A Structured Methodology for New Product Development Combining QFD and MCDM: Case Study on Router Bits

Giulia Polensig[1], Domenico Marzullo[2(✉)], Iacopo Bodini[1], Elio Padoano[2], and Massimo Tolazzi[1]

[1] Freud S.p.A, Via Remigio Solari, 7, 33050 Pavia di Udine, Italy
[2] Department of Engineering and Architecture, University of Trieste, Via Alfonso Valerio, 6/1, 34127 Trieste, Italy
dmarzullo@units.it

Abstract. An integrated approach to product development methods is necessary to connect and rationalize in a single framework the different design phases. Moreover, it allows to map and facilitate the decision-making process, especially when many stakeholders are involved. This paper presents a methodology for the design and development of a new product or component that integrates Quality Function Deployment (QFD) and Multi Criteria Decision Making (MCDM) methods, from the definition of the user requirements to the generation and simulation of the concept models. The evaluation of the results is carried out at different stages of the process with a customer-driven approach. Initially QFD, combined with the Analytic Hierarchic Process (AHP), is applied to define the product requirements from the customer needs. Thereby, the focus of the subsequent development is identified. The concept generation phase is therefore implemented throughout a series of brainstorming sessions. A first selection among the generated solutions is conducted using a summarizing function, according to the level of requirement satisfaction. Several refinements of the chosen concepts are then derived from manufacturability considerations and Finite Element Analyses. Finally, according to the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) a ranking of the developed products is obtained following the performance specifications. The presented methodology was applied to the development of a new router bit with insert knives, allowing to report the decision-making reasoning and to consider the user needs throughout the product design.

Keywords: Quality Function Deployment QFD · Multi Criteria Decision Making MCDM · Concept design

1 Introduction

Product development includes a series of activities that begins with the perception of a market opportunity and ends with production, sale and delivery of a product [1]. It is an interdisciplinary process that involves design, manufacturing and marketing. In the majority of product development projects, the process can be divided into several phases [2, 3]. The first is the *project definition and planning* phase. A project usually starts with the identification of an opportunity, which can be motivated by market demands or driven by the availability of a new technology. The scope should be clearly reported and the product mandatory requirements, e.g. related to safety, are considered. Afterwards, the *conceptual design* phase can begin with the identification of the target market needs. Several alternatives of product concepts with different working principles are generated and evaluated to select one or few for further development. It is the most crucial phase in the product development lifecycle since the main cause of failure in projects relates to the early design stage. This usually depends on unclear and imprecise design requirements [4]. During the subsequent stage of *embodiment design*, or *system-level design*, the product components, materials, all the specifications and an initial manufacturing plan are defined. To support this activity, simulations are usually run on the generated CAD models according to the problem in exam. The *detailed design stage* is consequently implemented and followed by further testing and refinement.

In such design process, a structured methodology is beneficial to drive the design requirements identification and analysis, as well as the concept development and evaluation. According to the main notions of the Concurrent Engineering, all activities connected with product development should be assessed in a unified and simultaneous way. Several combinations of Quality Function Deployment (QFD) and different methods of Multi-Criteria Decision Making (MCDM), which aim to support many product development phases and the related service and supply selections, can be found in the literature [5, 6]. However, it is commonly found that this process should be adapted to the project and the organization context.

This paper proposes an integrated methodology that combines QFD and MCDM methods, following the main steps of the design and development of a new product. It aims to incorporate the whole product life cycle and the tasks of different business units to optimize all these relative aspects from the early stages. A suitable MCDM method is used according to both the current development phase and the progress status of the product design. The selection criteria respectively consider different evaluation perspectives. Firstly, they are based only on the customer needs, then the organization and manufacturing requirements are introduced and finally more technical factors are considered. In Sect. 2, the employed methods are briefly described and their proposed integration is presented in a structured design process. Section 3 involves the application of this process to the case study of an innovative router bit for wood milling, carried out as industrial case at Freud S.p.A. Final considerations and further developments are then reported in Sect. 4.

2 Structured Methodology

The proposed integrated methodology was developed combining QFD and MCDM methods (Fig. 1). This structured approach allows to rationalize and map all the decision-making process, from the definition of the user requirements for the new product, to the generation and simulation of the concept models. The evaluation of the outcomes is carried out with a customer-driven approach at different stages of the process.

Initially, the QFD permits the interpretation of the customer needs and the identification of the related technical characteristics of the product, constructing a framework as a base for further design. QFD allows to transform subjective needs and requirements of customers into objective and technical criteria, and then to discover product characteristics that are most critical and important to quality. The Voice of Customers (VOCs) are hence translated in Critical to Quality specifications (CTQs). Finally, the level of quality of the product is quantified and verified with a set of testable specifications with measurable targets [7]. In this context, the prioritization of the customer requirements is made applying the Analytic Hierarchy Process (AHP) [8, 9]. Eventually, the technical characteristics can be classified in terms of importance, related to the capacity to bring quality and satisfy the customer needs, and in terms of difficulty in reaching the target values. A threshold on the maximum acceptable level of difficulty and a minimum limit on the relevance can be applied, defining thereby the development focus.

