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Research Article

A Combined Model Design for Developing and Optimizing Product Platform Architecture Considering Parameters of DFV, DFC, DFSC, and DFAv, Case Study: Phased Array Radar

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Abstract

Developing a robust platform architecture can give companies a competitive edge and enhance product future generations and customer satisfaction. However, in order to develop a product platform architecture, there is a need for some kind a product variety design that concurrently manages costs and the supply chain process, and focuses on ease of use and improved availability to components. In this research, the design for variety (DFV) approach and two indices, generational variety index (GVI) and coupling index (CI) are used to measure a product architecture. Using the quality function deployment (QFD) and design structure matrix (DSM), design indices for product diversity are identified and ranked. Additionally, the design for variety approach is modeled simultaneously with the concepts of design for cost (DFC), design for availability (DFAv), and design for supply chain (DFSC) to yield a practical mathematical model for the development of the product platform architecture, which aims for product diversity, improved availability, reduced costs, and supply chain management. The case study of the current research is a phased array radar, which is optimized using the latest techniques (genetic algorithm) and MATLAB software to solve the problem. After implementing the model, considering four objectives including total cost, availability, supplier evaluation score (competency) and replaceability (variety), and seven main parameters of the model, sensitivity analysis and other comparisons and results are presented, which analyzes the relationships between objectives, the impressment and affectability of objectives and model parameters on each other. Regarding the comparison of objectives, the results generally show the inverse relationship between the total cost objective and the other objectives, and the direct relationship between the other objectives with each other. Additionally, the results of the sensitivity analysis performed indicate that the availability objective had the highest effect and variety and the evaluation score of suppliers and total cost also took next place.

***Keywords*:** Product Platform; Design for Variety (DFV); Design for Cost (DFC); Design for Availability (DFAv), Design for Supply Chain (DFSC); Phased Array Radar.

1. Introduction

Developing a novel product that meets the customer's needs is crucial for the profitability and competitiveness of a company and is considered one of the key factors contributing to the company's success. (Dadfar et al., 2013). One of the ways to reach the market is to provide products tailored to meet the requirements of the consumers and to assess the specific needs of customers. Many companies categorize their products into families and develop various platform-based variations to obtain a range of products. Additionally, the complexity of markets and the extensive needs of customers for new and diverse products with lower costs have posed a new challenge for manufacturers. Based on this, they must be able to produce and distribute a wide range of products in a short amount of time. Under these conditions, the production of diverse products requires an extensive range of factors such as primary resources, equipment, and production sets, leading to numerous complexities in management and operational levels. In general, design for X (DFX) refers to using a systematic approach to improving a particular aspect of a design or product to its highest potential. The variable X represents the focus of the optimization. Various DFX techniques are mapped and categorized in a shared design, and the interactions and relationships between them are identified (Itani et al., 2019). Typically, design guidelines suggest relevant techniques and procedures that may help to produce and utilize technical knowledge to control, improve or even innovate specific product features. In essence, it is a proactive management approach to coordinate and manage the requirements (Sassanelli et al., 2016). Therefore, the desired strategies are those that consider simultaneous integration of design for variety, design for supply chain, design for availability, and design for cost in a combined model, to improve product design.

2. Related Work

In this section, some background examples of research conducted in the fields discussed in this research are described, including product platform architecture, design for cost, design for variety, design for availability and design for supply chain.
Jiao et al. (2007) introduced a decision framework for revealing a holistic view of product family design and

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product development based on a platform approach, encompassing both forward and backward aspects. This study covers various subjects related to product families, including fundamental concepts and definitions, product portfolio, product family positioning, platform-based product family design, and supply chain management.

Meireles Carniro (2020) conducted several research methods such as QFD and FMEA to complete the framework and aid product development. These methods were adapted from several software programs like the Fuzzy Set Theory to the LeanDfX software. As a case study, implementing these methods was tested and developed on an internal AGV (Automatic Guided Vehicle) project in a Portuguese company. The results showed that this method improved the LeanDfX framework and made it easier to use. With its help, the focus was placed from the start on what was important to the customer, rather than on what could be added to the project. As a result, the time spent on the design process was reduced, and in the end, a better product was produced in the same amount of time.

Shojaeefarda et al. (2017) used an innovative design approach (AD) to provide a framework for interpreting the reduction of the generational variety index (GVI) and the coupling index (CI) to aid in the development of automobile architecture in the study of automobile underbody architecture. This study included standardization and modeling to reduce costs and future efforts.

Kwansuk et al. (2019) proposed a framework for modular architecture development for modular products (cross-domain vision management). In these studies, they actually introduced Developmental Architecture (DA) to illustrate the relationships between elements in the market, design, and production domains for cross-domain diversity management during product development. The proposed framework for development architecture focuses on the use of modular body family modules.

Stapelberg (2009) conducted studies on the methodology of integrated design, automation, and integrated design, reliability, and performance in engineering design, availability and maintainability in engineering design, and presented the results as a collected book. This book combines different design methods for reliability, availability, sustainability, and safety also the latest techniques of probabilistic modeling, mathematical algorithmic modeling, evolutionary algorithmic modeling, symbolic modeling, artificial intelligence modeling, and object-oriented computer modeling in a logically structured approach to examine the integrated engineering design.

Lamothe et al. (2018) have studied a mixed integer linear programming model, used for selecting product families and designing supply chains, aimed at minimizing the operational cost of the supply chain in addition to selecting the types of products. This has been applied to the automobile supplier problem.

Amid et al. (2006) have proposed a multi-objective fuzzy linear model for supplier selection in a supply chain based on three factors: price, quality, and services, using the non-cooperative fuzzy decision-making technique. In this research, the non-cooperative fuzzy decision-making technique is employed for the first time with a practical example in the problem of fuzzy supplier selection, allowing the decision maker to assign different weights to various factors.

Vinay (2020) conducted a study to enhance the productivity of the production of capital and industrial goods by improving the supply chain model. The study was based on the current situation of Indian manufacturing companies and their need for supply chain management to improve their competitive position. A pilot study was conducted before the research to test the content and validity of the final questionnaire. The target population was determined, and responses were obtained through multiple follow-ups. The data was analyzed and a linear regression model was created as a relationship between the SCSFs and the PIPs. The ranking of the SCSFs was done using descriptive statistics.

Li et al. (2022) introduced a multi-objective analysis method to obtain an optimal conceptual scheme considering various aspects of product. Due to the complexity of product conceptual solution generation, this study divides the multi-objective analysis process into multi-objective solution optimization and multi-objective solution selection. The non-dominated solution set can be obtained from all the potential solutions in the former step. Then, the optimal conceptual solution can be obtained from the non-dominated solutions set in the latter step. Conceptual design is the crucial stage of selecting and determining product composition and configuration, which greatly affects product performance and cost. In conceptual design stage, designers have the maximum design freedom in order to put forward to the optimal design solution in terms of assembly, manufacturing and cost.

