The Optimization of Photovoltaic Systems Design Using Mathematical Modeling and QFD-DSM Methods

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ABSTRACT:
The application of renewable energy sources such as Photovoltaic Systems (PV) can be effective in minimizing damage to the environment. As the use of PV systems increases, questions and concerns about higher quality and reliability have been raised. The aim of this study, which has been conducted in the high-tech electronic industry, is to select the optimal components for designing photovoltaic systems. It has been done to achieve goals such as increasing customer satisfaction and system efficiency, reducing the overall cost and procurement time of the system. In this regard, after extracting Customer Needs from the first stage of the systems engineering process, they have been interpreted to Functional Requirements using the first matrix of QFD. Then, the FRs have been prioritized by use of Analytical Network Process and entered the second matrix of QFD. They have been examined along with leveled components based on the alternatives available for each component. Also, the Design Structure Matrix has been used to evaluate the effect of elements upon each other. Finally, a mathematical model is developed to select optimal components according to the defined objective functions and constraints. After solving the model in GAMS software, the results indicate that type B of Solar Panels, a type E of Controller, a type F of Combiner Box, a type H of Inverter, type L of Batteries, type Q of Disconnects, and type T of Miscellaneous Components must be selected to achieve mentioned objectives.

KEYWORDS: Photovoltaic Systems, Renewable Energy, New Products Development, Functional Requirements, Mathematical Modeling, Systems Engineering, Solar Power System.

1. INTRODUCTION:

The term Photovoltaic systems (PV) primarily refers to solar cells or solar modules. The solar PV system with delicate advantages and a robust evolution in renewable energy sources is the fastest-growing field, which makes the researchers choose it as a study [1]. The International Renewable Energy Agency (IRENA) reported that the statistics of an overall renewable energy capacity as 171 GW is added in the world in 2018. Asia alone is accounted for 61% of the total renewable energy installation with a growth rate of 11.4% [2]. A photovoltaic system generates electricity using solar panels, each of which is made up of some solar cells. Solar cells are semiconductors and are made of silicon. When sunlight shines on a photovoltaic cell, a potential difference is created between the negative and positive electrodes, causing the current to flow between them. Photovoltaics can be classified as renewable energy technologies. As the use of solar power systems increases, questions and concerns about higher quality and reliability have been raised for them. If a solar power system is properly designed and installed, it can be useful enough to supply energy [3]. The use of renewable energy sources can be effective in minimizing damage to the environment. Because it stops the release of hazardous gases from the energy supply with fossil fuels and cleans the energy [4]. Challenges such as the reduction of fossil fuels have also led to renewable energy sources such as solar energy being considered as sustainable alternatives. This technology has become one of the significant fields of research and development for researchers in recent years and various patents in this field [5]. In addition to the many advantages of using photovoltaic systems, there are some disadvantages such as high

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initial installation costs, dependence on atmospheric conditions and the state of the sun, not always available, and so on. Removing these barriers will make the use of this renewable energy more general and effective [3]. The purpose of this study, which has been conducted in the high-tech electronics industry, is to select the optimal components for designing and operating of the photovoltaic systems to reduce or eliminate the mentioned disadvantages. The goals such as increasing customer satisfaction, increasing system efficiency, and system life, reducing the overall cost of the system, and time to prepare system components are other achievements of this study.

One of the most common reasons for designing a new system or product is to reduce the capabilities of existing systems, increase maintenance costs, intensify competition for more efficient systems, and improve existing technologies or the emergence of new technologies. Today, increasing complexity of manufactured products and their components, the analysis of customer needs and their application in development of systems is one of the major challenges of the industry [6]. Therefore, identifying and prioritizing customer needs to improve the quality of systems or new product development based on, is essential for survival in today's competitive markets [7]. In this regard, the first stage of the Systems Engineering process (SE), requirements analysis, has been used [8].

In the process of system design, the customer's needs must first be translated into functional requirements that can meet those needs. Then, based on the specified functional requirements, the components of the system are assigned. This is done by system design engineers under the supervision of industry experts. This process is called functional design [9]. For getting the best result, a design review checklist is also used by system designers. it is a checklist in which the system designers can verify that inadequate information has been provided to meet the needs of the designed system [10].

One of the useful methods that can be used in this field is QFD. In a study conducted by Jariri and Zegordi to manage design costs, the first QFD matrix was used to translate customer needs into functional requirements [11]. In their study, three popular design cost management methods, such as QFD, Value Engineering (VE), and Target Costing (TC) have been applied. Each method is adequately good in the cost management of the design process. These methods have been incorporated into a mathematical programming model, to get the maximum advantages of each method. the approach of their research is the same as [12] , which was developed for manpower planning. They developed the mathematical model was presented in [12] to manage the costs of system design. In the present study, in order to provide a basis for the optimization, the initial mathematical model is obtained from [11] and it has been used as a reference. To achieve the specified goals, the mathematical model presented in [11] has been developed and new goals and constraints have been added to the model. In addition, in the present study, the second stage of the QFD process has been used to determine the system components according to the functional requirements. While in [11] only the first stage of the QFD process is used to determine the functional requirements. Also in this research, the selection of optimal components for the system from the defined levels of components has been considered. This leveling is done by consideration of different procurement times and costs for each component.

The application of this research is planning for production, improving the quality level of PV systems, increasing customer satisfaction, and their commitment and loyalty, and recognizing their needs. By conducting this research, the customer needs are interpreted into functional requirements for system design, and these requirements are prioritized. By the prioritized functional requirements, the components are determined to produce the system. After leveling the components according to the alternatives available for each of them, the optimal components are selected using mathematical modeling and introduced to the design team. This increases customer satisfaction because all his needs are considered and applied in all stages of system design and manufacturing. This has many political and economic benefits for companies.

In addition, examining the relationships between QFD components with the DSM approach to extract the ANP communication network can greatly reduce the complexity of network mapping and pairwise comparisons. This is because using the DSM matrix, it is necessary to interact with the decision-maker about the communication network and pairwise comparisons between the components only once, and all the necessary information is extracted from the DSM matrix.

In the following sections of the article, first, by reviewing the research background, the efforts of researchers in this field will be considered and a summary of them will be presented in the research background tables. Then, the research method and tools in each phase will be mentioned. After that, the case study will be introduced and analysis of results and findings is performed and the multi-objective mathematical model for selecting optimal components of the new product is presented. Finally, conclusions and suggestions for future studies will be provided.

2. LITERATURE REVIEW

This section consists of two parts:

2.1. Theoretical Definitions of Research

This section provides a brief explanation of basic concepts and methods to understand the research. Developing a new system is a costly and time-consuming process, so deciding to start this process requires a comprehensive and precise study. This system must be able to meet the needs of its customers and stakeholders as one of the major goals of most organizations. In this regard, Organizations must provide the knowledge, skills, and resources needed to satisfy their customers [13].