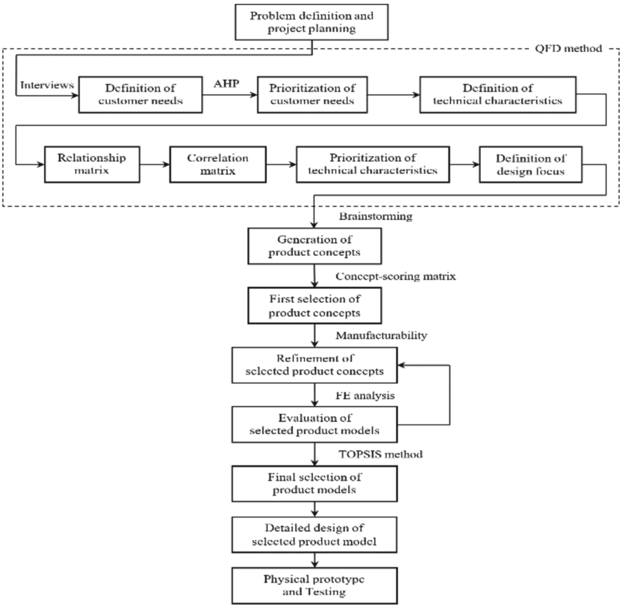

Fig. 1. Methodology structure for new product development

All the information and data collected with QFD are used as input in the concept generation phase, with the aim of developing a new product and defining the solutions to satisfy the engineering requirements. In this paper, the concept solutions are focused on the customer's most relevant engineering specifications that do not require excessive resources. A series of structured brainstorming sessions are therefore conducted with an interdepartmental team, that should include design engineering and manufacturing functions [10]. The first selection among the generated solutions is based on the level of requirement satisfaction and made using a summarizing function on the concept scoring matrix [1]. In this way a smaller number of concepts will be further studied, thus avoiding waste of resources on an excessive number of ideas.

The next step is a detailed refinement of the model that transforms the concept into a proper product. Several modifications of the chosen concepts are derived following the notions of Design for Manufacturing (DFM) and Design for Assembly (DFA). A first manufacturing workflow is created, defining the required machinery and tools. The evaluation of the manufacturing tasks performed at the predevelopment stage, in fact, allows to reduce the production costs and to introduce any alterations without impact.

The product concepts are then analysed in depth to ensure the functionality and compare their characteristics. For instance, Finite Element Analyses are performed to assess the response of the model to certain loads. The model geometry is consequently adapted, establishing an iterative process of refinement and verification. Moreover, some important parameters can be extracted and used to compare the different concepts in further phases.

The final product evaluation is made using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) with technical criteria [11]. TOPSIS allows the ranking of the developed products, which make up the selection set, according to their overall performance on the criteria. To this end, the method defines two hypothetical alternatives: a positive ideal solution, which presents the best performance in all criteria, and a negative ideal solution, with the worst performances. The best alternative in the selection set is the one closest to the positive ideal solution, according to a measure of closeness defined in the method. To compute the distance between the alternatives the Euclidean distance is usually employed: this requires that all the criteria be expressed with numerical values [12].

3 Methodology Application: Case Study on a New Clamping System for Router Bit Knives

The presented methodology was applied to the development of a new clamping system for router bit knives with a particular focus on the end-user friendliness of the knife exchange and assembly process. The possibility to change only the worn-out cutting part has several environmental and economic benefits. The overall product can have a longer lifetime, reducing waste and allowing to easily separate materials for recycling. The user needs are considered throughout all the product design phases and the decision-making reasoning can be consequently reported to the company organization.

3.1 Project Planning and Product Requirements Definition with QFD and AHP

The main phases of the project are laid out in a schematic plan, which includes the project milestones and the estimated due dates. The project can be visualised in a Gantt chart. In order to define the quality and so the value-adding elements starting from the design conception phase, the customer is chosen as the final user of the Router Bit (RB).

Several interviews are conducted, principally with sales and marketing representatives, to gather the necessary information and define the customer requirements. During the meetings, a particular attention is paid to the latent needs and the reasons behind the statements. The outcome is a list with more than 100 voices. These sentences are then analysed according to QFD and summarized in a smaller and more manageable Demanded Quality chart with about 30 VOCs, clustered into different categories. A prioritization of the VOCs is then realized with the AHP. Each interviewee filled a pairwise comparison matrix using the 9-point scale of Saaty [8]. This process is also useful to have a VOCs review directly from the interviewees and understand if the list is accurate and complete. A global pairwise comparison matrix is eventually obtained where each element is the geometric mean of the pairwise assessments performed by all the interviewees. Both the singular and the final matrices have a consistency ratio below 0.2 and mainly lower than 0.1; given the large matrix size the ratings are accepted [9].

