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RESEARCH PAPER

Fault Tree Analysis Integrated with DFMEA Approach and Combined AHP-TOPSIS Technique to Improve Product Configuration Considering Reliability and Total Cost, A Real-Life Case Study

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Abstract

Product configuration plays a vital role in product customization. Customers require products with reasonable cost and reliability, so manufacturers should exchange between reliability and production cost through product configuration. To investigate this problem, a novel combined FTA-DFMEA method is presented that implements integrated AHP-TOPSIS to improve product configuration. In this procedure, customer's needs and market's feedbacks are considered to identify possible product failures, and an integrated AHP-TOPSIS is applied in order to select the most crucial potential failure based on some identified and extracted criteria. Then, minimal paths are obtained through fault tree analysis and an inverse search method is done to identify related functions and defective components. Failure modes and effect analysis is implemented to conclude modes of failure, effects, and causes. Subsequently, a combined AHP-TOPSIS method is utilized for ranking failure modes and selecting the most crucial failure mode. Failure modes are addressed according to their importance and corrective actions are carried out to improve product configuration. Suppliers with various policies, reliability, warranty and purchasing costs are considered. In addition, for the first time all configuration models like series, parallel, and joint series-parallel as well as redundancy allocation are taken into consideration. A minimum improvement index is considered, which is determined by the decision-maker based on risk-averseness. Eventually, a case study of a laptop system is introduced to evaluate the practicality of the developed algorithm. The results indicate that the proposed method creates different efficient alternatives for the decision-maker to enhance reliability, total costs, and product configuration. Also, the proposed framework consisting of the integration of failure analysis and MADM techniques, effectively identifies failure modes and prevents them from occurring.

Keywords:
Product Configuration, Reliability, AHP, TOPSIS, FTA, DFMEA

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Introduction

Product configuration denoted to the organization of components that meets customer needs and satisfies product limitations. A good-designed product configuration leads to a competitive benefit by increasing customer satisfaction (Zheng et al. 2020). Customer requirements grow day by day and production technology developments have led to the production of complex products with various components (Omidzadeh et al. 2021). Products' complex nature has made customer expectations higher in terms of product properties, reliability, price, and performance during product life cycle. Also, manufacturers are obligated to produce with appropriate cost to remain in the competitive market (Hemmati and Seifbarghy 2022). In addition, reliability should be considered throughout the entire product development process, and reliability analysis is important due to market competitiveness, the complexity of products, and customer satisfaction (Paganin and Borsato 2017).

Customers demand reliable products with reasonable costs, so manufacturers should perform an appropriate trade-off between product reliability and production cost (Myrodia et al. 2017). The trade-off should be made through product configuration. In order to develop complex products, there are several suppliers for components, and they have different policies, costs of warranty and purchasing (Azadeh et al. 2015). Also, redundancy allocation and various configuration systems like series, parallel, and joint series-parallel configuration are also considered in the production system. Thus, the main objective of this research is to better aid Decision-Makers (DMs) in the trade-off between reliability and cost by product configuration. This study contributes to the literature on product configuration by designing an appropriate framework for recognizing and addressing potential failures modes, which provides DM with wise decisions to enhance product reliability at a reasonable cost. To attain this goal, this study investigates the following main research questions:

- How customers' needs and feedbacks should be analyzed and addressed?
- How to prioritize failure modes using the FMEA approach and integrated AHP-TOPSIS method?
- What are the main criteria for identifying the most significant possible failure?
- How to reduce potential failures of defective components using an FTA based on the functional model of a product?
- What are the different ways to improve product configuration based on DM's risk aversion towards the reliability and entire cost of the product?

To answer the above-mentioned questions, in this study, an integrated Fault Tree Analysis (FTA) and failure modes and effect analysis (FMEA) are used to identify potential failures and their related failure modes and effects. Then, Analytic Hierarchy Process (AHP) and the technique for order preference by similarity to ideal solution (TOPSIS) methods are integrated to select the most crucial potential failure and the most critical failure mode to take corrective actions and improve product configuration. The proposed method presents various alternatives for the DM to make better product configuration, reliability, and total cost.

The organization of this article is as follows: the next section provides a relevant literature about reliability concept and product configuration. In addition, a few of the relevant papers are compared to some problem instances to reach research gaps. We present the proposed model in section 3. Afterward, a real-life case study is studied in section 4. Also, a sensitivity analysis is performed on important problem parameters in this section. Conclusions are expressed in final section.

Literature review

In the case of a Design-for-Reliability approach, Barnat et al. (2015) proposed a methodological approach coupling experiments and simulations. They used two examples of virtual prototyping to express the applicability of the method and emphasis the criticality of the failure criterion definition. Paganin and Borasto (2017) focused on the importance of failure analysis in maintaining reliability through the entire product lifecycle. They did a bibliometric analysis on 50 articles with keywords related to Design-for-Reliability to identify the conceptual basis of topic and challenges, and future research directions it provides. Cho and Park (2019) presented functional modelling guidelines in a Design-for-Assembly approach. They considered customer needs in the early design stages of product development to have cost-effective product concepts, reducing costly functions in the assembly process. Goswami et al. (2021) focused on new product development in an uncertain supply chain to attain risk averse product design concepts, and proposed an analytical framework based on Bayesian network. Garcia Aguirre et al. (2021) concentrated on product design phase of new product development and proposed an integrated framework of FMEA, Pythagorean fuzzy sets, and dimensional analysis in order to improve the risk assessment process of product design. Zhou et al. (2021) investigated on risk assessment of product design and developed a novel FMEA approach that involved causalities among failure modes, interactions among risk factors, and correlations among risk evaluations. Also, the Choquet integral was applied for prioritizing potential failure modes. Chen et al. (2022) proposed an integrated quality function deployment (QFD) and FMEA approach considering failure causality relationships between failure modes and customer requirements of the product component for risk analysis of product design. Sharifi et al. (2022) developed an integrated FMEA-TOPSIS approach for risk analysis of new product development in a dairy company, and proposed risk reduction strategies.

Zhang (2014) focused attention on the importance of product configuration and did a review of 158 articles related to this topic. In order to better develop and make use of product configuration, definitions and concepts regarding this topic were studied, and 14 related issues were identified to be further researched. Product configuration is of great importance and Aldanondo and Vareilles (2008) analysed the impacts of product configuration system implementation on the improved requirement and process configuration, as well as the increased profitability and performance of the configure-to-order manufacturing companies. Dou et al. (2016) also worked on the concept of complex product configuration design, considering the participation of customers in the design stage.

Consideration of product complexity elements and product reliability together provided the basis of a study done by Thomas (2017) in the field of product development. The method presented involves understanding the complexity that a product portfolio brings and using the Six Sigma concept to minimize such complexity which potentially can lead to better quality and reliability management. The game theory came in hand with the work of Du et al. (2014) as they proposed a Stackelberg game theory model to optimize both approaches in product family design which are module-based and scale-based. They developed a bi-level non-linear programming model to obtain an optimal configuration of modules and an optimal individual module performance by scaling design parameters.

Improving reliability was the concern of Zhang et al (2020), where they developed a strategy for early fault removal that was systematic, according to sales data driven from CNC machine tools. Their approach involved four phases of collecting fault data; determining early faults, analyzing them, assessing the criticality of fault causes, and eliminating them. FTA and fault mode, effects, and criticality analysis (FMECA) approaches were utilized in the model. Goo et al. (2019) studied reliability, where they denoted to the hardness of reliability prediction in the design stage and maintaining reliability in search of design alternatives. Ouyang et al. (2022) focused on improving quality of products with respect to reliability and proposed a novel FMEA approach considering combinations of risk factors to avoid interaction effect caused by simultaneous analysis of risk factors.