In 1839, Edmond Becquerel introduced the principles of the process of converting solar energy into electrical energy [2]. A photovoltaic system generates electricity using solar panels which are made up of solar cells [5]. This cell absorbs photons in the light energy to give electric energy known as the PV effect. The availability of renewable energy sources such as PV has made it one of the most sustainable energy sources in the world in recent years [2]. PV system is one of the renewable energy systems that has received a lot of attention in recent years and has become increasingly widespread in business. PV converts the energy of solar radiation directly into electrical energy. Depending on the weather and the level of sunlight, the amount of produced energy varies [14].

Accordingly, the International Council of Systems Engineering describes Systems Engineering as a field of engineering whose mission is to implement and manage the process of meeting customer and product stakeholder needs in a satisfactory, reliable, cost-effective, and timely manner, and also it is defined in terms of a life cycle [8]. So the first stage of SE process was applied to analyze of customer needs.

There are several approaches and methods to design and develop of systems, including reverse engineering, value engineering, the Taguchi method, and Quality Function Deployment (QFD). The first three emphase on the amount of product production, and have less attention to customer needs. But QFD is highly focused on customer needs [15]. QFD is a powerful tool to translate Customer Needs (CNs) to Functional Requirements (FRs) [16]. It is a customer-oriented approach to improve quality in a system or product as well as ensure that the customer is engaged throughout the product's specification [17]. Therefore, it has been used to translate CNs to FRs in the research under the supervision of industry experts.

QFD uses a matrix called the House of Quality (HOQ) that translates CNs to FRs or in some resources to Design Requirements (DRs) [18]. The amount of communication between CNs and FRs is qualitative and relative in traditional QFD. So, using the Network Analysis Process (ANP) method, more accurate prioritization of customer needs and functional requirements can be achieved [19]. Moreover, the interactions of components upon each other (in terms of performance and functionality) are examined using the Design Structure Matrix (DSM). As a result, they can be used in the ANP communication network to simplify complex analysis [20].

On the other hand, the alternatives of each design component have a different quality in meeting the functional requirements of the system according to procurement time and cost. This can create the levels of components and challenge the decision-making process of selecting optimal components [11]. Therefore, applying mathematical modeling with consideration of several goals simultaneously can greatly help to solve this problem. The model input parameters are entered from the second stage of the QFD process.

Multi-objective modeling is a multi-criteria decision logic related to mathematical optimization problems that have more than one objective function for simultaneous optimization. For a problem, the goals are usually conflicting, and none of the available solutions optimizes all the goals at the same time [21].

In this research, the LP-metric method has been used to solve the mathematical model. LP-metric method is a multi-criteria decision making (MCDM) that solves multi-objective decision making (MODM) models. In the method without the information of the decision-maker, the desired point of a decision can be determined. The purpose of this method is to minimize the deviation of existing objective functions from an ideal point. Because closer the objective functions to their optimal values are more desirable, so, it looks for a goal function by which all functions get closer to their optimal value [22].

2.2. Review of Studies Related to the Research Topic

By reviewing the recent studies conducted in the field of PV systems, it concluded that most studies were related to cleaning systems or the presentation of hybrid systems in energy production. Furthermore, few studies have been done on optimizing the design of these systems based on customer needs and functional requirements. Some of the most relevant ones are presented as follows. Therefore, optimizing the design of PV systems based on the selection of optimal components and according to the customer needs and functional requirements derived from the needs is essential. Because it leads to achieving goals such as increasing customer satisfaction and system efficiency, reducing the overall cost and procurement time of the system.

In [5], an extensive definition of the technological system of photovoltaics in terms of its components and structure is provided. It was done to identify its relevant patent applications and to analyze their technical, geographical, and organizational trends. Because the comprehensive PV system review was done in this paper, it can be a resource to know the latest achievements in this field. Moreover, it provides an available research perspective for future studies and also highlights study gaps in the field of PV systems.

In the reference [23], the purpose of the study is to present a new method for finding an optimal combination of hybrid systems. The hybrid system consists of a set of electricity generation systems including photovoltaic panels, wind turbines, and batteries that are fed from different energy sources. In this research, the need of reducing investment costs had been considered as a customer need in designing hybrid systems. Also, the HOMER software is used to impose the best possible trade-off between cost and reliability for the presented hybrid energy system.

In [4], the major emphasis is on solar photovoltaic (PV) and concentrated solar power (CSP) technologies. Their types, efficiency and cost factors, and mechanism have been discussed. In order to effectively utilize the PV systems, it is important to know the technology and its suitability according to the customer requirements and nature of utilization. It has been observed that solar energy, which is a stable and consistently available source of energy has the significant potential to meet growing world electricity requirements.

A study in [24], attempt to minimize costs through the selection and configuration of inverter and PV modules for a PV system. The purchasing costs can be decreased by using this model. the presented model can be used only at the lowest price and is not applicable to achieve the highest efficiency in power production.

A mathematical procedure is presented in [25-27] to maximize the profit during PV plant lifetime, by considering the effect of shading on the PV module output power.

In [28] binary linear programming was used to get an economical design. This method has been applied to convert the design of PV power plants. In the presented method, the design variables are only the number of inverters and PV modules connected in series and parallel.

In reference [29], an optimal configuration of the PV power plant of different PV technologies has been presented with consideration of economic, technical, and environmental criteria and using the GA technique.

In [30], an economic design for PV systems is presented by using the combination of multi-objective optimization and a decision-making method. The framework simultaneously optimizes technical, economic, and environmental criteria for the system design. Also, the use of a multi-objective Genetic Algorithm (NGSA II) optimization loop generates a set of Pareto solutions to trade-off between the defined objectives. Then select the solution providing the best agreement with the TOPSIS method. After analyzing the first results for removing redundant objectives, the Principal Component Analysis (PCA) method was applied. It caused to remain only four inconsistent objectives.

Authors in [31], discussed the modeling of PV system components, which consist of PV panels and battery systems. To gain final compositions for design parameters, the study attempts to give explanations on approach by previous researchers. In this paper, the multi-objective design was used as an optimization method in finding optimal sizing. IT is important to do as early step in PV system design based on customer's requirements and system constraints.

In [32], the proposed methodology has been applied to the development of the optimal design of a PV plant connected to the electric grid and implemented in MATLAB software. According to the presented results, the PV plant optimal design variables depend on the selected objective function. The optimization process selects from a list of several alternatives, only one PV module and inverter which presents the optimum combination.

Optimal selection of components in the design or development of new products was also done in other systems and products. In the following, these researches will be discussed focusing on the methods and tools used in each study:

Shvetsova et al. [17], proposed an approach for B2B product enterprises that evaluate and select new product concepts based on Customer Requirements (CR). The case study of this research is the evaporator in automotive air conditioning systems. The main objective of this research is developing an integrated analytical approach, combining quality function deployment (QFD) and analytic hierarchy process (AHP) and data envelopment analysis (DEA) that leads to increase the effectiveness of product design. Also, it used mathematical methods to evaluate and select the best new product concept.