Fig. 2. House of Quality of the project

An interdisciplinary team is composed by many product and manufacturing engineers, to carry out the rating activities about technical topics during the implementation of QFD. Afterwards, the team defines the CTQs from the VOCs according to the what-not-how principle [1], since solution independent CTQs provide more creative freedom in a new product concept generation. Hence 32 CTQs are eventually clustered into different categories with a measurement standard and the respective units for each one.

The Relationship Matrix, that displays the connection intensities between each VOC and each CTQ characteristic, is created with grades in a 1-3-9 scale from no correlation to strong correlation. In an analogue way, the team creates the Correlation Matrix according to four intensity levels (strong positive, positive, negative, strong negative), in order to clearly understand how the technical specifications influence each other and to manage the possible trade-offs. The prioritization of the CTQs is then calculated through the weighted sum, combining the ranking of the VOCs and the relationship matrix values. Thus, they are ordered according to their ability to influence the customer satisfaction on the most important requirements. A target value for each CTQ is also decided, nevertheless it can be modified afterwards if necessary. Eventually, each member of the team individually votes the target difficulty level according to a predefined scale. In case of outliers, the values are mediated after a brief discussion.

All the charts and matrices are composed into the House of Quality, the multifunctional tool used as a guide for all the future product development. For the sake of brevity, among all the matrixes generated only the House of Quality is reported in this paper in Fig. 2, where the main VOCs and CTQs developed as described above are listed.

Finally, to better visualise the level of importance and the difficulty of each CTQ, these are plotted in a graph including a threshold on the difficulty level according to the resources available in terms of people and time (Fig. 3). The team identifies the CTQs that will be the future development focus based on the area where they are located and it evaluates the possible trade-offs.

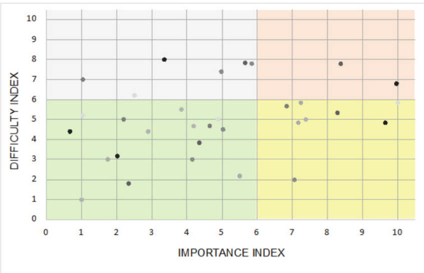

Fig. 3. Importance and Difficulty Index of the CTQs

3.2 Conceptual Design and Evaluation

The concept generation starts individually and the people, mainly part of the core team, attempt to find solutions to the selected CTQs. Then several brainstorming sessions are performed with different teams, composed by design engineer, product engineer, product expert and manufacturing engineer. Starting from the most important CTQs, the team tries to find solutions that permit to reach the targets. Initially, the selected technical requirements are related to technical solutions, as a feature, a partial product concept or a design characteristic (Fig. 4). A first group of partial features of the product is therefore obtained. Then, during the discussions, more complex solutions and product concepts emerge. Whiteboards with markers or post-it are widely used to sketch, write and visualise the ideas with a gallery method that incentive debate. All the observations and comments are also written down by a designated record keeper. The collected data, a series of drawings and notes, are elaborated after the brainstorming. Ideas and partial solutions are combined to form complete concepts, firstly as sketches, then as CAD models. During the modelling process, some problems, inconsistencies or missing features of the concept emerge and are resolved. A 3D model in this early stage is therefore very useful to better understand the working principle of the idea. A total of 16 concepts with different clamping system of the knives were conceived and modelled.

Once the RB concepts are defined, a MCDM selection is performed with the concept scoring matrix, where the performance of every concept is rated according to various criteria. The criteria used are the CTQs, obtained from the customer needs during QFD, and the requirements of the manufacturing and the organization. The final ranking of the concepts is calculated with a weighted sum where the rating of the concept performance in each criterion is multiplied by the importance index of the criterion. The first four concepts are selected to be developed forward according to the available resources. Afterwards, the people involved in the requirement definition phase of QFD are interviewed to validate the choice.

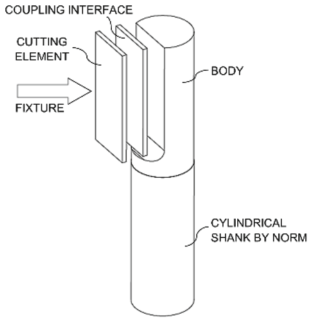

Fig. 4. Conceptual elements of a RB system

3.3 Embodiment Design and Selection

The RB models are refined according to DFM and DFA considerations, setting the final geometry of every part, the sequence of manufacturing operations, machinery and set of tools. FEA are then conducted to evaluate each RB until the components are verified.