Failure analysis in reliability concept is crucial, and Li and Soares (2022) concentrated on assessing failure of onshore and floating offshore wind turbines, and proposed a failure rate correction model, a failure rate analogy model, and a Bayesian network for analyzing reliability. Peeters et al. (2018) focused on identifying and assessing critical failure modes by applying FMEA and FTA at the system, function, and component levels. In a similar work, Zhang et al. (2019) developed a hybrid multi-level FMEA and FTA method for a Flexible Manufacturing System (FMS) at the system, and meta-action/component levels to specify serious fault causes. After that the TOPSIS technique was utilized for analysing criticality. In the work of Mzougui and El Felsoufi (2019), an altered FMEA approach for outperforming the traditional FMEA approach was presented. They supposed TRIZ anticipatory failure determination approach to determine and prioritize failures by the AHP method based on maintainability and cost. Li et al. (2021) assigned weights to the risk factors of the FMEA approach to investigate the failures related to floating offshore wind turbines. Yu et al. (2023) developed a novel FMEA approach including the rough cloud model and Multi-Objective Optimization on the basis of Ratio Analysis plus full multiplicative form (MULTIMOORA) method considering randomness and uncertainty of expert opinions, for risk assessment of the single-point mooring system.

In another work, Azadeh et al. (2015) focused on reliability of product configuration and their approach involved integrated FTA-DFMEA for identifying product failures. They took into account supplier’s warranty and purchasing cost, allocation of redundancy, and configuration systems to assess each product configuration. Recently, Beiki Ashkezari et al. (2022) proposed an integrated FTA-FMEA method to improve construction project configuration and better respond to obstacles encountered during project completion processes. They demonstrated the efficiency of Multiple Attribute Decision Making (MADM) techniques, namely AHP and TOPSIS, in the improvement of construction project configuration based on the client’s requirements and the contractor’s obligation. Cui et al. (2023) focused on production of solid propellant rocket engines and developed an integrated FTA-FMEA approach for reliability assessment and applied the Bayesian network method for reliability calculation.

Researches gaps

According to the above-mentioned literature review, features of some studied articles have been classified in table 1 to investigate their gaps. Based on the literature review, although there are many studies in the area on product configuration and reliability analysis, most of the work implemented FTA, and FMEA to specify potential failure and their effect on the system; however, in these tools, conventional crucially analysis according to the risk potential number (RPN) is not enough to assess failure modes and effects. Therefore, a new approach is needed in this field to cover the weaknesses of solely using RPN. In addition, implementing FTA to different potential failures is a time-consuming process with raise challenges toward its ease of implementation, and a sufficient way to identify the most significant failure has not been considered yet. Beiki Ashkezari et al. (2022) utilized a novel approach by integrating FTA and TOPSIS methods in project configuration to avoid delays in construction activities and to deal with challenges in fulfilling project goals, however, no research has used such methods in product configuration field. Moreover, studied articles considered product configuration systems to be a parallel system or a series system, while considering both of these two systems simultaneously and combining them, that is, series-parallel systems can also be considered. However, no previous study has paid attention to series-parallel systems in product configuration. Hence, our goal is to cover these gaps. Contrary to the research conducted by Azadeh et al. (2015), in our proposed approach, we extracted eight criteria to be utilized in ranking the possible failures based on customers' feedback and identifying the most important cause of failure. Furthermore, unlike Azadeh et al. (2015), in our model, a minimum improvement index, determined by DM based on risk-averseness, is considered, and the process of identifying and ranking possible failures should continue until this index is reached.

Table 1: the proposed approach vs. recent articles

Article	Product configuration	FTA	DFMEA	PFMEA	Reliability	Purchasing cost	Warranty cost	Parallel system	Series system	Combination of series and parallel systems	Redundancy	AHP	TOPSIS
The proposed approach	+	+	+		+	+	+	+	+	+	+	+	+
Zhang et al. 2019		+		+									+
Mzougui and El Felsoufi 2019			+									+	
Peeters et al. 2018		+		+									
Goo et al. 2019	+			+	+								
Azadeh et al. 2015	+	+	+		+	+	+	+	+		+		
Zhang et al. 2020		+	+	+	+								

The main contributions of this paper, which differentiate our effort from related studies such as Azadeh et al. (2015), are as follows:

- Implementing the AHP and TOPSIS method to identify the most significant possible failure resulted from consideration of customer's feedbacks and market's needs.
- Identifying and applying several criteria from the perspective of customers and the companies for ranking and prioritizing possible failures.
- Using the AHP and TOPSIS methods instead of implementing FTA to each various possible failure, which is so time-consuming.
- Implementing the AHP method to calculate the weight of criteria in RPN and ranking failure modes and effects resulted from the FMEA method using the TOPSIS approach.
- Considering different systems such as series, parallel, and the combinations of series and parallel systems, that is, joint series-parallel, for product configuration.

Methodology

In this section, the methodology is provided and explained in detail. The proposed approach is according to the work of Azadeh et al. (2015) and extends their work by considering joint parallel-sequential systems. Also, it uses their model until the identification of possible failures, where the proposed approach integrates AHP with TOPSIS to find the most significant possible failure based on some relevant criteria. In addition, it continues using their model until the end of the FMEA section and RPN calculation, where the proposed approach improves RPN by AHP method to calculate the weight of criteria in RPN and ranking fault modes using TOPSIS method. The main assumptions of the model are as below:

1. Products are formed from different components and they are configurable helping the DM to reach optimal product configuration;

2. Components are provided from several suppliers;
3. Purchasing costs, reliability and warranty costs for each component purchased from each supplier is identified;
4. Redundancy is taken into account in product configuration to examine reliability of system;
5. Components can be changed in the configuration step and a new component is substituted.
6. Series, parallel and joint series-parallel systems are available to form products from components.

The step-by-step description of the model (figure 1) is as follows:

1. Customer’s needs and feedbacks should be obtained and Product’s possible failure during production process should be identified.
2. The most significant possible failure must be recognized from all possible failures. Therefore, some related criteria should be introduced and then, the AHP tool is applied to determine these criteria's weight. Next, the TOPSIS technique is used to prioritize various potential failures to recognize the most crucial and critical failure.
3. Based on the abovementioned steps, a fault tree is organized to demonstrate diverse failure modes and effects for the most crucial potential failure.
4. Imperfect components must be specified through analysing the fault tree’s top event.
5. By using FT and imperfect components, design FMEA (DFMEA) is conducted for various failure modes and effects.
6. Integrated AHP-TOPSIS is applied to perform criticality analysis on failure modes and effects, resulting in prioritization of failure modes.
7. For the first iteration, a random product configuration is created.
8. For the random product configuration, reliability and total cost are obtained. If these criteria are tolerable to DM, steps ahead will be either step 11 or 3. If not, step nine will be the following step.
9. Current product configuration is advanced by FMEA and corrections are made for the most serious failure mode.
10. A fresh product configuration should be formed and reliability and total costs are measured. If both factors are desirable to DM, step 11 or 3 is the next step. In contrast, if either reliability or total cost is not acceptable to DM, let Z be the unacceptable item. If the improvement of Z is less than the minimum improvement index considered by the DM, step 5 is the subsequent step (short loop). Otherwise, ninth step is the subsequent step, and corrective actions must take place for the next critical failure mode.
11. In situations where FT is updated, third step will be the following step (large loop). If update of fault tree is not required, the last product configuration is the result. Detection of new faults, the Existence of new causes, the occurrence of new failures and alteration of customer’s needs are reasons to update fault tree.

Customer’s needs and feedbacks

In the product development processes, customer’s requirements and feedbacks are substantial items that should be considered and related to product configuration. Also, identifying possible product failures during the production process is significant and should be regarded. To have a great product, FMEA and quality function deployment (QFD) are applied to take into account customer’s needs (figure 2).

