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Advanced Fuzzy Rule-based Failure Mode and Effects Analysis

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Summary

In my thesis, I proposed advanced methods to improve Fuzzy rule-based Failure Mode and Effect Analyses (F-FMEA) models.

In Chapter 1, I described my research goals, the methods used, and the structure of the thesis. In Chapter 2, I reviewed the theoretical background of the scientific approaches used in my research. In Chapter 3, I introduced the fuzzy rule-based hierarchical FMEA (H-FMEA) model, which extends the standard risk analysis method. I demonstrated that fuzzy-based FMEA is advantageous since it can provide an efficient solution by merging numerical and linguistic factors while accounting for subjectivity. Simultaneously, the hierarchical structure proved to improve the efficiency of the assessment and the model's flexibility. A case study was devoted to illustrating the proposed method making a preliminary risk analysis of the wheel speed sensor's reliability and safety. In Chapter 4, I proposed a novel methodological approach to implementing H-FMEA as a further development of an existing hierarchical case study. In the novel method, membership functions are different depending on the level. Furthermore, I showed if information transmitted across the levels is a fuzzy number instead of an exact value, then reliability and safety can be further improved. In Chapter 5, I used the F-FMEA technique to describe, classify and assess risk factors of big (Installation problem, short fatigue life) and small (Slack-running fit, early failure) that may materialize in the bearing manufacturing process. In the F-FMEA model, I investigated various defuzzification approaches and proposed Summative-defuzzification methods that combine different fuzzy subsystems outcomes.

Summary in Hungarian language – Magyar nyelvű összefoglaló

Értekezésemben a Fuzzy Szabálybázisú Hibamód- és Hatáselemzés (Fuzzy Failure and Effect Analysis – F-FMEA) továbbfejlesztett módszereit dolgoztam ki.

Az 1. fejezetben ismertetem kutatási céljaimat, az alkalmazott módszerekét és az értekezés felépítését. A 2. fejezetben áttekintem a kutatásom során alkalmazott tudományos megközelítések elméleti hátterét. A 3. fejezetben bemutatom a Fuzzy Szabálybázisú Hierarchikus FMEA (H-FMEA) modelljét, amely kiterjeszti a hagyományos kockázatelemzési módszereket. Bemutatom, hogy a fuzzy szabálybázisú FMEA azért előnyös, mert a numerikus és nyelvi tényezők összevonásával, a kockázatbecslők szubjektivitásainak figyelembevételével hatékony megoldást nyújthat. Ezzel egyidejűleg a hierarchikus struktúra javítja az értékelés hatékonyságát és a modell rugalmasságát. A javasolt módszer előnyeit egy olyan esettanulmány segítségével mutatom be, amely egy keréksebesség-érzékelő előzetes megbízhatóságát és biztonságát elemzi. A 4. fejezetben egy új módszertani megközelítést dolgoztam ki a H-FMEA megvalósításához egy meglévő hierarchikus esettanulmány továbbfejlesztéseként. Az új módszerben a tagsági függvények szinttől függően eltérőek. Továbbá bemutatom, hogy ha a szinteken átvitt információ pontos (crisp) érték helyett egy fuzzy szám, akkor a megbízhatóság és a biztonság becslésének pontossága tovább javítható. Az 5. fejezetben az F-FMEA technikát használtam a csapágygyártási folyamatban jelentkező nagy (például beszerelési vagy gyors kifáradási problémák) és kicsi (például lazafutás vagy korai meghibásodás) kockázati tényezők leírására, osztályozására és értékelésére. Az F-FMEA modellben különféle defuzzifikációs módszereket vizsgáltam, és olyan összegző defuzzifikációs (Summative-defuzzification) eljárásokat dolgoztam ki, amelyek kombinálják a különböző fuzzy alrendszerek eredményeit.

1 The Actuality of the Topic

Nowadays, the qualified functions of the engineering system play a more significant role in our daily lives than ever before. During the design and development of engineering systems and their components, safety and dependability become increasingly important [1]. The main reason for this is that when engineering goods and designed systems develop, they grow more complex.

Total quality and reliability awareness has nearly become a requirement for industries to keep up with the constantly developing and changing global competitive environment. In this context, the spread of high-quality and continuous improvement philosophy has paved the way for new strategies, techniques, and applications.

In the innovative automotive industry, the focus of companies has been on the quality and reliability of their products as a strong management strategy. The quality and reliability cannot be linked solely to the manufacturing process but to various methods and measures from the time the product is created until it is in the hands of the customer. As a result, the prevention of function failures is essential to the end product's quality since the goal is to produce long-lasting and user-friendly products that satisfy customers' expectations. Thus, implementing quality evaluation methodologies is a strategic tool that leads to more profitable products [2].