Long (2020) did a research entitled "System Excess Placement for Improving Lifecycle Value" in the field of design for variety in systems. The objective of this research is understanding, modeling, and evaluating the use of strategic overdesign (excess) as a method for minimizing the cost of system change to maximize system lifecycle value. This research is necessary because the design and construction of modern complex engineered systems is costly, and these systems operate in a context that changes over time. Reducing (and ideally minimizing) the cost of executing system adaptations is therefor advantageous. Prior research provides guidance for how system changeability can be supported by encapsulating functionality within modules, but little research has been dedicated to optimal design variable (or component sizing) selection to support future system changes.

Greve et al. (2021) suggest that since change drivers, such as changing customer and production requirements, result in changes having to be made to the initially developed modular product family, which not only causes a great effort but also prevents the long-term benefits from being fully exploited. So with the Change Allocation Model, they introduced a tool that makes it possible to align the essential future changes to the product architecture and to identify and redesign the change-critical components taking into account the existing component variety of the product family. This enables future changes in variety to be considered in the product architecture and a future robust

modular product family to be developed. The new visualization is illustrated using the example of a product family of pressure regulating valves and is finally discussed with regard to further potentials and challenges.
Bortolini et al. (2023) propose a two-step methodology for product platforms design and assessment in high-variety manufacturing. The design step involves the use of a novel modified algorithm for solving the longest common subsequence (LCS) problem and of the k-medoids clustering for the identification of the platform structure and the assignment of the variants to the platforms. The platforms are then assessed against a set of industrial and market metrics, i.e. the MTS cost, the variety, the customer responsiveness, and the variants production cost. The evaluation of the platform set against such a combined set of drivers enhancing both company and market perspectives is missing in the literature. A real case study dealing with the manufacturing of a family of valves exemplifies the efficiency of the methodology in supporting companies in managing high-variety to best balance the proposed metrics.
Barrar et al. (2023) discuss issues in the field of supply chain design. their research aims to explore the role of the supply chain (SC) in the design of the Product-Service System (PSS). In particular, the study focuses on the Design for Supply Chain (DfSC) approach in order to understand its role and contribution to the Design for Product Service Supportability (DfPSSu) approach in supporting PSS design. The study reveals how a better design of the SC is required for the development of a service supportability approach that, in turn, facilitates the design of the PSS. Additionally, Internet of Things (IoT) technologies support MFs to analyse the ongoing development of the PSS business model. Finally, a better design of PSS is essential for strengthening the integration of Product and Service Offerings. This study suggests that MFs can build dynamic SC capabilities to deal with fundamental changes that occurred when adopting servitization. This research is among the first attempts to study the design process of the PSS business model in a real business context taking into account different design strategies.
According to the examination and comparison of multiple sources and the analysis of their results, it was determined that each of the sources holds one or several important and fundamental principles in relation to product platform design. However, in this study, due to the appealing and feasible nature of some of the topics analyzed in the sources, DFV was modeled using a combined approach incorporating elements from DFC, DFAv, and DFSC.

Nomenclature

A. Indices

i, i', l	Component
j	Product
k	Supplier
p	Platform

B. Decision Variables

X_{ijk}	If component i of product j is purchased from supplier k 1 and zero otherwise
V_{ijp}	If component i is selected to produce product j on platform p 1 and zero otherwise
$R_{ii'j}$	If component i' can be replaced instead of component i in product j 1 and zero otherwise
Z_{pi}	If component i is used on platform p 1 and zero otherwise
L_{pj}	If product j uses platform p 1 and zero therwise
P_p	If platform P is used 1 and zero otherwise
D_j	If there is demand for product j 1 and zero otherwise
H_{ik}	Amount of component i purchased from supplier k
U_{ijp}	Production rate of product j with component i on platform p
fx_{il}	If along the x-axis, component l is after component i and is completely separated from it, 1 and zero otherwise
fy_{il}	If along the y-axis, component l is after component i and is completely separated from it, 1 and zero otherwise
fz_{il}	If along the z-axis, component l is after component i and is completely separated from it, 1 and zero otherwise
x_{il}	If component l is separate from component i in the direction of the x axis (fxil=1) and they interfere in the direction of y and z, 1 and zero otherwise
y_{il}	If component l is separate from component i in the direction of the y axis (fyil=1) and they interfere in the direction of x and y, 1 and zero otherwise
zil	If component l is separate from component i in the direction of the z axis (fzil=1) and they interfere in the direction of y and x, 1 and zero otherwise

C. Parameters

SC_{ijk}	The cost of purchasing component i of product j from supplier k
SD_{ijk}	The discount amount of supplier k for the purchase of component i of product j
DI_k	Distance from supplier k
TC_k	The transportation cost of component i from supplier k
MC_{ijp}	The production cost of product j with component i on platform p
CAP_i	Production capacity of Product j
DE_j	Demand of product j
M	A big number
C_p	The cost of producing platforms
CO_{ik}	The selection score of the supplier k from which the component i is purchased (supplier's competence level)
$CR_{ii'j}$	The cost of replacing component i' instead of component i in product j
VA_i	Criteria for the need to redesign the component i
GVI_i	The Generational Variety Index of component i
CI_R_i	The Coupling Index – Receiving of component i
CI_S_i	The Coupling Index – Supplying of component i

3. Literature Review

The strong development of the product platform architecture brings an important competitive advantage to a company and its main advantage is to reduce the design effort and time to market for future generations of products and to meet the needs of customers. Product design teams seek to design a specific architecture for the product platform that will improve the future generations of the product and reduce the negative impact of diversity and on the other hand, ensure the profitability and success of the company and consider all the elements of a successful design.

Therefore, achieving a product strong platform architecture requires an integrated model focusing on issues of design for variety and other fundamental approaches of design for excellence, which in addition to product design diversity, include other factors such as economic savings and access to components (ease of use, better performance and repairability) and supply chain management (choosing the right supplier, etc.) and other things to be relevant and effective. Because things like variety or ease of accessibility and cost management or reforming the system of material procurement, sourcing and supplier selection in the category of supply chain management have a positive impact on the quality and quantity parameters of the product and ultimately lead to customer satisfaction. Also, despite the combination of conditions that we face in real world projects, in the set of previous studies conducted in the field of product platform architecture, the effective factors in this field have not been considered simultaneously, but DFXs have been examined separately and limited. For this reason, a comprehensive and combined study including effective factors is needed.

In this research, the design for variety method and two generational variety indexes (GVI) and coupling index (CI) are used to measure a product architecture and using the quality function deployment (QFD) and design structure matrix (DSM), design indexes for variety are identified and ranked and the design for variety (DFV) approach is modeled for product platform architecture development with design for availability (DFAv) and design for supply chain (DFSC) and design for cost (DFC).

In addition, the conceptual model of the current research is according to Fig. 1.