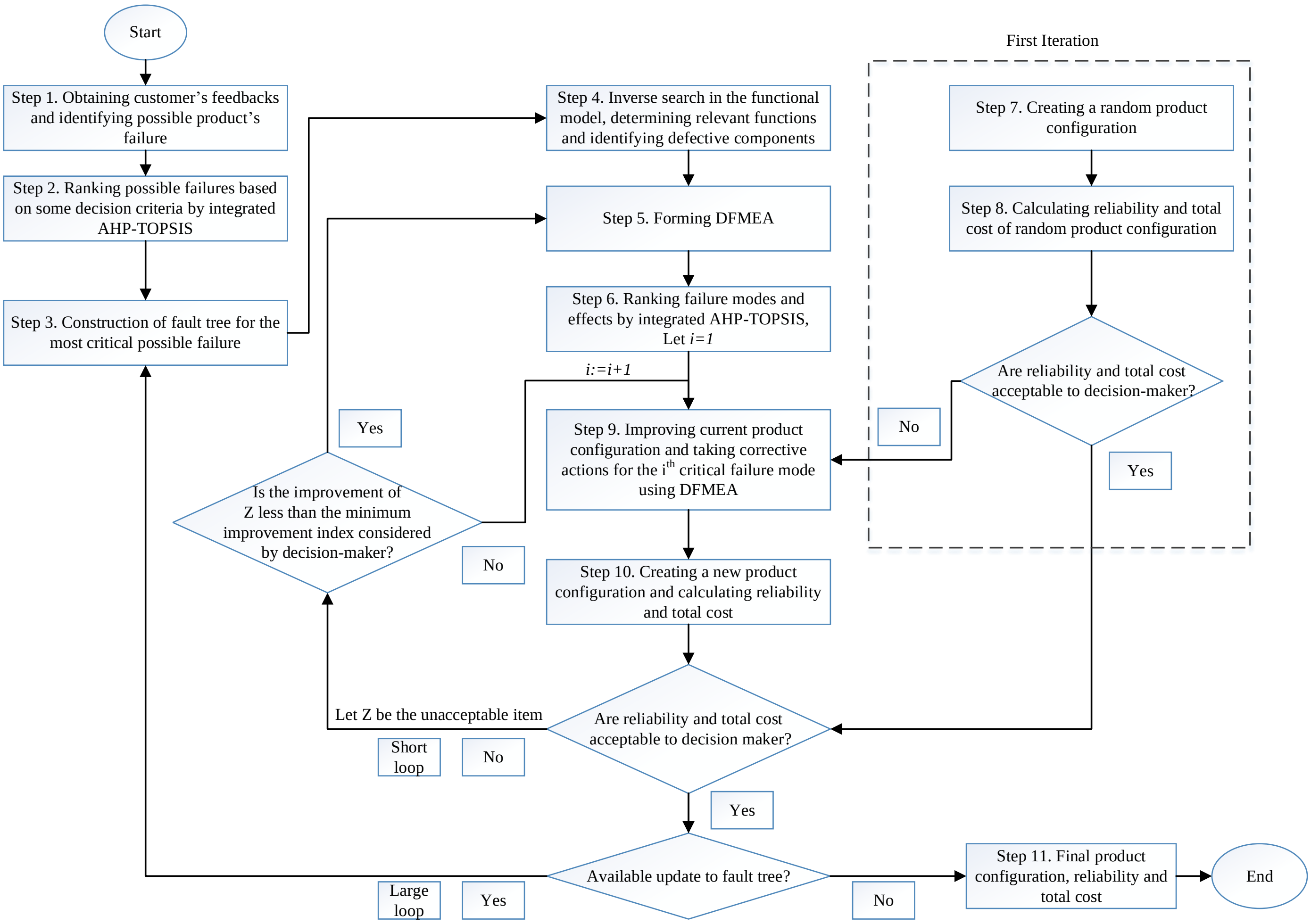

Figure 1: The proposed approach

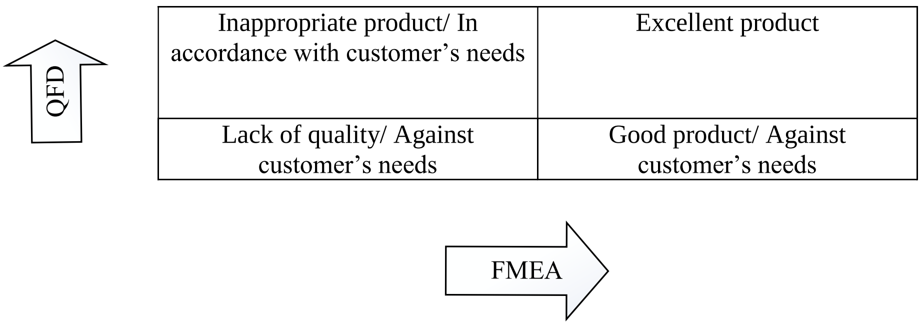

Figure 2: The FMEA and QFD interface

Ranking possible failures

Possible product failures are identified based on customer's feedbacks and market's requirements. Then, it is of great importance to devote effort and time to the most acute potential failure since exploring all potential failures and forming fault trees for everyone takes a lot of time that greatly expands the total optimization time and negatively affects the efficiency. Thus, the most significant possible failure is identified through an integrated AHP-TOPSIS method. In this regard, eight different criteria are defined in aid of DM to find the critical possible failure, which are:

- Failure occurrence rate (1/ Mean Time to Failure (MTTF))
- Failure related repair time (MTTR)
- Failure related costs

- Level of failure significance from customer's understanding
- Level of failure significance from business's understanding
- Subsequent failure occurrence
- Failure effect on product's utility
- Failure related missed opportunity cost (e.g., lost sales)

AHP approach is applied to determine criteria's weights and then TOPSIS is used to rank possible failures based on their score in each criterion. The most critical possible failure is identified as the result.

FTA

Failures can be demonstrated by a fault tree, in which the causes of each failure are determined. It is possible to construct a fault tree for each defect or functional requirement. In fault trees, different failure modes and their effects are presented. The hierarchical relationship between different functions of a product can be explained by a functional model. Figure 3 is an illustration of functional model of a laptop computer and displays how functions break down to their sub-functions.

FTs are based on functional level that can be transmitted into a functional model. Specifying functions that present as fault tree's top event results from the relationship between functional model and fault tree. Knowing which functions of functional model are depended to event node of the FT is important for specifying functions in top event. In this step of the model, an inverse search is applied as below:

- In the functional model, m_i represents the ith main function of the product and a node at the functional model's lowest level.
- In the technological model, n_{jk} represents the kth component of component type j. In product configuration, such component is the basic and main unit. J and k are positive integers.

Matrix A is demonstrated as:

$$A = [a_{ij}] \quad (1)$$

where $a_{ij} = 1$ if function i is accomplished by part j, otherwise 0. Matrix A is fixed.

In fault tree, a minimal cut set is defined as the fastest procedure to initiate an event from fault. Minimal cuts are practical in computing the probability of a top event occurring. In inverse search, keywords from the fault tree's minimal cuts are utilized to explore nodes of the functional model. When all keywords are tested and nodes are matched with keywords, the inverse search is finished (Azadeh et al. 2015).

Feasible product configuration Creation

In the presented method, a random feasible product configuration is used for the iteration 1, and for other ones, the latest formed product configuration is applied. A binary matrix is used to define each product configuration. Index i represents rows and index j represents columns, and the element of i and j shows the relationship between components i and j. Matrix r states the relation between parts and matrix w indicates the connection status of parts in a product configuration. The relation between matrices r and w is represented by matrix s and is computed as follow:

$$s_{ij} = r_{ij} \times w_{ij} \quad (2)$$

Matrix s can be a feasible product configuration (Azadeh et al. 2015).

