

A Methodology for Integrating Design for Quality in Modular Product Design

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With inspection-based quality control techniques, the quality of a product remains undetermined until the product is built and tested, an expensive process that also delays the release of new products to the market. This paper brings the quality issues at early stages of product development, and enhances the existing work on design for quality by integrating with modular design concepts. Conceptually, modular design theory optimizes product quality at the conceptual phase by considering the underlying principles of axiomatic design and robust design along with the perceived quality of the product. Fuzzy logic is employed to estimate cost and quality performance indices of the candidate modules by analyzing ambiguous product information at the conceptual stage. We consider two objectives for product modularization: minimization of modularization costs and maximization of overall product quality. The Chebychev's goal programming model is used to solve the multi-objective optimization problem. The methodology is demonstrated using an example of a coffeemaker. The results of the case study identify the optimal number of modules, which are intuitive and also offer more design resolution for forming the product development team.

Keywords: Design for quality, Product development, Goal programming, Modular design

1. Introduction

In order to meet customers' ever-increasing expectations, manufacturers must integrate quality function into engineering design at the conceptual stage. Over the years there have been essentially four quality management techniques (Garvin, 1988): inspection, statistical quality control, quality assurance, and strategic quality management. In the first three methods, quality is largely managed through internal standards set by the manufacturer. However, the fourth method is defined by customer satisfaction over the product's lifecycle (Sivaloganathan *et al.*, 1994). Furthermore, inspection and statistical quality control techniques can never fully compensate for flaws in design. Therefore, it becomes necessary for quality to be built into a product right from the design stage. The main aim of design for quality (DFQ) is to design a "robust product" that improves quality and reliability of product to excel the customer expectations (Kuo et al., 2001).

The objective of this research is to develop an enhanced DFQ framework by synthesizing the current practices with modular design concepts. Modularizing the product based on the quality principles such as axiomatic design (Suh, 1995) and robust design (Phadke, 1989) help build the quality into product during conceptual design stage. The other important factor to design for quality is to measure and accommodate the customer's perception about the product's quality. Since product architectural knowledge is vague and highly dependent on the experience

of the designer at the early stage of product development (PD), the paper presents a set of guidelines to evaluate the effects of components interactions on quality metrics in the form of rating scales. The subjective scales are then quantified into a crisp set of performance indices (e.g., quality and cost) using fuzzy logic. Finally, these indices are used as the criteria for modularization in multi-objective optimization framework.

The remaining sections of the paper are organized as follows: In section 2, we review current DFQ tools and modular design methodologies. Section 3 describes the proposed methodology for integrating DFQ into modular design. The proposed methodology is demonstrated in section 4 using a coffeemaker case study. This section also presents sensitivity analysis and a comparison of the proposed framework with the current heuristic approach being used for modules identification. Finally, section 5 concludes the findings and also identifies areas for further research.

2. Literature Review

2.1 Recent developments in design for quality

This section presents a brief description of some of the major tools, techniques, or philosophies used in the DFQ practices. The extent of their uses varies with the nature and size of the industries.

2.1.1 Robust design or Taguchi Methodology for design for quality

Robust design is a methodology for building quality into a product during design by making the product insensitive to variability due to both downstream manufacturing processes and product's environment (Kuo et al., 2001; Phadke, 1989). In the late 1940s, Taguchi introduced this concept to bring quality improvement efforts into the design stage. He used statistical tools but simplified them by identifying a set of stringent guidelines using an energy transmission model (signal to noise ratio) analogy. He utilized this ratio to optimize engineering systems through design of experiments and analyses (Phadke, 1989). Instead of trying to eliminate or reduce the causes for variability in the product's performance, Taguchi's approach to quality by design was to adjust the design of the product so that it could be insensitive to the effects of uncontrolled or noise variation.

The Taguchi method is referred to as off-line quality control in the quality engineering domain. It considers three steps for ensuring quality by design: system design, parameter design, and tolerance design. In system design, a basic functional prototype design is developed based on the application of scientific and engineering principles. Parameter design focuses on identifying the settings of design parameters that optimize their performance measurements and reduce the sensitivity of engineering designs to the sources of variations (noise). In tolerance design, the best tolerance is determined around the optimal settings identified at the parameter design stage (Phadke, 1989).

2.1.2 Quality function deployment

Quality function deployment (QFD) is a customer-oriented approach to product innovation that was developed to establish a new paradigm in quality management techniques (Govers, 1996). The QFD process ranks both explicit and implicit customer requirements and eventually translates them into product functions and finally to measurable engineering design specifications of the product (Kuo et al., 1999). In other words, QFD is an overall concept that provides a means of translating customers' requirements into the relevant technical specifications for each stage of product development and production process planning, product design and

engineering, prototype building and evaluation, and production process development (Chan and Wu, 2002).

2.1.3 Axiomatic principles of design

According to Dr. Nam Suh, a quality product is one that satisfies its functional requirements within a specified tolerance and is also easily manufacturable (Suh, 1995). He says that there are basically two axioms in developing good design: the independence and information axioms. The “independence axiom” states that independence of functional requirements (FRs) must always be maintained, where FRs are defined as the minimum set of independent requirements that characterizes the design goals. The “information axiom” states that among different alternatives, a design with the smallest information content is the best design. To make the design work, information must be supplied by the user of the design output or by other means. As the information content is defined in terms of probability, the second axiom also states that “the design that has the highest probability of success is the best design” (Suh, 2001). “Good Design” here means a design that can be easily manufactured or can fulfill its functional requirements within the defined tolerance. Similarly, the “highest probability of success” means a design that has the maximum chance of fulfilling its functional requirements.

As stated earlier, in the design terms quality means we need to make sure that a product is meeting its functional requirements within agreed tolerance (Sohlenius, 2000). The functional requirements are derived based on the customers’ voice. The past literature presents the axiomatic design as a foundation for building quality into product during design stage. Suh (1995) presents several criteria that govern the design and manufacture of quality products based on his axiomatic principles of design. Some of the criteria are robust design, decoupled design, and minimization source of variations and errors. The author has shown that uncoupled and decoupled design satisfies the independence axiom. Similarly, the design that has least information content or has the highest probability of achieving the FRs (information axiom) is the best design. Sohlenius (2000) provides an insight about how axiomatic design can be used as a design criterion for quality. The author further outlines, “Axiom 1 defines a decision criterion for functionality and axiom 2 defines a decision criterion for success. Therefore, axioms 1 and 2 are the correct and useful decision criteria for quality” (Sohlenius, 2000). Hu (2000) has developed a framework for enhancing robust design or improve quality by integrating TRIZ and axiomatic design. The author has used a “crimping case study” to validate his methods.

2.1.4 Concurrent engineering

Concurrent engineering (CE) is a management and engineering tool that can be used to improve quality and reduce costs and lead time for new product development and product modifications (Creese and Moore, 1990). Furthermore, in CE, the design and development of the product and its associated manufacturing equipment and processes, as well as the repair tools and processes are done concurrently (Singh, 1996). According to CE philosophy, all these functions are treated as an integrated activity. The decision-making process in a CE environment differs from that in sequential engineering in that decisions are made with consideration of the constraints of all the stages of the product lifecycle and at every stage. The integration of other functional areas with the design process helps to envisage hard-to-solve problems at the design stage.

