.a.i, 4.b, and 8 to link the problem formulation process to the second part. Furthermore, we proposed the second part to allow designers to automatically extract essential data to construct IPG from the project's corpora.

Step1: At the beginning of this step, the initial problem is defined by considering the objective of the project. (1.a) Then, designers must verify whether they need to use the information contained in the database. If yes, they should go to the "Create What-Cause question" step of the Agile Automated – Question Answering System (AA – QAS) part to find the related problems. Otherwise, they could go directly to the second step of the Inverse Problem Graph.

Step 2: This step involves identifying the problems that caused the initial problem by applying knowledge from the database or personal knowledge.

Step 3: In this step, designers must then select the most important problem from the listed problems in the previous step.

Step 4: After selecting the problem, designers should determine the type of it in the fourth step. According to the structure of the Inverse Problem Graph method, there are two types of problems: a) Harmful-Useful Problem, b) Harmful problem. (a) If the selected problem was a Harmful-Useful problem, the designers should convert it to a partial solution. For this kind of problem, it is essential:

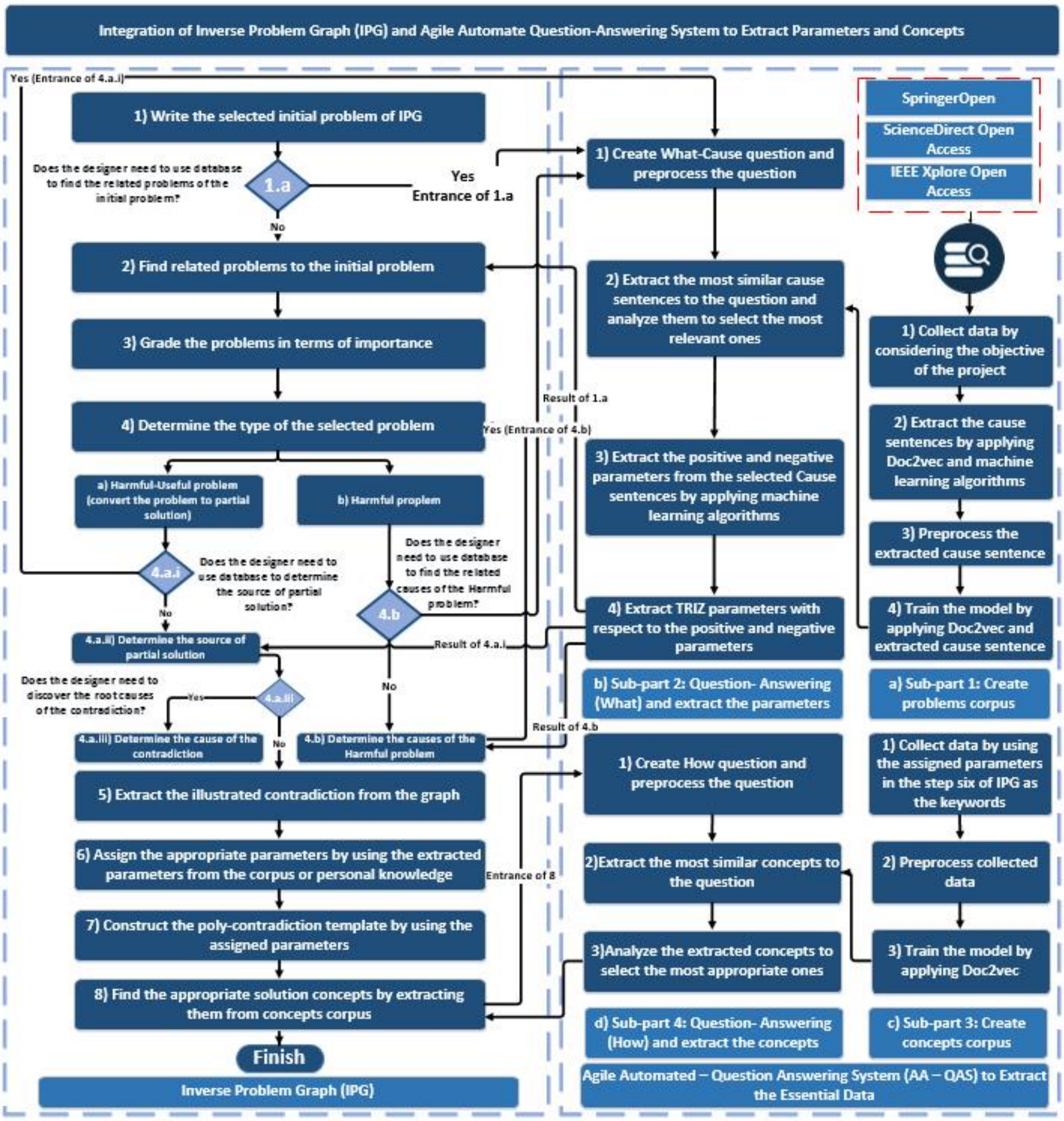


Figure 5.1. Different parts and the steps of Agile-Automated Question Answering System (Annex B)

- Sub-step (4.a.i): For designers to verify if they need to use the information in the database or not. If yes, they should go to the “Create What-Cause question” step of the Agile Automated – Question Answering System (AA – QAS) part to determine the source of the partial solution. If not, they could directly go to the next sub-step of the Inverse Problem Graph.
- Sub-step (4.a.ii): In this sub-step, the designers should determine the source (cause) of partial solution.

- Sub-step (4.a.iii): After determining the cause of partial solution, if the designers need to discover the root causes of the contradiction, they could continue the chain of the contradiction.

(4.b) If the selected problem was a Harmful problem, the designers should determine the causes by applying their personal knowledge or the information on the database. After determining the causes, they should go back to step 3 of the process.

Step 5: After demonstrating the contradiction on the graph, it is time to extract it from the IPG in the fifth step.

Step 6: In the sixth step, it is time to allocate the parameters to the problems and the partial solution by using the extracted parameters from the corpus.

Step 7: The allocated parameters in the previous step are used to construct the poly contradiction template in the seventh step.

Step 8: At the end of this part, "How Question" is used to extract the solutions from our concepts corpus. "How Question" is formulated in the sub-part 2.4 of the proposed method.

5.4.2. Part 2: Agile Automated – Question Answering System (AA – QAS)

This part of the system allows the designers to extract the essential data, including parameters and concepts, from project's corpora. This part is divided into four sub-parts: a) Creation of problems corpus, b) Question-Answering (What) and extraction of the parameters, c) Creation of concepts corpus, and d) Question-Answering (How) and extraction of the concepts.

5.4.2.1. Sub-part 2.1: Creation of problems corpus

In this sub-part, the collection of the data to create the problems corpus and its training are performed. This sub-part includes the following steps:

1. In the first step it is essential to collect a considerable amount of data considering the area and objective of the project.
2. Then, the cause sentences are extracted from the created corpus in the second step. To do so, it is necessary to train the doc2vec model and machine learning algorithms by using the provided data samples, including cause and no-cause labels.
3. In the third step, it is necessary to apply certain preprocessing techniques such

as Tokenization, Removing stopwords, and Lowercase conversion to remove unnecessary content from the data [115].

4. At the end of this sub-part, it is necessary to use doc2vec and the extracted cause sentences to train the model. To implement this training, it is possible to apply Gensim, which is a python library for unsupervised learning [125]. This library has a set of capabilities for semantic analysis [115]. The implementation of the doc2vec model in the Gensim library requires the definition of various hyper-parameters, including Vector size, Epochs, Minimum count, and Window size, that affect model performance [174].

5.4.2.2. Sub-part 2.2: Question-Answering (What) and extract the parameters

The second sub-part of the proposition plays the role of interface between Part 1 and the sub-part 2.1. Indeed, this part helps to extract the essential data such as the TRIZ parameters from the problems corpus. The second part consists of the following steps:

1. At the beginning of the first step of the second sub-part, the designers should formulate the question "What causes the problem?". The problem posed by the question could be an initial problem, partial solution, or any other problem that designers need to know the cause of it. Then, it is necessary to apply some preprocessing techniques to remove undesirable content from the question.
2. In the second step, the cosine similarity could help the designers to find the most similar cause sentences to the question. Subsequently, the designers should evaluate the sentences in order to select those that are closest to the problem.
3. After selection of the cause sentences, the system extracts the positive and negative parameters existing in the sentences by applying machine learning algorithm in the third step. For this purpose, the system uses our labeled data to train the used machine learning algorithm.
4. In the final step of this sub-part, TRIZ parameters related to each cause sentence are extracted with respect to the positive and negative parameters. To extract these parameters, the system also uses the provided labeled data.

5.4.2.3. Sub-part 2.3: Creation of concepts corpus

In this sub-part, the collection of the data to create the concepts corpus and its training are performed. This sub-part includes the following steps:

1. In the first step of this sub-part, it is essential to collect a considerable amount of data using the assigned parameters in the step six of IPG as the keywords.
2. In the second step, it is necessary to use certain preprocessing techniques such as Tokenization, Removing stopwords, and Lowercase conversion to remove unnecessary content from the data [115].
3. At the end of this sub-part, it is necessary to use doc2vec to train the model.

5.4.2.4. Sub-part 2.4: Question-Answering (How) and extract the concepts

The fourth sub-part contributes to extract the solution concepts from the concepts corpus. The steps of this sub-part are as the following:

1. The first step begins by formulating "How questions". To do so, it is possible to use the parameters, including TRIZ, positive and negative parameters, as the keywords. Subsequently, it is time to apply some preprocessing techniques to remove undesirable content from the formulated questions.
2. In the second step, the cosine similarity could help the designers to find the most similar concepts to the questions.
3. At the end of this sub-part, the designers should evaluate the concepts in order to select the most appropriate ones.

5.5. Application of the proposal to Lattice Structure case study

In this section, we apply the proposed method "Integration of Inverse Problem Graph (IPG) and Agile Automated Question Answering System" to the Lattice Structure case study to evaluate its applicability. Lattice Structures (LS) are three-dimensional open-celled structures formed by one or more reproductive unit cells [175]. Figure 5.2 shows a lattice structure. Compared to solid materials, LSs have many superior properties, which make them applicable in various engineering fields as energy absorber, heat transfer, biological bone graft, and lightweight structural component [176]. Due to the wide use of LS in energy-absorbing applications, the energy absorption of this kind of structure has always been an interesting research topic for materials scientists and engineers [177]. Energy-absorbing structures are the components that convert kinetic energy into other types of energy, such as plastic strain through large deformations of the material [178]. In this case study, we are going to identify the factors that affect the energy absorption of the lattice structure and extract the possible solution concepts. To do so, we first created the problems corpus by collecting about seven thousand articles. We then applied the proposed method to formulate the inventive problems related to the lattice structure case and extract their possible concepts. In the following, we explain the steps of this application. The first part relates to the creation of the problems database, the second part includes the steps for formulating the problem situation, the third part consists of the steps to create the concepts database, and the fourth part relates to the extraction of the solution concepts.

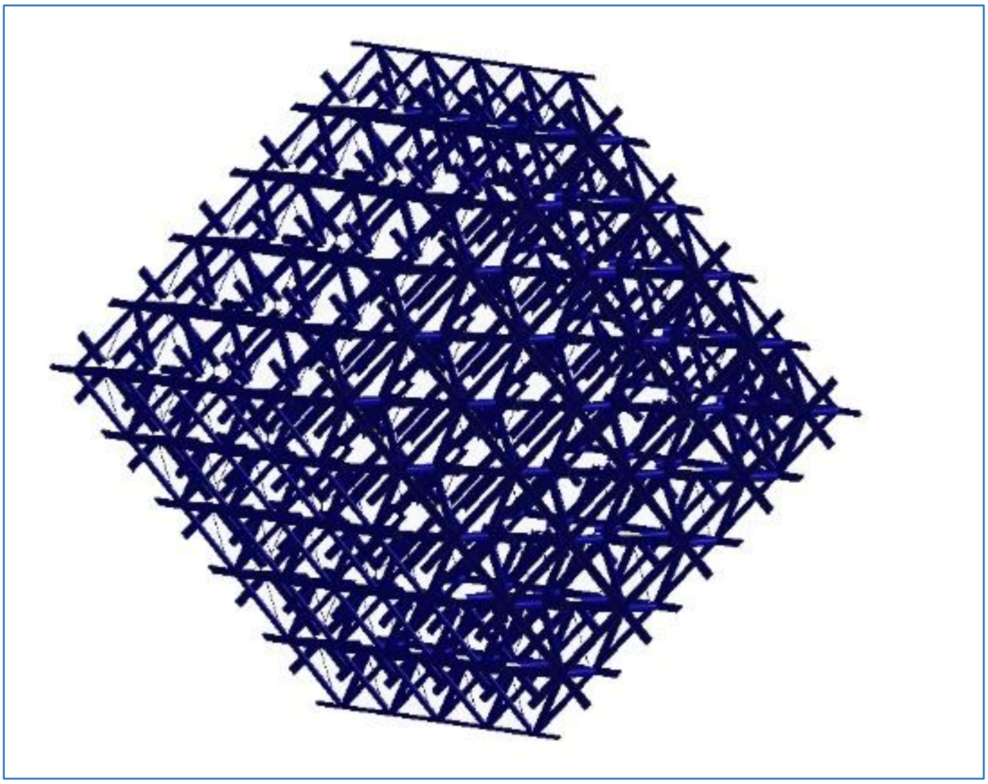


Figure 5.2. A lattice structure

In the first part of the case study, we created a problem database by following these steps:

At the beginning of the first step of this part, we chose “Improvement of the energy absorption of the Lattice Structure” as the objective. Then, we downloaded about 7,000 articles, including 231360 sentences, on Lattice Structure from the ScienceDirect Open Access, SpringerOpen, and IEEE Xplore Open Access data sources.