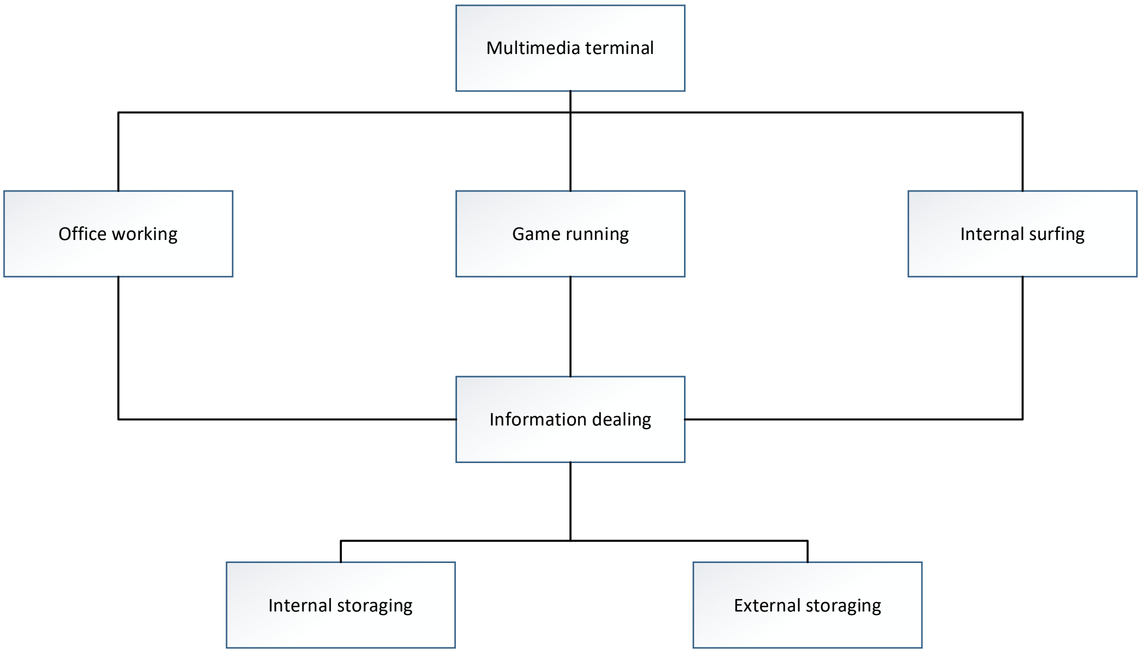

Figure 3: Laptop computer functional model of function Multimedia terminal

Reliability calculation

In the proposed approach, to connect different components, we consider four systems: series configurations, parallel configurations, series-parallel configurations, and parallel combination of series configurations. In each feasible product configuration, the probability that components are defect regarding the functions related to the top event are considered. Therefore, the reliability of product is calculated by failure probability of components.

Each FT has k Minimal Paths (MPs) that lead to the top event. Failure probability of MP k is presented by p_k and failure probability of the product according to a special fault tree is presented by p^*.

$$p_k = \prod_{j \in p_j} p(x_j) \tag{3}$$

The failure probability of part j related to an event in the MP is presented by $p(x_j)$. Based on equation (3), failure probability of the product according to a special FT is calculated as follows:

$$p^* = \max(p_k) \tag{4}$$

Thus, reliability of product is computed as below:

$$R = 1 - p^* \tag{5}$$

in the case of multiple FTs, failure probability is obtained as below:

$$p^* = b_1 p^1 + b_2 p^2 + b_3 p^3 + \cdots \tag{6}$$

where p^i is the failure probability and b_i is the mean weight of FT i in which the sum of average weight of fault tree is calculated as follows (Azadeh et al. 2015):

$$\sum_i b_i = 1 \tag{7}$$

Series configuration

The product configuration is carried out by series system in which the faulty components regarding to the MP k are linked. If all components work without malfunction in series systems, they are active. Thus, the reliability of such system is calculated as follows (Azadeh et al. 2015):

$$R_s = \prod R_i \tag{8}$$

R_i is the reliability of component i. Reliability of the MPs received from FTs should be considered and each MP results in several imperfect components which are used for reliability calculation. Therefore, s_k indicates a set of series components that are faulty in MP k and R_{ij} indicates the reliability of component i received from supplier j.

$$p_k = 1 - \prod 1 - p_{s_k} \tag{9}$$

$$p_{s_k} = 1 - R_{ij} \tag{10}$$

The failure probability for series system is calculated as follows:

$$p_k = 1 - \prod\nolimits_{i \in s_k} R_{ij} \tag{11}$$

Figure 4 displays a series configuration with its components.

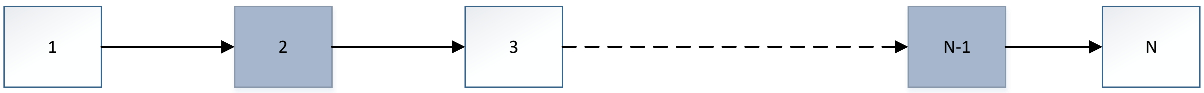

Figure 4: A series configuration as a segment of product configuration with defective components highlighted

Parallel configuration

The product configuration is carried out by a parallel system in which the faulty components regarding to the MP k are linked. If all components become defective in parallel systems, the system would be inactive. So, the reliability of such system is calculated as follows (Azadeh et al. 2015):

$$R_s = 1 - \prod (1 - R_i) \tag{12}$$

Figure 5 displays a parallel system with its components.

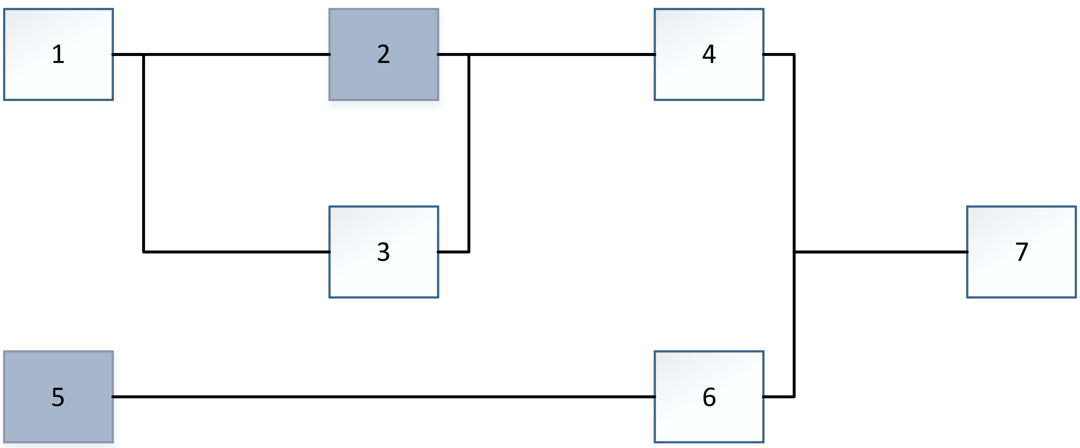

Figure 5: A parallel system as a segment of product configuration with defective components highlighted

Series-Parallel configuration

The product configuration is carried out by series-parallel system in which the faulty components regarding to the MP k are linked. In such systems, there are T stages and, in each stage, there are more than one workstation designed to keep the system functioning when a malfunction occurs. This system remains active when at least one workstation is functioning in each stage. R_{ab} indicates reliability of workstation a in stage b of the system. The reliability of such system is calculated as follows:

$$R_s = \prod_{b=1}^{T} (1 - \prod_{a=1}^{n_b} (1 - R_{ab}) \quad (13)$$

Figure 6 displays a series-parallel system with its components.

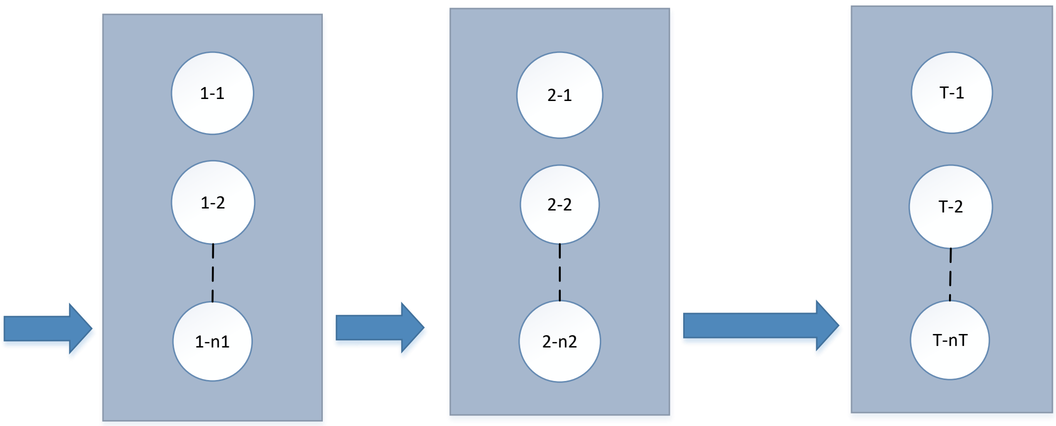

Figure 6: A series-parallel system as a segment of product configuration

Parallel combination of series systems configuration

The product configuration is carried out by parallel combinations of series systems in which the faulty components regarding to the MP k are connected. In such systems, there are T series systems, and in each system, there are more than one workstation designed. These series systems are linked parallel-wise to ensure system remains active when at least one series system is functioning. R_{ab} indicates the reliability of workstation b in series system a of the system. The reliability of such system is calculated as follows:

$$R_s = 1 - \prod_{a=1}^{n} \left(1 - \prod_{b=1}^{T_b} R_{ab} \right) \quad (14)$$

Figure 7 displays a parallel combination of series systems.