The usefulness of concurrent engineering for improving quality of the product and process design has been widely addressed in the published literature (Singh, 1996; Hu, 2000). Singh (1996) cites a result of survey on the application of concurrent engineering in the areas of quality improvement, cost reduction, and reduced development time. It is reported that the survey was conducted by Institute of Defense Analysis for the U.S. Undersecretary of Defense

for Acquisition. The measurable quality improvements due to concurrent engineering included the following (Singh, 1996):

- ◆ Yield improvements of up to four times
- ◆ Field failure rates reduced up to 83%
- ◆ AT&T achieved a fourfold reduction in variability in a poly-silicon deposition process for very large scale integrated circuits and achieved nearly two orders of magnitude reduction in surface defects.
- ◆ AT&T reduced defects in the ESS programmed digital switch up to 87% through a coordinated quality improvement program that included product and process design.
- ◆ Deere reduced the number of inspectors by two-thirds through emphasis on process control and linking the design and manufacturing processes.

More recently, a study of 244 manufacturing firms presented in Kouteros et al. (2002) shows that the concurrent energy has a significant and positive effect on product quality.

2.1.5 Product safety and standards for quality management

Among other factors such as competitive price and high quality, strong commitment to safe and reliable products has become an important criterion for business survival. Lacking to such commitment means less likely to become successful in the business (Ryan, 1996). Today, a manufacturer without a formal quality and safety program and effort is not only on the losing side of race but also acquires a high risk of facing expensive lawsuits due to laxity in its efforts to prevent the product failures, more particularly the hazardous failures (Goodden, 2001).

Although there is no debate on some amount of correlation between product quality and safety, researchers and practitioners opine differently with regards to linear and strong relationship between the two product attributes. Manning (1989) argues that “quality is not equivalent to safety”. He further adds, “Quality assurance (QA) is concerned with a designer’s success or failures in meeting the functional specification of the product. QA is also concerned with ensuring product design engineering so that a quality product is created”. Regarding product safety, he says that “it is concerned with those failures that result in hazardous situations. Not every product failure will result in hazardous condition. Many product failures are customer nuisances, but will not cause an electrical shock or burn down a house” (Manning, 1989). On the other hand, Ryan (1996) suggests that “in the total quality management world, product safety is integral to product quality”. In order to minimize the product liability or maximize the product safety, the areas that should be well addressed are: management support, design evaluation, legal review and counsel, quality assurance and control, product labels and packaging, and marketing and customer service (Ryan, 1996).

Various types of standards are available in the industries for ensuring high quality (conformance to specifications) and safety of new products and processes. These are: “measurement or metric standards, process oriented or prescriptive standards, performance standards, and interoperability (among different systems) standards” (Allen and Sriram, 2000). The standards can be categorized as de facto, regulatory and consensus. For examples, de facto standards in the computer industry may be computer architecture; environmental or health safety standards imposed by the government fall under second category; and the ISO is one example of international consensus standards organization. Similarly, American Society of Mechanical Engineers in the US, Deutches Intitut fur Normung (DIN) in Germany, and British Standards Institution (BIS) are few other examples of national consensus standards for design (Allen and Sriram, 2000). For quality, ISO 9000 standards are worldwide quality system guidelines published by the International Organization for Standardization. Clause 19.0 of ISO 9004-1

specifically addresses product safety and provides guidance to create safe products (Ryan, 1996). In the United States, the American National Standards Institute (ANSI), a private and non-profit organization, coordinates to develop standards for the US industries on consensus basis. Likewise, the National Institute of Standards and Technology (NIST) is a Federal government body that takes care of technological basis of measurements and standards in industries (Allen and Sriram, 2000).

2.1.6 Measurement of perceived quality of product

The actual quality of products resulting from changes in the manufacturing process will have little or no impact on the buying behavior of consumers unless they perceive that the quality of products meets or exceeds a given expectation (Garvin, 1988). In other words, perceived quality is what influences buying decisions (Takeuchi and Quelch, 1983). It is important to note that there may be a significant difference between the way manufacturers and consumers perceive the quality of a product. While manufacturers' measure of quality is the degree of conformity with engineering standards, the consumer's perception of product quality may be its shape, elegance, or size. Moreover, the consumers' priority or perception of quality varies from one product to another. In this context, Garvin (1988) presents the following examples: "power tools are said to be of good quality if they are durable and reliable; physical elegance of such products may be of little concern to consumers. In contrast, for jewelry and eveningwear, attractiveness may be a higher priority as a measure of quality than durability. In yet other cases, such as automobiles, reliability, elegance, and durability may all have equal weight in consumers' judgments about product quality".

Through confirmatory factor analysis, Stone-Romero et al. (1997) present the following four criteria for measuring the perceived quality of a product:

Flawlessness: Flawlessness or defects prevention strategy is defined as the product's conformance to a given standard of shape, size, fit, strength, purity, and so forth (Crosby, 1979).

Durability: Durability is defined as the consumer's perception about the life expectancy of a product.

Appearance: The appearance criterion is used to judge the product's physical appearance or its aesthetics (Garvin, 1988).

Distinctiveness: The other important yet intangible attribute of a high quality product is the uniqueness, distinctiveness, and luxuriousness that can enhance the customer's satisfaction (Stone-Romero et al., 1997).

While all these methodologies focus on the same objective of designing good quality products, they are implemented at different stages of the PD cycle. QFD and CE are widely spread over the entire PD cycle. Axiomatic design principles are more pertinent to product functionality design at the concept development stage. The Taguchi method or robust design focuses on optimizing engineering parameters. On the other hand, the use of perceived quality of a product is not as widely documented as the other four techniques even though customer's perceptions are studied through customer satisfaction, among other means. Past studies show that product architecture is often responsible for poor quality and high manufacturing cost (Ulrich, 1995; Anderson, 2001). Certainly the above-mentioned methods are well practiced and proven tools in the field of design for quality. However, these methods do not address product architecture and related issues.

2.2 Modular design methodology

Modular design can be viewed as the process of producing units that perform discrete functions that are connected together to provide a variety of functions. Modular design emphasizes the

minimization of interactions between components in order to design and produce those components independently. Each component, designed for modularity, is supposed to support one or more function. When components are structured together to form a product, they support a larger or general function (Salhieh and Kamrani, 1999). Moreover, by conceiving products in terms of modules, firms can take responsibility for the design and development of separate modules; hence they can develop new products at a faster pace, as the integration process is just a matter of ‘mix and match’ (Prencipe, 1998). Pahl and Beitz (1996) refer to modular products as machines, assemblies, and components that fulfill various overall functions through the combination of distinct building blocks or modules. In other words, modular products are designed as building blocks that can be grouped together to form a variety of products. This approach promotes standardization and the reuse of existing modules to develop new products.