Ocampo et al. [33], provided an integrated multiphase fuzzy QFD-MADM framework. A Philippine meat processing industry was implemented as a case study to demonstrate the proposed approach. This research attempts to advance the gaps in previous research by proposing a framework that combines QFD, analytic network process (ANP), analytic hierarchy process (AHP), decision-making trial and evaluation laboratory (DEMATEL), and fuzzy set theory. The results show that the customer requirements are integrated into all product development stages, which is a strong indication that these requirements are addressed in each phase.

Fargnoli and Haber [34], proposed a methodology based on customer needs and the analysis of the market demand using the QFD for Product Service System (QFD for PSS) and the Analytic Network Process (ANP) methods. To verify the presented methodology, it was applied to a case study in the medical devices sector. Results showed that the methodology allowed engineers to make the assessment of the PSS requirements homogenous and comparable, accurate evaluation of their mutual interactions. Also, it considered those factors that are hidden to the customers and have an indirect effect on their satisfaction.

Liu et al.[15], proposed a new two-step approach to achieve a customer-oriented product. In the first stage, QFD, which is based on fuzzy multi-objective decision making and suppliers' budget constraints, is presented to maximize customer satisfaction. In the second stage, an effective approach is proposed to sequence the execution of several activities related to the minimum feedback time in a DSM.

Lam and Lai [35], By combining methods of QFD and ANP, examined the interdependence between the interior elements of a house of quality (HOQ) and presented a decision support model with systematic criteria. They first calculated the degree of importance of customer needs and functional requirements without considering the dependencies between them. In the next step, the correlation matrix between customer needs and functional requirements was designed and analyzed and their weights were calculated by ANP method. Finally, by multiplying these weights, a column matrix containing the priority of each of these criteria was obtained.

Zaim et al [36], proposed a hybrid fuzzy ANP method, to combine ANP capability and fuzzy logic, which leads to better recognition of the technical specifications of a product (or service) during QFD execution. In this model, which has been implemented on the equipment of polyethylene pipes to prevent the flow of gas without damaging the pipes, the ranking of the technical characteristics of the product has been done using fuzzy weights.

Prasad and Subbaiah [37], used cost management approach in the conceptual design phase of the product to develop the product with minimum cost and maximum customer satisfaction. In this regard, they used the integration of the QFD method and Target costing to achieve the mentioned goals. To optimize customer satisfaction and the total cost of the product, they formed a mathematical model that integrates QFD and TC under the multi-purpose optimization process, and using goal programming, the best components are selected to produce the product.

Yang and Chen [38], presented a linear programming model to determine the optimal level of functional requirements in which the objective function, customer satisfaction, and constraint were the cost of customer dissatisfaction. Finally, using a software product design, they showed that the proposed method can help the QFD team to achieve customer satisfaction and surpass competitors.

Prasad and Chakraborty [39], designed the initial steps to solve the problems in the selection of raw materials using a QFD-based application. The use of QFD in the selection of raw materials leads to a better understanding of the conceptual design of products. During its implementation, by eliminating parallel activities in product production, it is possible to reduce cost and time and increase product quality.

Nahm [40], Introduced a new approach for prioritizing customer needs from the point of view of companies' competitiveness. The main feature of the proposed approach is modeling the structure of customer preferences as a form of customer satisfaction function by combining the analysis of competitive criteria with the analysis of the Kano model.

Cao et al. [41], described the concept of the Economic House of Quality (EHOQ). The construction of the EHOQ model is presented based on qualitative economic analysis. The proposed method has transformed the traditional ten-step model into a new thirteen-step model. This is done through the introduction of three new steps that use the rate of price growth expected by the customer, the annual increase in total quality costs, and the expected revenue as input for economic analysis on the house of quality.

Zhang and Wang [42], introduced a new model of HOQ, Economic House of Quality (EHOQ), with a focus on the customer and maximizing value. This model has three dimensions: service features, customer expectations, and economic concerns to improve quality with economic benefits in the service industry. EHOQ adds an economic layer to the traditional HOQ model so that there is no worry about economic value while improving quality.

Mayyas et al [43], examined the choice of the original structure of the vehicle in the conceptual design stage that reduces costs and increases production capacity. In this research, the car body panels using QFD and the hierarchical analysis process are discussed. Also, a combination of the above two methods has been used in ranking the choices to increase their effectiveness in achieving the goals.

Malekly et al. [44], proposed a systematic decision-making process to select the best design idea using a new integrated QFD-based optimization method. In the first phase, QFD is used to translate project requirements into design requirements. In the second phase, TOPSIS was used to select the best method as an option based on the weighting criteria in the first phase.

Liu and Wang [45], presented an advanced model of fuzzy QFD based on the analytic network process (ANP) that systematically considers the relationship between QFD components as well as its internal relationships. The proposed method aims to expand the scope of research from the product planning stage to the stage of defining design components, to provide the developed product with valuable information extracted from the QFD. In this process, the use of customer needs and production needs as input for QFD increases the accuracy and reliability of the analysis results.

Lee et al. [46], provided a two-stage framework to facilitate the selection of technical specifications in product design. In the first stage, QFD with ANP and fuzzy set theory is used to calculate the priorities of technical specifications, taking into account the relationship between the factors and the existence of certainty and uncertainty in the available information. In the second stage, multi-criteria modeling has helped to select the most appropriate technical characteristic by considering the fuzzy results obtained from the first stage and other existing goals such as cost and production capability.

Lin et al. [47], using the QFD, interrelationships and interdependencies between requirements in the production of environmentally friendly products and sustainable production indicators have been identified and categorized. In this study, the QFD matrix is explained by considering "what" and "how" to be done, and the requirements are prioritized using fuzzy theory and analytic network process (ANP). The purpose of this study was to identify the most important criteria and pay attention to their criticality in the organization to produce environmentally friendly products.

Hung et al. [48], introduced a new framework for product design planning that uses the combination of QFD and DSM to calculate the cost and time required for the design process. The research by these researchers examines the relationships between the elements of the second matrix of the four-stage QFD matrixes.

Jariri and Zegordi [11], provided an integrated model of combining QFD, value engineering (VE), and Target costing (TC). This model compares customer satisfaction with Target costing and provides zero-one mathematical programming for it. The model starts with the QFD process and after identifying the customer needs and the technical specifications extracted from them, they are graded by value engineering analysis. After applying the target costing, mathematical modeling is performed and finally, it is analyzed.

Kaldate et al. [49], proposed a method to reduce a large set of engineering parameters and turn them into a more efficient subset using DSM and QFD. In the proposed method, first, the values of the QFD matrix body were divided into small modules using DSM, and then these modules were prioritized in terms of cost using mathematical modeling and several equations. This prioritization led to the combination or separation of some engineering parameters and ultimately led to cost control and reduction of engineering parameters.