In general, S_k indicates a set of component types related to MP k, S_{ks} and S_{kp} indicate a set of components linked in series and parallel systems, respectively. S_{ksp} and S_{kpcs} indicate a set of components connected in series-parallel systems and parallel combination of series systems, respectively. Therefore, S_k is calculated as follows:

$$S_k = S_{ks} + S_{kp} + S_{ksp} + S_{kpcs} \quad (15)$$

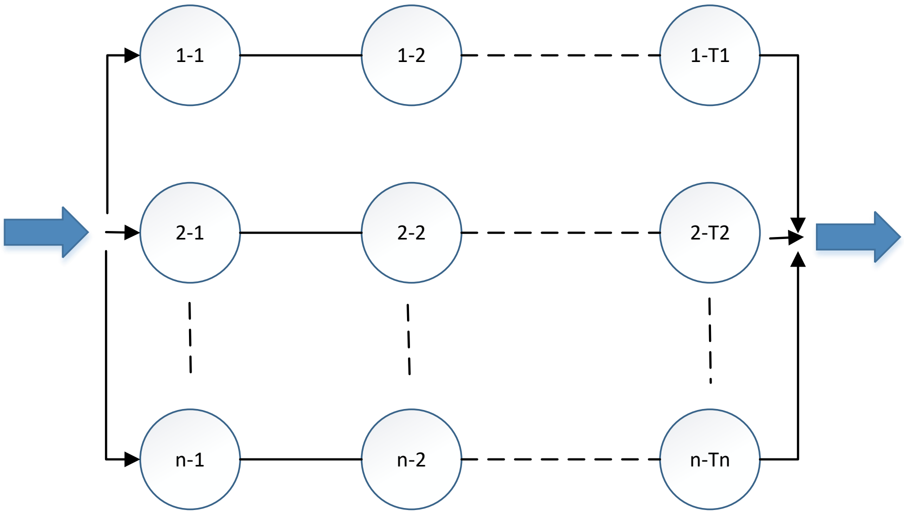

Figure 7: A parallel combination of series system as a part of product configuration

Redundancy

Consider h_i denotes the number of redundant components of type i. S_{kh} indicates subset of S_k with h redundancy and S_{kh} indicates a subset of other components. For example, if all components of S_k are connected in series configuration, p_k is calculated as below (Azadeh et al. 2015):

$$p_k = 1 - \left(\prod_{i \in S_{kh}} (1 - \prod_{j \in h_i} (1 - R_{ij}))\right) \times \left(\prod_{i \in S'_{kh}} R_{ij}\right) \tag{16}$$

Cost calculation

In the developed framework, components purchasing and warranty costs are considered and they are calculated as follows (Azadeh et al. 2015):

$$Purchasing\ cost = \sum C_{ijp} \times Q_{ijp} \tag{17}$$

$$Warranty\ costs = \sum W_{ijp} \times Q_{ijp} \tag{18}$$

where C_{ijp} shows the acquiring cost of component i from supplier j with warranty policy p, Q_{ijp} depicts the number of components i from supplier j with warranty policy p and W_{ijp} represents the warranty cost of component i form supplier j with warranty policy p. Warranty cost is measured as follow:

$$W = c \int_{l}^{u} [\int_{0}^{a} A(t)dt] h(a)da \tag{19}$$

where c stands for anticipated expense of each modification in the entire lifecycle. Warranty coverage duration (L) is stochastic; however, it is presumed $L = a$, in which a has a density function with a cumulative distribution that is computed as follow:

$$H(a) = \frac{e^{-\rho l} - e^{\rho a}}{e^{-\rho l} - e^{\rho u}} \tag{20}$$

where ρ is the exponential distribution parameter. The product failure intensity function, $A(t)$, is computed as follow:

$$A(t) = \frac{f(t)}{1 - F(t)} \tag{21}$$

where $F(t)$ is the cumulative distribution function and $f(t)$ is the density function. Total cost is calculated as follows:

$$Total\ cost = \sum C_{ijp} \times Q_{ijp} + \sum W_{ijp} \times Q_{ijp} \tag{22}$$

DFMEA Formation

FMEA is applicable in identifying failures and their effects with the purpose of reducing failure probability. This analysis involves conversion of failure information to quantitative risk. Two types of FMEA are available being DFMEA and process FMEA (PFMEA). In this study, DFMEA is applied to determine design failures and consider product failure related to design incompetence to improve product configuration. The descriptions of the factors in DFMEA are as below:

1. Component/activity/sector: components are regarded.
2. Failure mode: failure mode of the considered components.
3. Possible failure effect: According to customer's perception, the effects of failure are stated.
4. Cause of failure: possible causes related to failure modes.
5. Effect Severity (S): stands for potential failure effect significance.
6. Occurrence Probability (O): stands for potential failure cause probability.
7. Detection Difficulty (D): stands for potential failure detection probability.
8. RPN: risk potential number is normally computed by multiplying effect severity, occurrence probability and detection difficulty, but in this study the AHP approach is applied to assign weights to "severity, occurrence, and detection" [16] and the TOPSIS is implemented to obtain fault modes/causes priority. The purpose is that traditionally computing RPN by multiplication of three factors with the same significance lacks precision to prioritize fault modes/causes. For instance, 9*5*2 and 2*5*9 both result in RPN value of 90, where the effect severity of first fault mode is 9 and should be considered critical although it has a detection difficulty of 2 (Zhang et al. 2019).
9. Result: involving the completed task and recomputing the criteria.

Customer's requirements and market's feedbacks are used to identify all possible failures and the most significant possible failure is determined by applying an integrated AHP-TOPSIS. FTA is implemented to determine various failure modes and MPs, and their hierarchy is applied to indicate failure causes. Then, DFMEA is applied and the most crucial failure mode is obtained through combined AHP-TOPSIS approach. For the most crucial failure mode corrective actions are carried out and a new product configuration is created. Reliability and total costs are measured and if any of them are not acceptable to DM, the improvement of the unacceptable item (Z) should be compared with the minimum improvement index considered by the DM. If improvement of Z is less than expected value, DFMEA should be created and the process should be repeated. If improvement of Z is not less than expected value, current product configuration should be improved and corrective actions must happen for the next crucial failure mode and the process must continue as it was.

The AHP method

The AHP technique first starts with the yet-to-be-made decision and breaks down this decision into a hierarchy of evaluation criteria. Afterward, it goes beyond the structure to also analyze the alternatives. This strategy involves pairing up the elements from each level two by two while concerning the elements from higher levels. The steps in AHP are as below (Mzougui and El Felsoufi 2019):

1. To accomplish a pairwise comparison of the criteria, a matrix must be established. The relative importance of each criterion is evaluated in relation to the others. The linguistic scale of saaty (1986), which is shown in table 2, is utilized to obtain values through pairwise comparison.

Table 2: "The linguistic conversion scale of saaty (1986)"

Quantitative values	Verbal comparison
1	Equal significance of both elements
3	Moderate significance of one element over the other
5	Strong significance of one element over the other
7	Very strong significance of one element over the other
9	Extreme significance of one element over the other
2,4,6,8	Intermediate values

2. The normalization of the aforementioned matrix is accomplished in this phase by applying the following relationship:

$$b_{jk} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}} \quad (23)$$

3. To determine each criterion weight, the normalized matrix and the below relationship are utilized:

$$w_j = \frac{\sum_{l=1}^{m} b_{jl}}{m} \quad (24)$$

Hence, the suggested method executes the AHP technique to estimate the weight of various criteria.

