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► To cite this version:

Masih Hanifi, Hicham Chibane, Remy Houssin, Denis Cavallucci. Application of an FMEA Based Method to Prioritize the Initial Problem Choices in Inventive Design. TRIZ Future conference, Sep 2021, Bolzano, Italy. pp.233-244, 10.1007/978-3-030-86614-3_19 . hal-04067836

HAL Id: hal-04067836

<https://inria.hal.science/hal-04067836v1>

Submitted on 13 Apr 2023

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


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Application of an FMEA based method to prioritize the initial problem choices in Inventive Design

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Abstract. Initial Analysis of a complex situation is one of the most vital phase in inventive design. To ensure an exhaustive and formal method to draw a knowledge representation model, a problem-graph is proposed. However, one of the criticisms often leveled is that the application of these methods is time-consuming. For this reason, the Inverse Problem Graph method was introduced to increase the agility of the inventive design process through the beginning of the problem formulation from an initial problem, located in the lower level of a problem situation. Nevertheless, the way designers should select the most important initial problem among the others is not treated. The purpose of this article is to integrate a Failure Mode Effect Analysis (FMEA) based method into the IPG method in order to prioritize the initial problems in the initial analysis phase. The capability of the proposal is finally tested through its application in a case study.

Keywords: Inventive design, Complex problem, TRIZ, FMEA, AHP.

1 Introduction

In today's fast-changing business environment, many companies are seeking effective means to reduce their innovation cycle time [1]. Among them, it is possible to mention the TRIZ-based systematic approaches such as Inventive Design Methodology (IDM), which help firms to decrease the amount of time to obtain an optimal solutions [2] [3] [4]. Nevertheless, one of the drawbacks of these approaches is that they require to construct a complete map of a problem situation at the initial phase of their process, which make them time-consuming. To solve this, Hanifi et al.[5] [6] proposed Inverse Problem Graph (IPG) by applying Lean principles [7] to formulate a complex problem. IPG could help to improve the agility of inventive design process. However, authors did not mention how users should prioritize the initial problems to start a project. Hence, our proposal is to integrate the Inverse Problem Graph method with approaches such as failure mode and effect analysis (FMEA) to select the most important initial problem.

The remainder of the paper is organized as follows. In the second section, we present the related literature. Then, the third and fourth sections show the structure of the proposal and its application in a case study. In the fifth section, we provide a comparison

between the proposal and the classical method NoP. The last section presents the conclusion.

2 Literature review

2.1 FMEA method and its integration to improve TRIZ

Failure mode and Effect Analysis (FMEA) is a methodology widely applied to identify, prioritize critical failures in a system [8]. FMEA was first developed by National Aeronautics and Space Administration (NASA) in 1960 [9]. Since its introduction, it has been applied in various fields such as chemical, aerospace, automobile, marine, nuclear industries [10].

Several authors proposed to integrate FMEA into TRIZ. Among these integration, Russo et al [11]. developed a tool by the integration of FMEA, TRIZ function analysis and AFD to identify the cause of failure [11]. In addition, Regazzoni et al. integrated FMEA with the tools such as TRIZ functions analysis, and Su-Fields models. The aim of this integration was to reduce failure occurrence by increasing the capability of anticipating problems and technical solutions [12]. Besides, Mzougui et al. proposed to integrate the advantages of TRIZ Anticipatory Failure Determination (AFD) method into FMEA. The objective of this integration was to improve the process of identification of failures [13]. Further, Spreafico et al. proposed to empower FMEA approach by applying the functional analysis to map the main elements of the system, Film Maker and perturbed functional analysis to determine the failure effects, and subversion analysis to identify failure causes [14]. But closest to our research, Hakim et al. proposed to apply FMEA to prioritize the output contradictions of Network of Problem (NoP) [15]. This application can help to reduce the number of contradictions to solve in the next phases of inventive design. Furthermore, it can contribute 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 by means of Risk Priority Number (RPN), which is calculated through multiplying the scores of risk factors, namely, detection (D), severity (S), and occurrence (O), as Equation 1. Shows [16].