Chen et al. [50], established the house of quality and then the data inside it was transferred to an advanced DSM matrix and the degree of dependence of each design parameter was analyzed in the DSM matrix.

The research problem is to select optimal components for designing PV systems with maximum customer satisfaction and under resources' limitation by mathematical approaches. So, the main objective of this study is to develop a mathematical model for prioritization and selection of optimal components in the design of PV systems with the combined approach of QFD, DSM, and ANP. Combining the QFD model with MCDM methods and fuzzy theories has been investigated by many researchers [51]. But none of the researches has used the combination of three methods QFD, ANP, and DSM in the field of new product design and development. Also considering all available alternatives based on cost and procurement time of components simultaneously, to select optimal components of the new product have been neglected in other studies.

3. RESEARCH METHODOLOGY:

In terms of purpose, the present research is part of applied research and for information collecting, library and interview method have been used. This study consists of three main phases, in each of them, several steps are defined. The first phase consists of three steps: identifying customer needs and functional requirements, examining the relationship between customer needs and functional requirements with DSM and creating an ANP network, and finally prioritizing customer needs and functional requirements using the ANP technique. The second phase consists of four steps: identifying the components required for product design according to functional requirements, examining the effect of components on each other using DSM, components leveling and time and cost estimation for each level of components, investigating the impact of components in meeting the functional requirements with DSM and creation of ANP network. The third phase consists of three steps: the definition of model decision variables, model constraints, and objective function modeling, and ultimately model solving and model validation. According to the mentioned steps, the conceptual model of research in the present study is displayed as a graph of three phases and ten steps in Fig. 1.

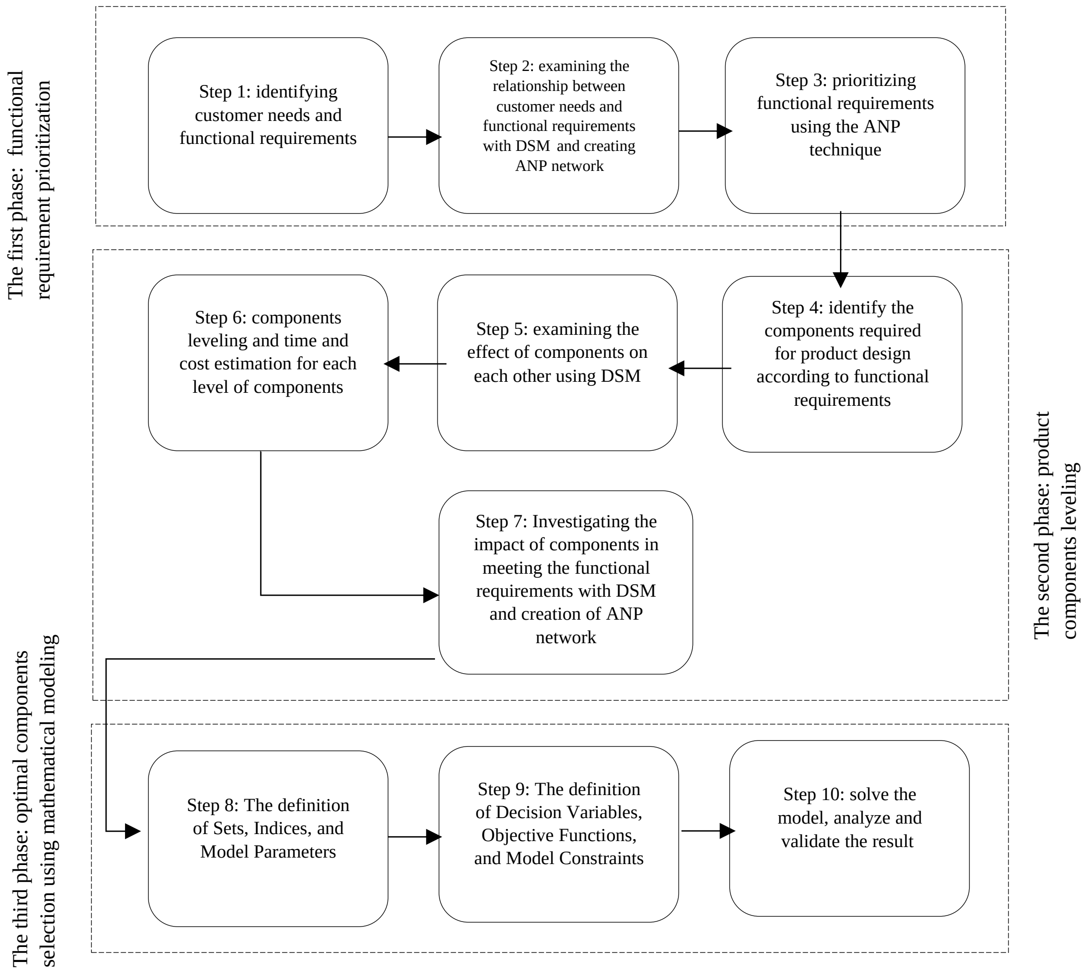


Fig. 1. The flowchart of the research.

4. RESULTS AND DISCUSSION

This section consists of three parts:

4.1. The First Phase: Functional Requirement Prioritization

The first phase is divided into the following steps:

4.1.1. Identifying customer needs and functional requirements:

Extracting the needs of system stakeholders and customers in the first stage of requirements analysis in the systems engineering process: This step is done by reviewing the relevant documents, items mentioned in the project contract and holding meetings with customers, and using Voice of Customer (VOC) tool. It is shown in Table 1:

Table 1. Customer needs.

Row	Customer Needs
CN1	Providing the highest voltage rate in different climatic conditions
CN2	High system efficiency
CN3	Reduce the overall cost of the system
CN4	Reduce components procurement time
CN5	High system life

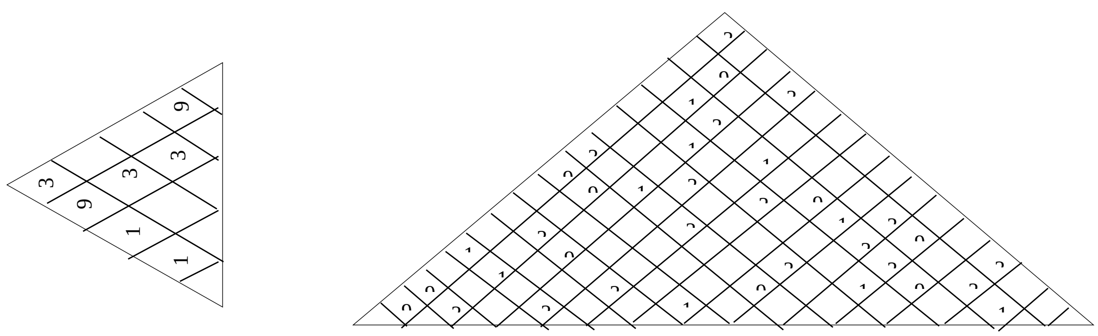
Interpret the needs of customers and stakeholders to functional requirements: this step is done according to the obtained needs and functional requirements in similar samples and with the opinion of experts and senior engineers. They are shown in Table 2:

Table 2. The functional Requirements.