After collecting the data, we extracted the cause sentences in the second step. To do so, we first trained our doc2vec model by applying the prepared data sample, including “Cause and No-cause” labels. Then, we used MLP as one of the evaluated machine learning algorithms to extract the cause sentences.

In the third step, we used the standard Natural Language Toolkit (NLTK) python library to implement the preprocessing of the extracted cause sentences. This step started with lemmatization, in which we removed the affixes of the words to get their basic form. Subsequently, we removed special characters and symbols to reduce the noise in our collected data and performed the lowercase conversion. Then, we removed stop words from the text to keep the words with maximum significance. Finally, we tokenized the sentences to split them into words.

We trained the doc2vec model by applying the extracted cause sentences in the last step of this part. To define the hyper-parameters of the doc2vec model, we used the research results of Lau et al [179] which proved that the most efficient parameter settings are as shown in Table 5.9 [174]. This helps to use cosine similarity to extract the similar cause sentences to the question from the corpus.

Table 5.9: The applied hyper-parameter to train the model

Number	Hyper-parameter	Setting
1	Epochs	400
2	Model	DBOW
3	Minimum count	1
4	Window	15
Epochs: This parameter specifies the number of iterations over training samples.		
Model: This parameter determines the training algorithms of the doc2vec model.		
Minimum count: This parameter determines the minimum frequency threshold of a word in the created database.		
Window: This parameter defines the maximum distance between the context word within a sentence and the predicted word.		

In the second part of the case study, we formulated the inventive problems related to the lattice structure by following the steps defined in Part 1 and Subpart 2.2 of the proposed method:

In the first step of this part, we determined the initial problem, which was "The energy absorption of the lattice structure is low", by considering the objective of the project.

After defining the initial problem, we had to determine the causes of this problem in the second step. Due to the lack of knowledge on this subject, we had to use the information in the database. For this purpose, we first created our question, which was "What causes the energy absorption of the lattice structure to be decreased?". Then, we preprocessed the question by lowercase conversion, tokenization, and lemmatization.

In what followed, we applied the most-similar method to find the cause sentences closest to our created question. Table 5.10. displays some of these sentences. In the table, there are four columns: 1) Texts column: this column contains the cause sentences in the database closest to our question. 2) Previous_Texts column: it consists of the previous sentences of the Texts column to facilitate the comprehension of the sentences proposed in the Texts column. 3) Next_Texts column: This column is made up of the next sentences of the Texts column to facilitate the comprehension of the sentences proposed in the Texts column. 4) Similarity column: this column displays the degree of similarity of the sentences with the question. It is worth noting that the minimum threshold for this case study is considered to be 0.70.

Table 5.10: Part of the similar sentences to the first question

	Previous_Texts	**Texts (cause sentences)**	**Next_Texts**	**Similarity**
0	10(a) shows that the standard grey resin specimen absorbs relatively more energy than the durable resin specimen and the EPS foam, although they can only tolerate a small displacement before brittle failure.	It is also evident that there is a monotonic increase in the absorbed energy with the density of the EPS foam and the relative density of the octet - truss lattice structure.	10(b) compare the SEA of the EPS foam and the 3D printing structure.	0.8712
…	…	…	…	…
710	for both the square and triangular lattice , if the strong chirality occur in the solid lump and connection simultaneously , the phononic bandgap will be improve .	this be because the strong rotation will make the structure easy to have local vibration , but at the same time , the strong chirality be more likely to yield a small porosity , result in the decrease of photonic bandgap .	in addition , the chirality degree and geometry of the connection will affect the pxc bandgap in the square lattice .	0.7014

Subsequently, we analyzed the proposed cause sentences and selected the most relevant ones, as shown in Table 5.11, for the defined initial problem of the Inverse Problem Graph.

We extracted the parameters, including the positive, negative, and TRIZ parameters, in the third step of the second part. To do so, we first trained our machine learning algorithm. Subsequently, this algorithm permitted us to extract the parameters. Table 5.11. shows the selected cause sentences and their related parameters.

Table 5.11: The selected cause sentences related to the first question and their extracted parameters

N°	Texts (cause sentences)	Positive Parameters	Negative Parameters	TRIZ Parameters
0	When the volume fraction is reduced from 40.4% to 12.5%, the maximum energy absorption efficiency increases from 35.20% to 46.95%, an increase of 11.75%.	Energy absorption	nan	Reliability, Shape
1	The energy absorption of the Gyroid LCS is improved by increasing the relative density.	Energy absorption	nan	Reliability, Shape
2	Find that the 316 L stainless steel Gyroid lattice exhibits higher stiffness and energy absorption capacity compared to the body - central cubic lattice.	Stiffness, Energy absorption	nan	Strength, Reliability, Shape
3	The same hold for the load-bear structure application, since the SU local closed cell lattice structure with small cell size gives high strength , high energy absorption compare to the open cell or global closed cell structure ;	Strength, Energy absorption	nan	Strength, Reliability, Shape
4	compare to diamond and BCC structure, tetrakaidecahedron structure can absorb high energy at high stress .	Energy absorption	nan	Reliability, Shape
5	Most hollow truss lattice have high strength and energy absorption capability than solid truss lattice due to the higher specific second moment of inertia of the constituent beam	Strength, Energy absorption	nan	Strength, Reliability, Shape
6	have discuss the energy absorption capability of functionally grade and uniform f2bcc lattice structure and demonstrate that the cumulative energy absorption per unit volume of grade lattice structure is higher than that of the uniform structure.	Energy absorption	nan	Reliability, Shape
7	With the increase in the ductility, the energy absorption of the structure also increase	Energy absorption	nan	Reliability, Shape

In the fourth step, we first wrote them down in an appropriate format and linked them to the initial problem, as Figure 5.3. illustrates. In this figure, the first cause "The volume fraction of the lattice structure has been increased" was inspired by the first row of Table 5.11, which is "when the volume fraction is reduced from 40.4 % to 12.5 %, the maximum energy absorption efficiency increases from 35.20 % to 45.95 %". The second cause "The relative density of the structure has been decreased" was extracted from the second row of Table 5.11, being "the energy absorption of the Gyroid LCS is improved by increasing the relative density". In the same way, we formulated the other causes of the initial problem based on the other rows of Table 5.11. Then, we graded the formulated causes, and as shown in Figure 5.3., we selected "The volume fraction of the lattice structure has been increased" as the most important problem that has an impact on the energy absorption of the lattice structure.

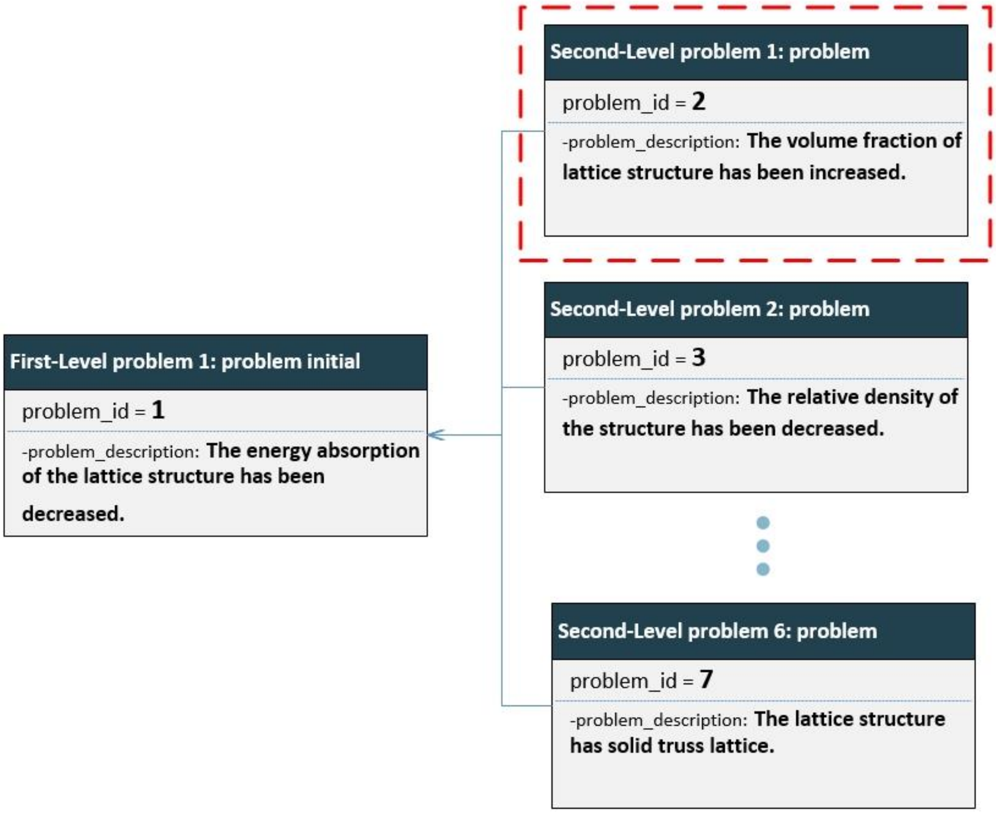


Figure 5.3. Connection of the causes to the initial problem and selection of the most important cause

In the fifth step, we needed to determine the type of selected problem. In this case study, our selected problem "The volume fraction of the lattice structure has been increased" was a Harmful-Useful problem. Hence, we had to convert this problem to the partial solution "To increase the volume fraction of the lattice structure", which means that we converted the structure of the problem to the structure of the partial solution, as Figure 5.4 demonstrates.

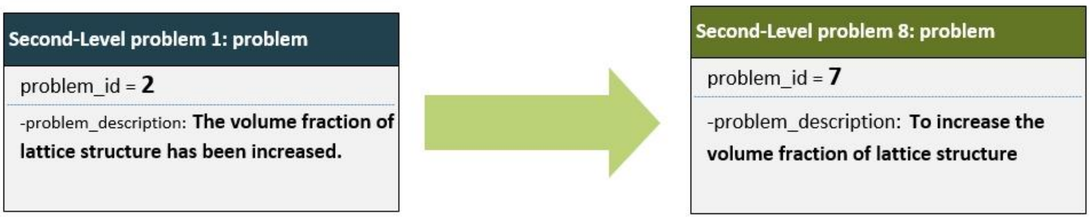


Figure 5.4. Conversion of the Harmful-Useful problem to the partial solution

Once the problem was converted to the partial solution, we created the following question "What causes the volume fraction of the lattice structure to be increased" at the beginning of the sixth step. We then preprocessed the question, and we applied python to find the cause sentences most similar to the question. Table 5.12 shows some of the extracted sentences from the database.

Table 5.12: Part of the similar sentences to the second question parameters

	Previous_Texts	**Texts (cause sentences)**	**Next_Texts**	**Similarity**
0	PT-2.4 have the high Young 's modulus , yield stress and ultimate stress , while the PT scaffold be the weak , as expect .	the stiffness and strength of the scaffold increase significantly with the diameter of the dense core , as the porosity be reduce .	the elastic modulus and yield strength of the test sample and human cortical bone be further visualize in Fig .	0.8823
…	…	…	…	…
1255	The design of a suitable host material, the application of a functional interlayer or the protection of the lithium anode have been considered an effective approach to significantly improve the electrochemical performance of lsb.	Porous carbon materials are attracting the attention of researchers largely due to their excellent electronic conductivity, confined nanospace, high specific area, and high structural stability.	Porous carbon matrix not only facilitates kinetic charge transfer during electrochemical process, but also alleviates the migration of polysulfide through physical absorption, as well as tolerates volume change during the lithiation/delithiation process .	0.7032

In the seventh step, we selected the most probable causes of partial solutions and extracted their parameters by applying our machine learning algorithm, as shown in Table 5.13. As it is obvious in the table, the system also proposed the sentences that include "porosity", which is one of the closest words to volume fraction. For example, in the first row of the table, we see the sentence "The stiffness and strength of the scaffold increases significantly with the diameter of the dense core, as the porosity is reduced", which includes the word "porosity". In this sentence, the reduction in porosity means that the volume fraction has been increased.

Table 5.13: The selected causes related to the second question and their extracted parameters

N°	Texts (cause sentences)	Positive Parameters	Negative Parameters	TRIZ Parameters
0	The stiffness and strength of the scaffold increases significantly with the diameter of the dense core, as the porosity is reduced.	Stiffness, Strength	nan	Strength, Strength
1	While porous T64 scaffold can reduce stiffness due to their increased porosity, the trade-off is a low mechanical and fatigue strength .	nan	Stiffness	Strength
2	For a small volume fraction, the influence of a rough surface is relatively greater than for a high volume fraction, resulting in lower strength.	nan	Strength	Strength
3	It is evident that stiffness increases with increase in volume fraction.	Stiffness	nan	Strength

We interpreted the selected causes of the partial solution to write them on the IPG in the eigth step. Figure 5.5. illustrates the Inverse Problem Graph of this case study in the first iteration.