The TOPSIS approach

In order to rank options, the TOPSIS approach first forms a positive ideal solution (PIS) and a negative ideal solution (NIS) of the examined decision. Next, for each option, it calculates the Euclidean distance to these PIS and NIS solutions. The PIS is the optimal value when all characteristics are at their desirable values, and the NIS is the worst value when all characteristics are at their worst values. Then, in order to rank alternatives, the distances between alternatives and these best and worst solutions are compared. The fault mode indicated by the worst option has to be removed since it has high priority. The steps of TOPSIS are as below [15]:

1. The decision matrix A is proposed as follow:

$$A = (a_{ij})_{m\times n} \quad (25)$$

The first step is to create a decision matrix with attributes and alternatives. After that, the matrix needs to be normalized as follow:

$$B = (b_{ij})_{m\times n} \quad (26)$$

The reason being that the attributes vary in terms of measurement units and value ranges. The normalization process is implemented as follow:

$$b_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}}, i = 1,2, \dots, m; j = 1,2, \dots, n \quad (27)$$

2. The weighted normalized decision matrix is created as follow:

$$C = (c_{ij})_{m \times n} \quad (28)$$

The matrix is created taking into account the attribute weights as follow:

$$w = (w_1, w_2, w_3, w_4)^T \quad (29)$$

The weights are gathered through the AHP technique, and the matrix is obtained as follow:

$$c_{ij} = w_j . b_{ij}, i = 1,2, \dots, m; j = 1,2, \dots, n \quad (30)$$

3. The PIS and NIS are calculated using the following relationships:

$$PIS = \{(max_i c_{ij}, j \in J), (min_i c_{ij}, j \in J^*)\} \quad (31)$$
$$NIS = \{(min_i c_{ij}, j \in J), (max_i c_{ij}, j \in J^*)\} \quad (32)$$

where

$$J = \{j \text{ associated with the benefit attribute}\} \text{ and } J^* = \{j \text{ associated with the drawback attribute}\} \quad (33)$$

4. The distances between alternatives and PIS and NIS solutions are measured as follow:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (c_{ij} - c_j^+)^2}, i = 1,2, \dots, m \quad (34)$$
$$d_i^- = \sqrt{\sum_{j=1}^{n} (c_{ij} - c_j^-)^2}, i = 1,2, \dots, m \quad (35)$$

where c_j^+ is the PIS of the jth attribute and c_j^- is the NIS of the jth attribute.

5. Prioritizing alternatives and the comprehensive assessment index should be determined as follow:

$$f_i = \frac{d_i^-}{(d_i^- + d_i^+)}, i = 1,2, \dots, m \quad (36)$$

According to f_i, the ranking of alternatives can be defined.

Model implementation: a case study

Case study description

These days, having a laptop is a must. Laptops have made our lives easier over time. Today we can easily do more things in less time, with a laptop anywhere and anytime. Whether you are traveling on a train or going to a party, laptops can always be by your side and rush to your aid when needed. When choosing the right laptop, it is very important to pay attention to its performance. Nowadays, with rising prices, buying a laptop that has wide functionality and performance is considered a long-term investment. laptops can be utilized in a broad spectrum of activities from watching movies and surfing the Internet, to doing specialized work such as programming. For this reason, customers try to make sure that they have found the right laptop with their needs and budget before buying.

The surge of online users due to the pandemic and consequent lockdowns reminded and doubled the importance of laptops, especially in the field of education and business. Laptops are sensitive electronic devices that can be damaged due to carelessness or negligence. Laptops are one of the devices that are constantly moving to different places and are more likely to be worn and damaged than desktop computers. Despite the manufacturers' efforts to modify these devices, there is still a high probability of problems and malfunctions with the laptop hardware as well as software, and every small problem that arises for the laptop will be costly for the user. For this reason, when users decide about a suitable laptop to buy, they pay careful attention to the feedback and opinions of other users of a particular brand. In this regard, the comments and reports of failures and dissatisfactions can significantly deter customers of a brand from buying its products. Therefore, it is of great importance that the various laptop manufacturers' brands take proper care of these complaints when improving their products. Manufacturers may lose market share if they do not improve their products based on the most significant and critical defects that affect product performance and brand image. Therefore, in this research, an attempt has been made to improve the laptops of one of the brands according to customers' feedback and expectation as well as experts' opinion based on the product configuration model proposed in this research.

Model implementation

To evaluate the applicability of the proposed approach, a laptop computer is investigated as a case study. The manufacturer has received customer’s feedbacks on the product. Different potential failures are determined (step1) and they are listed as below:

- Blank screen when running high graphic required software
- Loud noises related to fan unit when running system for a long time
- Screen freeze when multi-tasking
- Touchpad malfunction after skin sensitivity loss
- System shutdown when playing network games
- Poor quality audio output after full audio volume usage
- Keyboard malfunction after rough and rapid keyboard usage

Integrated AHP-TOPSIS is conducted (step 2) to determine the most acute potential failure according to the criteria described in section 3.2. Determining criteria could be done based on table 3. Using the AHP approach, each criterion's weight is calculated and reported in table 4.

After calculating the weight of each criterion implementing the AHP technique, the TOPSIS is utilized to prioritize possible failures according to these criteria. The obtained results have been displayed in table 5 and table 6.

Table 3: "Conversion scale of linguistic terms of qualitative criteria"

Level of failure significance from customer's understanding	Level of failure significance from business's understanding	Subsequent failure occurrence	Failure effect of product's utility	Scale for conversion
Very low				1
Low				3
Moderate				5
High				7
Very high				9
Intermediate values				2,4,6,8

Table 4:" Weight of criteria related to identifying the most critical potential failure"

Criteria	Weight of criteria
Failure occurrence rate (1/ Mean Time to Failure (MTTF))	0.030
Failure related repair time (MTTR)	0.028
Failure related costs	0.057
Level of failure significance from customer's understanding	0.082
Level of failure significance from business's understanding	0.088
Subsequent failure occurrence	0.225
Failure effect on product's utility	0.376
Failure related missed opportunity cost (e.g., lost sales)	0.113

Table 5: The decision matrix of potential failures

	Failure occurrence rate (1/ Mean Time to Failure (MTTF))	Failure related repair time (MTTR)	Failure related costs ($)	Level of failure significance from customer' s	Level of failure significance from business' s	Subsequent failure occurrence	Failure effect on product' s utility	Failure related missed opportunity cost (e.g., lost sales) ($)
Blank screen when running high graphic required software	100.00	24.00	500000.00	7.00	7.00	7.00	7.00	700000.00
Loud noises related to fan unit when running system for a long time	500.00	14.00	100000.00	3.00	1.00	5.00	5.00	400000.00
Screen freeze when multi-tasking	200.00	20.00	400000.00	5.00	5.00	1.00	7.00	600000.00
Touchpad malfunction after skin sensitivity loss	300.00	16.00	100000.00	5.00	3.00	1.00	5.00	300000.00
System shutdown when playing network games	100.00	36.00	600000.00	7.00	7.00	7.00	9.00	800000.00
Poor quality audio output after full audio volume usage	300.00	20.00	300000.00	5.00	5.00	3.00	5.00	400000.00
Keyboard malfunction after rough and rapid keyboard usage	200.00	10.00	200000.00	5.00	3.00	1.00	5.00	300000.00

Table 6: Assessment index of potential failures

Potential failure	Evaluation index (f_i)
Blank screen when running high graphic required software	0.680416
Loud noises related to fan unit when running system for a long time	0.455438
Screen freeze when multi-tasking	0.308795
Touchpad malfunction after skin sensitivity loss	0.266174
System shutdown when playing network games	0.740477
Poor quality audio output after full audio volume usage	0.338264
Keyboard malfunction after rough and rapid keyboard usage	0.255368

According to table 6, the results indicate that the evaluation index corresponding to 'system shutdown when playing network games' has the highest amount. Thus, this potential failure is indicated as the most critical one.

Figure 8 illustrates the fault tree that is created (step 3) for this failure. It depicts two possible failure outcomes, namely 'load or save errors' and 'virus invasion'. The MPs of the fault tree display 'internal and external storage failures' as failure modes for 'load or save errors' failure effect, 'hard firewall failure' and 'soft firewall failure' as failure modes for 'virus invasion' failure effect (step 4).