No.	Functional Requirements	No.	Functional Requirements
FR1	Absorb photons from the sunlight	FR9	Takes (DC) from batteries and turns it into (AC)
FR2	Convert absorbed photons to the electrical energy	FR10	Have durability and performance under extreme weather conditions
FR3	Combine multiple of solar panels in parallel or series	FR11	Be resilient to rough atmospheric conditions
FR4	Prevent overcharging of the batteries	FR12	Convert the AC to DC to charge the battery from direct AC power supply
FR5	Regulate the amount of current, the PV modules feed into a battery bank	FR13	Storage and backup operation at overnight
FR6	Block battery bank current from leaking back into the photovoltaic array at night or on cloudy days	FR14	Cutting off power to and from the inverter
FR7	Prevent from draining the battery bank	FR15	Connect all the parts together safely and securely
FR8	have enough capacity (in rated Amps) to handle the total current of the solar array safely		

4.1.2. Examining the existing relationships between customer needs, functional requirements and between both of them with the DSM approach

Fig. 2 represents the House of Quality matrix made by the set of communications extracted from the first step of the study. The interrelationship matrix between functional requirements and customer needs to be designed to improve the product. The technical correlation matrix between functional requirements is more often referred to as the Roof. Also, the relationships between customer needs have to be placed on the left side of the interrelationship matrix as shown:



	FR1	FR2	FR3	FR4	FR5	FR6	FR7	FR8	FR9	FR 10	FR 11	FR 12	FR 13	FR14	FR15
CN1	9	9	9		3	1	3	9	1	3	3		3		
CN2	3	3	3	9	3	3	3	9	1	3	9		3		9
CN3			9		3	1	1		1		3	9		1	
CN4				9	9			3	3	3					
CN5						1	1		1				9		3

Fig. 2. The house of quality matrix of this research.

4.1.3. The prioritization of functional requirements using the ANP technique

In the above House of Quality matrix, due to the existence of network relationships between its elements, it is not possible to calculate the weights and requirements priority using the simple relationships defined in the traditional QFD. Therefore, the ANP technique is used to prioritize them. This network has been analyzed in Super Decision Software 2.10.0 version, and the final results of this process are shown in Table 3:

Table 3. The prioritized functional requirements.

Functional requirement	Final weight	Priority number	Functional requirement	Final weight	Priority number
Absorb photons from the sunlight	0.4942	1	Takes (DC) from batteries and turns it into (AC)	0.0766	13
Convert absorbed photons to the electrical energy	0.3325	5	Have durability and performance under extreme weather conditions	0.2101	8
Combine multiple of solar panels in parallel or series	0.3932	3	Be resilient to rough atmospheric conditions	0.1971	9
Prevent overcharging of the batteries	0.0921	12	Convert the AC to DC to charge the battery from direct AC power supply	0.0480	14
Regulate the amount of current the PV modules feed into a battery bank	0.2406	7	Storage and backup operation at overnight	0.2985	6
Block battery bank current from leaking back into the photovoltaic array at night or on cloudy days	0.1240	10	Cutting off power to and from the inverter	0.0192	15
Prevent from draining the battery bank	0.1023	11	Connect all the parts together safely and securely	0.3671	4
have enough capacity (in rated Amps) to handle the total current of the solar array safely	0.4512	2			

4.2. The Second Phase: Product's Components Leveling

4.2.1. The identification of components to product design according to the functional requirements after translating operational objectives into functional requirements, another important activity is how to assign these functions to subsystems or system components. The purpose of this work is to prove the feasibility of achieving the desired functions through efficient system visualization [52]. These seven introduced components were extracted and collected during the meetings that were conducted in the form of interviews with industry experts. Each of these components may be capable of meeting one or more functional requirements. These components are the columns of the second QFD matrix and are examined concerning functional requirements. The required components are listed in Table 4:

Table 4. The Main Components of the Solar Panel System

No.	The Main Components	No.	The Main Components
1	Solar Panel or PV module	5	Batteries for Solar Electric Systems
2	Solar Charge Controllers	6	DC and AC Disconnects
3	Solar Inverter	7	Miscellaneous Components
4	Combiner Box		

4.2.2. Investigating the effect of components on each other using DSM

The components in this step are tangible items that are combined to produce the final product. Here the system elements and the relationship between them are displayed as a structure that can be designed and evolved in the future [53]. As previously described, the DSM identifies the behavior of elements and the relationship between them as an important tool for system modeling and architecture [54]. Therefore, it has been used in the design and analysis of components. The information has been considered after conducting interviews and meetings with industry experts. Then it is entered as the roof of the second matrix of QFD and analyzed along with other information in Fig. 4.

4.2.3. Leveling components and estimating cost and procurement time for each level

After identifying the components needed to make the product, during meetings with experts and design engineers, all the alternatives and choices available for each component were extracted and the time and cost required to produce, order, and purchase these components were estimated. All available alternatives for each component provide the levels for the selection of each component. These levels can make a difference in the choice of these alternatives due to the cost and time required to prepare these components. That is, a component that has three levels has three alternatives with different prices and procurement times. As a result, considering this and considering the goals of the product, it is possible to have different choices between these three levels of the component.

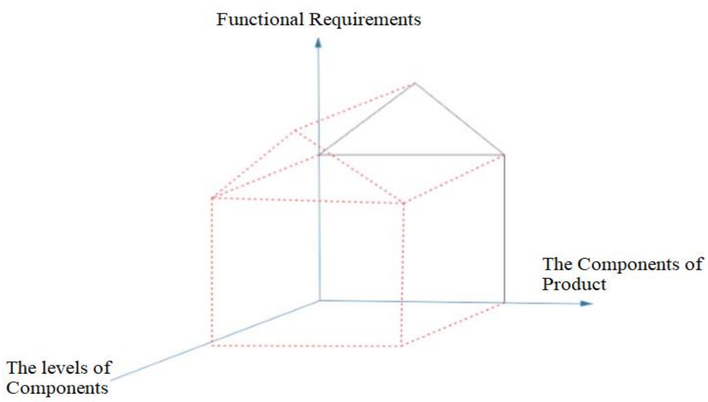


Fig. 3. Schematic of a three-dimensional matrix due to leveling of the components

All available alternatives for components with acronyms whose identification code is shown in Table 5. It should be noted that costs are in dollars and preparation time is in months. These defined levels for the components, along with other information extracted for product design, enter the second phase of the four-stage QFD model and convert the existing matrix into a three-dimensional matrix [11]. The schematic of three-dimensional matrix is shown in Fig. 3.