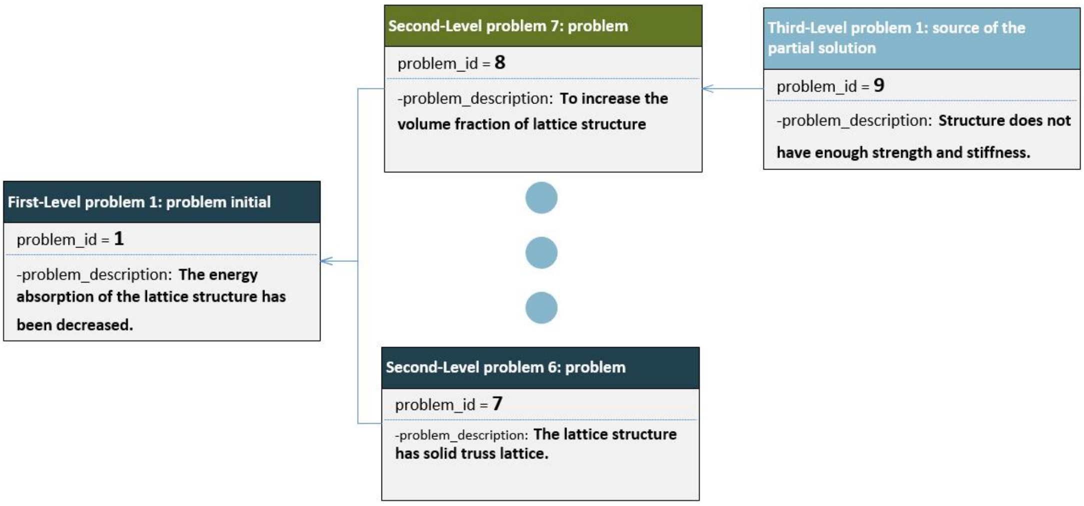


Figure 5.5. Inverse Problem Graph of Lattice Structure

In the ninth step, we extracted the illustrated contradiction from the IPG, as shown in Figure 5.6. The contradiction in this image is between the strength of a structure and its energy absorption. This means that in order to increase the strength, it is necessary to enhance the volume fraction or reduce the porosity of that structure. This results in decreasing its deformation and energy absorption. In contrast, efforts to enhance the capacity of a structure to absorb kinetic energy, it is necessary to decrease its volume fraction or increase its porosity, which leads to a reduction in its strength. Figure 5.7.

demonstrates two different structures, one with a low volume fraction, Figure 5.7-a, and the other with a high-volume fraction, Figure 5.7-b. As shown in sub-figure (a), the structure with a low volume fraction is deformed due to the absorption of kinetic energy. Conversely, as shown in sub-figure (b), the structure with a high-volume fraction leads to the rebound of the object.

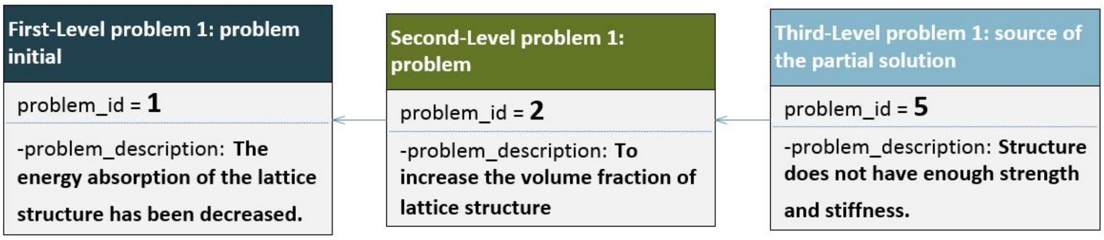


Figure 5.6. Extraction of the contradiction from the IPG graph

Figure 5.7. Comparison of the energy absorption and strength of two structures with a high and low volume fraction [180]

We assigned the evaluation parameters to the problems and the action parameter to the partial solution in the tenth step, as Figure 5.8 demonstrates. To do so, we used the extracted parameters by our system. These parameters help us to extract the concepts from our database. In this allocation, as Figure 5.8 shows, we assigned two parameters to the energy absorption. The first one is "Reliability of the structure", which refers to the ability of the structure to perform its intended function in a predictable manner, and the second one is "Shape of the structure", referring to the deformation of the structure. In the first iteration, we decided to select the shape parameter for the energy absorption.

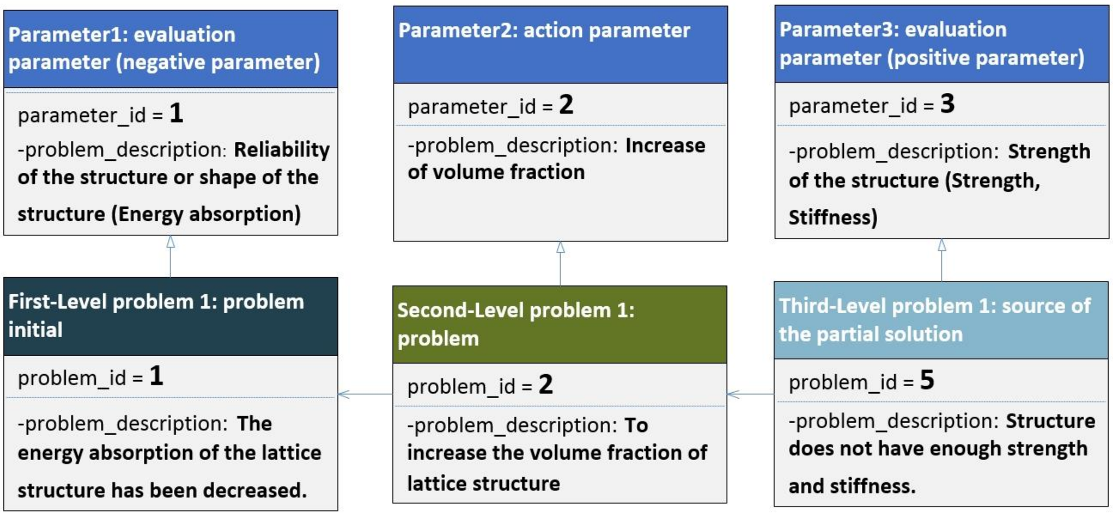


Figure 5.8. Allocation of parameters to the problems and partial solution

In the final step of the second part, we should apply the assigned parameters in the previous step of the proposal to construct our poly-contradiction table, as presented in Figure 5.9.

	Increase of volume fraction	
	Low	High
Shape of the structure (energy absorption is increased – deformation is increased)	☺	☹
Strength of the structure	☹	☺
Shape of the structure: The external contours, appearance of a system.		
Strength of the structure: The extent to which the object is able to resist changes in response to force.		

Figure 5.9. Construction of poly-contradiction by applying the parameters

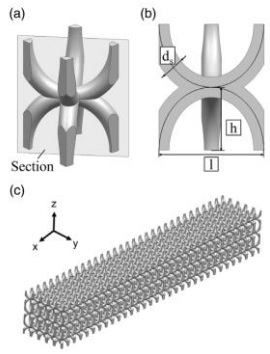
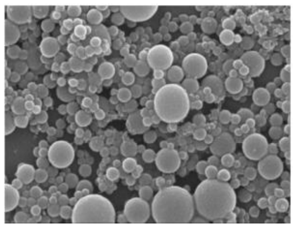
In the third part of our case study, we created a concepts database using the assigned parameters of the ninth and tenth steps of the second part of the case study. This part consists of the following steps:

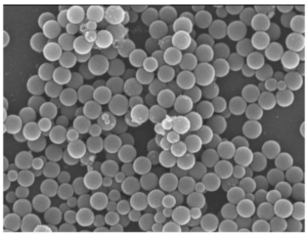
In the first step of the third part, we downloaded the articles from the scientific data sources by using the assigned parameters, including energy absorption and strength, in the nine and tenth steps of the second part as the keywords. We used the standard Natural Language Toolkit (NLTK) python library to implement the preprocessing of the extracted data in the second step. In the last step of the third part, we trained the model by applying doc2vec.

In the fourth part of the case study, we extracted the solution concepts from the created concepts database through the following steps:

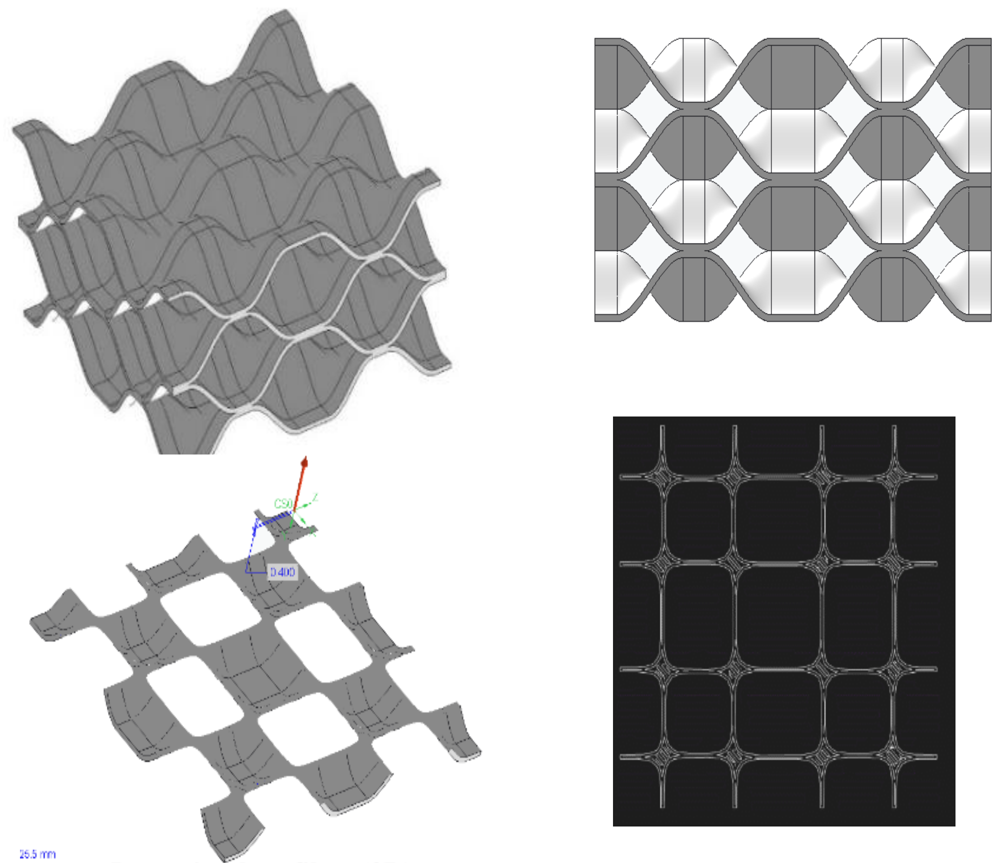
In the first step of this part, we formulated the question "How is it possible to increase the energy absorption (positive parameter) without reducing the strength (negative parameter) of the lattice structure?". This question helped us to extract the solution concepts from the concepts database in the second step of the fourth part. In the final step, we analyzed the extracted concepts to select the most appropriate ones. Table 5.14 displays the extracted concepts by the system.

Table 5.14: The extracted solution concepts from the concepts database for the formulated contradiction

N°	Solution concepts	Similarity	Images
1	The ARCH lattice structures have superior energy absorption and mechanical properties [181].	0.8880	 [181],[182]
2	The composition ratio of micro and nano silica particles contributed to the significant effects on the dynamic stiffness, stress transmissibility, and energy absorption performance [183].	0.8501	

			Micro silica particles [184]
			
			Nano silica particles [184]
3	They believed that the energy absorption capacity of rubber concrete could be accurately reflected using the normalized energy absorption value of compressive strength, which was 54–79% higher than that of ordinary concrete [185].	0.7850	 Rubber [186]
4	Moreover, dispersed chopped glass and carbon fibers were used to produce fiber reinforced polymer concrete with enhanced strength, stiffness and energy absorption.	0.7730	 Glass fiber [187]  Carbon fiber [187]
5	The auxetic lattice reinforced composites with a unique combination of stiffness and energy absorption [188].	0.7605	 Auxetic lattice [188]

At the end of this case study, we combined the first (application of the arch geometry) and the fourth concept (application of glass fiber and carbon fiber as the material) to develop our solution. We were inspired by the first concept “The ARCH lattice structures have superior energy absorption and mechanical properties” to add arch geometry to the interior surface of our lattice structure. Besides, the fourth concept helped us to use glass fiber as the material of one of the layers of the structure. This concept also served us to apply Onyx (a mix of carbon fiber and plastic) to construct other layers. Figure 5.10 displays the different views of our proposed lattice structure.



Layer in glass fiber (3D) **Layer in glass fiber (Top)**

Figure 5.10. Different views of our proposed lattice structure

5.6. Comparison of the automatic system based on the IPG process and the classical system

In this section, we compare IPG’s automatic system with the classical system based on the Problem Graph method. To analyze the Problem Graph's automatic system, we used Lattice Structure as a keyword to find the patents related to this subject in the system's database. Then, we randomly selected five patents among 30,640 patents to test the system's capability to extract the elements, including partial solutions, problems, and parameters. As shown in Table 5.15, the number of extracted elements for the first patent was five. Considering that the analysis of each element required 5 minutes, the analysis of the first article took 25 minutes. The automatic system extracted seventeen elements from the second patent. Hence, the analysis of the whole patent required 85 minutes. Table 5.15 shows the number of extractions for the other three patents, as well as the needed time for their analysis. The table also displays the average time (68 minutes) required to analyze the extracted data from the classical system.

Table 5.15: Analysis of Problem Graph's classical system

Problem Graph's classical system			
Article	**Number of extracted elements**	**Needed time to analyze each element**	**Total time**
Patent 1	5	5 min	25 min
Patent 2	17	5 min	85 min
Patent 3	7	5 min	35 min
Patent 4	30	5 min	150 min
Patent 5	9	5 min	45 min
Average time to analyze one patent	**13.6**	**5 min**	**68 min**
Keyword used to extract	**Lattice structure**		

Table 5.16 illustrates the information about the capability of the IPG's automatic system in extracting the sentences from the articles. To construct this table, we used the results of the Lattice Structure case study. As shown in the Table, the system extracted 710 cause sentences for the question "What reduces the energy absorption of the lattice structure ?" Hence, considering that the total number of articles in the system was 7000, the number of sentences extracted from an article for this question was 0.101 ($710 \div 7000 = 0.101$). It took us about 10 minutes to analyze each extracted cause sentence, so the total time to review an article for the first question was 1.014 minutes ($0.101 \times 10\ min = 1.014$). For the second question, our system extracted 1255 cause sentences. Therefore, we obtained 1.792 minutes ($0.179 \times 10\ min = 1.792$), which is the

essential time to analyze one article. Table 5.16 also illustrates the average time (1.403 minutes) required to analyze one article in this system.