Even though modularity has been considered a new technology for improving product quality and reliability (Pimmler and Eppinger, 1999), past studies do not seem to have considered quality as a criterion for product modularization. Much of the prior works on product modularization focus on maximizing some sort of similarity index (Salhieh and Kamrani, 1999; Ericsson and Erixon, 1999) or on clustering the components based on functional heuristics (Stone *et al.*, 2000). Pahl and Beitz (1996) consider the manufacturing cost of a particular cluster/module and the assembly cost of the entire product to form the modules. In the matrix-based method (Pimmler and Eppinger, 1999), clustering is done based on the priority of interactions between the components. Salhieh and Kamrani (1999) have employed a group technology approach (P-median model) to maximize the similarity index between the components in a module.

Erixon and Ericsson (1999) present modular function deployment (MFD) methodology based on “module drivers” heuristics. Tsai and Wang (1999) use fuzzy cluster identification method by considering correlation in design of components. Four years later, the authors extended this work by incorporating total maintenance costs of modules in the “predetermined life cycle” of the modules (Tsai *et al.*, 2003). Stone *et al.* (2000) present three heuristic methods for identifying modules from “functional structure” according to the flow patterns shown in the product “functional structure diagram”. Gu and Sosale (1999) consider the various aspects of lifecycle engineering such as serviceability, reusability, and disposability factors while modularizing the components. Huang and Kusiak (1999) synthesize the modular architecture of electronic products by considering the testability perspectives.

More recently, Kusiak (2002) formulates a cost minimization problem subject quality and testability levels constraints to identify the modules. The author also analyses the component interactions to identify the modules but it is not clear that how he measures the testability and quality of the modules. Another paper on QFD based modular product design (Kreng and Lee, 2004) consolidates the modularity drivers from the prior research and employs the interaction between the modular drivers and components to identify the optimal module. Few examples of modular drivers include carry over, technology evolution, product variety, manufacturability, serviceability, product upgrading and so on (Kreng and Lee, 2004). The authors also consider functional and physical interaction between components. However there might be two concerns about this approach. First, the methodology seems to be overly complex; and second it employs a constraint that restricts each model to hold only one modular driver. Where as, in the real world the optimal modules should either satisfy more than one modular driver or at least have a reasonable trade-offs among these drivers.

3. Proposed Framework

Figure 1 shows the IDEF0 model of the proposed framework for integrating design for quality in modular design. In general, the proposed modularization approach can be divided into three steps: (1) the knowledge acquisition phase, (2) the performance evaluation phase, and (3) the product modularization phase.

The IDEF0 (**I**ntegrated **D**efinition for functional modeling) is a process mapping technique based on combining graphics and text that are then presented in an organized and systematic graphic presentation to gain understanding, support analysis, provide logic for potential changes, specify requirements, or support systems-level design and integration activities (URLa). The advantage of IDEF0 modeling over simple process flow diagram is that it can be used graphically to represent the inputs, outputs, controls, and mechanisms related to each activity or phase of the methodology. The overview of the IDEF0 model is shown in Figure 2.

An activity can include information gathering, material processing, or even service providing. For example, for the activity '*acquire product knowledge*,' the input is a general analysis of the product and the outputs are formation of candidate modules, and identification of cost and quality metrics. This activity (amount of knowledge acquired) is controlled or constrained by the designer's knowledge of and past experience with a similar product, and also by the levels of analysis (e.g., component level or system level). Likewise, the mechanisms for acquiring knowledge includes product decompositional analysis, human resource (design engineer), and other tools. The same analogy is used for modeling the other three phases. Each step of the methodology is described briefly in the following sections.

3.1 Knowledge acquisition phase

The knowledge acquisition phase consists mainly of the general analysis of the product, which is carried out after the product planning or during the concept development phase. It consists of functional and physical decomposition of product and identification of performance metrics for product architecture. The decomposition process helps to map a gross relationship between a product's functionalities and its physical components. At the end of the physical decomposition process, a list of basic components is identified from which a number of candidate modules are constituted in pairs. Thus, the performance evaluation will be centered on two components at a time. In this paper, the performance measures being studied are quality and cost of modularization. The quality performance index of a candidate module is judged through evaluation of component interactions with respect to quality metrics. While product safety and meeting design standards can also be a part of quality issue, a large body of current quality literature talks only about other factors like reduced number of defects, robustness, perceived quality, ability to fulfill functional or customer's requirements and so forth (Garvin, 1988, Liu and Yang, 1999; Kuo et al., 2001) as metrics of product quality. Therefore, although there are many factors that influence product quality, as a proof of concept, this paper utilizes following metrics to evaluate the quality of each candidate module.

- Perceived quality of product
- Robustness
- Compliance to axiomatic design principles