Table 5. The alternatives of the components along with the estimated cost and time of procurement.

No.	Components	Types	leveling	Cost ($)	Time (M)	No.	Components	Types	leveling	Cost ($)	Time (M)
1	Solar Panels	Monocrystalline	A	495.95	.5	5	Batteries	FLA	K	3942.80	1
		Polycrystalline	B	375.25	1			AGM	L	1074.00	.5
		Thin-film	C	115.00	1.5			Gel	M	5365.00	1.5
2	Controllers	PWM	D	315.00	2			Lithium-lon	N	11360.00	2
		MPPT	E	550.00	1	6	Disconnects	Square D H364 NRB 200A 3-pole	O	1120.00	1.5

3	Combiner Box	MNE 175 TM-240	F	570.20	1.5			Square D HU361 RB 30A 3-pole	P	175.00	2
		MNP V4 - MC4	G	254.25	2			Square D HU362 RB 60A 3-pole	Q	380.00	1
4	Inverter	Off-grid	H	2100.00	1	7	Miscellaneous Components (Brackets)	Slotted L-Bracket	R	6.75	.5
		On-grid	I	1040.00	.5			Mount Bracket	S	14.00	1
		Hybrid	J	4330.00	2			Skirt Bracket	T	9.95	1

4.2.4. Investigating the Impact of Components in Meeting the Functional Requirements with DSM and Creation of ANP Network

At this stage, the effectiveness of system components in meeting customer expectations has been analyzed. Given that each of the specified components has a set of alternatives due to different time and costs, the generated matrix becomes a three-dimensional matrix. Each of the alternatives available for each component can have a different effect on meeting the functional requirements. Therefore, during interviews with experts and considering the effectiveness of each of the identified alternatives for the components in meeting the desired functional requirements, the third dimension of the matrix was formed. As shown in Fig. 4, the matrix rows represent the functional requirements that have been entered from the first stage of the QFD process, the house of quality matrix.

The matrix columns also represent the specified components to meet the functional requirements, which have different alternatives. According to each level of the components, a number corresponding to meeting functional requirements using the range (1-3-9) is placed in the matrix. This three-dimensional matrix forms the body of the second stage of the QFD matrix.

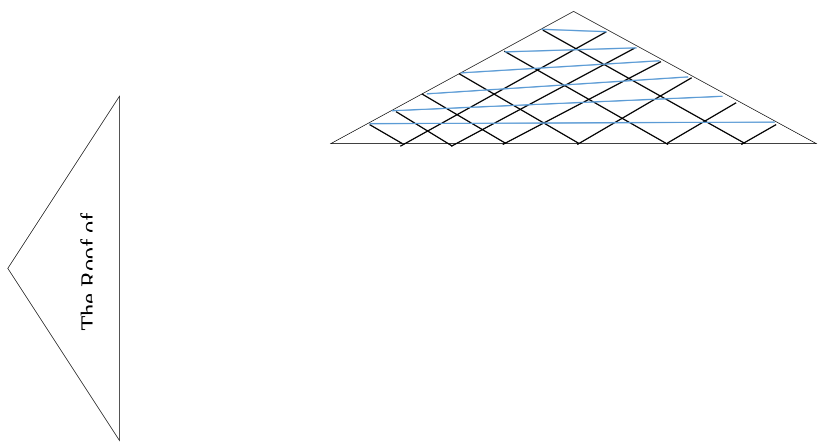


Fig. 4. The second matrix of QFD with consideration of components levels.

FRs ↓ Solar panels → Levels	Solar panels			Controllers		Combiner Box		Inverter			Batteries				Disconnects			Brackets		
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
Absorb photons from the sunlight	9	9	3																	
have enough capacity (in rated Amps) to handle the total current of the solar array safely				3	9															
Combine multiple of solar panels in parallel or series						3	3													
Connect all the parts together safely and securely																		3	1	9
Convert absorbed photons to the electrical energy	3	3	1																	
Storage and backup operation at overnight											3	9	3	1						
Regulate the amount of current the PV modules feed into a battery bank				3	9															
Have durability and performance under extreme weather conditions								9	3	9										
Be resilient to rough atmospheric conditions								3	1	3										
Block battery bank current from leaking back into the photovoltaic array at night or on cloudy days					3	3														
Prevent from draining the battery bank					3	3														
Prevent overcharging of the batteries					3	3														
Takes (DC) from batteries and turns it into (AC)								3	1	3										
Convert the AC to DC to charge the battery from direct AC power supply								9	3	9										
Cutting off power to and from the inverter															3	1	9			

4.3. The Third Phase: Optimal Components Selection Using Mathematical Modeling

The phase is divided into the following steps:

4.3.1. The definition of Sets, Indices, and Model Parameters

In this research, the approach is the same as [11, 12], which were developed for design costs management and manpower planning respectively. The authors developed them to maximize customers' satisfaction, minimize components procurement time and components procurement costs. Also, new constraints have been defined in the model due to the industry conditions. Table 6 and Table 7 are presented to describe it.

Table 6. Sets and Indices.

Sets		Indices		
Requirements' Set	I	Requirements	i	i=1,2,…,15
Components' Set	J	Components	j	j=1,2,…,7
Levels of the Components' Set	L	Levels of the Components	l	l=1,2,...,4

Table 7. Model Parameters.

Parameter	Definition
w_i	Indicates the weight of the functional requirement i extracted from the third step in the first phase
y_i	Indicates the total importance of component levels for functional requirement i
R_{ijk}	Indicates the effect of components on each other (the roof of the second matrix of the QFD)
r_{ij}	The effect of component j on meeting the functional requirement i (the body of the second matrix of the QFD)
Tc_j	Indicates the total cost for component j
Tt_j	Indicates the total procurement time for component j
c_{jl}	Indicates the cost of level l for component j
T_{jl}	Indicates the procurement time of level l for component j

4.3.2. The definition of Decision Variables, Objective Functions, and Model Constraints

Here decision variables are:

x_{ku}, x_{jl}: if component j performs at level L = 1, Otherwise = 0.

The model consists of three objective functions, which are described in Table 8.

Table 8. Objective functions of the model

Objective Functions	Definition
Maximize customer satisfaction	Maximizing customer satisfaction according to the information extracted from the first and the second matrixes of the QFD, which are based on customer needs.
Minimize components procurement time	Minimizing components procurement time considering the set of available alternatives for each component
Minimize components procurement cost	Minimizing components procurement cost considering the set of available alternatives for each component

The model consists of three constraints, which are given in Table 9.