Table 5.16: Analysis of Inverse Problem Graph's automatic system

Automatic system based on IPG					
Number of articles	**Number of sentences in the data base**	**Number of extracted cause sentences**	**Number of extracted cause sentences from one article**	**Essential time to analyze each cause sentence**	**Total time for one article**
7000	231360	710	710/7000 = 0.1014	10 min	1.014 min
Question used to extract		**What causes the energy absorption of the lattice structure to be decreased?**			
Number of articles	**Number of sentences in the data base**	**Number of extracted cause sentences**	**Number of extracted cause sentences from one article**	**Essential time to analyze each cause sentence**	**Total time for one article**
7000	231360	1255	1255/7000 = 0.1792	10 min	1.792 min
Question used to extract		**What causes that the volume fraction of the lattice structure to be increased?**			
Average time to analyze one article					**1.403 min**

Figure 5.11 shows a comparison between the average time to analyze one article in the IPG's automatic system and in the classical system.

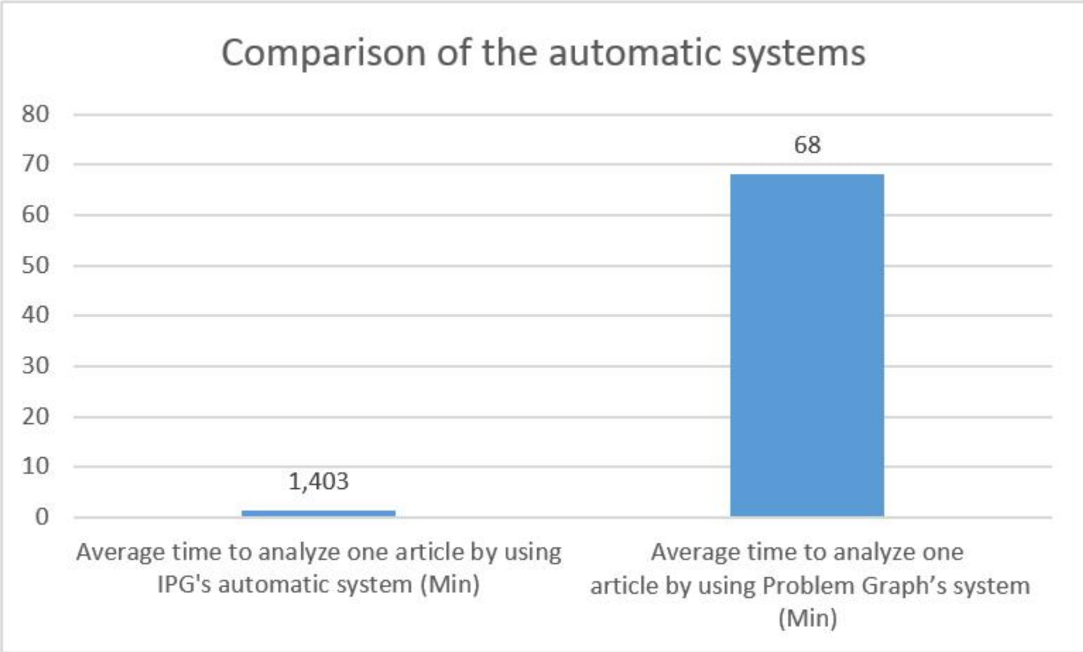


Figure 5.11. Comparison of automatic systems in average time to analyze one article

5.7. Conclusion and contribution of the chapter

In this study, we developed a new method and process to extract essential information, including parameters and solution concepts, in the inventive design process. To propose our method, we reviewed firstly some of the most important document embedding techniques to highlight their limitations and advantages. Accordingly, we selected doc2vec, which could extract the semantic and order information from the text. Next, we analyzed one of the most popular methods, called cosine similarity, to measure the similarity between extracted vectors by doc2vec. In what followed, we reviewed several machine learning algorithms. In the end, we proposed to integrate doc2vec, cosine similarity, and machine learning into the IPG method. We then tested the method's ability in collecting data through its application in the Lattice Structure case study. Based on this application, we realized that the integration of such an automatic system to the Inverse Problem Graph method could facilitate and accelerate problem formulation and concepts extraction in the inventive design process.

Chapter 6. Conclusions and perspectives

In recent decades, companies have continually sought approaches that help them reduce the innovation cycle time due to its importance to their success. Among these approaches are TRIZ-based systematic inventive design processes, such as Inventive Design Methodology (IDM). Nevertheless, the application of these methods in the initial analysis, which demands an exhaustive gathering of information at the beginning of the innovation project without considering its impact on the final solution, decreases the agility of these types of processes.

These research works aim to facilitate and accelerate inventive design in the companies. To achieve this goal, a Lean-based method to formulate a problem situation was first developed. This method was called Inverse Problem Graph (IPG). Subsequently, an FMEA-AHP based method was integrated into IPG to prioritize the initial problems in the initial analysis phase. Finally, the doc2vec model and machine learning text classification algorithms were proposed to be applied to facilitate and accelerate contradiction formulation and concepts extraction in the inventive design process.

In the following sections, the research works of each chapter are firstly summarized. Then, we present the main contributions of our thesis. Finally, several prospective points are proposed to improve this research in the future.

6.1. Summarization of the chapters

In Chapter 1 of this thesis, we mentioned that one of the criticisms often levelled to the Inventive Design Methodology (IDM) is that this approach is time-consuming, and it does not have the necessary agility. In order to increase the agility and efficiency of IDM, we proposed "Agile Automated System to Extract Essential Data (TRIZ Parameters, Contradictions, and Concepts) by Considering Priorities of Initial Problems". Finally, the structure of this thesis was presented.

Chapter 2 presented a literature review about TRIZ and the TRIZ-based frameworks. In the TRIZ part, we presented an introduction of TRIZ and the notions of TRIZ, such as technical and physical contradiction. Further, we introduced TRIZ's tools, including analytical tools and knowledge-based tools. In the part of TRIZ-based frameworks, we provided an overview of xTRIZ, OTSM-TRIZ, and IDM frameworks.

In Chapter 3, we firstly presented a literature review about the initial situation analysis methods and Lean theory. Then, the structure of the Inverse Problem Graph (IPG) method and its steps were displayed, and we applied the method to the COVID-19 case study. At the end of this chapter, we made a comparison between IPG and other techniques with the ability to formulate the problems.

Chapter 4 presented a review of the FMEA method and a description of the AHP method. Subsequently, this chapter displayed the structure of the proposed method, resulting from the integration of FMEA-AHP based method into the IPG process. Then, the application of the proposal to the Biomass Power Plant case study was presented. Finally, we made a comparison between the proposal of the chapter and the classical method (Network of Problem).

In Chapter 5, we presented a literature review about automatic extraction related to the first phase of IDM, a description of several document-embedding techniques, a method for measuring the similarity, and a review of several machine learning text classification algorithms. Then, this chapter presented the structure of the proposed method, resulting from the integration of the doc2vec model and the machine learning algorithms into the IPG process. Subsequently, the proposal of the chapter was applied to formulate the inventive problems related to the lattice structures. Finally, we made a comparison between the proposal and another automatic technique that helps in the problem formulation.

6.2. Contributions

By solving the research problems, (1) the Inverse Problem Graph (IPG) method has been developed to formulate a problem situation in the initial analysis phase of IDM, (2) FMEA-AHP based method has been proposed to prioritize the initial problems in the initial phase, and (3) Agile Automated – Question Answering System (AA-QAS) has been introduced to automatically extract the essential data, including TRIZ parameters, contradictions, and concepts, in the inventive design process. The contributions of this thesis are presented as follows.

6.2.1. Inverse Problem Graph's contributions

The contribution of the Inverse Problem Graph method to the inventive design process reflects in several aspects. First of all, the IPG method optimizes the time taken for problem formulation by keeping only the essential elements of the study to be collected by applying Lean principles. These are, therefore, the elements that are most closely related to the objective retained throughout the process. As a second contribution, it is possible to mention the feature that is added to the method by iteration capacity. Unlike other methods, we did not develop all the chains at the beginning of the project. Instead, we integrated the solution phase in developing the chains of causes.

6.2.2. FMEA-AHP based method's contributions

The contribution of the integration of the FMEA-AHP based method into the IPG process to the inventive design process is reflected in the following aspects. First of all, this FMEA-AHP based method could help us to prioritize the identified problems in a system according to the existing criteria. Secondly, it permits the contradiction formulation based on the priorities of the initial problems.

6.2.3. Agile Automated – Question Answering System's contributions

The contribution of the integration of the Agile Automated-Question Answering System into the inventive design process is reflected as follows. First of all, this automatic system could optimize data collection time in the inventive design process. As the second important contribution, it can be mentioned that this system could significantly reduce the amount of effort that the designers put into collecting the essential data, including TRIZ parameters, contradictions, and concepts. Thirdly, we could mention that this proposal could significantly increase the accuracy of the collected information by extracting the most probable reasons related to a selected problem. As a result, the designers could develop more accurate chains of causes during this phase.

6.3. Limitations

The Inverse Problem Graph (IPG) method aims to increase the agility and efficiency of the initial analysis phase of IDM. However, it cannot completely do this increment. In order to solve the drawbacks of IPG, FMEA-AHP based method was developed to prioritize the initial problems in the initial phase. Besides, Agile Automated –Question Answering System was integrated into the process of IPG to facilitate and accelerate the gathering of essential data to formulate a problem situation and extract the most appropriate solution concepts. The final result of these integrations was "Agile Automated System to Extract Essential Data (TRIZ Parameters, Contradictions, Concepts) by Considering Priorities of Initial Problem". Nevertheless, this system has several limitations, as follows.

First of all, the performance of the automatic system relies on the creation of the question by the designers. Therefore, if they do not formulate an appropriate question, the system will not extract adequate solutions. One of the solutions for solving this drawback could be the presence of an automatic system that proposes questions to designers by entering the keywords of the question.

Secondly, a high similarity score does not necessarily mean that the proposed sentence could be a desirable candidate for the created question. This shortcoming may be due to the low number of collected sentences in the database, an increase in which could solve the problem.

Thirdly, the analysis of our case study related to the FMEA-AHP based method reveals that mathematical calculations of such a method can significantly reduce the agility of the process. Therefore, further researches are necessary to appreciate this part of the automatic system.

6.4. Perspectives

In this thesis, a new automatic approach for the initial analysis phase of inventive design is introduced. This new approach will help to facilitate and accelerate innovation in the companies. For this purpose, future research deals with the above limitations as follows.

As the first survey, in order to facilitate the question formulation, it is possible to integrate a question/suggestion system, proposing the appropriate questions to the designers by applying the keywords related to a formulated problem in IPG. Secondly, it is possible to add the capability of automatic formulation of Harmful-Useful problems to the system. Thirdly, another future survey might be to develop software to decrease the calculation procedure during the formulation of problems in the initial analysis phase.

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Annex A

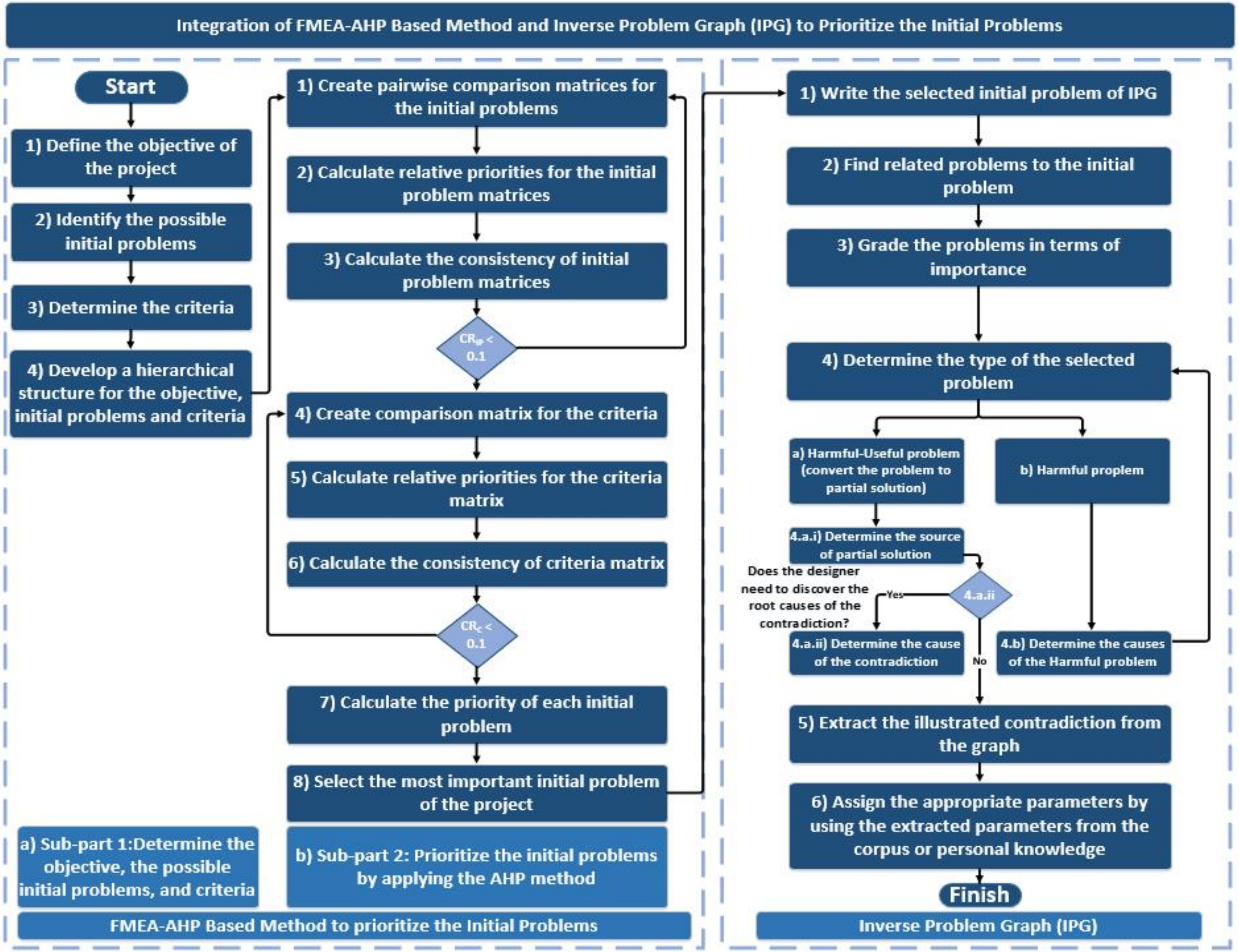
Journals :