According to the researchers, continuous efforts must be made to prevent the causes of failures Furthermore, it is inferred that preparing each action yields more significant quality results [3]. Hence, this dissertation's primary purpose is to identify and evaluate the failures in some critical parts of automotive components (hardware and software). Using some recent studies, I have introduced first Failure Mode and Effect Analysis (FMEA) and mainly focused on Fuzzy rule-based FMEA (F-FMEA) as the risk assessment method.

FMEA has proven to be an excellent systematic approach for assessing failures in a system, product, or process. During the product development cycle, specialists in the respective domains often perform it [4]. This approach can be used to improve the quality of new or current systems, products, or processes. Furthermore, studies show that successful FMEA implementations can improve a company's ability to compete on a worldwide scale [5][6]. This method is sometimes perceived as simple, but there are some flaws in obtaining adequate measurements against evaluations. As a result, a large number of scholars have developed a new risk assessment methodology based on fuzzy sets and rule-based inferences. Furthermore, scientists have stated that the F-FMEA technique is an excellent foundation for obtaining reliable results [7]. In contrast to the language concepts employed in FMEA, the vulnerability of theoretical relations is transformed into numerical systems in fuzzy set theory [8].

Fuzzy sets and inference systems have made significant advances in every modern scientific research field. It has a wide range of theoretical and practical research applications, ranging from life sciences to physical sciences, engineering to health and sciences, computer science to arts and humanities. In recent years, the fuzzy sets have expanded into new types, and these extensions have been employed in numerous domains such as economics, energy, medicine, materials, and pharmaceutical science [9]. In addition, the considerable volume of Fuzzy logic has been reflected in several fields like automobile speed control [10], water filter automation [11], operating systems of automatic trains [12], and management of robotic manipulators [13].

The fuzzy logic approach has advantages and disadvantages compared to classical methods. The most crucial advantage of fuzzy logic is that it is very close to the human brain's functioning when comparing binary logic. It, therefore, appears to be a reflection of human thought. Fuzzy logic is used most successfully in uncertain and nonlinear systems. However, a specific method cannot use whether the system is uncertain or nonlinear. Because the membership functions are system-specific based on experiences, this adaptation process is very demanding and time-consuming. This means that enough data must be collected by experts and an appropriate rule base established to function optimally in any system. As a result, collecting data and establishing a rule base takes time through trial and error.

Currently, Fuzzy sets theory is a massive approach for gaining computer reasoning systems. Over the last four centuries, mathematical models have demonstrated their importance for understanding natural processes.

2 Research Objective

In my dissertation, I aim to develop mathematical modeling of the fuzzy inference process for risk assessment of engineering components required for automobiles.

From the introduction of analysis and background, the aims are:

- Addressing the Mamdani-type Fuzzy Inference Process (MFIP) concept to minimize overall losses, identify risk context and acceptability.

- To work out novel risk assessment methods by modeling MFIP for Failure Mode and Effect Analysis (FMEA).

3 Research Methodology

The primary research approach for this study is a review of the literature and elaboration. Thus, I first reviewed various past publications in my thesis to understand better the Failure Mode and Effects Analysis (FMEA), fuzzy sets theory, and risk assessment behavior and properties. Many works have been investigated before about the combination of FMEA with fuzzy logic. However, I have focused on projects that contain modern fuzzy sets applications based on risk analyses. Therefore, I present below some introductory studies that contributed to the progress of my dissertation.

By Pokorádi [14], "Modern equipment and systems should meet technical, safety and environmental protection requirements.", the author studied the fuzzy rule-based risk assessment method to manage a specific helicopter mission. By expert's (pilot's) reports, the author has determined the severity and probability of possible air-crashes. The article also reports the importance of expanding the fuzzy rule-based theory of use, research, and methodology and its practical use in modern Hungarian military science.

Zolotukhin and Gudmestad show how experts' information and assessment can be appropriately used to quantify possibilities for an accident in a risk analysis. They have used fuzzy set theory, which is a tool that is mathematically stringent and well established to quantify possibilities of accidental scenarios relying on the expert's assessment. The risk of lifting an offshore module onto a live platform and the risk of an offshore tow operation are both assessed in their research using the fuzzy sets approach [15].