$$RPN = S \times O \times D \quad (1)$$

The classical RPN formula is straightforward and very simple to understand [17]. However, the RPN considers only three factors to prioritize the failures, which may neglect other important factors such as time, cost, urgency, etc [18]. Besides, it does not take into consideration the possible weights for the importance of its risk factors [19]. To overcome the mentioned limitations, a number of studies in the literature have developed various models [19]. The analytic hierarchy process (AHP) is one of these models.

2.2 Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is an approach that was developed to support multi-criteria decision making [20]. This approach was introduced by Satty [21]. The aim of applying the AHP method is to determine a ranking of the choices when all the decision criteria are considered. [22]. The process of the AHP method consists of the following steps [23]:

- In the first step of the AHP process, a hierarchical structure is established [24]. To do so, AHP decomposes a complex decision problem into a hierarchy of interrelated decision alternatives and criteria [23]. This hierarchy includes at least three levels: the decision alternatives are located at the bottom, the criteria are in the middle of the hierarchy, and the objective is at the top level [20].
- The second step is to construct the pairwise comparison matrix to indicate the importance of criteria and alternatives [25].
- In the third step, the pairwise matrices should be normalized to calculate the priority weight of alternatives and criteria [25].

AHP can consider a large number of qualitative and quantitative criteria to prioritize the failure modes [22]. Furthermore, it has ability to address the relative importance of the risk factors [26].

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. 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.

The first phase of the methodology includes the following steps:

1. Define the project objective: the project objective is defined in the first step of the process.
2. Identify the initial problems: In the second step, the possible initial problems should be identified as failure modes in FMEA.

3. Determine the criteria: This step relates to determine the criteria of the project as risk factors in FMEA.

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

1. Develop a hierarchical structure for the objective, initial problems and criteria: In this step, the hierarchical structure related to the determined criteria, the identified initial problems and the defined objective should be developed, as shown in Fig. 1.

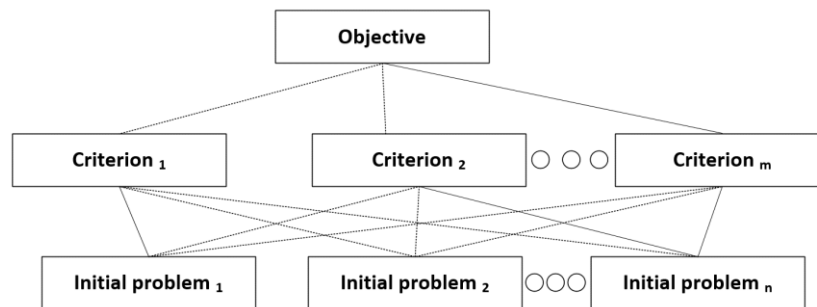


Fig. 1. A three-level hierarchical structure for the objective, criterion and the initial problems

2. Create pairwise comparison matrices for the initial problems: The second step of this phase relates to create the pairwise comparison matrices of the initial problems by considering each criterion. In this step, it is possible to use a numerical rating including nine rank scales, as Table 1 shows. Let A represents $n \times n$ pairwise contradiction matrix related to the initial problems.

Table 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

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

3. Calculate relative priorities for the initial problem matrices: In this step, the priorities related to each initial problem in the matrices should be calculated. To do so, each set of column values is summed. Subsequently, each value of the matrices is divided with the sum of its column. Finally, the average of row values is calculated to obtain the priorities of the matrices.
4. Calculate the consistency of initial problem matrices: In the fourth 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:

$$CI_{IP} = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

- Sub-step 3: Calculate the consistency ratio(CR_{IP}): In the final sub-step of step 4, the consistency ratio is calculated as the ratio of CI_{IP} and the random index (RI), as the following equation shows:

$$CR_{IP} = \frac{CI_{IP}}{RI} \quad (4)$$

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.