1. ***Hanifi, M***., Chibane, H, Houssin, R., and Cavallucci, D.. 2021. "IPG as a new method to improve the agility of the initial analysis of the inventive design." *FME Transactions Journal* , *49*(3), 549-562.
2. ***Hanifi, M***., Chibane, H, Houssin, R., and Cavallucci, D.. 2021. "Problem formulation in inventive design, using Doc2vec as an Artificial Intelligence method and Scientific Paper" *Engineering Applications of Artificial Intelligence Journal*. **Accepted.**
3. ***Hanifi, M***., Chibane, H, Houssin, R., Cavallucci, D, and Ghannad, N. 2021. "A method for facilitating and accelerating extraction of the essential data in inventive design." *Artificial Intelligence for Engineering Design, Analysis and Manufacturing Journal*. **Request to revise after reviewing**.
4. Slim, R., Houssin, H, Coulibaly, A., ***Hanifi, M***., and Chibane, H.. 2021. "Framework for resolving problems resulting from lean integration from the early design phases of production 3D printing machine." *FME Transactions Journal* , *49*(2), 279-290.

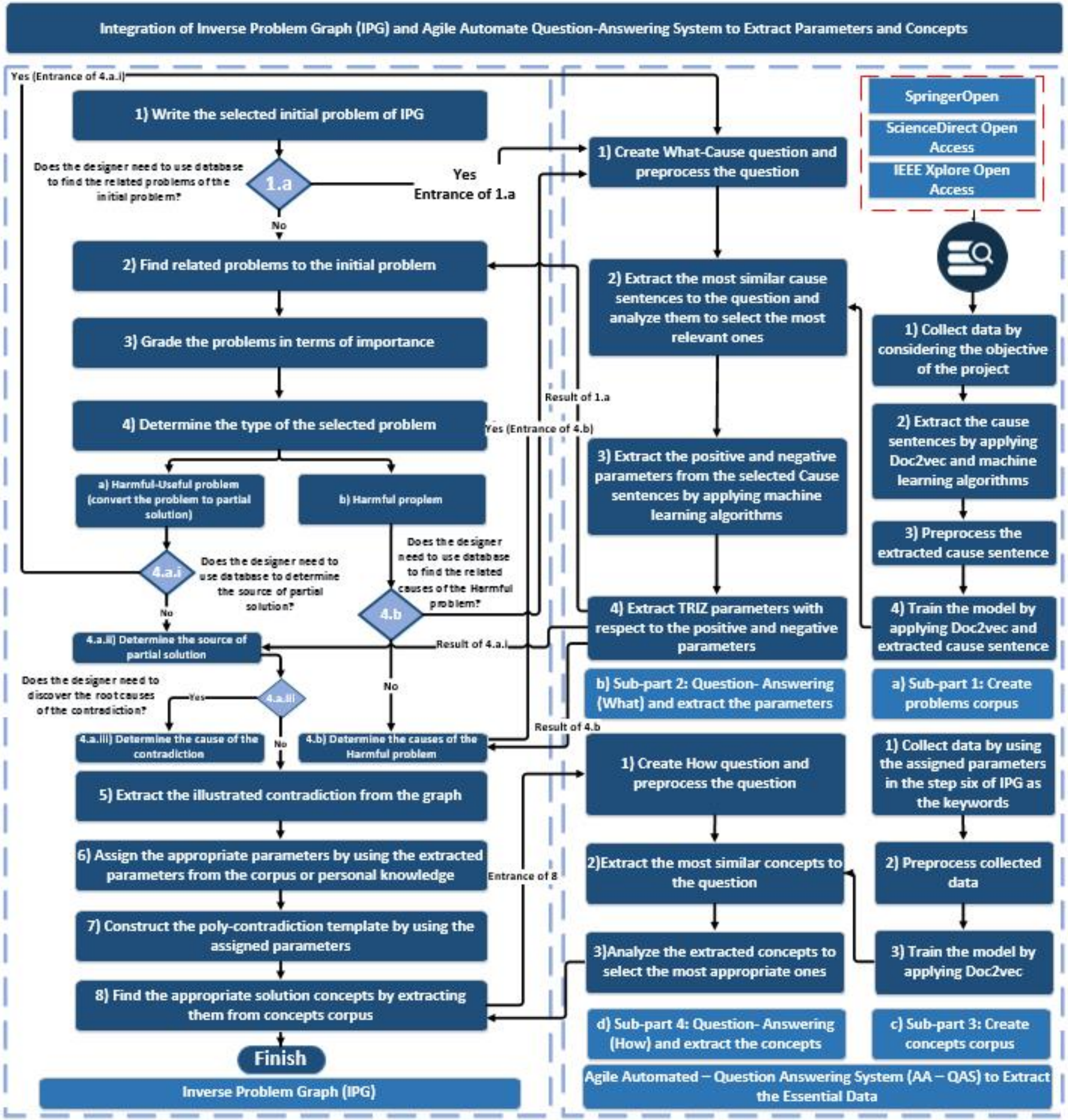
International conferences:

1. ***Hanifi, M***., Chibane, H, Houssin, R., and Cavallucci, D.. 2019. "Improving inventive design methodology's agility" *International TRIZ Future Conference* (pp. 216-227). Springer, Cham.
2. ***Hanifi, M***., Chibane, H, Houssin, R., and Cavallucci, D.. 2020. "A Method to Formulate Problem in Initial Analysis of Inventive Design" In *IFIP International Conference on Product Lifecycle Management* (pp. 311-323). Springer, Cham.
3. ***Hanifi, M***., Chibane, H, Houssin, R., and Cavallucci, D.. 2020. "Contribution to TRIZ in Combining Lean and Inventive Design Method" In *International TRIZ Future Conference* (pp. 280-291). Springer, Cham.
4. ***Hanifi, M***., Chibane, H, Houssin, R., and Cavallucci, D.. 2021. "Application of an FMEA based method to prioritize the initial problem choices in Inventive Design" In *International TRIZ Future Conference*, (pp 233-244). Springer, Cham

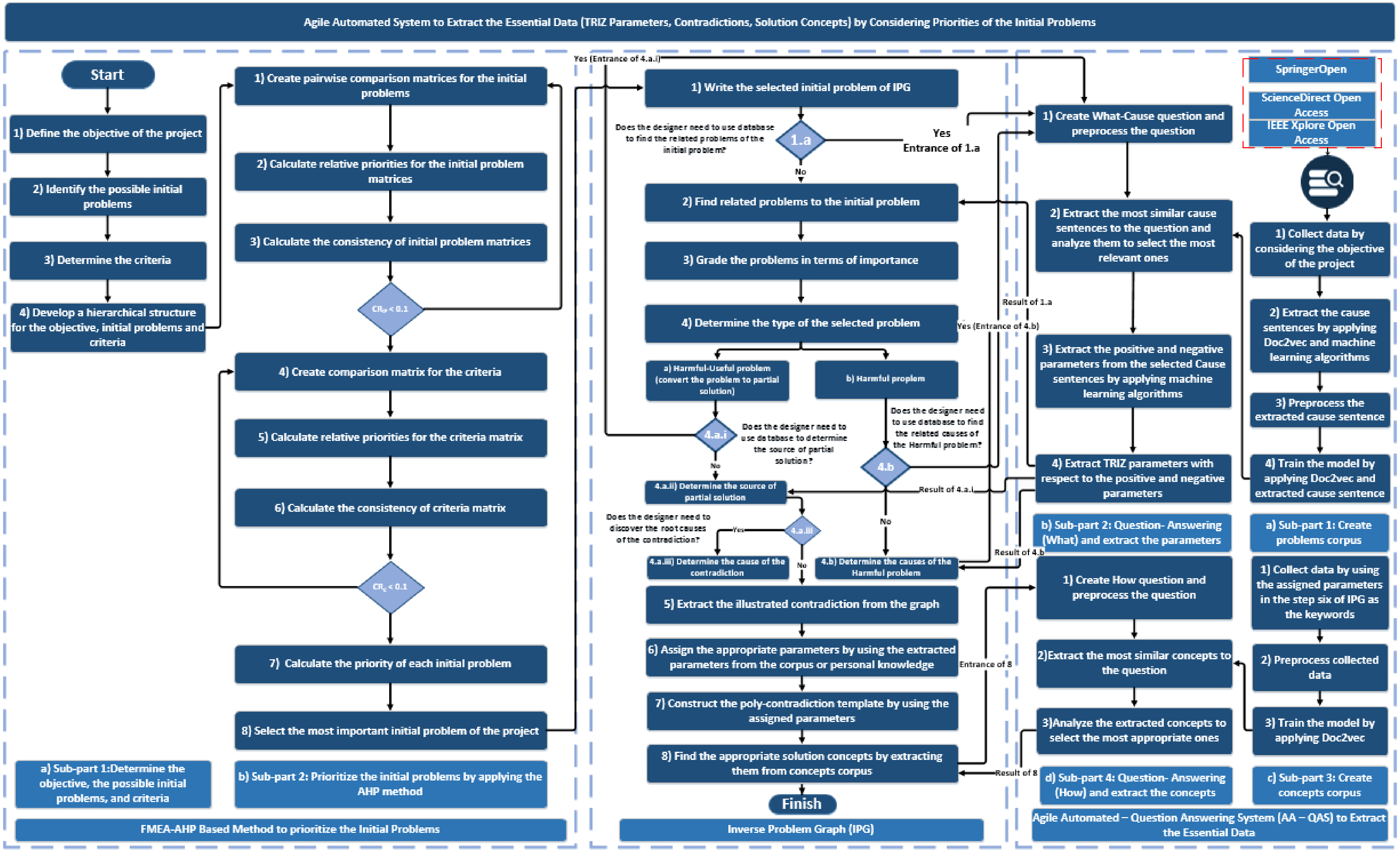
Annex B



Integration of FMEA-AHP Based Method and Inverse Problem Graph (IPG) to Prioritize the Initial Problems
Start
1) Define the objective of the project
2) Identify the possible initial problems
3) Determine the criteria
4) Develop a hierarchical structure for the objective, initial problems and criteria
1) Create pairwise comparison matrices for the initial problems
2) Calculate relative priorities for the initial problem matrices
3) Calculate the consistency of initial problem matrices
CR_ip < 0.1
4) Create comparison matrix for the criteria
5) Calculate relative priorities for the criteria matrix
6) Calculate the consistency of criteria matrix
CR_c < 0.1
7) Calculate the priority of each initial problem
8) Select the most important initial problem of the project
a) Sub-part 1:Determine the objective, the possible initial problems, and criteria
b) Sub-part 2: Prioritize the initial problems by applying the AHP method
FMEA-AHP Based Method to prioritize the Initial Problems
1) Write the selected initial problem of IPG
2) Find related problems to the initial problem
3) Grade the problems in terms of importance
4) Determine the type of the selected problem
a) Harmful-Useful problem (convert the problem to partial solution)
b) Harmful proplem
4.a.i) Determine the source of partial solution
Does the designer need to discover the root causes of the contradiction?
Yes
4.a.ii
4.a.ii) Determine the cause of the contradiction
No
4.b) Determine the causes of the Harmful problem
5) Extract the illustrated contradiction from the graph
6) Assign the appropriate parameters by using the extracted parameters from the corpus or personal knowledge
Finish
Inverse Problem Graph (IPG)



