CONSIDERATIONS ABOUT DESIGN OPTIMIZATION METHODS USED IN ADVANCED MANUFACTURING TECHNOLOGIES

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The entire history of humanity can be defined by its quest for greatness. Every time a solution was reached, the need for a better one became immediately apparent. This is exemplified by the development of advanced manufacturing technologies that have changed and improved the way products are manufactured. Over the years, many methods have been devised to find the best solution in various applications. In engineering, the focus has been on data analysis, and recently it expanded to other areas such as design development. This paper attempts to present methodologies that have been used widely in a variety of industries to develop better solutions. A discussion of the findings will focus on the possible application of these techniques to manufacturing and design.

Keywords: engineering design, QFD, Taguchi, TOPSIS, TRIZ, axiomatic design.

1. Introduction

In 1990, advanced manufacturing technologies (AMT) [1] were defined as new technologies directly used in the production of a product, but in the following years [2, 3] AMTs were classified as either hard-based technologies, such as physical technologies used in engineering, processing and administration, or soft-based technologies, such as Total Quality Management (TQM) and Just In Time (JIT). TQM is a management model focused on improving quality all around [4], while JIT is a manufacturing philosophy focused on improving product quality and production efficiency through waste reduction [5]. These technologies are nowadays widely used in the development of the next generation of AMTs by reducing waste and improving product quality and performance. In a Flexible Manufacturing System (FMS), both hard and soft based technologies, such as physical equipment and a computer control system, are involved, while in a Material Requirement Planning (MRP) system, only soft based technologies, such as a computer system, are utilized. According to [6], a modern approach to manufacturing is the total integration of manufacturing functions with computers,

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design being included, it is also known as Computer Integrated Manufacturing (CIM) systems which include many AMTs, such as Computer-Aided Manufacturing (CAM), Computer-Aided Design (CAD), Computer-Aided Engineering (CAE) and Computer-Aided Process Planning (CAPP).

In the fields of engineering and business, the main priority is finding the optimized solution within the spectrum of a specific set of objectives and constraints affecting certain critical variables. Oxford English Dictionary [7] defines optimization as a process of obtaining the best while Cambridge Dictionary [8] has a similar definition but uses “as good as possible”. Therefore, something like a product, process, design, or decision can be improved by following a process. Many times, the best solution is equivalent to achieving a maximized potential for minimum resources and the process by which this is obtained can include several techniques and/or mathematical algorithms.

According to Sinha [9] the elements of an optimization problem are the system, the variables, the constraints, and the objectives. The system is typically defined by some functions, a combination of constant and variable attributes. The variables are usually system parameters that impact the desired output. The constraints are a set of data affected by some features of the system. The objectives are goals to be achieved, such as minimum or maximum values.

Over the years many great mathematicians studied and developed this field of science, of which I would mention Fermat, Lagrange, Newton, Gauss, and Dantzig. Their work led to the development of many methods for various applications, which are classified according to the number of objectives (one vs. multiple), the number of constraints (zero vs. multiple), the shape of the objective functions (linear vs. non-linear), the domain of the objective functions (unimodal vs. multimodal), the types of variables (discrete, continuous, mixed), the type of values (deterministic vs. stochastic) [10].

Directly influenced by the type of functions used in applications, numerous methods have been developed, such as numerical, analytical, graphical, and experimental methods [11]. Numerical methods, also known as mathematical programming, are typically applied to complex problems that require iterative applications for the convergence of results. Analytical methods are used for functions that are linear and use a small number of variables. The very popular graphical methods are used with functions that use one or two variables. There are situations where the problem cannot be described mathematically, in these situations, experimental methods are employed to determine the best response for the various variables describing the problem.

There is much literature developed on mathematical programming, but there is less clarity on experimental methods. A study of the most used experimental methods is undertaken to propose the best approach to product development. The results of this study should be very helpful to practitioners acting in design engineering.