Table 9. Model Constraints

Constraints	Definition
Cost constraint	This constraint seeks to reduce the cost of components procurement in the product. This means choosing a level for each component that minimizes cost [37].
Time constraint	This constraint seeks to reduce the time of components procurement in the product. This means choosing a level for each component that minimizes time.
Selection constraint of the components' levels	This constraint is designed to select only one of the available levels for each component. This means that only one of the available alternatives for each component is selected as the best alternative [37].

According to the previous steps and all the defined parameters, variables, and constraints, the three-objective mathematical model is formulated as follows:

$$Max\ z_1 = \sum_{i=1}^{m} w_i\ y_i \quad (1)$$

$$Min\ z_2 = \sum_{j=1}^{n} TC_j \quad (2)$$

$$Min\ z_3 = \sum_{j=1}^{n} Tt_j \quad (3)$$

Subject to:

$$\sum_{i=1}^{l_j} C_{jl} \times x_{jl} = TC_j \quad (4)$$

$$\sum_{i=1}^{l_j} T_{jl} \times x_{jl} = Tt_j \quad (5)$$

$$\sum_{i=1}^{l_j} x_{jl} = 1 \quad (6)$$

$$y_i = \sum_{j=1}^{n} \sum_{i=1}^{l_j} r_{ijl}\ (x_{jl}) + \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} \sum_{i=1}^{l_j} \sum_{u=1}^{l_k} R_{ijk}\ (x_{jl})(x_{ku}) \quad (7)$$

$$X_{jl}, X_{ku} \in \{0,1\} \quad (8)$$

To explain the mathematical modeling, Equation 1 as the first objective function, maximizes customer satisfaction. y_i, which is computed by Equation 7, reflects the impact of customer preference by the first term. The second term reflects the impact of the roof of the House of Quality. R_{ijk} represents the interaction between the components k, and j for the ith functional requirement. When the second term is the product of two x's and each x is the number between zero and one. The second term does not dominate the first term [11]. Equation 2 as the second objective function, minimizes the total cost of components procurement. Equation 3 as the third objective function, minimizes the total time of components procurement. Equation 4, calculates the cost of selecting level l for component j. Equation 5, calculates the procurement time of selecting level l for component j. Equation 6, ensures that only one level of each component can be selected. Equation 8, Represents the decision variables that can only take the value 0 or 1.

4.3.3. Model solving and validation

The mathematical model is a three-objective model that was analyzed based on the information of the second QFD matrix using the L-P metric method and Gams v25.1.3 software. The model is also validated by sensitivity analysis and confirmation of the answers by experts. In this model, increasing customer satisfaction, reducing the time and cost of components procurement have been considered as objectives. According to experts and considering the type of product and its sensitivity for the industry, the first objective, "increasing customer satisfaction" is more important than other objectives. Reducing costs and time have equal importance in the production of the product. Therefore, S_1 indicates the weight of the first objective function, increase customer satisfaction, according to experts, is considered 0.4. S_2, the weight of the second objective function, reduction of procurement cost, and S_3, the weight of the third objective function, reduction of procurement time, are also considered 0.3.

Each objective was optimized separately, along with other constraints defined in the mathematical model, under single-objective optimization. Using GAMS software, the value of the objective function "customer satisfaction" was estimated at 192.682. The value of the objective function "procurement cost" and the value of the objective function "procurement time" was calculated at 169 million and 8.3 months, respectively. After no scaling the objective functions, the L-P metric objective function, which calculates the minimum deviations of the objective functions from an ideal solution, was obtained with Equation 9 as follows. Other model inputs are also given in Table 10.

Table 10. The model inputs.

S_1	The weight of the first objective function	z_3^*	The optimal value of the objective function of procurement time after solving in a single-objective mode
S_2	The weight of the second objective function	z_1^{Nad}	Nadir value of the first objective function
S_3	The weight of the third objective function	z_2^{Nad}	Nadir value of the second objective function
z_1^*	The optimal value of the objective function of customer satisfaction after solving in a single-objective mode	z_3^{Nad}	Nadir value of the third objective function
z_2^*	The optimal value of the objective function of production cost after solving in a single-objective mode	P	1,2,3,∞

$$Min\left(s_1\left(\frac{z_1^*-z_1}{z_1^*-z_1^{Nad}}\right)^p+s_2\left(\frac{z_2-z_2^*}{z_2^{Nad}-z_2^*}\right)^p+s_3\left(\frac{z_3-z_3^*}{z_3^{Nad}-z_3^*}\right)^p\right)^{1/p} \tag{9}$$

The following model was obtained based on the values of the objective functions after solving the model as a single objective along with other information entered in the model. Due to a large number of restrictions, a small number of each are given here as an example:

$$\text{Min } [\ .4\ [\ \frac{192.682-Z_1}{192.682-85.422}\ ]^{P}\ +\ .3\ [\ \frac{Z_2-169}{1412.521-169}\ ]^{P}\ +\ .3\ [\ \frac{Z_3-8.3}{52.4-8.3}\ ]^{P}\ ]^{1/P}$$

s.t.

$495.95x_{11} + 372.25x_{12} + 115x_{13} = TC_1$

$315x_{21} + 550x_{22} = TC_2$

$570.20x_{31} + 254.25x_{32} = TC_3$

.

..$5x_{11} + x_{12} + 1.5x_{13} = Tt_1$

$2x_{21} + x_{22} = Tt_2$

$1.5x_{31} + 2x_{32} = Tt_3$

.

..

$x_{11} + x_{12} + x_{13} = 1$

$x_{21} + x_{22} = 1$

$x_{31} + x_{32} = 1$

.

..

$$y_i = \sum_{j=1}^{n}\sum_{i=1}^{l_j} r_{ijl}\,(x_{jl}) + \sum_{j=1}^{n-1}\sum_{k=j+1}^{n}\sum_{i=1}^{l_j}\sum_{u=1}^{l_k} R_{ijk}\,(x_{jl})(x_{ku})$$

.

Table 12. The results of solving the mathematical model with single-objective and multi-objective approaches.