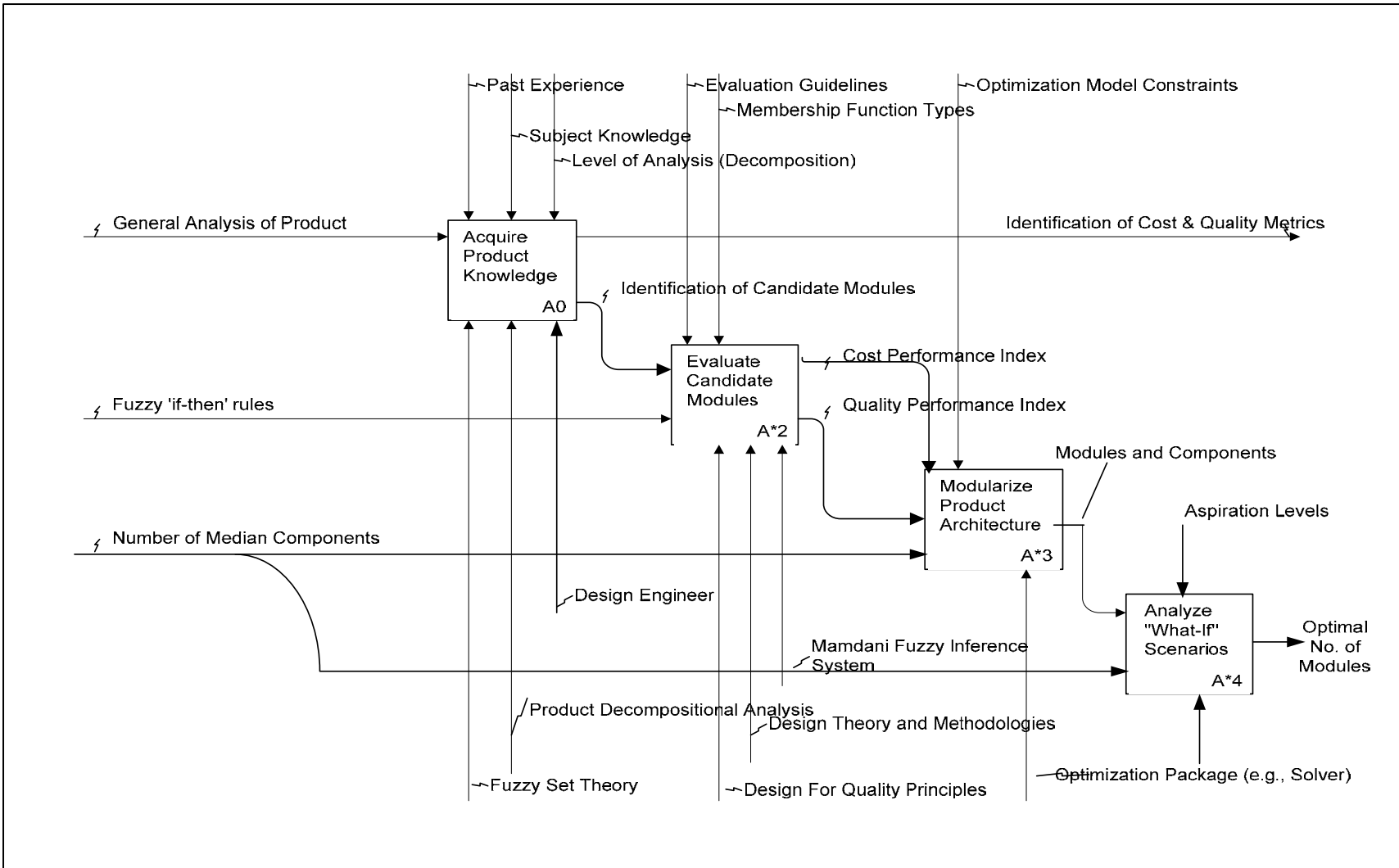


Figure 1: IDEF0 model for Methodology for integrating design for quality in modular design

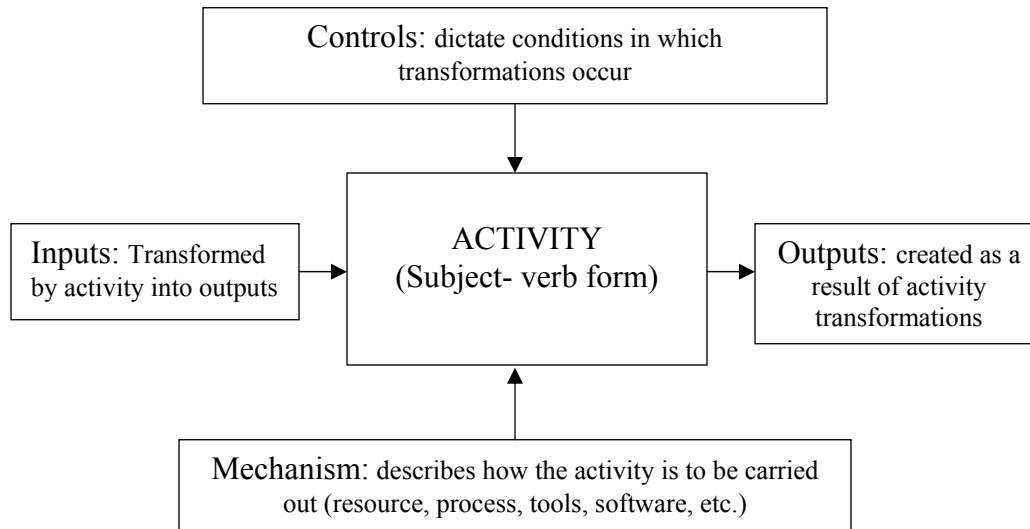


Figure 2: Overview of IDEF0 notation

Perceived quality level of product: This is measured by considering four criteria: flawlessness, durability, appearance, and distinctiveness (Stone-Romero et al., 1997).

Robustness: The fundamental principle of robust design is to improve the quality of a product by minimizing the effect of the causes of variation without eliminating the causes themselves (Phadke, 1989).

Axiomatic Design Principles: As mentioned in section 2.1.3, there are two axioms presented in a good design. The “Independence Axiom” says that design decisions must always be made without violating the independence of each functional requirement from other functional requirements. The goal of a good design is to have a minimal number of independent functional requirements. The “Information Axiom” minimizes the information content in the design. In other words, among those designs that satisfy the Independence Axiom, the design that has the highest probability of success is the best design (Suh, 2001).

For evaluating the cost performance index, we refer to our previous work (Nepal et al., 2005), which considers three types of modularization costs: cost of interface, cost of assembly resource requirements (such as setup and accrual assembly times), and product variety related or cost of reusability.

3.2 Performance evaluation phase

The performance evaluation phase consists of two sub-tasks: evaluation of candidate modules with respect to quality and cost metrics, and computation of quality and cost performance indices using fuzzy logic models.

3.2.1 Evaluation of candidate modules with respect to quality and cost metrics

As shown in the literature (Arjunajadai et al., 2004), there are more opportunities to improve the design of a product at the early stages than at later stages of PD processes. However, during the early stages of PD, the designer will not have the precise information about the actual design or architecture of the final product. Therefore, the evaluation process at the early stages becomes highly subjective and its accuracy depends upon the level of experience of the designer and the availability of the historical data, perhaps from a similar product. Therefore, in order to

streamline the subjective evaluation process at the conceptual stage, we present a set of structured guidelines that will allow the designer to evaluate the candidate modules in a rating scale of 1-10. In other words, the interactions between the components in the candidate modules are evaluated with respect to the previously identified quality and cost metrics.

Basically, the evaluation guidelines for quality have been developed based on the DFQ theories and methodologies stipulated in the section 1. For example, the perceived quality level of a module is measured based on the concepts of ‘flawlessness’, ‘durability’, ‘appearance’, and ‘distinctiveness’ (Stone-Romero et al., 1997). Because the perceived quality may vary from product to product, the manufacturer should conduct a survey or focus group about a similar product to determine specific guidelines. With regard to flawlessness, an approximate DFMEA (Design failure mode and effect analysis) can be conducted at the conceptual stage. Robustness measurement guidelines have been developed based on Taguchi's methodology (Phadke, 1989). Similarly, guidelines to evaluate the compliance of product architecture to axiomatic design principles are based on the two axioms given in Suh (2001). Tables 1, 2, and 3 depict the evaluation guidelines for quality performance index of candidate modules. Please see Nepal et al. (2005) for guidelines to evaluate modularization costs metrics.

Table 1: Guidelines for measuring perceived quality level of product architecture

Rating	Quality Level	Description of Perceived Quality
1, 2	Poor	The candidate module does not or poorly complies with the customers’ expectations about product size, shape, serviceability etc. and also has some safety-related issues.
3,4	Fair	The candidate module complies with the customers’ expectations about product size, shape, and distinctiveness but is somewhat flawed.
5,6	Moderate	The candidate module partially complies with the customers’ expectations about product flawlessness, serviceability, maintainability etc., but it may not be elegant from an aesthetic point of view.
7,8	High	The candidate module fairly complies with the customers' expectations about product size, shape, flawlessness, distinctiveness etc.
9,10	Very High	The candidate module significantly complies with the customers’ expectations about product size, shape, flawlessness, distinctiveness etc.

Table 2: Guidelines for measuring robustness of product architecture

Rating	Robustness Level	Description of robustness
1	Very Poor	The candidate module is highly sensitive to any type of noise, e.g., process variability or variability due to product operating environment.
2,3,4	Poor	For the candidate module, if chances of variability due to assembly process are low but those due to its operating environment are very high or vice versa.
5,6	Moderate	For the candidate module, if chances of variability due to both assembly process and its operating environment are medium.
7, 8	High	For the candidate module, if chances of variability due to both assembly process and its operating environment are low.
9,10	Very High	For the candidate module, if chances of variability due to both assembly process and its operating environment are very low or negligible.