2. Experimental Methods

There are many design methods, focused on either creating, modifying, and attribute decomposition [12] such as brainstorming for creative designs, Theory of inventive problem-solving technique (TRIZ) for modifying a design, as well as Quality Function Deployment (QFD), Axiomatic Design (AD), and The Taguchi Methods for concrete results through attribute decomposition. A short presentation of the most popular methods is given below.

TRIZ theory was developed by G. Altshuller [13] in order to develop a systematic way to create new designs. The method looks at both the problem and its system by providing analytical tools for problem analysis as well as knowledge base tools for system change. It builds functional models for problems associated with existing technological systems and analyzes their interaction inefficiencies. Contradiction analysis reframes the problem as either a technical contradiction or a physical contradiction. Required function analysis matches system objectives with elements of a predefined function list.

The Taguchi Methods was introduced by G. Taguchi [14] in order to develop a product that maintains its functions regardless of the external factors, processes used, or other variables. The method is also known as Robust Design and it uses statistical methods to determine the best design, known as Design of Experiments. It is done in three steps: system (concept) design, parameters (values) design, and tolerance (variation) design [15].

QFD method was developed by Y. Akao [16] to translate customer needs into design requirements in a matrix setting called the House of Quality. The design requirements are divided into Functional and non-functional requirements, selection and optimization criteria, and constraints.

AD theory was developed, by N.P. Suh [17], to streamline the decision-making process utilized in product design. The method uses four domains such as customer, functional, physical, and process domains that are linked to each other through a mapping process so that one domain's requirements are mapped to the parameters found in the adjacent domain. The mapping of domains generates matrices such as the concept design matrix for customer and functional domains, the product design matrix for functional and physical domains, and the process design matrix for physical and process domains. To obtain the best solution two axioms are used. Axiom 1, known as the independence axiom, requires functional requirements to be independent, also known as uncoupled design, while Axiom 2, known as the information axiom, requires the design to minimize the information content.

3. Discussions

These methods can be used as a standalone approach interchangeably to an application or they can be used synergistically to their inherent insufficiencies in certain applications.

Some studies [18] found that between the years 2002 to 2014, there were 693 articles focused on AD and 1325 about TRIZ, while only 51 articles combined these two methods. The author researched Web of Science databases for articles focused on AD, TRIZ, and both between the years 2015 to 2023 and found that a total of 791 articles were published, of which 248 focused on AD, 540 on TRIZ, and 3 on combined methods, as shown in Fig. 1. The research was limited to the year 2023, as it was performed at the beginning of the year 2024. The combined use of the methods has lost priority to the innovative capacity of AD and TRIZ.

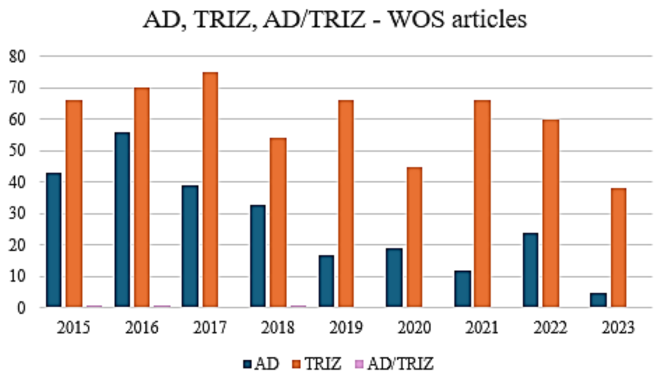

Fig. 1. AD, TRIZ, AD/TRIZ articles published between 2015 to 2023

If in the previous studies [19], between 2002 and 2014, TRIZ was mostly used in product development in almost all engineering fields as well as in agriculture, mining, food, healthcare, and management, AD was mostly used in management and system design. But between 2015 to 2023, both AD and TRIZ methods were mostly used in engineering and for less than 20% of business.