Objectives	Single-objective approach			Multi-objective approach
	The first state	The second state	The third state	The fourth state with p=1
Customer Satisfaction	192.682	92	113.124	174.265
Total Cost	322.5	169	184	330.5
Total Time	21.3	10.4	8.3	14.7
Decision Variables	$X_{11}=1, X_{12}=0, X_{13}=0, X_{14}=0$ $X_{21}=0, X_{22}=1, X_{23}=0, X_{24}=0$ $X_{31}=1, X_{32}=0, X_{33}=0, X_{34}=0$ $X_{41}=0, X_{42}=0, X_{43}=1, X_{44}=0$ $X_{51}=0, X_{52}=0, X_{53}=1, X_{54}=0$ $X_{61}=1, X_{62}=0, X_{63}=0, X_{64}=0$ $X_{71}=0, X_{72}=1, X_{73}=0, X_{74}=0$	$X_{11}=0, X_{12}=0, X_{13}=1, X_{14}=0$ $X_{21}=1, X_{22}=0, X_{23}=0, X_{24}=0$ $X_{31}=0, X_{32}=1, X_{33}=0, X_{34}=0$ $X_{41}=0, X_{42}=1, X_{43}=0, X_{44}=0$ $X_{51}=0, X_{52}=1, X_{53}=0, X_{54}=0$ $X_{61}=0, X_{62}=1, X_{63}=0, X_{64}=0$ $X_{71}=1, X_{72}=0, X_{73}=0, X_{74}=0$	$X_{11}=1, X_{12}=0, X_{13}=0, X_{14}=0$ $X_{21}=0, X_{22}=1, X_{23}=0, X_{24}=0$ $X_{31}=1, X_{32}=0, X_{33}=0, X_{34}=0$ $X_{41}=0, X_{42}=1, X_{43}=0, X_{44}=0$ $X_{51}=0, X_{52}=1, X_{53}=0, X_{54}=0$ $X_{61}=0, X_{62}=0, X_{63}=1, X_{64}=0$ $X_{71}=1, X_{72}=0, X_{73}=0, X_{74}=0$	$X_{11}=0, X_{12}=1, X_{13}=0, X_{14}=0$ $X_{21}=0, X_{22}=1, X_{23}=0, X_{24}=0$ $X_{31}=1, X_{32}=0, X_{33}=0, X_{34}=0$ $X_{41}=1, X_{42}=0, X_{43}=0, X_{44}=0$ $X_{51}=0, X_{52}=1, X_{53}=0, X_{54}=0$ $X_{61}=0, X_{62}=0, X_{63}=1, X_{64}=0$ $X_{71}=0, X_{72}=0, X_{73}=1, X_{74}=0$

- **Pareto optimal answer set**

In the L-P metric model, the algorithm tries to achieve different pareto optimal solutions. This set of answers, which are a set of non-dominant answers in the whole search space, is such that in this set, one cannot be superior to another between two different answers. The set of solutions obtained from solving the model by L-P metric method is extracted as a Pareto set which is shown in Table 11. In this table, the result of solving the L-P metric objective function for p = 1, p = 2, p = 3, and p =∞ is obtained. This set of Pareto answers was provided to industry experts to select one of the answers as the optimal answer according to the importance of the objective functions. After reviewing, the experts chose Pareto's answer for p = 1 as the optimal answer. Its application was described in the previous paragraphs.

Table 11. Results of solving the L-P metric objective function.

	Z_1	Z_2	Z_3
p = 1	174.256	330.5	14.7
p = 2	148.231	301.7	12.5
p = 3	139.374	317.4	11.3
p =∞	156.98	210.5	13.6

The results of solving the above model are given in Table 12. Also in this table, a comparison between solving the model by considering each of the objectives separately and also solving the model with a multi-objective approach is done and displayed separately.

In Table 12, the column corresponding to the first state, belongs to solving the model in a single-objective condition with the objective function of maximum customer satisfaction. The column for the second state also displays the information of solving a single-objective model with the objective of minimum cost. The column for the third state shows the information of solving a single-objective model with the objective of minimum procurement time. In the fourth state, the solution is presented with a multi-objective approach with p=1 compared to the previous three states. In the proposed approach, all three objectives are considered simultaneously.

Accordingly, after solving the model as a single objective with the objective function "Customer Satisfaction", the amount of customer satisfaction was estimated at 192.682. Cost and procurement time was calculated at 322.5 and 21.3, respectively. In the second state, the objective function of "procurement cost of components" was analyzed separately with all the limitations of the model. The result of this analysis was 169 million for procurement cost, but the amount of customer satisfaction and procurement time were 92 and 10.4, respectively. In this state, although the procurement cost and time of components have decreased by 153.5 units and 10.9 units compared to the previous state, customer satisfaction has also decreased by 100.682 units.

So the cost has been managed significantly, but it could not be made any progress in terms of customer satisfaction, which outweighed the other two objectives. In the third state, customer satisfaction is 113,124 units, the cost is 184 units and parts procurement time is 8.3 units. In this case, although the time index has decreased by 13 units compared to the first case and 2.6 units compared to the second case, the amount of customer satisfaction has decreased by 79.558 units compared to the first case and only by 214.12 units has increased compared to the second case. Also, the cost of procurement has decreased by 138.5 units compared to the first case and has increased by 15 units compared to the second case. In the proposed multi-objective approach, all three objectives are considered simultaneously. Customer satisfaction, cost, and time are estimated at 174.265 units, 330.5 and 14.7 units, respectively.

Validation is defined in engineering project management standards as an external checking process that guarantees that the system meets the needs of the stakeholders [55]. Accordingly, the validation process here refers to the formal checks done by the experts to assure that all customer needs have been considered in design process of PV system. In the proposed approach, the calculated amount for all three objectives is at its best. All selected levels for the components were determined as follows according to the approval of the answers by the experts. The results indicate that type B of Solar Panels, a type E of Controller, a type F of Combiner Box, a type H of Inverter, type L of Batteries, type Q of Disconnects, and type T of Miscellaneous Components (Only Brackets are considered here) must be selected to achieve all the above objectives.

5. CONCLUSION

The purpose of this study, which has been conducted in the high-tech electronics industry, is to select the optimal components for designing and operating the photovoltaic system (PV) to provide high system efficiency and get other goals. A photovoltaic system can be classified as renewable energy technologies. As the use of PV systems increases, questions and concerns about higher quality and reliability have been raised for them. If a PV system is properly designed and installed, it can be useful enough to supply energy.

Achieving goals such as increasing customer satisfaction, increasing system efficiency, and system life, reducing the overall cost of the system, and time to prepare system components are other achievements of this study. In this regard, after identifying customer needs and extracting functional requirements, the main components required to meet these requirements have been determined. Then the alternatives of each component are leveled according to their cost and procurement time. Finally, a multi-objective mathematical model is developed and its output is the selection of optimal components from the levels of the components that meet the objectives of the problem according to the defined constraints. The results indicate that type B of Solar Panels, a type E of Controller, a type F of Combiner Box, a type H of Inverter, type L of Batteries, type Q of Disconnects, and type T of Miscellaneous Components (Only Brackets are considered here) must be selected to achieve all three of the above objectives. The methodology presented in this research can be extended to all industries to design or develop a new system or product.

For future research, it is suggested that other effective variables such as availability, firm capability, and flexibility in volume and speed of production of the system's components should also be considered in their decision-making. In addition to the methods used in this research, methods in other algorithms such as goal programming or a combination of the above method with other models should be examined and their findings evaluated with the findings of this study. The proposed method could be applied to evaluate the third stage of the QFD process, the process planning stage, and select the best production process. It is also suggested that to further validate, conducting the proposed method in another system will provide an opportunity for future research. It should be noted that changes in research conditions or assumptions can enhance the innovative aspects of the proposed method.

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