Finally, the performances of the refined product concepts are compared according to the new available information and a final selection is carried out. The final RB concepts present similar characteristics according to the CTQs used in the first selection, in terms of ease of use and customer requirements. Therefore, a different MCDM approach is implemented with TOPSIS method, using the data obtained from FEA on the models and other technical aspects. The weights of the criteria are calculated using two ‘objective’ methods based on their information content, the Standard Deviation Method (SDM) [13] and the Entropy Method (EM) [14], and the stakeholders' subjective assessments. The RBs are therefore sorted according to their performances in the criteria, weighted with the different importance values. The two objective weights from SDM and EM provide the same ranking. Comparing the objective rankings with the one obtained from the subjective weights, the first and second place do not change, while the third and fourth ranked concepts are reversed.

4 Conclusions

Overall, the structured approach aided and supported the decision-making process, improving its transparency. The explication of the decision rationale was in fact mapped, ensuring that the important topics were addressed, and reducing the possibility of proceeding with unsupported decisions. Moreover, the implementation of QFD was found significantly beneficial by all team members during the whole process and it facilitated the design activities, although it required non negligible time and resources. The case study topic was in fact already preliminary addressed, but the results at such pre-conceptual design stage were considered negative, probably due to a non-structured and supported design approach. During the first stages, QFD allowed to comprehend and reflect about the development project with a customer perspective. Having already thought about the product in terms of requirements and being familiar with the problem facilitate the design activities. In further stages, the information about customer needs and their correlations with the technical product requirements are well organized and could be retrieved rapidly, due to the composition of the House of Quality matrix. The elaboration itself of all the data to arrive to the matrix helped each designer and the extended team to better understand the design conditions and what the product should do. Therefore, it is important to underline that the utility of QFD in product development resides largely in the process, rather than in the results alone.

The next phases of the product development correspond to the detailed design, which should be implemented on the selected concept. A functional prototype can therefore be manufactured, tested and evaluated according to the CTQs criteria, which are already defined with a measurement standard and a target value.

References

1. Ulrich, K.T., Eppinger, S.D.: Product Design and Development, 6th edn. McGraw-Hill, New York (2016)
2. Pahl, G., Beitz, W., Feldhusen, J., Grote, K.-H.: Engineering Design. Springer, London (2007). https://doi.org/10.1007/978-1-84628-319-2
3. Di Gironimo, G., Lanzotti, A., Marzullo, D., Esposito, G., Carfora, D., Siuko, M.: Iterative and participative axiomatic design process in complex mechanical assemblies: case study on fusion engineering. Int. J. Interact. Des. Manuf. **9**, 325–338 (2015)
4. Marzullo, D., Di Gironimo, G., Lanzotti, A., Mazzone, G., Mozzillo, R.: Design progress of the DEMO divertor locking system according to IPADeP methodology. Procedia CIRP **34**, 56–63 (2015)

5. Marini, C.D., Fatchurrohman, N., Azhari, A., Suraya, S.: Product development using QFD, MCDM and the combination of these two methods. 2016 IOP Conf. Ser. Mater. Sci. Eng. **114**(1), 012089 (2016)
6. Mohammadshahi, Y.: A state-of-art survey on TQM applications using MCDM techniques. Decis. Sci. Lett. **2**, 125–134 (2013)
7. ISO 16355-1, Application of statistical and related methods to new technology and product development process - Part 1: General principles and perspectives of quality function deployment (QFD), pp. 1–61 (2021)
8. Saaty, T.L.: The Analytic Hierarchy Process. McGraw-Hill, New York (1980)
9. Saaty, T.L.: Some mathematical concepts of the analytic hierarchy process. Behaviormetrika **18**(29), 1–9 (1991). https://doi.org/10.2333/bhmk.18.29_1
10. Goldenberg, J., Mazursky, D.: Creativity in Product Innovation, pp. 45–51. Cambridge University Press, Cambridge (2002)
11. Hwang, C.L., Yoon, K.: Multiple Attribute Decision Making: Methods and Applications. Springer-Verlag, New York (1981)
12. Hwang, C.L., Lai, Y.J., Liu, T.Y.: A new approach for multiple objective decision making. Comput. Oper. Res. **20**(8), 889–899 (1993)
13. Wang, Y., Luo, Y.: Integration of correlations with standard deviations for determining attribute weights in multiple attribute decision making. Math. Comput. Model. **51**(1–2), 1–12 (2010)
14. Zhu, Y., Tian, D., Yan, F.: Effectiveness of entropy weight method in decision-making. Math. Prob. Eng. **2020**, 1–5 (2020). https://doi.org/10.1155/2020/3564835