There is a clear tendency to use only one of the methods in product design, but when functional requirements are not independent, TRIZ would consider that situation as a contradiction for which a solution is needed. As a result, in combining these methods, AD is applied first followed by TRIZ until the best solution is obtained. This approach was applied to case studies of paper handling machine design [20], laser cutting design [21], jig design [22], water faucet design [23], satellite omni selector design [24], locomotive ballast redesign [25], kids' chair [26], fish peel design [27], cutterhead design [28], and two-wheeled vehicle design [29].

Previous studies reveal that TRIZ has difficulties handling functional coupling and triangular matrices developed through AD[30], and while AD seeks to minimize the number of functional requirements, TRIZ may introduce new functions if the solution demands that [31]. In addition, AD focuses only on customer requirements which may lead to a lower value that would otherwise be achieved by TRIZ. The benefits of combining AD and TRIZ include a better definition of the problem, a more detailed analysis of the problem, a more practical solution generated, and a better utilization of resources [32].

The Taguchi Methods has been used in engineering [33], medical [34], sales [35] ae well as alongside AD, such as in the design of a facet [36].

In considering Robust design alongside TRIZ and AD, considerations are given to their specific approach. Robust design applies within a given structured design, while AD focuses on defining the perfect structure, but TRIZ is best at solving conflicts [37]. AD is used to map customer needs while the Taguchi Methods was later used to investigate process conditions variance, and this can be reprocessed until optimized results are achieved [38].

A method combining QFD and AD [39, 40] proposed that QFD is applied first to convert customer attributes to functional requirements and then AD is applied to map the functional domain to the physical domain. If the functions are not independent, then apply TRIZ to find the solution.

Multi-criteria decision-making (MCDM) techniques, such as The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is used when selecting an alternative based on a finite number of criteria [41] using Euclidean distance to rank alternatives. TOPSIS steps include:

1.Construct a decision matrix of the alternatives and the criteria and fill it (x_{ij}, for i = 1, 2, 3 ,…, m) with their relative importance using a scale from 1 to n, 1 being the most important.

2. Normalize the decision matrix, using eq. (1):

$$R_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (1)$$

3. Form a criteria weighted (w_j) normalized decision matrix, using eq. (2):

$$y_{ij} = w_j * r_{ij} \quad (2)$$

4. Identify positive and negative ideal solutions using eq. (3) and eq. (4).

$$S^{+} = (y_1^{+}, y_2^{+}, \dots, y_n^{+}) \quad (3)$$

$$S^{-=} = (y_1^{-}, y_2^{-}, \dots, y_n^{-}) \quad (4)$$

5. Calculate the Euclidian distance for each alternative and the positive and negative ideal solution using eq. (5) and eq. (6)

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (y_{ij} - y_i^+)^2} \quad (5)$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} (y_{ij} - y_i^-)^2} \quad (6)$$

(6)

6.Calculate the closeness of each alternative using eq. (7).

$$V_i = \frac{D_i^-}{D_i^- + D_i^+} \quad (7)$$

7. Rank the results and select the best alternative.

4. Proposed integrated model

In developing a solution in product development, considering the inherent characteristics of each of the methods discussed above, a structured use of them is presented in Fig. 2 and the steps are:

1. Identify product requirements through market research. The needs that product must accomplish include functional, social, and emotional needs.
2. Map customers' needs into the most critical parts of product characteristics according to QFD methodology (Voice of the Customer and benchmarking).
3. Finite mapping of these elements across functional, design, and process domains according to AD.
4. Once the product functions have been mapped, apply Taguchi Methods (S/N analysis) to refine process factors affecting product quality.
5. If the functions are not independent, apply TRIZ to solve the conflicts
6. Iterate until optimal results are obtained or select one configuration using multi-criteria decision-making (MCDM) techniques.