5. Create comparison matrix for the criteria: This step relates to create 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.

$$B = (b_{ij})_{m \times m} = \begin{bmatrix} 1 & b_{12} & \dots & b_{1m} \\ b_{21} = \frac{1}{b_{12}} & 1 & \dots & b_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} = \frac{1}{b_{1m}} & b_{m2} = \frac{1}{b_{2m}} & \dots & 1 \end{bmatrix} \quad (5)$$

6. Calculate relative priorities for the criteria matrix: In this step, the priorities related to each criterion in the matrix should be calculated.
7. Calculate the consistency of criteria matrix: In the seventh 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:

$$CI_C = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

- 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:

$$CR_C = \frac{CI_C}{RI} \quad (7)$$

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.

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

The third phase of the methodology relates to construct Inverse problem graph of the selected initial problem to identify the possible contradiction. This phase includes the following steps:

At the beginning of this phase, 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 second step, the problems are ranked to select the most important one among determined ones. The third 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 fourth step of the phase. Finally, the appropriate parameters are allocated to the problems and partial solutions of the extracted contradiction.

4 Application of the proposal method into “Biomass Power Plant” case study

In this section, we applied the proposed method to Biomass Power Plant case study. It is worth noticing that this subject has been extracted from [27] to illustrate the application of the proposal. 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 “IP1: Constant supply of powder increases the costs of power plant.”, “IP2: The efficiency of power plant has been reduced.”, and “IP3: Cleaning operation is expensive.” as the existing initial problems in this case study. In the following, we determined “C1: Financial”, “C2: Strategic”, and “C3: Urgency” as three criteria of the “Biomass Power Plant” case study.

In the first step of the second phase, the hierarchical structure of the objective, initial problems, and criteria was developed. The Fig. 2 shows this hierarchical structure.

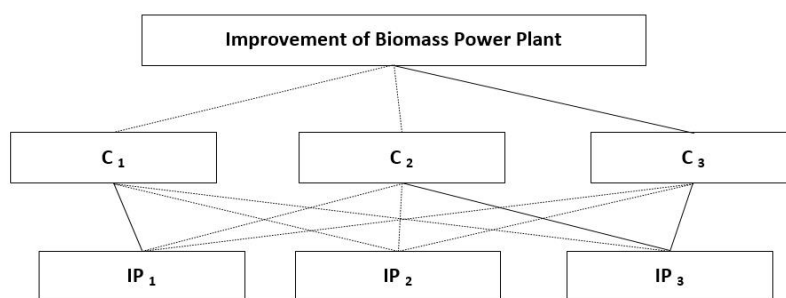


Fig. 2. The hierarchical structure for the Biomass Power Plant case study

Subsequently, we construct the pairwise matrices of the initial problems by considering each criterion. Then, the priorities related to each initial problem in matrices was calculated. In the following, we checked the consistency of the pairwise matrices. Table 2, 3, and 4 show the pairwise matrices of the initial problems related to each criterion.

Table 2. Pairwise matrix for the initial problems by considering criterion C₁

C ₁	IP ₁	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	$\lambda_{\max} = 3.09$, $CI = 0.04$, $CR = 0.08 < 0.1$ (Acceptable)			

Table 3. Pairwise matrix for the initial problems by considering criterion C_2

C_2	IP_1	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	$\lambda_{max}= 3.06, CI = 0.03, CR = 0.053 < 0.1$ (Acceptable)			

Table 4. Pairwise matrix for the initial problems by considering criterion C_3

C_3	IP_1	IP_2	IP_3	Priority
IP_1	0.157	0.272	0.148	0.193
IP_2	0.052	0.090	0.106	0.083
IP_3	0.789	0.636	0.744	0.723
Consistency	$\lambda_{max}= 3.11, CI = 0.055, CR = 0.096 < 0.1$ (Acceptable)			

According to the process, we constructed also the pairwise matrix of the criteria. Then, we calculated the relative priorities and the consistency of the matrix. Table 5 shows the pairwise matrix related to the criteria.