Table 3: Guidelines for measuring compliance level to axiomatic design principles for product architecture

Rating	Compliance Level	Description of axiomatic design principles
1,2	Very Poor	The candidate module does not comply with both independent and minimum information content axioms. OR, Although the candidate module maintains its independence in the overall product functional domain, but its design has a slim chance of achieving the functional requirements.
3,4	Poor	The candidate module is fairly independent with respect to the functional requirement in the overall product functional domain, but the information content in the module design is so high that the design is very complex. That is, its design has little chance of achieving the functional requirements.
5,6	Moderate	The candidate module is independent with respect to the functional requirement in the overall product functional domain. However, its design is fairly complex, so chances of achieving the functional requirements are medium.
7,8	High	The candidate module is significantly independent with respect to the functional requirement in the overall product functional domain. Furthermore, its design has less information content. The chances of achieving the functional requirements are high.
9,10	Very High	The candidate module is absolutely independent in the overall product functional domain, and also the information content in the module design is much less, meaning that the chances of achieving the functional requirements are very high.

3.2.2 Computation of quality and cost performance indices using fuzzy logic model

The term fuzzy means imprecise and uncertain. In fuzzy set a data is represented along with its membership function (Jang et al., 1997). The membership function is defined as the degree of belongingness. Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth- truth-values between ‘completely true’ and ‘completely false’. As its name suggests, it is the logic underlying modes of reasoning which are approximate rather than exact. Human reasoning based on experience or common sense largely comes under this category. Since this study also mainly focuses at early stages of PD process, much of the information is subjective and approximate in nature. Therefore, we use fuzzy logic to synthesize the subjective evaluation of product architecture into a set of crisp performance indices. Fuzzy logic model primarily consists of four components: input and output linguistic variables, fuzzy if-then rules, fuzzy aggregated output, and defuzzification techniques. In order to capture the uncertainties associated with both input and output variables and imprecise knowledge about their relationship, fuzzy set theory provides a fundamental basis to map the approximate relationship between the fuzzy variables (Bellman and Zadeh, 1995). (For more details on fuzzy logic, readers are encouraged to see Jang et al., 1997)

The quality and cost metrics mentioned in the previous section are treated as input or linguistic variables to the fuzzy logic model. The detailed list of input, and the output variables along with their membership functions used in this research are given in Table 4. Figure 3 shows an example of trapezoidal membership function used for fuzzy logic input and output linguistic variables.

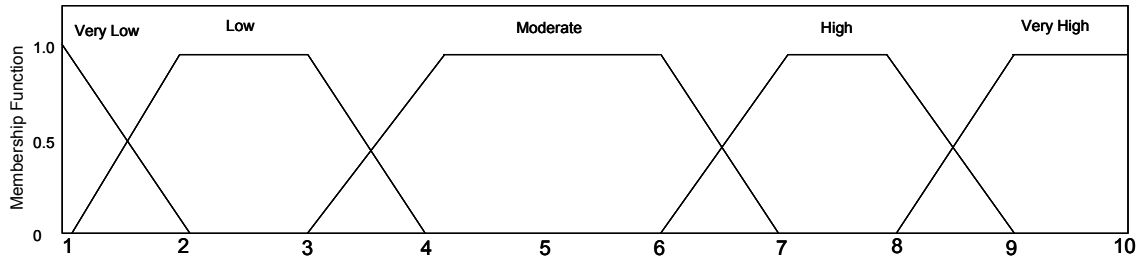


Figure 3: Example of Fuzzy set definition for input and output variables

The fuzzy ‘if-then’ rules are developed to relate input to output variables. These rules represent the expert’s knowledge about the interactions between input variables and their effects on the output. A fuzzy rule is expressed as ‘if x is A then y is B.’ Here, A and B are the linguistic values defined by fuzzy sets on the universe of discourse X and Y.

Table 4: List of input metrics and performance indices used for evaluating modular architecture

Type of Performance study	Input Variables		Output Variables	
	Linguistic Variables	Membership functions	Linguistic Variable	Membership functions
Quality	Perceived Quality level of Product	Very High, High, Moderate, Low, Very Low	Quality performance index (QPI)	Very High, High, Moderate, Low, Very Low
	Robustness	Very High, High, Moderate, Low, Very Low		
	Compliance to Axiomatic Design Principles	Very High, High, Moderate, Low, Very Low		
Cost	Cost of Interface	Very low, Low, Moderate, High, Very high	Cost Performance Index (CPI)	Very low, Low, Moderate, High, Very high
	Assembly Resource Requirements	Very low, Low, Moderate, High, Very high		
	Cost of Reusability	Very low, Low, Moderate, High, Very high		

The ‘if-part’ of the rule ‘x is A’ is called the antecedent or premise, while the ‘then-part’ of the rule ‘y is B’ is called the consequent or conclusion. All the rules that have any truth in their antecedent will fire and contribute to the fuzzy conclusion set. The following are samples of rules developed for estimating the quality performance index:

Rule# 1: If (Perceived Quality Is Very Low) AND (Robustness Is Very Low) AND (Axiomatic Compliance is Very Low) THEN (Quality Performance Index Is Very Low)

Rule# 42: If (Perceived Quality Is Low) AND (Robustness Is High) AND (Axiomatic Compliance is Very Low) THEN (Quality Performance Index Is Moderate)

Rule# 60: If (Perceived Quality Is Moderate) AND (Robustness Is Low) AND (Axiomatic Compliance is Very High) THEN (Quality Performance Index Is High)

In this case we have three input metrics, viz., perceived quality level, compliance level to robustness, and compliance level to axiomatic design principles, each with five levels. Therefore, at the most, there will be 125 (= 5*5*5) rules altogether. However, some designers write only few rules that are mostly applicable and leave out all the other redundant combinations. This research employs Mamdani fuzzy inference system (Jung et al., 1997) for analyzing the inputs through a set of ‘if-then’ rules and a T-norm aggregation operator. The aggregated fuzzy output is eventually defuzzified using the ‘centroid of area’ technique. The formula for defuzzification using COA method is as given below (Jung et al., 1997).

$$z_{COA} = \frac{\int_z \mu_A(z)zdz}{\int_z \mu_A(z)dz} \quad (1)$$

Where $\mu_A(z)$ is an aggregated output membership function. This is the most widely adopted defuzzification strategy, which is reminiscent of the calculation of expected values of probability distributions.

However, the Mamdani fuzzy inference system automatically generates a crisp output therefore we do not need to perform any separate defuzzification calculations. Except the input variables, all the other components of fuzzy logic models are same for quality and cost performance indices. The crisp outputs obtained from fuzzy logic model are known as quality or cost performance index, as the case may be.