Integration of Inverse Problem Graph (IPG) and Agile Automate Question-Answering System to Extract Parameters and Concepts
Yes (Entrance of 4.a.i)
1) Write the selected initial problem of IPG
Does the designer need to use database to find the related problems of the initial problem?
1.a
Yes
Entrance of 1.a
No
2) Find related problems to the initial problem
3) Grade the problems in terms of importance
4) Determine the type of the selected problem
a) Harmful-Useful problem (convert the problem to partial solution)
b) Harmful proplem
4.a.i
Does the designer need to use database to determine the source of partial solution?
Does the designer need to use database to find the related causes of the Harmful problem?
4.b
No
4.a.ii) Determine the source of partial solution
Result of 4.a.i
Does the designer need to discover the root causes of the contradiction?
Yes
4.a.iii
No
4.a.iii) Determine the cause of the contradiction
No
4.b) Determine the causes of the Harmful problem
5) Extract the illustrated contradiction from the graph
6) Assign the appropriate parameters by using the extracted parameters from the corpus or personal knowledge
7) Construct the poly-contradiction template by using the assigned parameters
8) Find the appropriate solution concepts by extracting them from concepts corpus
Finish
Inverse Problem Graph (IPG)
Result of 1.a
Yes (Entrance of 4.b)
Result of 4.b
Entrance of 8
1) Create What-Cause question and preprocess the question
2) Extract the most similar cause sentences to the question and analyze them to select the most relevant ones
3) Extract the positive and negative parameters from the selected Cause sentences by applying machine learning algorithms
4) Extract TRIZ parameters with respect to the positive and negative parameters
b) Sub-part 2: Question- Answering (What) and extract the parameters
1) Create How question and preprocess the question
2)Extract the most similar concepts to the question
3)Analyze the extracted concepts to select the most appropriate ones
d) Sub-part 4: Question- Answering (How) and extract the concepts
SpringerOpen
ScienceDirect Open Access
IEEE Xplore Open Access
1) Collect data by considering the objective of the project
2) Extract the cause sentences by applying Doc2vec and machine learning algorithms
3) Preprocess the extracted cause sentence
4) Train the model by applying Doc2vec and extracted cause sentence
a) Sub-part 1: Create problems corpus
1) Collect data by using the assigned parameters in the step six of IPG as the keywords
2) Preprocess collected data
3) Train the model by applying Doc2vec
c) Sub-part 3: Create concepts corpus
Agile Automated – Question Answering System (AA – QAS) to Extract the Essential Data


Agile Automated System to Extract the Essential Data (TRIZ Parameters, Contradictions, Solution Concepts) by Considering Priorities of the Initial Problems
Start
1) Define the objective of the project
2) Identify the possible initial problems
3) Determine the criteria
4) Develop a hierarchical structure for the objective, initial problems and criteria
a) Sub-part 1:Determine the objective, the possible initial problems, and criteria
1) Create pairwise comparison matrices for the initial problems
2) Calculate relative priorities for the initial problem matrices
3) Calculate the consistency of initial problem matrices
CR < 0.1
4) Create comparison matrix for the criteria
5) Calculate relative priorities for the criteria matrix
6) Calculate the consistency of criteria matrix
CR < 0.1
7) Calculate the priority of each initial problem
8) Select the most important initial problem of the project
b) Sub-part 2: Prioritize the initial problems by applying the AHP method
FMEA-AHP Based Method to prioritize the Initial Problems
Yes (Entrance of 4.a.i)
1) Write the selected initial problem of IPG
Does the designer need to use database to find the related problems of the initial problem?
1.a
Yes
Entrance of 1.a
No
2) Find related problems to the initial problem
3) Grade the problems in terms of importance
4) Determine the type of the selected problem
a) Harmful-Useful problem (convert the problem to partial solution)
b) Harmful proplem
4.a.i
Does the designer need to use database to determine the source of partial solution?
No
Does the designer need to use database to find the related causes of the Harmful problem?
4.b
4.a.ii) Determine the source of partial solution
Does the designer need to discover the root causes of the contradiction?
Yes
4.a.iii
No
No
4.a.iii) Determine the cause of the contradiction
4.b) Determine the causes of the Harmful problem
5) Extract the illustrated contradiction from the graph
6) Assign the appropriate parameters by using the extracted parameters from the corpus or personal knowledge
7) Construct the poly-contradiction template by using the assigned parameters
8) Find the appropriate solution concepts by extracting them from concepts corpus
Finish
Inverse Problem Graph (IPG)
Result of 1.a
Yes (Entrance of 4.b)
Result of 4.a.i
Result of 4.b
Entrance of 8
Result of 8
1) Create What-Cause question and preprocess the question
2) Extract the most similar cause sentences to the question and analyze them to select the most relevant ones
3) Extract the positive and negative parameters from the selected Cause sentences by applying machine learning algorithms
4) Extract TRIZ parameters with respect to the positive and negative parameters
b) Sub-part 2: Question- Answering (What) and extract the parameters
1) Create How question and preprocess the question
2)Extract the most similar concepts to the question
3)Analyze the extracted concepts to select the most appropriate ones
d) Sub-part 4: Question- Answering (How) and extract the concepts
SpringerOpen
ScienceDirect Open Access
IEEE Xplore Open Access
1) Collect data by considering the objective of the project
2) Extract the cause sentences by applying Doc2vec and machine learning algorithms
3) Preprocess the extracted cause sentence
4) Train the model by applying Doc2vec and extracted cause sentence
a) Sub-part 1: Create problems corpus
1) Collect data by using the assigned parameters in the step six of IPG as the keywords
2) Preprocess collected data
3) Train the model by applying Doc2vec
c) Sub-part 3: Create concepts corpus
Agile Automated – Question Answering System (AA – QAS) to Extract the Essential Data

Amélioration du processus de la conception inventive par l'utilisation de méthodes agiles et d'algorithmes d'apprentissage automatique

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Amélioration du processus de la conception inventive par l'utilisation de méthodes agiles et d'algorithmes d'apprentissage automatique.

Résumé

1. Introduction

La réduction de la durée du cycle d'innovation est un enjeu crucial pour la compétitivité des entreprises [1], [2]. Dans cette optique, les entreprises sont constamment à la recherche d'approches méthodologiques qui les aident à réduire le temps du processus d'innovation sans sacrifier la valeur de leurs résultats. Parmi ces approches, on peut citer les systématiques telles que La conception inventive basée sur TRIZ.

1.2. TRIZ et ses inconvénients

Genrich Altshuler a développé TRIZ ou Théorie de la Résolution Inventive de Problèmes. Cette approche indique que les problèmes rencontrés par les concepteurs dans leurs projets ont probablement également été traités par d'autres concepteurs [3]. TRIZ pourrait aider à réduire le temps nécessaire pour révéler une solution optimale [4]. Cependant, l'application de la méthode TRIZ dans le département R&D présente plusieurs limites. Le premier est qu'il ne fournit aucune méthode pour formuler les problèmes dans les situations initiales. Deuxièmement, TRIZ ne propose aucun moyen pour amener ses utilisateurs à sélectionner les meilleures solutions parmi celles proposées. Troisième limitation, TRIZ ne fournit pas non plus un moyen précis de révéler une contradiction. Enfin, il n'y a pas de description complète de ses composants et de la relation entre eux dans le corpus de connaissances de TRIZ. Pour surmonter ces limitations, les chercheurs ont développé de nombreux cadres, parmi lesquels la Méthodologie de Conception Inventive (MCI) peut être mentionnée.

1.3. Méthodologie de conception inventive et ses inconvénients

La méthodologie de conception inventive (MCI) est un cadre qui a été développé au cours de plusieurs années de recherche pour résoudre les limites de TRIZ et pour compléter son corpus de connaissances avec d'autres théories telles que la théorie de Pugh ou la théorie des graphes [5]. Cette méthodologie comprend les quatre phases suivantes : 1) Phase d'analyse initiale, 2) Phase de formulation des contradictions, 3) Phase de synthèse du concept de solution et 4) Phase de sélection du concept de solution. Néanmoins, une des critiques souvent formulées est que cette approche n'a pas l'agilité nécessaire, et qu'elle est chronophage [6] [7] [8]. Cela est principalement dû à la recherche implicite dans chaque étude pour construire une carte complète d'une situation problématique dans la phase initiale en interrogeant des experts impliqués dans l'étude et en extrayant toutes leurs connaissances, quelle que soit leur efficacité pour résoudre le problème, pour clarifier la situation. Cette étape conduit à de nombreuses contradictions dont seules certaines sont utilisées dans la phase finale pour obtenir la solution [9]. Par conséquent, il était nécessaire de combiner MCI avec d'autres méthodologies qui donnent à son processus les caractéristiques d'une méthodologie agile, y compris la capacité de développement évolutif et itératif, la capacité de générer une réponse rapide et flexible au changement, et la capacité de promouvoir la communication et capacité de planification adaptative [10]. Une de ces méthodologies est la méthode Lean.

1.4. Lean et son application à MCI

L'origine de la théorie du lean se trouve dans les pratiques de la Toyota Motor Corporation dans les années 1950 [11]. [12] and [13]. sont concentrés sur l'aspect de fabrication de l'entreprise. Cependant, leurs auteurs ont insisté sur la mise en œuvre des mêmes principes dans d'autres secteurs industriels, comme l'innovation, afin d'éliminer les activités sans valeur ajoutée dans une démarche d'excellence [14]. En conséquence, nous avons proposé d'appliquer les principes Lean pour augmenter l'agilité et l'efficacité de la phase d'analyse initiale de MCI. Dans cette application, les premier et deuxième principes nous ont aidés à mettre en évidence les activités sans valeur ajoutée au sein de cette phase. Nous nous sommes ensuite inspirés des troisième et quatrième principes pour développer Graph de Problème Inverse (GPI).

1.5. Structure de la thèse

La structure de la thèse est organisée comme suit :

- Chapitre 1 : Introduction générale (contexte et objective de la thèse)
- Chapitre 2 : Revue détaillée de la littérature sur les approches innovantes des problèmes, la théorie de la résolution inventive des problèmes (TRIZ) et les cadres basés sur TRIZ.
- Chapitre 3 : Revue de la littérature sur les méthodes d'analyse initiale et la théorie Lean. Ensuite, la méthode du GPI proposée est détaillée, une application sur l'étude de cas « Covid-19 » est illustrée. Une comparaison entre GPI et d'autres techniques de formuler des problèmes est discutée à la fin de ce chapitre.
- Chapitre 4 : Intégration des méthodes AMDEC, PHA pour l’amélioration du GPI, application sur une étude de cas industriel « Biomass Power Plant ».
- Chapitre 5 : Revue de techniques de Fouille de textes « Text-Mining », et d’algorithmes d'apprentissage automatique. A la fin de ce chapitre, la structure globale de la méthode est représentée.
- La fin de cette thèse, la conclusion et les suggestions pour des travaux futurs ont été développés.

2. L’état de l’art

L'analyse initiale en conception inventive est une phase de collecte de connaissances. Elle repose sur l’analyse de plusieurs ressources, à savoir, des brevets et des documents internes à l'entreprise, consignant le savoir-faire des expert ainsi que des données existantes relatives au sujet étudié [5] [63] [55]. Il existe plusieurs méthodes pour formuler un problème lors de la conception d'un produit ou d'un processus innovant, des méthodes basées sur la recherche de causes, et d'autres sur la recherche d'effets.

Le premier groupe est lié aux méthodes et techniques qui sont utilisées pour identifier les causes qui créent les problèmes dans un projet d'innovation. Certaines méthodes dans ce groupe ne permettent pas de formuler de contradictions telles que : Ishikawa, les 5 Pourquoi et l'Analyse des chaînes causes-effets [67] [68]. Ces méthodes permettent de classer les causes explorées dans plusieurs catégories, ce qui permet d'identifier les domaines dans lesquels des informations devraient être recueillies pour une étude plus approfondie [67] [68] [71]. D'autres méthodes sont basées sur la formulation de contradictions, on trouve par exemple: l'analyse des contradictions racines plus (ACR+), l'analyse de la chaîne de cause à effet plus" [68] [69] [79] [36]. Les méthodes basées sur la formulation de contradictions sont les plus adaptés pour le traitement des problèmes inventifs et des problèmes complexes. Cet ensemble de méthodes est limité par l'importance du nombre de problèmes à traiter, ce qui alourdit considérablement le temps du traitement et d'analyse lors de l'activité de conception. Le deuxième groupe de méthodes est basé sur la recherche des effets des problèmes initiaux. Dans ce groupe, nous trouvons le Réseau de problèmes (RP), et le graphe de problèmes qui est une version améliorée du RP. Ces méthodes permettent de décomposer un problème global en un ensemble de sous-problèmes, plus faciles à résoudre [72]. Étant donné que la définition initiale du problème est souvent trop générale, le réseau de sous problèmes reste vaste et trop complexe, ceux qui implique un temps considérable pour assurer le bon déroulement du processus de conception [78] [74].

Toutes ces méthodes ont cependant une limite, elles n'optimisent pas l'usage des chaînes de causes et d'effets créées lors de l'étape de solution. Ajoutons à cela le temps que les concepteurs consacrent inutilement à la collecte des informations au début du projet sans savoir à l'avance si ces dernières seront utiles à la caractérisation de la solution finale ou non. Notre méthode propose de ne pas retenir tous les sous-problèmes à résoudre afin d'augmenter l'agilité du processus et réduire ainsi considérablement le temps nécessaire de la conduite d'un projet. Dans la section suivante, nous présentons cette méthode.

3. Méthode proposée : Graphe de Problèmes Inverse

La méthode proposée se base sur le Graphe de Problèmes Inverse (GPI), dans cette section la définition et le processus de ce dernier sont illustrées.

3.1. Définition du Graphe de Problèmes Inverse (GPI) :

La méthode du Graphe de Problèmes Inverse considère 5 notions importantes : Les problèmes, les solutions partielles, les paramètres, les niveaux, et les itérations.

Problème : un problème décrit un obstacle qui empêche la réalisation de ce qui doit être fait. Dans notre méthode, nous comptons 5 types de problèmes :

- Problème Initial : il définit la problématique globale du projet et il est placé dans le premier niveau du graphique.
- Problème Nuisible : Nuisance pour le système.
- Problème Source de Solution Partielle : Le caractère nuisible associé au problème conduit à une solution partielle.
- Problème Nuisible-Utile : Combinaison de nocivité et d'utilité pour le système (convertibilité en solution partielle).
- Problème en lien avec les limites de capacité (hors domaine ou technologie, budgétaire, etc.)