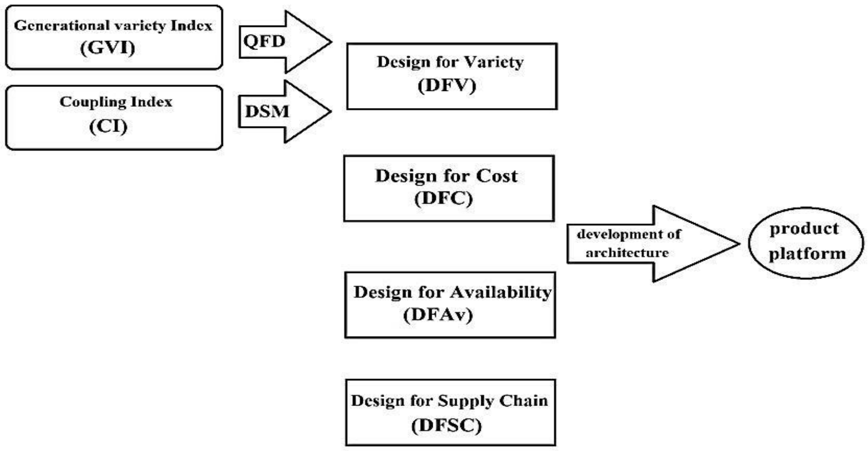

Fig. 1. conceptual model

4. Primary Definitions

4.1. Platform design

A platform can be defined as a set of shared components, modules, or parts through which a stream of product derivatives can be efficiently developed, launched, and implemented in a wide range of products. Platforms are a collection of standard parameters, features, or components that remain constant from one product to another in a specific product family. In other words, a brief definition of a platform is "a shared set of physical or non-physical modules through which multiple products can be derived" (Holtta-Otto, 2005). Modularization can also be considered a gradual characteristic that, according to Salvador, can be described by decoupling, commonality, combinability, functional binding, and interface standardization (Dambietz, 2021).

4.2. Design for variety (DFV)

The term design refers to the construction activities that determine the shape and dimensions of components, their arrangement, couplings, and materials. Variety also traditionally refers to products that satisfy a wide range of customer needs. Production diversity can appear in the diversification of products, production processes, and resources (Landahl and Johannesson, 2018). This study focuses on product diversification. A high degree of component diversification causes different effects during the product life cycle (Rennpferdt et al., 2021). Design for variety (DFV) or diversification is defined as product design and architecture features that minimize production and development costs (Kipp and Krause, 2008). Therefore, the DFV is a structured process that helps design teams develop a specific architecture for a product platform, i.e., DFV is an approach to developing a product platform architecture.

DFV uses factors external to product change (e.g., customer requirements, regulations, and the like) to estimate components that need to be changed. This method also includes product coupling effects to determine how changing one component will affect others. Companies use the DFV to construct a product platform that can more easily influence future product generations. Some studies suggest that DFV aims to help manufacturers manage and mitigate the negative impact of product variety on operational performance (Boer, 2018).

4.2.1. Generational variety index (GVI)

GVI indicates the amount of redesign effort required for a component to conform to the future engineering metrics (EMs). Alternatively, it measures the degree of redesign effort required for future product designs. GVI is based on necessary changes in components influenced by external (i.e., uncontrollable) factors. The external stimuli include customer needs, reliability requirements, price reductions, etc. Changing external stimuli over time leads to changes in the production component generations (Martin and Ishii, 1999).

The GVI estimation process is as follows:

Step 1 – Determine markets and desired life of product platform

Step 2 – Create a QFD matrix: QFD is one of the most successful methods used in the product design process. It is a method for linking customer requirements with design components, a structural unit for calculating GVI (Moubachir and Bouami, 2015).

Step 3 - List expected changes in customer requirements: Add a column to Step 1, and qualitatively (high/medium/low) estimate the range of changes for the customer's needs.

Step 4 – Estimate the engineering metric target values (EMTVs): At this stage, EMTVs are defined when the product platform is being developed.

Step 5 – Calculate normalized target value (NTV): The target values obtained in Step 4 can be normalized based on the current market values, and the changes are represented visually.

Step 6 – Create GVI matrix: The team applies engineering expertise and judgment to estimate the costs of changing components to conform to future EMTVs. The GVI matrix uses a 9/6/3/1 rating system for these estimations.

Step 7 – Calculate GVI: Finally, the GVI for each component is obtained by summing the values in each column of the GVI matrix (Martin and Ishii, 2000).

4.2.2. Coupling index (CI)

The Coupling Index (CI) indicates the coupling strength within the product.Ulrich's definition of coupling indicates that two components are coupled if changing one requires changing the other. The team explains the coupling relationships between components by drawing specification flows at the beginning of the design process. Two indices are derived from the coupling matrix.

(1) Coupling index - supplying (CI-S) indicates the strength of the information provided by each component for other components. CI-S shows the strength of specifications that one component supplies to another component.

(2) Coupling index - receiving (CI-R) is the information received by each component. CI-R demonstrates the strength of specifications that a component receives from other components. In general, CI-S and CI-R represent the coupling strength in a component. A high CI-S implies that a component supplies information to other components. If that component changes, it is more likely to change other components. A high CI-R in a component suggests that as other components change, it is more likely to lead to a change in that component (Martin and Ishii, 2000).

The CI development process is as follows:

Step 1 – Develop basic physical layout for the product

Step 2 – Draw control volume (CV) around components being analyzed: Control volume is a boundary around the system representing the system's inflows and outflows.

Step 3 – Determine the specification flows required for the components: The specification flows are put into matrix forms using a DSM. The upper row of the matrix contains the components supplying the information. The left column shows the components receiving the information. The DSM is a network modeling tool used to represent a system's constituents and interactions, thereby highlighting the system's architecture or designed structure (Liu et al., 2017). The DSM designates a particular layout and architecture for system partitioning, so modules have maximum interdependencies and minimum external dependencies (Karbasian et al., 2015).

Step 4 – Create a graphically present specification flows: This phase is optional, but it can be beneficial for visualizing the flows between different components. Listing the required and supplied information for generational and spatial variety is helpful. The components that supply specifications for other components are the ones that the design team tends to keep constant, thereby mitigating redesign costs.

Step 5 – Estimate sensitivity of components to changes: For each specification (specification flow), the team must estimate the components' sensitivity to a slight change in that specification. If a slight change in specification involves a change in a component, then that component has high sensitivity. If the specification entails a significant change in the component, then the component has low sensitivity. High sensitivity specifications are given 9, and low sensitivity specifications are given 1.

Step 6 – Calculate coupling index: The sum of one column of the matrix represents the strength of the information that the component supplies for other components, referred to as CI-S. The sum of one row indicates the information received by each component, which is called CI-R. The sensitivities for each row and column are summed. If, for example, the CI-S is high for a component, implying that its design has a strong influence on other components. If the CI-R is relatively high for a component, indicating that other components can strongly affect it (Martin and Ishii, 2000).