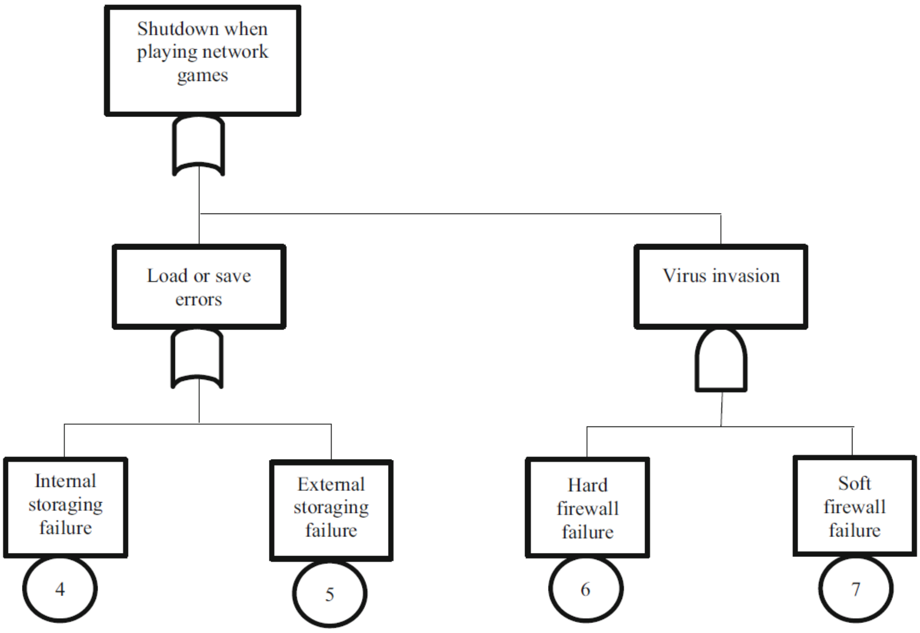

Figure 8: Fault tree for 'shutdown when playing network games' [3]

DFMEA is carried out (step 5) for each MP presented in figure 8 and failure modes' severity, occurrence, and detection are determined. These criteria are presented by table 7 and a combined AHP-TOPSIS is utilized for identification of the most crucial failure mode (step 6). Table 8, 9 and 10 consist of computational results.

Table 7: Indexes for severity, occurrence and detection in FMEA

Failure probability	Detection	Severity index
Dangerous-without warning	Uncertain	10
Dangerous-with warning	Very remote	9
Very high	Remote	8
High	Very low	7
Moderate	Low	6
Low	Moderate	5
Very low	Highly moderate	4
Slight	High	3
Very slight	Very high	2

Table 8: Weight of each criterion related to failure modes

Criteria	criteria weight
Severity	0.5
Occurrence	0.25
Detection	0.25

Table 9: The decision matrix of failure modes

	Effect severity	Occurrence probability	Detection difficulty
Internal storage failure	7	4	3
External storage failure	5	4	4
Hard firewall failure	6	3	4
Soft firewall failure	4	5	3

Table 10: Evaluation index of failure modes

Failure modes	Evaluation index (f_i)
Internal storage failure	0.745262
External storage failure	0.406897
Hard firewall failure	0.55783
Soft firewall failure	0.308076

Based on table 9, ‘internal storage failure’ is the most severe failure mode since it has the greatest evaluation index. Based on Azadeh et al. (2015), in matrix A, in the third row, element 1 in thirteenth column represents the internal memory as follows:

$$A(3) = [000000000000100] \tag{37}$$

Thus, the relevant MP is mapped to ‘internal memory’. A random product configuration is created (step 7) and there are 2 vendors for internal memory. The random product configuration is shown in figure 9.

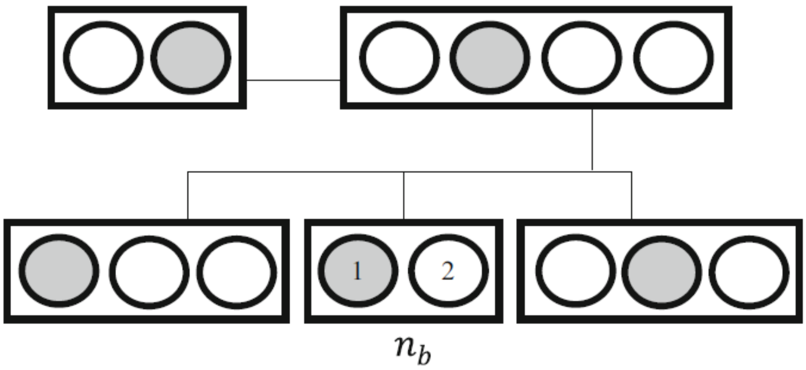

Figure 9: A random product configuration [3]

Based on figure 9, n_b represents internal memory in this product configuration. Data related to suppliers have been provided in table 11 as follows:

Table 11: Data related to suppliers [3]

Supplier	**Failure probability**	**Purchasing cost**	**λ**	**β**	**c**	**ρ**	**L**	**U**	**Occurrence of failure**	**Severity of failure**	**Detection of failure**
Supplier 1 with policy 1	0.30	150	0.443/year	2	100	0.2/year	1	3	Very low	High	High
Supplier 1 with policy 2	0.20	220	0.443/year	2	100	0.2/year	1	5	Slight	High	High
Supplier 2 with policy 1	0.15	220	0.4/year	2	100	0.2/year	2	5	Very slight	High	High
Supplier 2 with policy 2	0.10	250	0.4/year	2	100	0.2/year	3	5	Very slight	High	High

$A(t)$ is the failure intensity function with λ and β as parameters. c is the expected cost of each modification during lifetime, L and U are lower and upper limit of a, respectively and a has a density function. ρ is the exponential distribution parameter.

According to figure 9, failure probability of MP related to internal memory supplied by supplier i with policy j is shown by P_{bij}. Also, if redundancy allocation takes place, the failure probability is derived as below:

$$P_{relevant\ minimal\ path} = \prod P_{bij} \quad (38)$$

For the first iteration, according to the random product configuration depicted in figure 9 and supplier data provided in table 11, supplier 1 under policy 1 is chosen randomly. Total cost is calculated (step 8) as follows (Azadeh et al. 2015):

$$Warranty\ cost = 100 \times \int_1^3 (0.443a)^2 \frac{0.2e^{-0.2a}}{e^{-0.2} - e^{-0.6}} da = 76.29 \quad (39)$$

$$Purchasing\ cost = 150 \quad (40)$$

$$Total\ cost = 226.29 \quad (41)$$

Also, reliability of the relevant MP is calculated as follows:

$$Reliability = 1 - P_{b11} = 0.7 \quad (42)$$

Reliability and total cost of supplier 1 with policy 1 should be compared to the required values by the DM. If they are both acceptable and there is no update available for the fault tree, the final product configuration, reliability, and total costs are gathered. The fault tree should be updated if there are any updates (step 3) and the remaining steps are carried out in the manner described up until this point. If one of them is not acceptable to DM, Given the FMEA created earlier, the current product configuration had better modify and corrective activities (step 9) had better consider for the most serious failure mode, which is ‘internal storage failure’.

If the manufacturer takes the remaining corrective action by supplier 1 but modifying policy 1 to policy 2, S, O, and D would be altered for the most crucial failure mode, that is ‘internal storage failure’. So, an updated product configuration is created (step 10) and the prioritization of failure modes need to be carried out once more. Table 12 and 13 demonstrate the updated decision matrix for recognizing the most crucial failure mode and the evaluation index for each failure mode, respectively. Moreover, the reliability and total cost should be calculated again as follows:

Table 12: The decision matrix for determining the most crucial failure mode after improving

	Effect severity	Occurrence probability	Detection difficulty
Internal storage failure	7	3	3
External storage failure	5	4	4
Hard firewall failure	6	3	4
Soft firewall failure	4	5	3

Table 13: Assessment index of failure mode after improving

Failure mode	Evaluation index (f_i)
Internal storage failure	0.643362
External storage failure	0.408581
Hard firewall failure	0.548564
Soft firewall failure	0.320153

$$Warranty\ cost = 100 \times \int_1^5 (0.443a)^2 \frac{0.2e^{-0.2a}}{e^{-0.2} - e^{-1}} da = 172.67 \quad (43)$$

$$Purchasing\ cost = 220 \quad (44)$$

$$Total\ cost = 392.67 \quad (45)$$

$$Reliability = 1 - P_{b11} = 0.80 \quad (46)$$

Based on the obtained results, ‘internal storage failure’ remains the most important failure mode and reliability and total cost are increased. If reliability and total cost are acceptable to DM and there are no updates existing to the FT, the final product configuration, reliability, and total costs are obtained. In case there exist updates, the fault tree needs to be updated (step 3) and the remaining steps are carried out. If one of them is not acceptable to DM, Z is the unacceptable item.