Solution partielle : Une phrase qui expose les connaissances du concepteur ou présente dans un brevet déposé par l'entreprise ou sa concurrence et leur expérience.

Paramètres : les paramètres existants dans la structure du GPI sont divisés en deux groupes :

- Paramètres d'évaluation : ce sont les paramètres qui donnent au concepteur la capacité d'évaluer ses choix de conception.
- Paramètres d'action : leur nature réside dans la capacité de modification de l'état du système.

Niveau : Précise l'emplacement du problème et de la solution partielle dans le GPI, à partir problème initial.

Itération : Numéro d'entrée au GPI, afin de choisir une contradiction. Cette notion a été ajoutée à la structure de la méthode proposée. Elle définit le principe dans Lean selon lequel nous devrions créer un flux d'informations.

3.2. Processus du Graphe de Problèmes Inverse

Dans cette section, nous présentons les étapes du processus du Graphe de Problème Inverse (GPI). Ces étapes sont les suivantes, Figure 1 :

1. Étape 1 : Définir l'objectif du projet
2. Étape 2 : Définir le problème initial
3. Étape 3 : Trouver des problèmes liés au problème initial
4. Etape 4 : Classifier les problèmes en fonction de leur importance
5. Étape 5 : Déterminer le type de problème sélectionné : Un problème peut être Nuisible-Utile ou Nuisible.

- Si le problème sélectionné était un problème Nuisible-Utile, il est essentiel de convertir le problème nuisible-utile en une solution partielle. Par la suite, les concepteurs doivent identifier les causes de la solution partielle.

- Si le problème sélectionné était un problème Nuisible, le concepteur doit continuer la chaîne des causes jusqu’à obtenir un problème Nuisible-Utile.

6. Étape 6 : Extraire la contradiction illustrée du graphe
7. Étape 7 : Attribuer les paramètres appropriés aux contradictions

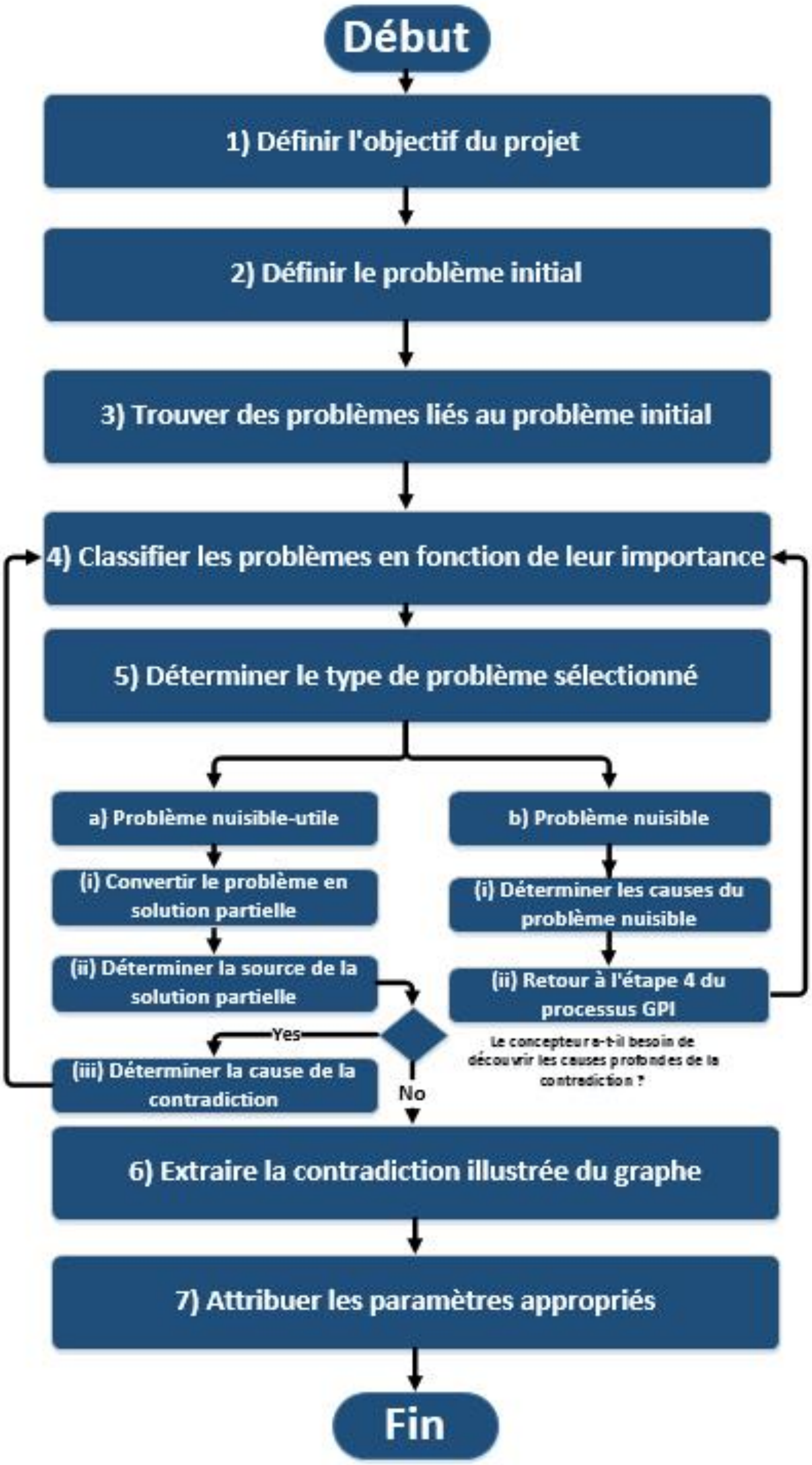

Figure 1. Les étapes du Graphe de Problèmes Inverse (GPI)

4. Compléments au Graphe de Problèmes Inverse

Le GPI augmente considérablement l'agilité du processus de la conception inventive. Cependant, la version initiale du GPI présente nécessite une étape de priorisation des problèmes initiaux, et GPI faciliter/automatiser la collecte des données essentielles.

4.1. La priorisation des problèmes initiaux pour l'GPI :

IPG pourrait contribuer à améliorer l'agilité du processus de conception inventive. Cependant, il ne peut pas montrer la manière de prioriser les problèmes initiaux pour démarrer un projet. Par conséquent, il est nécessaire d'intégrer la méthode du Graphe de Problème Inverse aux approches telles que les méthodes AMDEC (Analyse des Modes de Défaillances, de leurs Effets et de leur Criticité) et PAH (Processus d'Analyse Hiérarchique) pour sélectionner le problème initial le plus important.

L'AMDEC est une technique d'ingénierie largement appliquée pour améliorer un système en identifiant et en éliminant les défaillances potentielles [15]. La version originale de cette technique utilise la méthode Risk Priority Number (RPN) pour hiérarchiser les défaillances identifiées [90]. Cependant, la méthode RPN a été critiquée dans la littérature en raison de certains inconvénients [91]. Par conséquent, de nombreux auteurs ont proposé d'intégrer l'approche AMDEC avec des méthodes alternatives telles que Processus d'Analyse Hiérarchique (PAH) [16]. PAH est une méthode mathématique pour hiérarchiser un ensemble donné d'alternatives en considérant les critères de décision [92]. Depuis l'introduction de PAH, cette méthode a été appliquée à de nombreux types de problèmes de décision, tels que la justification de nouvelles technologies de fabrication ou l'évaluation d'alternatives stratégiques [93]. Afin de résoudre le premier inconvénient de GPI, nous avons proposé d'intégrer les méthodes AMDEC, PAH dans le processus de graphe de problèmes inverse. Cette proposition se compose de trois phases pour montrer la contradiction la plus importante dans la première itération du graphe du problèmes inverse. Figure 2 illustre ces phases. Dans une première phase, l'application de la méthode AMDEC permet de déterminer l'objectif, les éventuels problèmes initiaux et les critères du projet. La deuxième phase concerne la hiérarchisation des problèmes initiaux en appliquant la méthode PAH. Dans la troisième phase, le graphe du problème inverse du problème initial sélectionné doit être construit. Les étapes de chaque phase sont les suivantes :

4.1.1. Première phase :

1) Définition de l'objectif du projet
2) Identification des problèmes initiaux en tant que les modes de défaillance en AMDEC
3) Détermination des critères en tant que les facteurs de risque de la méthode AMDEC

4) Développer une structure hiérarchique pour l’objectif, les problèmes initiaux et les critères

4.1.2. Deuxième phase :

1) Créer des matrices de comparaison par paire pour les problèmes initiaux
2) Calculer les priorités relatives pour les matrices des problèmes initiaux
3) Calculer la cohérence des matrices des problèmes initiaux
4) Créer une matrice de comparaison pour les critères
5) Calculer les priorités relatives pour la matrice des critères
6) Calculer la cohérence de la matrice des critères
7) Calculer la priorité de chaque problème initial
8) Sélectionner le problème initial le plus important du projet

4.1.3. Troisième phase (Les étapes du GPI) :

1) Ecrire le problème initial choisi sur le graphe
2) Déterminer les problèmes liés au problème initial sélectionné
3) Classifier les problèmes en termes d’importance
4) Déterminer le type de problème sélectionné
5) Extraire la contradiction illustrée du graphe
6) Attribuer des paramètres appropriés aux problèmes et à la solution partielle de la contradiction

4.2. La collecte des données essentielles pour l’GPI

GPI ajoute à MCI les caractéristiques des méthodologies agiles [10], qui sont le développement évolutif et itératif, la réponse flexible et rapide au changement, la promotion de la communication et la planification adaptative. Par conséquent, elle pourrait augmenter de manière significative l'agilité de cette approche systématique basée sur TRIZ. Néanmoins, la collecte des données essentielles (paramètres positifs, paramètres négatifs, paramètres TRIZ, contradictions, concepts) par l'application de GPI se fait toujours manuellement, ce qui nécessite des efforts et du temps et réduit considérablement l'agilité de la méthode. Par conséquent, il est essentiel d'intégrer une technique de recherche automatique d'informations, telle que le modèle doc2vec de réseau neuronal et les algorithmes de classification de texte par apprentissage automatique, dans la méthode GPI afin d'accroître son agilité.

Le modèle Doc2vec est proposé par Le et al. dans [17] (vecteurs de paragraphe) comme méthode d'plongement de documents en 2014. Ce modèle est applicable dans la classification de textes et le calcul de similarité de documents [113]. La classification de texte est connue comme la tâche de classer un texte donné dans un ensemble de classes prédéfinies [114]. Pour ce faire, il est possible d'appliquer des algorithmes d'apprentissage automatique [115]. Afin de résoudre le deuxième inconvénient, nous avons proposé d'intégrer le modèle doc2vec et les algorithmes d'apprentissage automatique dans la méthode GPI. Cette intégration nous a permis d'introduire une nouvelle méthode pour les phases d'analyse initiale et de conception de solutions du processus de conception inventive. Cette méthode se compose de deux parties principales : 1) Graphe de Problèmes Inverse (GPI), et 2) Agile Automatisé-Système de Réponse aux Questions (AA-SRQ). Les sous-parties et les étapes de chaque partie sont les suivants, Figure 3.

4.2.2. Part1 : La version modifiée du Graphe de Problèmes Inverse (GPI)

1) Définir le problème initial en considérant l'objectif du projet, et passer à l'étape « créer un question What-Cause » de la partie « Agile Automatisé-Système de Réponse aux Questions (AA-SRQ) » afin de trouver les problèmes associés.
2) Trouver les problèmes liés au problème initial en appliquant les connaissances de la base de données
3) Classifier les problèmes en termes d'importance
4) Déterminer le type de problème sélectionné
5) Extraire la contradiction illustrée du graphe
6) Attribuer les paramètres appropriés à la contradiction en utilisant les paramètres extrait du corpus de problèmes
7) Construire le modèle de poly-contradiction en utilisant les paramètres attribués
8) Trouver les concepts de solution appropriés en les extrayant du corpus de concepts (un corpus général)

4.2.2. Part2 : Agile Automatisé-Système de Réponse aux Questions (AA-SRQ) : Cette partie est divisée en quatre sous-parties :

Sous-partie 2.1 : Créer un corpus de problèmes. Cette sous-partie comprend les étapes suivantes :

1) Recueillir des données en tenant compte de l'objectif du projet
2) Extraire les phrases de cause en appliquant Doc2vec et des algorithmes d'apprentissage automatique
3) Prétraiter les phrases de cause extraite

4) Entraînez le modèle en appliquant Doc2vec et en extrayant les phrases de cause

Sous-partie 2.2 : Question-Réponse (What) et extraire les paramètres. Cette sous-partie comprend les étapes suivantes :

1) Créer une question What-Cause et prétraiter la question
2) Extraire les phrases de cause les plus similaires à la question et les analyser pour sélectionner les plus pertinentes
3) Extraire les paramètres positifs et négatifs des phrases de cause sélectionnées en appliquant des algorithmes d'apprentissage automatique
4) Extraire les paramètres TRIZ par rapport aux paramètres positifs et négatifs

Sous-partie 2.3 : Créer un corpus de problèmes. Cette sous-partie comprend les étapes suivantes :

1) Collecter des données en utilisant les paramètres attribués à l'étape six de GPI en tant que les mots-clés
2) Prétraiter les données collectées
3) Entraîner le modèle en appliquant Doc2vec

Sous-partie 2.4 : Question-Réponse (How) et extraire les paramètres. Cette sous-partie comprend les étapes suivantes :

1) Créer une question How et prétraiter la question
2) Extraire les concepts les plus similaires à la question
3) Analyser les concepts extraits pour sélectionner les plus appropriés