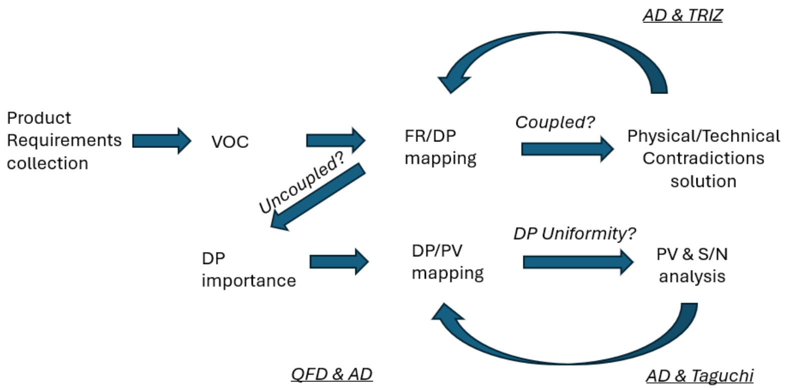

Fig. 2. QFD, AD, Taguchi Methods and TRIZ correlations

5. Case study

A solar power system includes the following main elements: solar panels [to convert sunlight into electricity], inverters [to convert DC into AC power], batteries [to store usable energy on-site], monitoring software, and a mounting system [to secure the system in place].

Once customer requirements are collected, per step 1, they are mapped to functional requirements according to QFD theory, per step 2. Customer requirements are typically vague, as seen in Fig. 3.

1: low, 5: high	Desired direction of improvement (↑,0,↓)	↑	↑	↑	↑	↑	
	Functional Requirements (How's)						
Customer importance rating	Customer Requirements - (What's) ↓	Monitor performance	Convert energy	Generate energy	Store energy	Provide mounting	Weighted Score
5	Stable and controllable	3	3		9		75
5	Durable	3	9				60
4	Easy to operate	9				9	72
3	Aesthetics					1	3
5	Efficient	9		3			60
5	Energy output	9		9			90
1	Light weight				3		3
2	Low cost	3		9	1	1	28
5	Low cost to operate	3	9	3	1	3	95
	Technical importance score	177	105	93	47	69	486
	Importance %	36%	22%	19%	10%	14%	101%
	Priorities rank	1	2	3	5	4	

Fig.3. QFD matrix

QFD is used to obtain product design specifications from which the functional requirements and the associated design parameters are derived. A finite mapping of functional requirements and design parameters is performed according to AD theory. Only the upper level is shown in Fig. 4.

Functional req.	Design par.
FR1 to generate energy	DP1 solar power
FR1.1 to convert sunlight	DP1.1 solar power
FR1.2 to monitor performance	DP1.2 conversion assessment
FR1.3 to replace panel	DP1.3 panel frame
FR2 to convert dc to ac	DP2 current inverter
FR2.1 to determine alternative inverter	DP2.1 inverter data matrix
FR2.2 to monitor performance	DP2.2 inverter assessment system
FR2.3 to replace inverter	DP2.3 inverter frame
FR3 to store energy	DP3 battery
FR3.1 to charge battery	DP3.1 charging module
FR3.1.1 to determine alternative batteries	DP3.1.1 battery attribute matrix
FR3.2 to monitor battery status	DP3.2 battery assement system
FR3.3 to replace battery	DP3.3 battery frame
FR4 to monitore peformance	DP4 software
FR4.1 to communicate to user	DP4.1 visual interaction
FR4.2 to load software	DP4.2 wireless link
FR4.3 to store software	DP4.3 memory card
FR5 to provide mounting	DP5 structural frame
FR5.1 to affix hardware	DP5.1 clamping system
FR5.2 to replace hardware	DP5.2 clamping system

Fig. 4. AD decomposition

Battery sizing requires a finite determination of its performance. A Taguchi Design of the Experiment (DOE) needs to be performed to select the best approach. After identifying the Control Factors (CF) and their ranges, the experiment is planned, as seen in Fig. 5 and 6.