Table 5. 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	$\lambda_{max}= 3.05, CI = 0.027, CR = 0.047 < 0.1$ (Acceptable)			

At the end of the second phase of the process, we calculated the priorities of the initial problems with respect to the objective of the project, as Table 6 illustrates. Then, we selected “IP2: The efficiency of power plant has been reduced.” as the most important initial problem.

Table 6. Prioritization of the initial problems with respect the objective

Initial problems	C_1	C_2	C_3	Objective	Priority
IP_1	0.178	0.056	0.020	0.255	2
IP_2	0.407	0.185	0.008	0.601	1
IP_3	0.046	0.017	0.076	0.140	3

In the third phase, we constructed the Inverse Problem Graph of the selected initial problem, Fig. 3. , and we extracted the following contradiction, Fig. 4, from the first iteration of the IPG process.

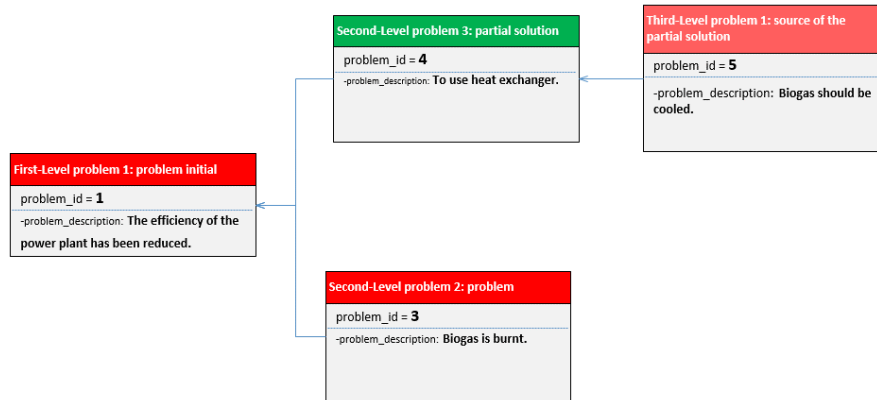


Fig. 3. The inverse problem graph related to the selected initial problem

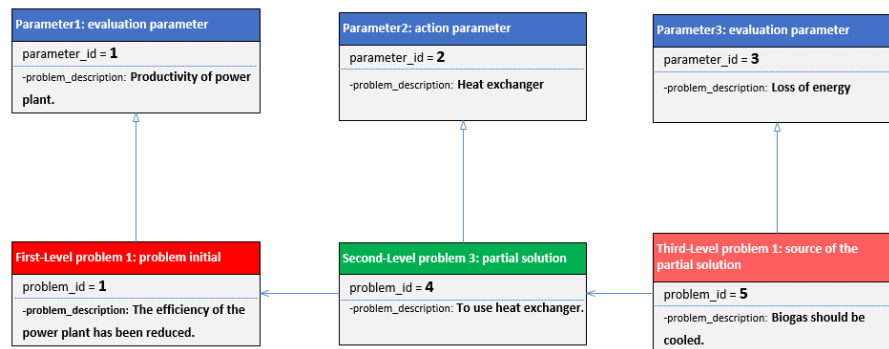


Fig. 4. The extracted contradiction in the first iteration

The formulated contradiction in the last phase of the process can help us to apply the TRIZ's tools such as contradiction matrix and inventive principles to generate solution concepts.

5 Comparison of 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 [27], as shown in Table 7 & Fig. 5 (a) & (b). The figures and table displays that designers formulated all the problems and partial solutions related to the "Biomass Power Plant" subject without considering their priorities. As illustrated in Fig. 5 (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.