4.2.3. The DFV process

The DFV steps are as follows:

Step 1 – Generate GVI and CI for the design

Step 2 – Order the components based on GVI: This step consists of two parts:
a) Rank Order the GVI: Components are ranked from the highest to lowest GVI value. These components will most likely change due to external stimuli during the product platform period.
b) Include Coupling Indices in Table: GVI and CI-R vs. CI-S can be compared because they are indices of how much a component is expected to change, and the CI-S measures how these changes propagate.
Step 3 – Determine where to focus efforts, i.e., where to standardize or modularize: For standardization, it is essential to focus on components with high design cost and GVI. Another noteworthy point is to standardize components with high CI-S since they have a high potential to make changes in other components. Standardization involves minimizing the GVI and reaching the CI-R to zero. It implies that no external or internal coupling needs to change the component. Components that cannot be standardized and need to be modified should be modularized, i.e., when the components are changed, there is no need to change any of the other components. This modularization refers to geometric changes and changes in the component's signal, material, and energy flow. The component modularization requires CI-S to be decreased to zero. The techniques used to reduce GVI and CI-R are also used to minimize the CI-S (Shojaeefard et al., 2017).
Step 4 – Develop the product platform architecture: This helps the team decide how to rearrange the mapping between physical parts and functions and define interfaces (Rubio-Maya et al., 2014).
In general, it can be said that the goal of the team is to design the product architecture platform in such a way that most of the possible designs are standardized among different generations. In the DFV method, standardization and modularization focus on parts that cost more to redesign in future generations. (Veenstra et al., 2006).

4.3. Design for Cost (DFC)

DFC, as a design methodology and one of the supporting tools for concurrent engineering (CE), is an integral part of DFX, emphasizing price and quality equally. By using design tools, maintaining product quality, and influencing all activities in different departments of an organization, DFC designs the product in a way that results in the lowest cost and highest level of customer satisfaction (Xiaochuan et al., 2004). DFC is a product development principle aiming to optimize the total cost of a product and its life cycle processes, including the costs of materials, supply chain, manufacturing, land services, product maintenance, warranty, design and development, and time to market (TTM) (Moroson, 2022).

4.4. Design for availability (DFAv)

The availability of system components is defined as a feature of a system component that indicates the level of difficulty in observing and accessing that component during maintenance and repair activities. The availability of a system component is defined as the number of objects or obstacles that must be removed to access the component by clearing its path. The maintenance and repair availability index for a component is the minimum availability level in different possible deassembly directions (Xu et al., 2014).

4.5. Design for supply chain (DFSC)

DFSC is carried out early in the design cycle, helping to identify the number of selected manufacturer components to be considered for lifecycle, availability, process compatibility, or process validity before the initial design. The DFSC process includes a bill of materials (BOM) review, lifecycle analysis, and value-added (Morrison, 2016). The DFSC aims to design a new product and its related supply chain concurrently. DFSC optimizes product design and supply chain design decisions to concurrently realize design goals related to product quality, costs, and environmental impacts (Hou et al., 2021). Lee defined the DFSC or design for logistics (DFL) basics. Lee's works emphasize different interests in adapting the design of a product family in order to decrease the costs and lead-time of a given supply chain. They mainly examine how to reduce production diversity. The consequences on safety stock are mitigated thanks to different types of product variant postponement (time, place, or form postponement), process and product standardization or modularization, and reversal of operations that causes the reversal of components in the BOM. Recently, Van Hoek has incorporated the postponement developments applied to the supply chain. Anderson and Pine also emphasized integrating these concepts to offer mass-customized products (Lamothe et al., 2018). DFSC denotes design for improved supply chain productivity, inventory rotation, and lead time, design for high assembly and production efficiency, design for improved logistics efficiency, and minimized product logistics costs (packaging, shipping, and so forth) (Sharifi et al., 2006).

5. Research Method

In terms of research classification based on the main goal, The current study can be categorized as a development-applied research, since it uses methods like DFV and focuses on cost reduction resulting from redesign, other costs and design for availability and supply chain management. Additionally, this research is descriptive-survey in nature. Expert survey (experts and specialists in the relevant industry) is used to advance and analyze the data. Data processing is also quantitative. Therefore, in terms of its application in an industrial project, this research is practical.
The research process consists of six steps, including:
1- determining the structure of QFD, 2- forming the QFD matrix and determining the range of changes, 3- obtaining Generational Variety Index (GVI), 4- forming the Design Structure Matrix (DSM) matrix and determining the coupling indices (CI-R and CI-S), 5- data analysis and calculation of the Design for Variety (DFV) criterion, and

6- Creating a model for the architecture of the product platform through solving the combined model obtained in step 5 using the Non-dominated Sorting Genetic Algorithm II (NSGAII) and assessing the sensitivity of the model by studying case data using MATLAB software.

6. Assumptions of the Problem

Assumptions of the mathematical model for the problem include: 1) the parameters are certain and definite, 2) the model is multi-product, 3) the platforms are determined through multiple means, 4) suppliers offer discounts for part purchases, 5) components (parts) can be purchased from both internal and external suppliers, 6) The purchase cost of components from each supplier is identifiable, 7) production capacity is limited, and 8) It is possible to replace components in the product The mathematical signs and symbols of the problem model are as follows.

7. Mathematical Model

The present model is a mixed mathematical model aimed at optimizing four important indicators in the architecture of the product platform, namely design for variety (DFV), design for availability (DFAv), design for supply chain (DFSC), and design for cost (DFC). In other words, the purpose of this research is to design a model that can be used to redesign components of a product, which firstly leads to the development and production of diverse products with the least cost and effort (design for variety), and on the other hand, the arrangement of components during product production is structured to enhance availability, for example, more accessible to commonly used components in the product and reducing barriers to accessing components (design for availability), and at the same time, all costs are minimized, i.e., It means product production, supply and use of components and their replacement, and overall design of the platform should be economical (design for cost). In addition, in the supply chain discussions, issues such as the supply path (supplier selection), the number of components purchased, the amount of product produced, and so on are considered and managed, encompassing the supply chain design area.
In this section, according to the mentioned assumptions, signs and symbols, the mathematical model of the problem is presented.

$$\min Z_1 = \sum_i \sum_j \sum_k \sum_p SC_{ijk} . X_{ijk} . Z_{pi} . L_{pj} . H_{ik} - \sum_i \sum_j \sum_k \sum_p SD_{ijk} . X_{ijk} . Z_{pi} . L_{pj} . H_{ik} + \sum_k DI_k . TC_k . X_{ijk} + \sum_p C_p . P_p + \sum_i \sum_j MC_{ijp} . V_{ijp} . Z_{pi} . L_{pj} . U_{ijp} + \sum_i \sum_{i'} \sum_j CR_{ii'j} . R_{ii'j} \tag{1}$$

$$\max Z_2 = \sum_i \sum_k CO_{ik} . X_{ijk} \tag{2}$$

$$\min Z_3 = \sum_i V_{ijp} . \min \left(\sum_{\substack{l \\ i\neq l}} x_{il} , \sum_{\substack{l \\ i\neq l}} x_{li} , \sum_{\substack{l \\ i\neq l}} y_{il} , \sum_{\substack{l \\ i\neq l}} y_{li} , \sum_{\substack{l \\ i\neq l}} z_{il} \right) \tag{3}$$