Symbol	Parameter	Level1	Level2	Level3
A	Usable capacity	13.6 kW	14.4 kW	16 kWh
B	Peak power	9 kW	9 kW	11 kW
C	Continuous power	5 kW	7.5 kW	7 kW
D	Round-trip efficiency	89%	90%	97.50%

Fig. 5. DOE parameters

experim.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	1
8	3	2	1	3
9	3	3	2	1

Fig. 6. Experimental Design

After the experiment is performed, the results are expressed in terms of Mean Values, Signal to Noise Ratio, and Analysis of Variance (ANOVA) which leads to identification of the best design parameters configuration able to satisfy the functional requirements. With these results, a re-evaluation of the design parameters is to be performed until the design meets the requirements.

In this application, there is a potential conflict between clamping systems that are both durable and easy to operate. In this context, TRIZ can be used to develop alternative concepts through ideality, contradiction, and effect. Conflicts are processed within the domain of the problem by finding a key parameter. Effects are analyzed within the area with the problem by analyzing the flow of functions. Ideality attempts to define the ideal stage for the problem. The results need to be re-evaluated for compliance with customer requirements.

In this application, the design team can select solar panels from several internal or external sources using criteria and weight defined by the customer as seen in Fig. 3. QFD matrix. These sources are here identified as S1, S2, S3, and S4. The criteria are Easy to Operate (C1), Low Cost (C2), Low Cost to Operate (C3), and Durable (C4). Their weights are 4, 2, 5, and 5 respectively.

The design matrix, normalized design matrix per eq. (1), weighted design matrix per eq. (2) are shown below in Table 1, Table 2, and Table 3 respectively.

Table 1

Design Matrix

Crit/Alt	C1	C2	C3	C4
S1	4	5	4	2
S2	5	4	3	4
S3	5	4	4	3
S4	3	5	4	5

Table 2

Normalized Design Matrix

Crit/Alt	C1	C2	C3	C4
S1	0.462	0.55	0.53	0.27
S2	0.577	0.44	0.4	0.54
S3	0.577	0.44	0.53	0.41
S4	0.346	0.55	0.53	0.68

Table 3

Criteria Weighted Design Matrix

Crit/Alt	C1	C2	C3	C4
S1	1.848	1.1	2.65	1.36
S2	2.309	0.88	1.99	2.72
S3	2.309	0.88	2.65	2.04
S4	1.386	1.1	2.65	3.4

The positive and negative ideal solutions calculated with eq. (3) and eq. (4) as well as Euclidian distance from them and Closenss is shown in Table 4.

Table 4

Positive and Negative Euclidian Distance and Closeness

Crit/Alt	S1	S2	S3	S4
D^+	2.092845	0.9748538	1.3786342	0.9237604
D^-	0.8370844	1.6447447	1.3247237	2.1573233
V	0.2857012	0.6278614	0.490029	0.7001833

The best solution is found to be S4 alternative.

The method provides objective results for complex situations. The calculations were performed using a spreadsheet.

It can be observed that these methods, which are some of the most popular methods used in solving design problems, are applied on different segments of the final product as each method has limitations in solving all problems that occur in complex assemblies but used in synergy could lead to a better product. While QFD and AD define and refine the definition of a structure, TRIZ may propose a structure with added performance, Taguchi Methods finds the best performance of a structure, and TOPSIS selects the best structure.

6. Conclusions

This paper discussed various aspects of the most popular design methodologies such as TOPSIS, TRIZ, Taguchi/Robust Design, QFD, and AD as applied to the design of a solar power system. Investigating the applications of design methodologies leads to the following conclusions:

Each methodology is based on certain principles and requires a specific approach, the results may differ.

These methods can be used individually or simultaneously depending on the complexity of the problem to be solved. The synergy results in a better solution that eliminates waste of time and resources. Therefore, the TRIZ-QFD-Taguchi synergy leads to the application of TRIZ for solving the contradictions in the roof of the House of Quality and the Taguchi Methods for achieving the characteristics at the base of the roof of the House of Quality.

All these methods are useful in product design. In their combined application, the authors recommend using these methods in a certain order: QFD for design requirements identification, AD for requirements mapping, Taguchi Methods for function improvement, TRIZ for solution optimizing, and TOPSIS for best alternative selection.

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