Suppose that reliability is not acceptable and total cost is acceptable to DM. The improvement of reliability should be compared to the minimum improvement index considered by the DM. Suppose that the minimum improvement index desired by the DM is 10% and the reliability is improved by roughly 14%. Therefore, the improvement is more than the desired value and the manufacturer must switch to the next critical failure mode being ‘hard firewall failure’ according to table 13. For this failure mode, based on matrix A, assume the relevant MP is mapped to ‘Hardware firewall’ and different suppliers with different policies are considered. The current product configuration is used and reliability and total cost are calculated. If one of them or both of them are not acceptable to DM, improvement of the current product configuration should be considered and corrections (step 9) needs to be carried out for ‘hard firewall failure’. Then severity, occurrence, and detection of this failure mode should be obtained to check the ranking of failure modes after taking corrective actions and reliability and total cost should be calculated. If one of them or both of them are not acceptable to DM, Z is the unacceptable item, and improvement of Z should be compared to the minimum improvement index considered by the DM as mentioned above.

According to the results, different corrective actions can be taken into account such as altering policy, changing suppliers and changing the product configuration. These corrective actions improve reliability, total cost and ranking of failure modes. The DM is able to select supplier, policy and corrective action and denote the minimum improvement index based on risk-averseness. In this approach, the most crucial potential failure is determined. Each failure mode is scrutinized based on priority to improve reliability and total cost to reach different alternatives for the DM to select among suppliers and policies.

Discussion

The presented product configuration framework consisting of the integration of failure analysis, MADM techniques, acceptance criteria, and minimum improvement index, effectively and precisely identifies failure modes and prevents them from occurring. A significant number of studies such as Azadeh et al. (2015), Zhang et al. (2019), and Goo et al. (2019) have addressed product configuration considering reliability improvement perspectives. While in this study, product configuration and reliability analysis are investigated from a new point of view distinguishing this research from previous ones. This distinction is gained by considering customer’s feedbacks and requirements and investigating potential failures based on various identified criteria in minimum time. Also, none of them has taken into account all product configuration models like series, parallel, and joint series-parallel with regard to reliability management. In addition, although Beiki Ashkezari et al. (2022) utilized MADM techniques, namely AHP and TOPSIS, and risk management methods, namely FTA and FMEA in project configuration, none of them has taken into account the application of these quality management and risk assessment tools in the product configuration field.

Moreover, recognizing all possible failures in a product is a very time-consuming and impossible process, and no previous study has considered a minimum improvement index desired by the DM, by so doing, prioritizing potential failures and identifying the most significant ones must continue until it is reached. The minimum improvement index considered by the DM directs the algorithm in two ways. As the index value increases, the probability of the algorithm going through step 5 after having an unacceptable item that its improvement is less than the minimum desired value decreases. As the index value decreases, the probability of the algorithm going through step 9 after having an unacceptable item that its improvement is higher than the minimum desired value increases.

Suppose that an improvement to the current product configuration is done (step 9) and reliability and total cost are calculated (step 10). Reliability is not acceptable and the improvement of reliability should be compared to the minimum improvement index considered by the DM. Suppose that improvement of reliability is 14%. If the minimum improvement index is considered 20%, the algorithm continues forming DFMEA (step 5) and ranking failure modes should be done again Step (6). If the minimum improvement index is 5%, the algorithm continues to the second most critical failure mode, improving current product configuration and taking corrective actions (step 9). Creating a fresh product configuration and calculating reliability and total cost (step 10).

Thus, the minimum improvement index considered by the DM which represents DM's risk averseness impacts the direction of the algorithm. If the DM is risk-averse, the minimum improvement index is set high, and failure modes should be ranked again. If the DM is not risk-averse, the minimum improvement index is set low, and the second most critical failure mode is considered.

Although the current study makes use of the AHP and TOPSIS techniques with satisfactory results, several limitations and challenges associated with these methods are known. For instance, the limitations of AHP method include the subjectivity of pairwise comparisons, the potential discrepancy between weighted preferences and true preferences, the requirement for the quantification of criteria and alternatives, and the potential mismatch between the hierarchical structure and the true structure of the problem. In addition, the TOPSIS technique has some limitations. One issue associated with TOPSIS is the occurrence of rank reversal, where the preference order of alternatives changes when a new alternative is introduced, or an existing one is removed from the decision-making process. In certain scenarios, this can result in total rank reversal, where the original best alternative becomes the worst after adding or removing another alternative.

Managerial insights

Based on the provided methodology and results, here are some managerial insights:

- Customer-Centric Approach: In almost all businesses, it is essential to begin with understanding customers' needs and feedback. Incorporating these insights into the product development process in our model ensures alignment with market demands and enhances customer satisfaction.
- Risk Prioritization: the proposed algorithm by utilizing analytical tools such as AHP and TOPSIS aids in identifying and prioritizing potential failures. This enables managers to focus resources on addressing the most critical issues, thereby minimizing risks effectively.
- Integrated Approach: By integrating methodologies like AHP, TOPSIS, FMEA, and fault tree analysis, our study provides a comprehensive framework for analyzing failure modes and their effects. This holistic approach enhances decision-making by considering various factors and criteria.

- Continuous Improvement: In our model, implementing a minimum improvement index directed by decision-makers facilitates continuous improvement efforts. By setting thresholds for acceptable improvements, the presented approach ensures that corrective actions are prioritized based on their impact on reliability and cost.
- Supplier and Policy Selection: The analysis facilitates informed decisions regarding supplier selection, policy alterations, and corrective actions for the management. This enables managers to optimize reliability, total costs, and overall product performance.

Conclusion

Product configuration is an essential factor in product customization. The manufacturer prefers to produce with the lowest production cost possible and increase profit. The customer tends to receive products with high reliability and low price. In this study, the focus is on product configuration improvement and an integrated FTA-DFMEA method is developed that performs combined AHP-TOPSIS. Customer desires and market feedbacks are considered to detect possible failures. Combined AHP-TOPSIS was utilized to choose the most crucial potential failure after ranking potential failures. Afterward, FTA was applied to determine MPs, and inverse search in the functional model is done to identify related functions and defective components. Further on, Failure modes and effect analysis is implemented with the purpose of identifying failure modes, effects, and causes. Then, integrated AHP-TOPSIS was conducted to choose the most severe failure mode after ranking them to make modifications and enhance product configuration. Suppliers with various policies, reliability, warranty and purchasing costs are regarded. Diverse configuration systems and redundancy allocation are considered. The minimum improvement index is determined by DM based on risk-averseness. A case study of a laptop computer is introduced to evaluate the validity of the suggested approach. The results demonstrate that the algorithms provide some alternatives for the DM to enhance reliability, total costs and product configuration.

However, this study consists of some limitations that can be pointed to when proposing suggestions for future study. For example, some criteria other than the eight defined criteria can be identified and applied to rank and prioritize failures. Also, since AHP-TOPSIS is utilized to prioritize failures in this study, the comparison of the proposed method with other MCDM and ranking techniques and their benefits and disadvantages can be taken into account for further research. Moreover, further studies can contribute to studying the applicability of the proposed model for other real-life cases, especially products of companies operating in competitive markets that, unlike monopoly markets, are prone to losing customers due to low quality.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest. In addition, this article does not contain any studies with human participants or animals performed by the author. The undersigned authors declare that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere.

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