$$\min Z_4 = \sum_i \sum_{i'} \sum_j VA_i . R_{ii'j} \tag{4}$$

$$VA_i = \frac{GVI_i}{CI\_R_i + CI\_S_i} \tag{5}$$

$$\sum_i V_{ijp} = 1 \qquad \forall i \tag{6}$$

$$\sum_i X_{ijk} = 1 \qquad \forall i \tag{7}$$

$$H_{ik} \le M . X_{ijk} \qquad \forall p, i, j, k \tag{8}$$

$$H_{ik} \le M . X_{ijk} \qquad \forall p, i, j, k \tag{9}$$

$$U_{ijp} \le M . X_{ijk} \qquad \forall p, i, j, k \tag{10}$$

$$U_{ijp} \le CAP_j \qquad i, j, p \tag{11}$$

$$U_{ijp} \ge DE_j \qquad \forall p, i, j \tag{12}$$

$$U_{ijp} \le M . V_{ijp} \qquad \forall p, i, j \tag{13}$$

$$\sum_i \sum_{i'} R_{ii'j} = 1 \qquad \forall i, i' \tag{14}$$

$$R_{ii'j} \le V_{ijp} \qquad \forall p, i, i', j \tag{15}$$

$$R_{ii'j} \le V_{ijp} \qquad \forall p, i, i', j \tag{16}$$

$$\sum_p L_{pj} \le D_j \qquad \forall j \tag{17}$$

$$L_{pj} \le P_p \qquad \forall p, j \tag{18}$$

$$\sum_j L_{pj} \ge P_p \qquad \forall p \tag{19}$$

$$\sum_j L_{pj} \leq P_p.M \quad \forall p \tag{20}$$

$$D_j \leq DE_j \quad \forall j \tag{21}$$

$$U\_ijp\leq 〚M.Z〛\_pi \quad \forall p,i,j \tag{22}$$

$$U_{ijp} \leq M \,.L_{pj} \quad \forall\, p,i,j \tag{23}$$

$$U_{ijp} \leq M \,.L_{pj} \quad \forall\, p,i,j \tag{24}$$

$$Z_{pi} \leq L_{pj} \quad \forall\, p,i,j \tag{25}$$

$$V_{ijp} \leq Z_{pi} \quad \forall\, p,i,j \tag{26}$$

$$fx_{il} - fy_{il} - fy_{li} - fz_{il} - fz \quad \forall i,l\ ,\ i \neq l \tag{27}$$

$$Xil \leq f\,xi \quad \forall i,l\ ,\ i \neq l \tag{28}$$

$$xil \leq f\,xil \quad \forall i, l, i \neq l \tag{29}$$

$$xil \leq 1 - fyli \quad \forall i, l, i \neq l \tag{29}$$

$$xil \leq 1 - fzil \quad \forall i,\ l,\ i \neq l \tag{30}$$

$$xil \leq 1 - fzli \quad \forall i,\ l, i \neq l \tag{31}$$

$$xil \leq 1 - fzli \quad \forall i, l, i \neq l \tag{32}$$

$$zil \geq fzil - fyil - fyli - fxil - fxli \quad \forall i, l, i \neq l \tag{33}$$

$$yil \geq fyil - fxil - fxli - fzil - fzli \quad \forall i, l, i \neq l \tag{34}$$

$$yil \leq fyil \quad \forall i, l\ ,\ i \neq l \tag{35}$$

$$yil \leq 1 - fxil \quad \forall i, l\ ,\ i \neq l \tag{36}$$

$$yil \leq 1 - fxli \quad \forall i, l\ ,\ i \neq l \tag{37}$$

$$yil \leq 1 - fzil \quad \forall i, l\ ,\ i \neq l \tag{38}$$

$$zil \leq fzli \quad \forall i, l\ ,\ i \neq l \tag{39}$$

$$zil \leq fzil \quad \forall i, l\ ,\ i \neq l \tag{40}$$

$$zil \leq 1 - fyil \quad \forall i, l\ ,\ i \neq l \tag{41}$$

$$zil \leq 1 - fyli \quad \forall i, l\ ,\ i \neq l \tag{42}$$

$$zil \leq 1 - fxil \quad \forall i, l\ ,\ i \neq l \tag{43}$$

$$zil \leq 1 - fxli \quad \forall i, l\ ,\ i \neq l \tag{44}$$

$$Xijk, Vijp, Rii'j, Zpi, Lpj, Pp, Dj \in *0,1+ \tag{45}$$

$$Uijp, Hik \geq 0 \tag{46}$$

Equation (1) aims to minimize the total cost by minimizing the supply chain costs, including purchasing, production, supplier selection (supply path cost or transportation cost), platform costs, and minimizing design costs for various , including part replacement or redesign costs. Equation (2) aims to maximize the evaluation score (competence) in selecting suppliers, which is related to the supply path selection. The goal of equation (3) is to maximize the availability to component i, which determines the availability of components while considering five faces, with the minimum hindrance to component availability. Note that if part l blocks the path to part i in the +x direction (yz+ face), it will be equal to x_il = 1 and this equation $\sum_{i\neq l} 1\ x_{il}$represents the number of components that have blocked the access path to component i on the +yz face. Equation (4) aims to reduce the need for redesigning components in the design for a variety issues. As for Equation (5), which is the same as the need criterion for redesigning component i, the higher the GVI number, the more need for redesigning because GVI is an index that measures the amount of redesign required for a component to conform to future engineering standards. On the other hand, high CI-R and CI-S values in a component indicate that the redesign should be minimized since it impacts other internal components and reduces the need for redesign. Constraint (6) indicates that each component can only be selected once. Constraint (7) specifies that each component can only be supplied once by each supplier per product. Constraint (8) states that a component can only be purchased from a supplier if it has been selected. Constraint (9) indicates that if a component is not purchased from a supplier, it will not have an optimal value. Constraint (10) states that if a component is not purchased from a supplier for a product, the product cannot be produced. Constraint (11) represents the production capacity constraint. Constraint (12) represents the demand-supply constraint for the product. Constraint (13) indicates that if a component is not selected, the product cannot be produced. Constraint (14) indicates that each piece can only be used once in place of another piece in a product. Constraint (15) indicates that if a piece is not selected, it cannot be replaced. Constraint (16) indicates that a platform is used to create a product only if there is a demand for it. Constraint (17) implies that if the related platform is not used, the product cannot use that platform. Constraint (18) states that if no product is assigned to the platform, it will not be created. However, if platform p is formed, it can be used to develop various products, as shown in constraint (19). Constraints (20) and (21) indicate the demand for product j. Constraint (22) indicates that if a piece is not available on the platform, it cannot be produced. Constraint (23) indicates that if a product does not use a platform, it cannot be produced on that platform. Constraint (24) indicates that if a product does not use a platform, there is no requirement for a piece to exist on that platform. Constraint (25) implies that if a piece does not exist on the platform, it cannot be selected for production. Constraint (26) prevents writing repetitive constraints. Regarding availability constraints to ensure that common space parts are not occupied and there is no interference, six conditions, including fxli =1 ¬¬(Let piece "i" be completely separate and further along the "x" direction than piece "l"), *fxil=1*, *fyli =1*, *fyil =1*, *fzli =1*, and *fzil =1*, must be considered. Constraint (27) indicates the non-overlap (separation) of two pieces in the x-axis and interference in the y and z-axis. Constraint (28) shows that in situations where two pieces are not in the same x-axis, there may be interference in the y and z-axis, and vice versa. Constraint (29) specifies that pieces cannot be separated simultaneously in both x-axis and y-axis (next to each other). Constraint (30) shows that even with the displacement of pieces, they can't be separate in the x and y-axis. Constraint (31) indicates that pieces cannot be separated simultaneously in both x-axis and z-axis. Constraint (32) indicates that it is not possible for the components to be disengaged in the x and z axis directions even with components displacement. Constraint (33) ensures that two components are correctly disengaged in the z-axis direction, while maintaining interference in the x and y-axis directions. Constraint (34) ensures that two components are correctly disengaged in the y-axis direction, while maintaining interference in the x and z-axis directions. Constraint (35) indicates that when two components are disengaged in the y-axis direction, interference is possible in the x and z-axis directions, and vice versa. Constraint (36) indicates that it is not possible for the components to be disengaged in the y and x-axis directions together. Constraint (37) indicates that it is not possible for the components to be disengaged in the y and x-axis directions together even with components displacement. Constraint (38) indicates that it is not possible for the components to be disengaged in the y and z-axis directions simultaneously. Constraint (39) indicates that it is not possible for the components to be disengaged in the y and z-axis directions simultaneously even with components displacement. Constraint (40) indicates that if two components are disengaged in the z-axis direction, there is a possibility of interference in the x and y-axis directions, and vice versa. Constraint (41) states that it is not possible for two components to be aligned simultaneously in the z and y-axis directions. Constraint (42) states that it is not possible for two components to be aligned simultaneously in the z and y-axis directions even with components displacement. Constraint (43) indicates that it is not possible for two components to be aligned simultaneously in the z and x-axis directions. Constraint (44) indicates that it is not possible for two components to be aligned simultaneously in the z and x-axis directions even with components displacement. Relation (45) indicates the range of binary decision variables of the problem. Relation (46) indicates the range of decision variables of the integer number of the problem.