3.3 Product modularization phase

In the third phase, the cost and quality performance indices obtained from the outputs of fuzzy logic model are incorporated into a mathematical modeling framework and used as the criteria for modularization. Since we have more than one objective, we use Goal Programming (GP) model for identifying the optimal modules. More specifically, the Chebychev’s goal programming model has been formulated to optimize the overall product quality and cost performance indices subject to the clustering constraints adapted from the P-median model (Rajamani and Singh, 1996). The details of this mathematical model are given below:

Decision Variables and Parameters

X_{ij} = $\begin{cases} 1, & \text{If component } i \text{ belong to component family (module) } j \\ 0, & \text{Otherwise} \end{cases}$

Q_{ij} = Quality performance Index (QPI) w.r.t. Components i and j when both of them are in the same module

C_{ij} = Cost performance Index (CPI) w.r.t. Components i and j when both of them are in the same module

N = Predefined number of modules for a product (*Subjective decision of the designer*)

Objective Function

For maximizing the overall QPI of the modules

$$\text{Max } Z_1 = \sum_{j=1}^n \sum_{i=1}^n Q_{ij} * X_{ij} \quad (2)$$

For minimizing the total cost of modularization

$$\text{Min } Z = \sum_{j=1}^n \sum_{i=1}^n C_{ij} * X_{ij} \quad (3)$$

Subject to Constraints

1. Each component is assigned to exactly one module

$$\sum_{j=1}^n X_{ij} = 1 \quad \forall i \quad (4)$$

2. Components are assigned to a predefined number (N) of modules

$$\sum_{j=1}^n X_{jj} = N \quad (5)$$

3. Components are assigned to modules that have a median component

$$X_{ij} \leq X_{jj} \quad \forall i, \forall j \quad (6)$$

4. $X_{ij} = 0/1$ $\forall i, \forall j$ (7)

In order to solve both the objectives simultaneously, we need to convert above model into the Chebychev's goal-programming framework.

Formulation of the CGP model: The first step in the formulation of goal programming is to convert all objectives into goals, which are treated as 'soft' goals. On the other hand, all other constraints in the traditional linear programming model (in our case, clustering constraints) are treated as 'hard' goals. In order to compute 'aspiration levels', each objective (e.g., quality, cost, etc.) is optimized separately, subject to the common set of constraints, and the solutions are substituted in other objective functions. The 'aspiration level' is calculated as 'the best value' among the different objective function values obtained through solving linear programming models or upon substitution. (For further details about computations of 'aspiration levels', the readers are encouraged to refer to Ignizio and Cavalie,r 1994, Pp. 523-526.)

Mathematical model for CGP:

Let 'd' be the 'worst unwanted deviation' from any objective such as QPI and CPI goals and 'a₁', 'a₂' are the aspiration levels for those goals, respectively. The mathematical model for the proposed CGP is as given below:

Minimize d

Subject to:

$$\sum_{j=1}^n X_{ij} = 1 \quad \forall i \quad (\text{One component –one module constraint}) \quad (8)$$

$$\sum_{j=1}^n X_{jj} = N \quad (\text{Maximum possible number of modules constraint}) \quad (9)$$

$$X_{ij} \leq X_{jj} \quad \forall i, \forall j \quad (\text{Median component constraint}) \quad (10)$$

$$\sum_{j=1}^n \sum_{i=1}^n Q_{ij} * X_{ij} + d \leq a_1 \quad (\text{Quality performance goal constraint}) \quad (11)$$

$$\sum_{j=1}^n \sum_{i=1}^n C_{ij} * X_{ij} + d \geq a_2 \quad (\text{Cost of modularization goal constraint}) \quad (12)$$

$$X_{ij} = 0/1 \quad \forall i, \forall j$$

(Binary constraints)

(13)

4. Case Study

As a case study, the proposed framework of integrating DFQ with modular design has been implemented on a Mr. Coffee brand coffeemaker. The coffeemaker was chosen for comparison with other methodologies that have used the same example. Figure 4 shows a generic Mr. Coffee brand coffeemaker along with its major components, adapted from the company's website (URLb). As shown in Figure 1, following steps were followed for accomplishing the integrated product modularization processes.

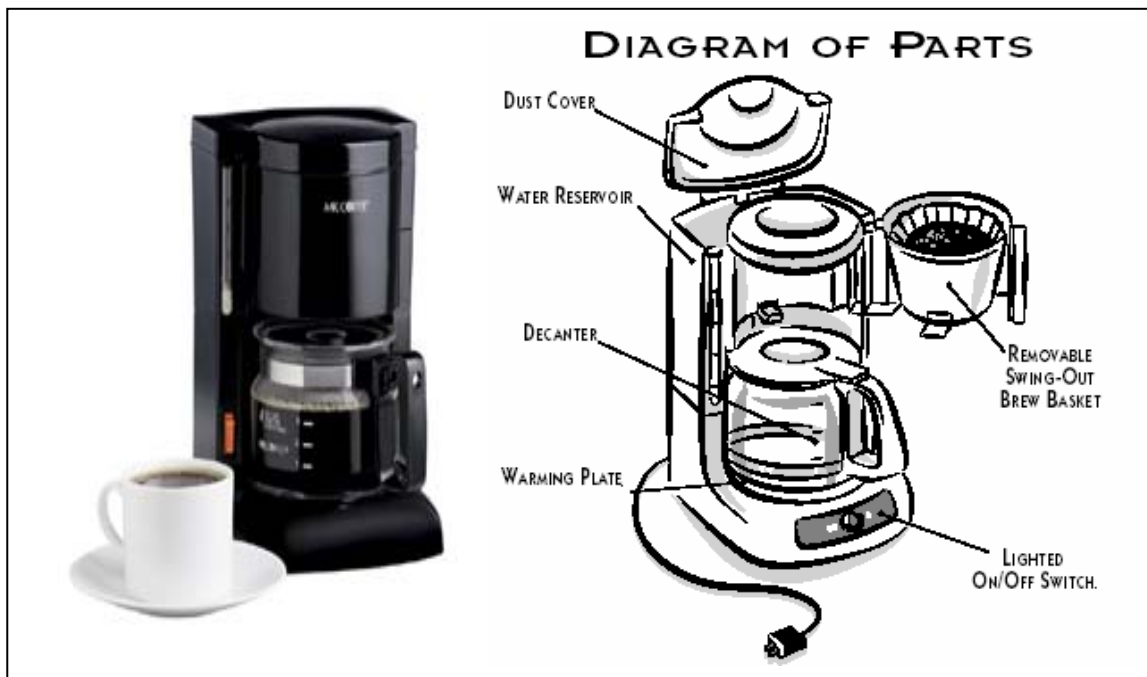


Figure 4: A generic Mr. Coffee Coffeemaker and its major components adapted from (URLb)

4.1 Step-1: Acquire product knowledge

Figures 5 and 6 illustrate the functional and physical decomposition of the generic Mr. Coffee brand coffeemaker. Twenty-two basic components have been identified: bucket, one-way valve, water intake cover, top surface, dripping surface, heating element, hot water tube, cold water tube, aluminum tube, brew basket, exit valve, decanter, handle, decanter cover, cables, connectors, sensors, indicator lights, switch, warming plate, bottom mounting, and bottom cover. The “basic” components are the lowest level components in a product hierarchy or, in other words, for all practical purposes further decomposition is stopped beyond them. Thus, $C(22,2) = 231$ candidate modules were formed out of the 22 basic components. However, to reduce the evaluation burden, some of the obviously infeasible combinations were excluded from the evaluation processes. Few examples of infeasible combinations are: hot water tube and decanter, brew basket and cables etc. All the other candidate modules were evaluated with respect to six metrics- three each for module quality and cost of modularization.