Dombi and Tóth-Laufer noted that the applicability of traditional Mamdani control is limited by high-level computational requirements in real-time and adaptive systems such as medical-related applications. They have suggested improvements to the conventional Mamdani model, such as the Mamdani-like formed by a discretized output and the arithmetic-based model. They introduced technical adjustments to the Mamdani type controller based on the features of triangular and trapezoidal membership functions, which resulted in a significant reduction in computational requirements compared to the original technique formulated for general shape membership functions [16].

Aliye and Nilsu have proposed a quantitative approach, the proportional risk analysis methodology, integrated with the fuzzy logic operation for occupational health and safety in a case study conducted at a textile firm that makes towels and bathrobes. They have used three parameters for appropriate membership function: probability, frequency, and severity, which are fuzzified. IF-THEN rules-based fuzzy operations are represented for inference to determine the riskiness. After this process, the risk score has found for each defined event using the defuzzification process [17].

Kwai-Sang Chin et al. have presented a fuzzy knowledge-based assessment system at the conceptual design stage of product development, emphasizing the design of high-quality products. They proposed a fuzzy FMEA assessment method for the new product concept. By integrating multiple areas, they investigated to automate the planning and evaluation, so-called expert product development system. The proposed framework's functions aim to assist inexperienced users in performing FMEA analysis as considering alternative development design concepts in the dimensions of material and component preference for product process planning, robust design, and estimation of product and tooling costs. In design and planning applications, their prototype has proved to be beneficial in fuzzy set theory and knowledge-based systems. Moreover, a world top micro-motor manufacturer has supported the researchers' development effort on a permanent magnet direct current micro motor optimizing project [18].

4 Scientific results

In this research, I aimed to develop mathematical modeling of the Mamdani-type Fuzzy Inference Process (MFIP) to minimize the possible failures in engineering components required for automobiles. I have presented the improved MFIP model by examining two different Failure Mode and Effect Analysis (FMEA) models that have studied before. I handled the developed MFIP concept with FMEA, minimizing overall losses and identifying the risk context and acceptability, ensuring success.

As a result of the thesis, my scientific developments are as follows:

Thesis 1 (T1): I have proposed a new fuzzy rule-based extension of the crisp Hierarchical Failure Mode and Effect Analysis named Fuzzy Hierarchical Failure Mode and Effect Analysis (FH-FMEA), which is used to define, classify, and assess risk factors **[KS1]**.

Thesis 2 (T2): I have proposed a new Level-specific Evaluation-based Fuzzy Hierarchical Failure Mode and Effect Analysis model (LsFH-FMEA) in which different membership functions can be applied at different levels. At the same time, from the System Level (SL) to Design Level (DL), the parameters are transmitted as a fuzzy number. In this way, different technicalities of levels can be presented. Furthermore, transmitting inputs as fuzzy numbers helps to transmit uncertain information between levels **[KS2]**.

Thesis 3 (T3): I have worked out a new evaluation structure, based on the conventional Fuzzy FMEA (F-FMEA) model, called Summative Defuzzification. I have proven their possibilities of use in case of fuzzy rule-based risk assessment. Its great advantage the ability of taking into account different expert opinions in the same model.

> **Thesis 3a (T3a):** I have worked out Summative Center of Gravity (SCoG) Defuzzification Method, where the sub-conclusions, and the aggregated fuzzy sets are evaluated by the CoG method as well **[KS3]**.

Thesis 3b (T3b): I have worked out Summative Center of Area (SCoA) defuzzification Method, where the sub-conclusions, and the aggregated fuzzy sets are evaluated by the center of Area (CoA) method as well.

Thesis 3c (T3c): I have worked out the Summative Combined CoA and CoG (SCoAG) Defuzzification Method, where the sub-conclusions are evaluated by CoA, then aggregated fuzzy sets are evaluated by the Center of Gravity (CoG) method **[KS3] [KS4]**.

Thesis 3d (T3d): I have proven their possibilities of use in Fuzzy rule-based FMEA **[KS3] [KS4]**.

5 Recommendations for future usage

Involving the Failure Mode and Effects Analysis (FMEA) projects at the production facilities can bring more advantages by observing System, Design, and Process failures. In my future research, I will focus on the risk assessment of electric vehicle subsystems and their components, such as Traction battery pack, Charge Port, Electric motor, etc.

Fuzzy rule-based hierarchical FMEA models, which I have developed in this dissertation, will bring more effective results. Moreover, summative defuzzification methods can improve the system based on different outcomes. In addition, new rule bases can be created according to the system's structure, and the Mamdani-type fuzzy inference process mathematically can be improved.

6 References

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7 Publications

7.1 Publications related to theses

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7.2 Further publications

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