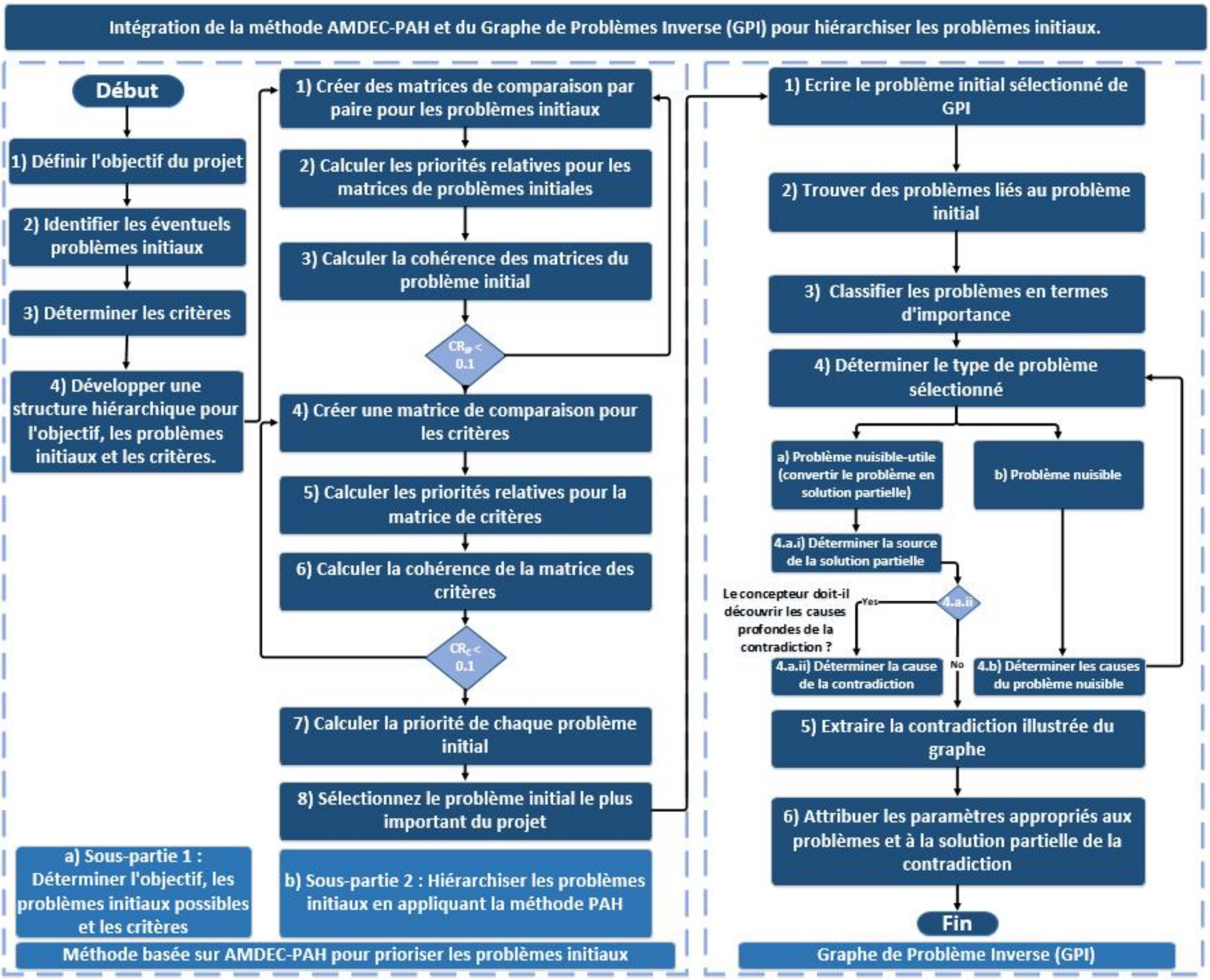

Figure 2. Les différentes parties de la méthode basée sur AMDEC-PAH

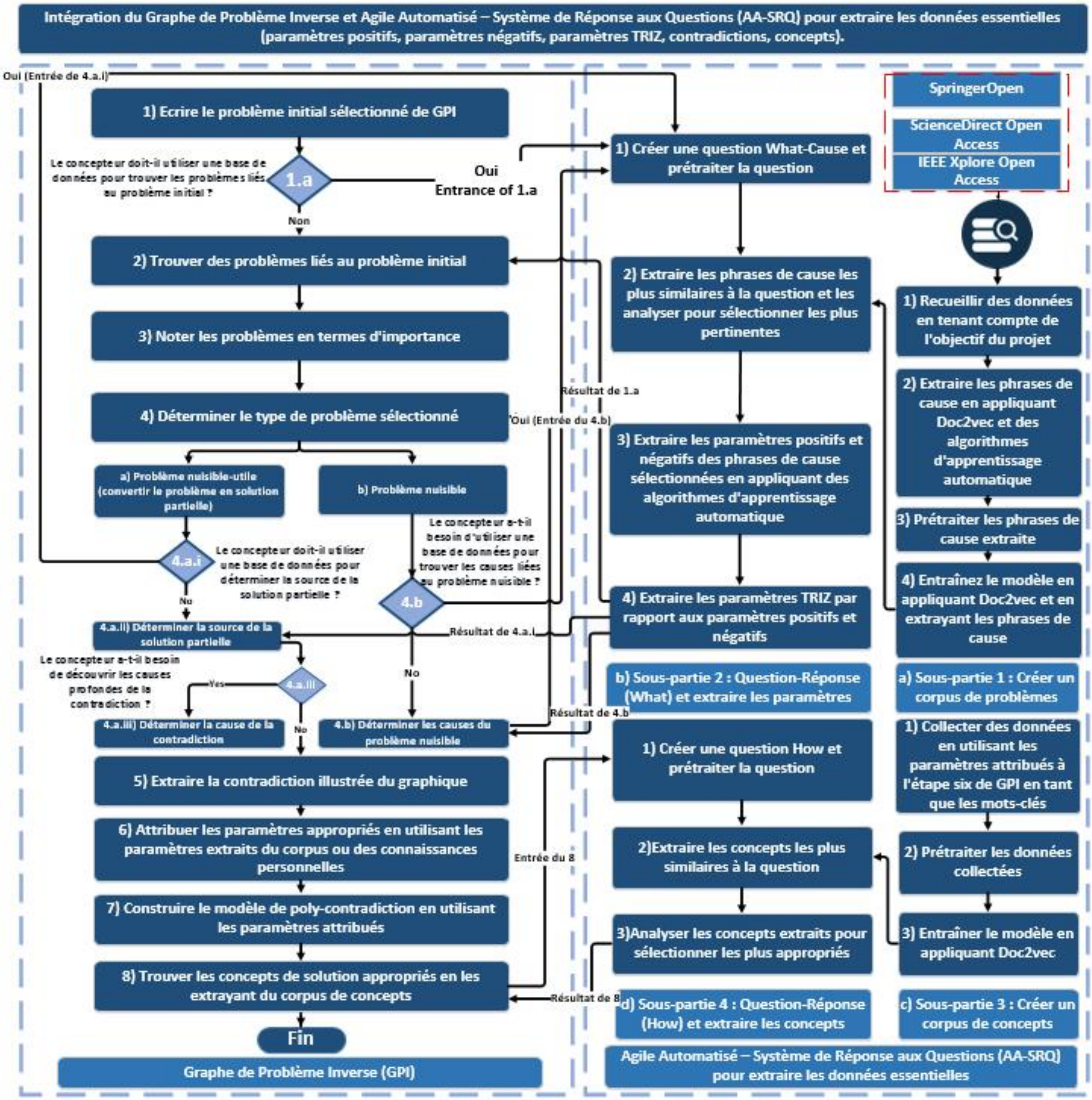

Figure 3. Les différentes parties de la méthode basée sur (AA – SRQ)

La relation entre des différentes parties du système avec les chapitres de la thèse est représentée dans la figure 4.

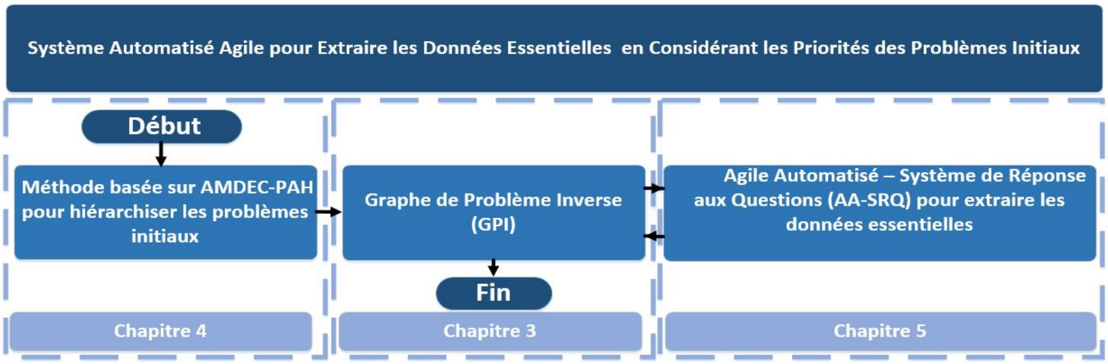

Figure 4. La relation des différentes parties du système ave les chapitres de la thèse

5. Contribution de la thèse

Les principales contributions de cette thèse au processus de conception inventive se reflètent sous plusieurs aspects. Comme première contribution, l'application des principes Lean est d'optimiser le temps de formulation du problème en ne gardant que les éléments essentiels de l'étude à collecter. Deuxièmement, l'intégration des méthodes AMDEC et PHA aide à formuler la contradiction la plus importante à chaque itération de l'analyse initiale de la conception inventive. Comme troisième contribution principale, l'application du modèle doc2vec et des algorithmes d'apprentissage automatique contribue à accélérer et à faciliter la collecte d'informations essentielles, y compris les paramètres et les concepts de solutions

Le processus final détaillé proposé est représenté par la figure

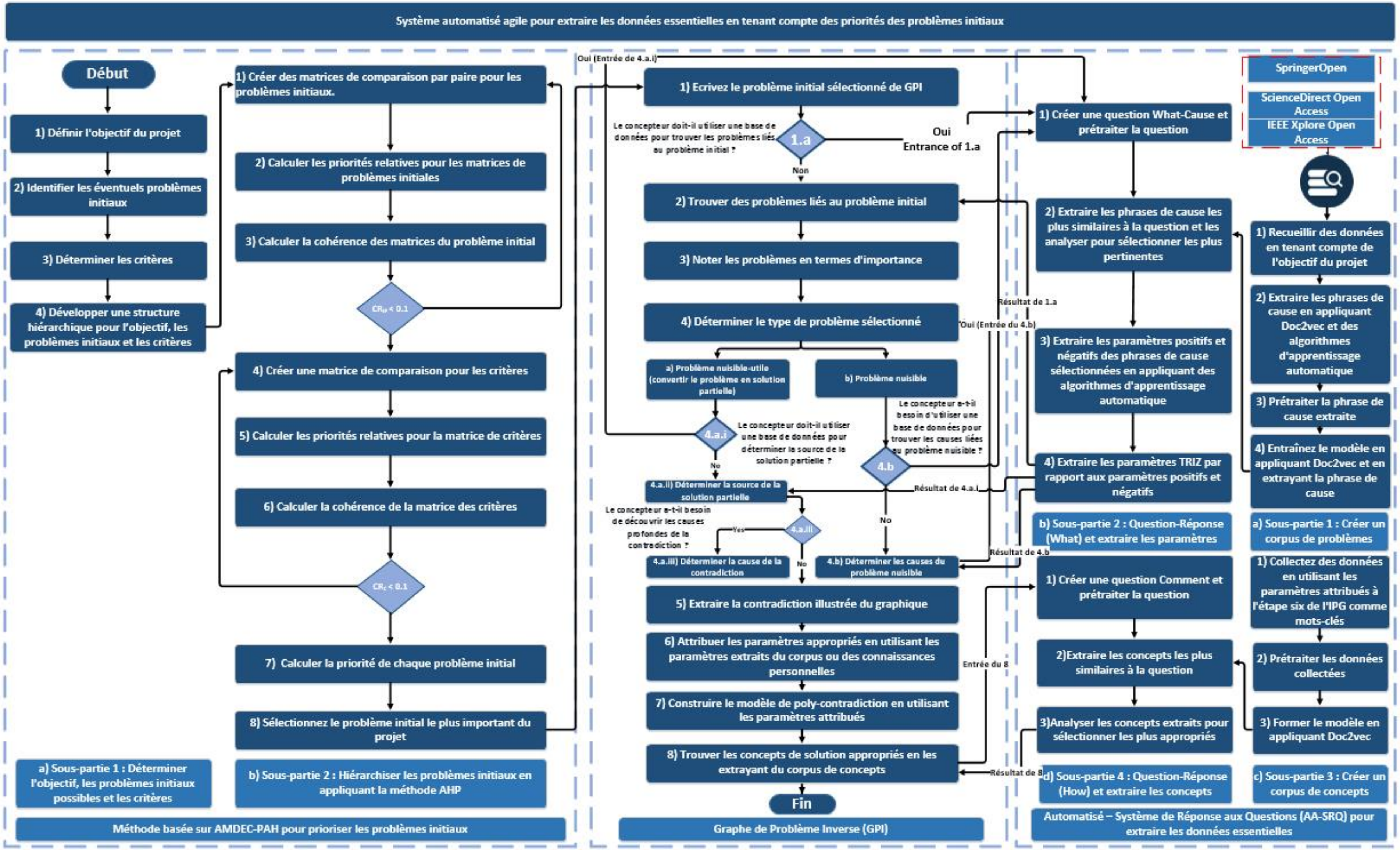

Figure 5. Le processus proposé complet