8. Operational Stages

8.1. Case study

In this research, phased array radar has been studied. The components of this product, which include 5 main modules, have been extracted during meetings with industry experts and after interviewing them and studying related sources. These components are shown in Table 1.

Table 1
Phased array radar components (Soheilifar, 2016)

Row	Abbreviated signs	Main components
1	S	Servo
2	C	Processor card
3	T/R	TRM & Phase shifters
4	A	Antenna array
5	P	Power section

8.2. The first stage of research: determining the structure of QFD

After identifying the components of the product under study, the expert group to create the GVI must first estimate what external drivers may require the product to change over time. A modified quality function extension structure is used to create the GVI. (Hauser, 1988).
For example, customer needs, cost, reliability, etc. can be considered drivers of change. For this research, customer needs and their relationship with engineering criteria are listed according to Table 2.

Table 2
Customer needs and related engineering criteria

Customer needs	Milli per second	Number of operations per second	Number in operation	Dots per inch	Mean Time Between Failures(hours)	Unit cost ($)
Fast scanning of the surrounding environment and detection o	X					
The ability to perform several different operations		X				
High resistance against anti-electronic operations and detection			X			
The quality of radar images				X		
Reliability to achieve results					X	
Low cost						X

8.3. The second stage of the research: forming the QFD matrix

This phase maps the EMs extracted from the previous step to the components used in the design. Mapping this phase contributes to GVI development. GVI estimates the number of redesign efforts required to meet future EMs. The GVI number varies for different architectures. Additionally, understanding where the market is headed is critical to the DFV approach, as the team must determine how long they are willing to sustain the product platform. Table 3 shows the QFD matrix. "X" indicates that the component can influence the EMs (Martin, and Ishii, 2000).

Table 3
QFD matrix

Engineering Metrics	Servo	Processor card	TRM & Phase shifters	Antenna array	Power section
Milli per second	X	X	X	X	
Number of operations per second	X	X		X	X
Number in operation	X			X	
Dots per inch	X	X	X	X	
Mean Time Between Failures(hours)	X	X	X	X	X
Unit cost ($)	X	X	X	X	X

8.4. The third stage of research: obtaining GVI

For determining the GVI matrix, the team uses its engineering expertise and judgment to estimate the component replacement cost. The GVI matrix applies a 9/6/3/1 rating system for these estimations. Based on its engineering expertise, the expert team must decide whether each component needs a major redesign, a minor redesign, and so on. The GVI for each component is computed by summing each column of the GVI matrix, as shown in Table 4.

8.5. The fourth stage of the research: forming the DSM matrix and determining the CI

The DSM matrix related to this research is shown in Table 5.

Table 4
Calculation of GVI

Engineering Metrics	Servo	Processor card	TRM & Phase shifters	Antenna array	Power section
Milli per second	1	6	3	9	
Number of operations per second	3	9		3	3
Number in operation	3			6	
Dots per inch	6	3	1	6	
Mean Time Between Failures(hours)	3	1	1	3	1
Unit cost ($)	3	1	1	3	1
GVI	19	20	6	30	5

Table 5
Calculation of design structure matrix (DSM) and determination of CI-R and CI-S

Components receiving specifications	Servo	Processor card	TRM & Phase shifters	Antenna array	Power section	**CI-R**
Servo		14	12	7	14	47
Processor card	7		7	7	22	33
TRM & Phase shifters	12	14		7	14	47
Antenna array	7	14	7		14	42
Power section	7	12	7	7		33
CI-S	33	54	33	28	54	

8.6. The fifth stage of the research: calculation of the DFV criterion

Parts are ordered from the highest to the lowest GVI index. These components are more likely to change during the product platform's lifespan due to external stimuli. Table 6 shows the Phased array radar results.

For each component, as shown in Table 7 add the CIs, i.e., CI-R and CI-S, to the GIV to obtain the indices involved in the DFV calculation.

Table 6
GVI index

Component	**GVI**
Antenna array	30
Processor card	20
Servo	19
TRM & Phase shifters	6
Power section	5

Table 7
DFV index

Component	**GVI**	**CI-R**	**CI-S**
Antenna array	30	42	28
Processor card	20	33	54
Servo	19	47	33
TRM & Phase shifters	6	47	33
Power section	5	33	54

8.7. The sixth stage of the research: development of the model

8.7.1. The solution method of research

In this research, library studies were first conducted and based on the studies, a mathematical model was designed. Then, the model is solved as a four-objective problem, while the design criteria for variety, cost, availability, and supply chain were taken into consideration, which, because the problem becomes complex and similar to NP-Hard problems, it is necessary to use meta-heuristic algorithms. Therefore, in order to evaluate the performance of the obtained results, the Non-dominated Sorting Genetic Algorithm II (NSGAII) is implemented and the model is solved by MATLAB software. Srinivas and Deb (1994) criticized the NSGA approach . They introduced the NSGA-II algorithm to reduce the problems of the prior algorithm and enhance the parent selection process in two previous algorithms that were performed randomly. The binary encoding technique was employed by Deb et al. (2002) to generate the initial response population for this algorithm (Bolhasani et al., 2014).The parameters of the genetic algorithm used in this research are according to Table 8.

8.7.2. Utilizing genetic algorithm to solve the model

For solving the model using the multi-objective genetic algorithm, Pareto charts are used. An example of the Pareto chart for the total cost objective and the availability objective is presented in Fig. 2, and the results of comparing other objectives are described later.