Table 7. List of partial solutions and problems related to “Biomass Power Plant” subject

PS or PB N°	Description of Partial Solution (PS) or Problem (PB)	PS or PB N°	Description of Partial Solution (PS) or Problem (PB)
1.PB	Power plant should be improved.	13.PS	Heat exchanger is used.
...
7.PS	Cause effecting pollution should be eliminated or neutralized somehow.	19.PB	Heat exchanger reduces efficiency of power plant.
...
9.PB	Biogas should be cooled before cleaning by modern technological devices.	48.PB	Technological efficiency.
...	...	68.PB	High speed, high temperature of flue gases destroy the post combustion chamber at the turn point.

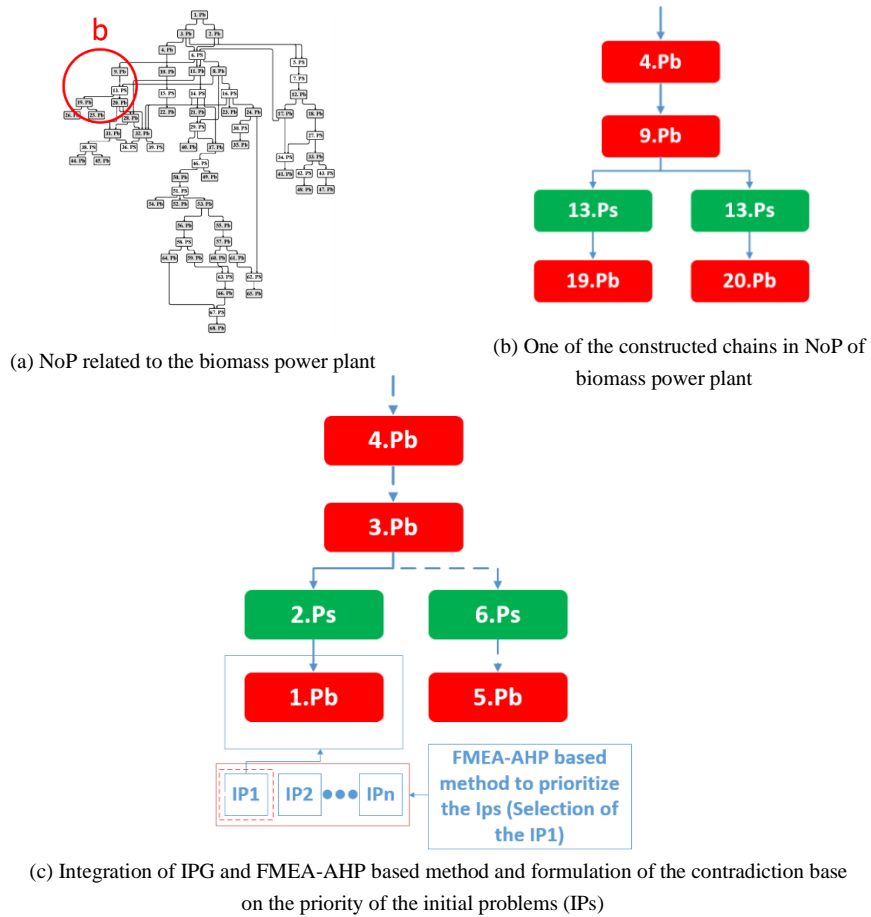


Fig. 5. Network of Problem and its difference with the proposal [50]

6 Conclusion

In this study, we proposed a new method, which integrates FMEA and AHP into Inverse Problem Graph to prioritize the initial problems in 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 the several researches on the Analytical Hierarchy Process. Finally, we proposed an integration of FMEA, AHP methods to prioritize the initial problems in Inverse Problem Graph method. We then tested the ability of the proposal by its application in Biomass Power Plant case study.

The analysis of this practical application demonstrated usability and usefulness of our proposal. However, it shows also several limitations. As the most important one, we can mention that mathematical calculations of such a method can significantly reduce the agility of the process. Therefore, future research needs to be done to improve the capability of this proposal such as its integration with other methods.

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