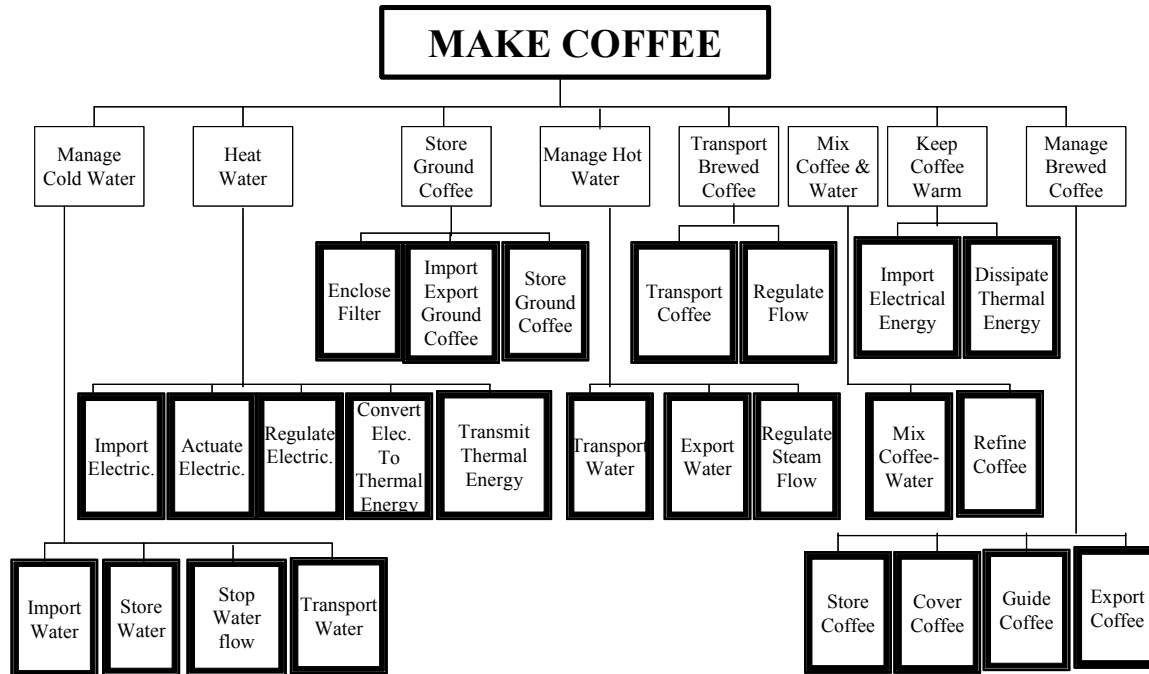


Figure 5: Functional decomposition of Mr. Coffee coffeemaker

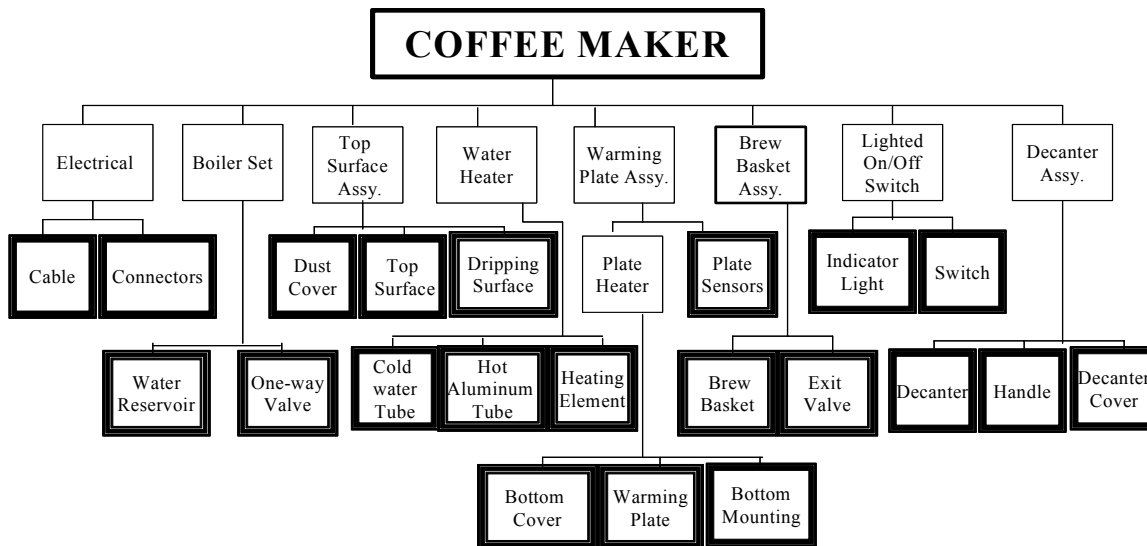


Figure 6: Physical decomposition of Mr. Coffee coffeemaker

4.2. Step-2: Evaluate candidate modules

According to the guidelines given in section 3.2.1, the component interactions in the candidate modules were evaluated with respect to all the quality and cost metrics. The evaluation was done in a continuous rating scale of 1-10, with 1 being *very low* quality and 10 being *very high* quality. Similarly, for CPI, 1 means *very low* and 10 means *very high* cost levels. Thereafter, the quality and cost performance indices are computed separately for each candidate module using the fuzzy logic model. For example, the quality metrics ratings for a candidate module with two components, *Water Reservoir* and *One way valve*, are found to be 8.5, 7.25, and 7.5 points with respect to ‘perceived quality,’ ‘robustness,’ and ‘compliance to axiomatic design,’ respectively. Finally, using the fuzzy logic model, the quality performance index for this candidate module has been found to be 8.21 (Table 5).

Similarly, the ratings for modularization cost metrics for the same candidate module were found to be as follows: assembly resource requirement (2.5), an interface cost (6.5), and a cost of reusability (2.5). Finally, using fuzzy logic model, its cost performance index was computed, which had a value of 4.12 (Table 6). Likewise, QPI and CPI for the rest of the candidate modules have been determined and presented in the matrix format in Table 5 and 6, respectively.

It may further be noted that some of the candidate modules, such as ‘Water intake cover’ and ‘one-way valve,’ have a QPI of 1. This means that these candidate modules are either not feasible or not technically appropriate for modularization, for all practical purposes. Basically, such a decision is made based on the experience of the designer. Similar intuition applies to a module consisting of ‘*Bucket*’ and ‘*Warming Plate*’ that has a very high CPI value (e.g., 10). A module with a CPI of 10 implies that the module is not viable economically. As mentioned earlier, fuzzy logic model was not used for all those obviously infeasible candidate modules. In other words, arbitrarily a very poor rating was assigned to all such infeasible modules.