Table 8
The parametrs of NSGAII

Parameters	**Amounts**
initial population	50
number of repetitions	100
mutation operator	0.2
intersection operator	0.7

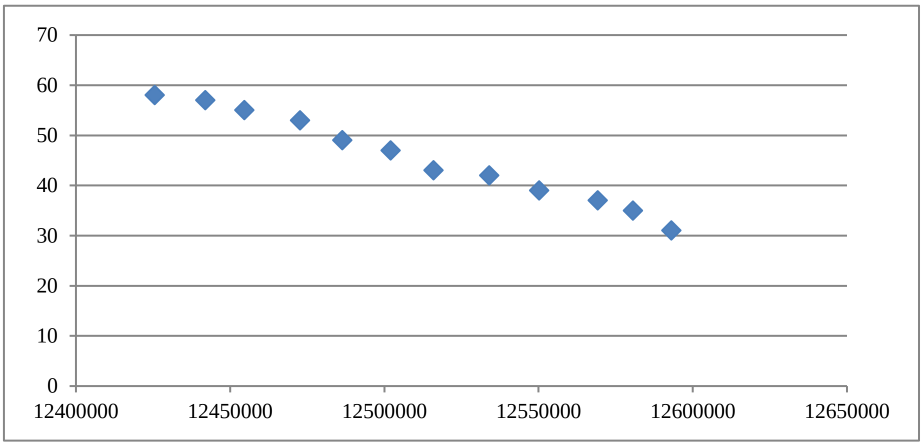

Fig. 2. Pareto diagram of total cost objective and availability

As shown in Fig.2 , total cost and availability are inversely related. That is, with an increase in cost, the level of availability in the product decreases, which can be a natural issue in the relationship between cost and availability. In the following analysis of the results of the model solution, it is observed that there is also an inverse correlation between the total cost and evaluation score (competence) objectives. The results also show that similar to the inverse and descending nature of the relationship between cost and availability, the relationship between cost and variety is also inverse, and with the increase in cost, the possibility of components replace ability decreases. According to the NSGAII algorithm, there is an ascending relationship between the evaluation score objective and availability, and with an increase in the evaluation score, And with the increase of the merit score, the availability in the product also increases. Furthermore, based on the results, the relationship between evaluation score and variety follows an ascending pattern, and with an increase in the evaluation score, the possibility of increasing the components replaceability ability in the product exists. According to the results of the multi-objective genetic algorithm, a direct relationship between availability and variety is shown, so that with an increase in availability, the possibility of increasing components replaceability ability also arises.

8.7.3. Sensitivity analysis

This section deals with the parameter sensitivity analysis of the problem. In this section, seven parameters (component purchase cost, discount rate, component transportation cost, production cost, production capacity, product demand, and replacement cost) are analyzed for their effect on the four objectives of the model. The parameters considered are the ones that can be altered and, therefore, their modification can have either a positive or negative effect on the objectives. For example, the sensitivity analysis outcomes for production cost parameter are presented in Table 9 and its related chart are shown, and the sensitivity analysis results for other parameters are examined subsequently.

Table 9
Sensitivity analysis of production cost

Production cost	Total cost	evaluation score (qualification-based)	availability	replaceability (variety)	The amount of change in cost	The amount of change in evaluation	The amount of change in availability	The amount of change in replaceability (variety)
0%	12592983	9298	31	485				
10%	12773638	9150	33	496	0.014346	0.015917	0.064516	0.02268
20%	13130175	8899	37	519	0.027912	0.027432	0.121212	0.046371
30%	13674970	8459	44	557	0.041492	0.049444	0.189189	0.073218
40%	14413435	7849	54	606	0.054001	0.072113	0.227273	0.087971
50%	15298956	7126	66	665	0.061437	0.092114	0.222222	0.09736

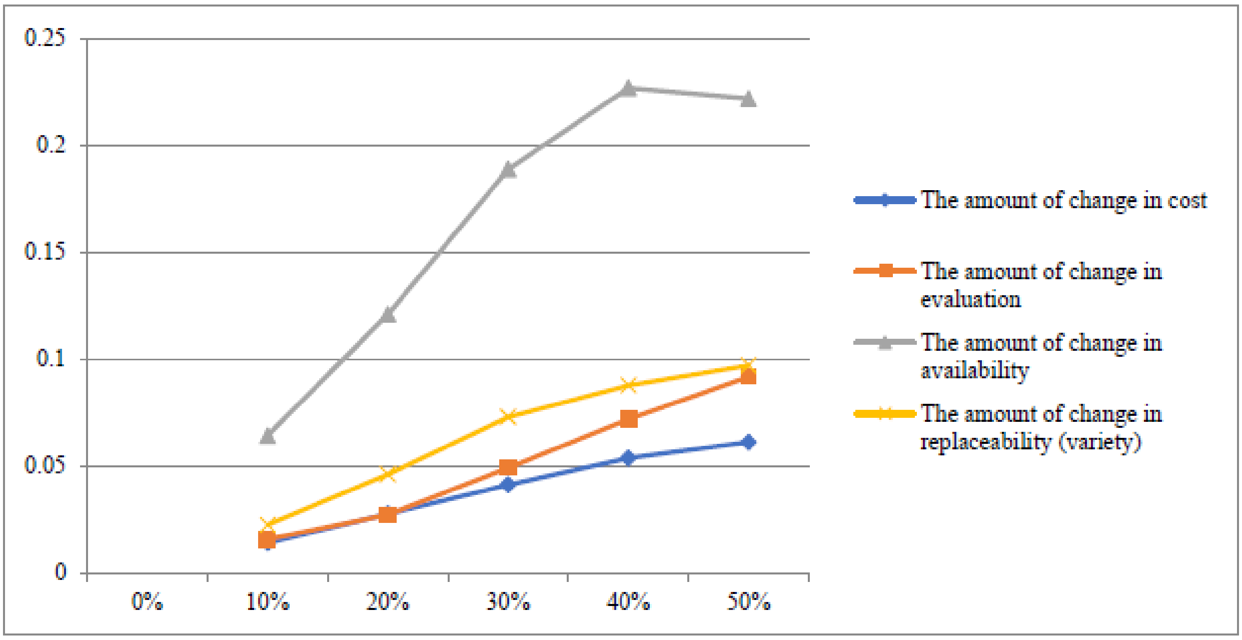

Fig. 3 .Production cost sensitivity analysis chart

As seen in Fig. 3, The production cost parameter has the most significant effect on the availability objective. After that, it has the most effect on the displacement (variety), subsequently, on the suppliers' evaluation (competence) and finally on the total cost. Moreover, an increase in the production cost can lead to improved availability. This increase has a positive effect on replacement and a negative effect on the evaluation score, as well as an overall increase in total cost. It is noteworthy that a 50% rise in the production cost can result in an approximately 6% increase in the total cost, while having an effect of around 9% on the evaluation score and slightly more than 9% on variety, but about 22% on availability. The results of the sensitivity analysis for the purchase cost parameter indicate that it has the most substantial effect on the availability objective. Next, the most significant effect is on the displacement and then on the evaluation score of suppliers and ultimately on the total cost. An increase in purchase cost can lead to an increase in the total cost, while this effect has reduced the evaluation score and increased replaceability and availability. In sensitivity analysis, the discount rate parameter also has a noticeable effect on availability by the discount amount. The discount rate parameter has a negative effect on the total cost objective and a positive effect on the evaluation score, while it also negatively affects availability and variety objectives. However, the effect on availability has a nonlinear nature, while for other objectives, it follows a linear pattern. In the sensitivity analysis, the effect of the transportation cost parameter is observed to have the most effect on availability, followed by variety and evaluation score, and ultimately on the total cost. Increasing the transportation cost leads to an increase in availability. This effect is increasing on variety, decreasing on evaluation score, and increasing on total cost. In terms of sensitivity analysis, the production capacity increase leads to an improvement in achieving the objectives of the total cost and evaluation score while having a negative effect on availability and variety. However, this improvement in availability has an exponential and non-linear effect, while on variety, evaluation score, and total cost, the effect is linear. Finally, the sensitivity analysis results for the demand and replacement cost parameters suggest that those two parameters have a negative effect on the evaluation score and worsen the result, while having a positive effect on the other three objectives. After conducting sensitivity analysis, it is necessary to compare the affectability of parameters to each objective. For example, in Table 10 the results for the availability objective and the corresponding graph are shown, and then the results are analyzed for other objectives.

Table 10
Comparison of the affectability of the parameters of the objective of availability

availability	purchase cost	discount rate	transportation cost	production cost	production capacity	demand rate	replacement cost
10%	0.096774	0.064516	0.064516	0.064516	0.032258	0.096774	0.064516
20%	0.117647	0.103448	0.121212	0.121212	0.066667	0.176471	0.090909
30%	0.157895	0.230769	0.162162	0.189189	0.178571	0.2	0.138889
40%	0.181818	0.4	0.186047	0.227273	0.347826	0.208333	0.170732
50%	0.173077	0.833333	0.176471	0.222222	0.666667	0.206897	0.166667

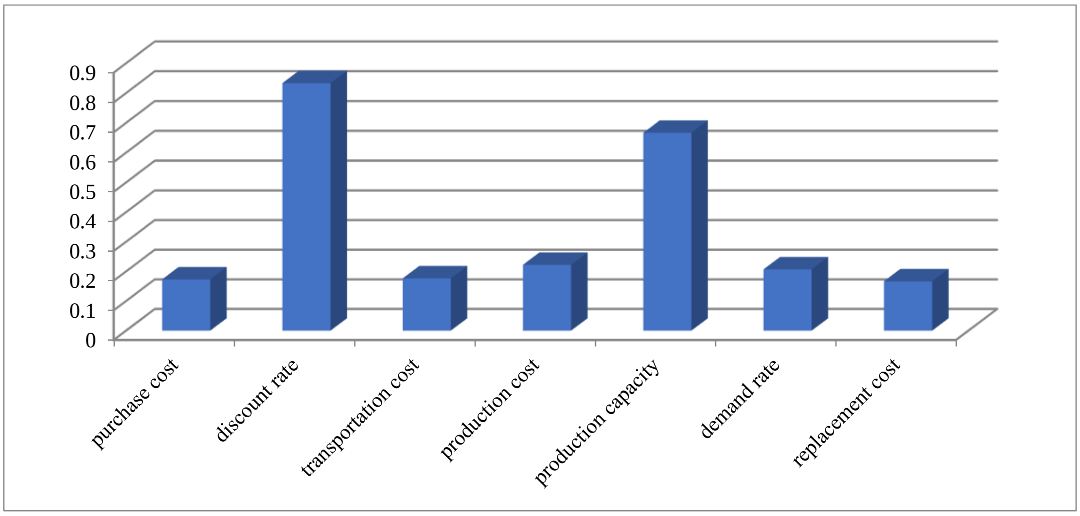

Fig.4 . Comparison diagram of the affectability of the parameters of the objective of availability

As seen in Fig.4 , the discount rate has a notable affectability of the availability objective and can be as high as 80%. In contrast, the affectability of more parameters is consistently less than 20%. Additionally, the production cost exhibits the most significant degree of affectability of the total cost objective, at around 6%, while the production capacity has an affectability of approximately 5%. On the other hand, the transportation cost has an affectability of approximately 5%. The parameter with the lowest level of affectability of the total cost is the purchase cost. As shown for the competency evaluation objective, the repalcement cost has the highest affectability around 11%. While the demand level takes the second spot with just over 10%, followed by the transportation cost at third place with slightly under 10%. Moreover, the most affectability of the variety objective is the discount rate, with a value of around 22%, while this affectability is predicted to be 17% by the production capacity and 12% based on the demand level.

9. Conclusion

A hybrid model is presented in this research for product platform architecture considering availability, cost, supply chain, and variety indices in order to improve them. It also provides analysis and technical results in each of the areas of design for X (intended in this research). The output of the model solution and sensitivity analysis also yields practical results and analyses. In terms of comparing the objectives with each other, the results show a negative correlation between the total cost objective and other objectives and a direct correlation between other objectives. The sensitivity analysis results indicate a high affectability of the availability objective on the investigated parameters. This sensitivity was observed in seven analyses, and the repeating pattern was that availability has the highest affectability with a large distance from the other three objectives. However, an interesting point was that this curve sometimes had a decreasing nature, for example if the purchase cost parameter has a substantial effect on availability, A 40% increase in the purchase cost parameter may lead to a relative reduction in availability, or the same situation can be observed for transportation cost. It is generally observed that for parameters whose increase leads to a worse outcome, this situation is noteworthy. However, in terms of parameters whose increase leads to a worse outcome, the availability curve shows an exponential trend and is not linear in nature, unlike other objectives. For example, Increasing the discount rate by 50% can improve availability by over 80%, whereas other objectives do not show the same level of improvement with such an increase.

Another recurring pattern that is notable in the analysis is the second rank of displacement. In fact, displacement (variety) is always placed in the second rank of the analyses and has a significant distance in terms of parameter affectability from availability, but it maintains a significant distance from other objectives and consistently remains distant from them, as observed in nearly all analyses. This situation is observed in nearly all analyses, except for the increase in transportation and production and replacement costs, where a 50% increase in these parameters brings displacement very close to the evaluation score and total cost. Thus, an increase in the parameters results in a decrease in the slope of the displacement change can be observed. The evaluation score of suppliers (competence) and the total cost are also rank third and fourth, respectively.

In the investigation of affectability of the parameters of the objectives, it can be summarized that comparing of affectability of the parameters of the total cost objective, the production cost has the highest affectability of the total cost, whereas the replacement cost has the highest impact on the evaluation score. In terms of availability, the discount rate has the highest impact, which shows a different effect compared to other parameters. In terms of displacement, the discount rate also plays the most important role. Therefore, it can be concluded that the discount rate parameter, in terms of frequency, has had a greater impact than other objectives, and in general, only three parameters of production cost, replacement cost, and discount rate have had the greatest impact.

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