4.3 Step-3: Modularize product architecture using multi-criteria optimization model

The crisp quality and cost performance indices obtained from fuzzy logic model were then fed into a CGP model for identifying the optimal modules. The goal-programming model was solved using the Excel based ‘*Premium Solver*’ package from the *Frontline Systems*®. The final solution identified the clusters along with their associated components. Thus, each cluster formed a module in itself. The number of clusters was controlled by the input parameter such as the number of median components. In order to determine aspiration levels, initially both QPI and CPI were optimized separately. The values of aspiration levels were substituted in Chebychev’s model for simultaneous optimization of quality and cost performance indices. In order to determine the optimal number of modules, a set of sensitivity analyses for QPI and CPI were also carried out against the number of modules.

Table 5: Quality performance index matrix for Mr. Coffee coffeemaker case study

	Water Reservoir	One way valve	Water Intake cover	Top Surface	Dripping Surface	Heating Element	Hot water Tube	Cold water tube	Alumium Tube	Warming plate	Bottom Mounting	Bottom Cover	Cable	Connectors	Plate sensors	Brew Basket	Exit Valve	Indicator Light	Switch	Decanter	Handle	Decanter Cover
Water Reservoir	0	8.21	9.25	4.51	8.21	1.8	4.51	2.8	1	1	8.21	1	1	1	1	2.8	1	1	1	1	1	1
One way valve	8.21	0	1	1	1	1	1.8	7.52	5.51	1	1	1	1	1	1	1	1	1	1	1	1	1
Water Intake cover	9.25	1	0	7.53	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Top Surface	4.51	1	7.53	0	8.21	1	3.51	1	1	1	1	1	1	1	1	6.52	1	1	1	1	1	1
Dripping Surface	2.8	1	1	8.21	0	1	3.51	1	1	1	1	1	1	1	1	6.52	1	1	1	1	1	1
Heating Element	1.8	1	1	1	1	0	1	1	7.52	8.21	7.53	2.8	1	1	1	1	1	1	1	1	1	1
Hot water Tube	4.51	1.8	1	3.51	3.51	1	0	1	9.2	1	6.52	1.8	1	1	1	1.8	1	1	1	1	1	1
Cold water tube	2.8	7.52	1	1	1	1	1	0	9.2	1	3.51	2.8	1	1	1	1	1	1	1	1	1	1
Alumium Tube	1	5.51	1	1	1	7.52	9.2	9.2	0	1	4.51	2.8	1	1	1	1	1	1	1	1	1	1
Warming plate	1	1	1	1	1	8.21	1	1	1	0	7.52	1.8	1	1	1	1	1	1	1	1	1	1
Bottom Mounting	8.21	1	1	1	1	7.53	6.52	3.51	4.51	7.52	0	9.2	1	1	1	1.8	1	1	1	1	1	1
Bottom Cover	1	1	1	1	1	2.8	1.8	2.8	2.8	1.8	9.2	0	1	1	1	1	1	1	1	1	1	1
Cable	1	1	1	1	1	1	1	1	1	1	1	1	0	9.29	1.8	1	1	7.52	8.21	1	1	1
Connectors	1	1	1	1	1	1	1	1	1	1	1	1	9.29	0	1.8	1	1	2.8	2.8	1	1	1
Plate sensors	1	1	1	1	1	1	1	1	1	1	1	1	1.8	1.8	0	1	1	2.8	4.51	1	1	1
Brew Basket	2.8	1	1	6.52	6.52	1	1.8	1	1	1	1.8	1	1	1	1	0	8.21	1	1	1	1	2.8
Exit Valve	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	8.21	0	1	1	1.8	1	1.8
Indicator Light	1	1	1	1	1	1	1	1	1	1	1	1	7.52	2.8	2.8	1	1	0	6.52	1	1	1
Switch	1	1	1	1	1	1	1	1	1	1	1	1	8.21	2.8	4.51	1	1	6.52	0	1	1	1
Decanter	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1.8	1	1	0	9.2	9.29
Handle	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	9.2	0	6.52
Decanter Cover	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2.8	1.8	1	1	9.29	6.52	0

Table 6: Cost performance index matrix for Mr. Coffee coffeemaker case study

	Water Reservoir	One way valve	Water Intake cover	Top Surface	Dripping Surface	Heating Element	Hot water Tube	Cold water tube	Alumium Tube	Warming plate	Bottom Mounting	Bottom Cover	Cable	Connectors	Sensors	Brew Basket	Exit Valve	Indicator Light	Switch	Decanter	Handle	Decanter Cover	
Water Reservoir	0	4.12	1.43	2.49	2.59	9.02	2.48	3.67	9.12	10	2.58	8.61	10	10	10	10	10	10	10	10	10	10	10
One way valve	4.12	0	10	10	10	10	2.58	1.4	2.48	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Water Intake cover	1.43	10	0	2.49	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Top Surface	2.49	10	2.49	0	2.64	9.14	5.81	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Dripping Surface	7.52	10	10	2.64	0	9.12	7.39	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Heating Element	9.02	10	10	9.14	9.12	0	10	10	5.26	6.77	5.84	5.84	5.84	9.02	7.51	10	10	10	10	10	10	10	10
Hot water Tube	2.48	2.58	10	5.81	7.39	10	0	2.4	1.98	10	5.83	8.51	10	10	10	10	10	10	10	10	10	10	10
Cold water tube	3.67	1.4	10	10	10	10	2.4	0	1.39	10	8.02	8.01	10	10	10	10	10	10	10	10	10	10	10
Alumium Tube	9.12	2.48	10	10	10	5.26	1.98	1.39	0	10	8.51	7.51	10	10	10	10	10	10	10	10	10	10	10
Warming plate	10	10	10	10	10	6.77	10	10	10	0	3.9	5.85	10	10	4.3	10	10	10	10	10	10	10	10
Bottom Mounting	2.58	10	10	10	10	5.84	5.83	8.02	8.51	3.9	0	2.25	10	10	10	10	10	10	10	10	10	10	10
Bottom Cover	8.61	10	10	10	10	5.84	8.51	8.01	7.51	5.85	2.25	0	10	10	10	10	10	10	10	10	10	10	10
Cable	10	10	10	10	10	5.84	10	10	10	10	10	10	0	2.49	4.22	10	10	4.22	4.22	10	10	10	10
Connectors	10	10	10	10	10	9.02	10	10	10	10	10	10	2.49	0	9.02	10	10	9.02	9.02	10	10	10	10
Sensors	10	10	10	10	10	7.51	10	10	10	4.3	10	10	4.22	9.02	0	10	10	8.02	5.06	10	10	10	10
Brew Basket	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	0	2.89	10	10	10	10	10	9.15
Exit Valve	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	2.89	0	10	10	9.02	10	10	9.02
Indicator Light	10	10	10	10	10	10	10	10	10	10	10	10	4.22	9.02	8.02	10	10	0	2.49	10	10	10	9.02
Switch	10	10	10	10	10	10	10	10	10	10	10	10	4.22	9.02	5.06	10	10	2.49	0	10	10	10	10
Decanter	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	9.02	10	10	0	1.34	1.34	1.34
Handle	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	1.34	0	8.02	8.02
Decanter Cover	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	9.15	9.02	9.02	10	1.34	8.02	0	0

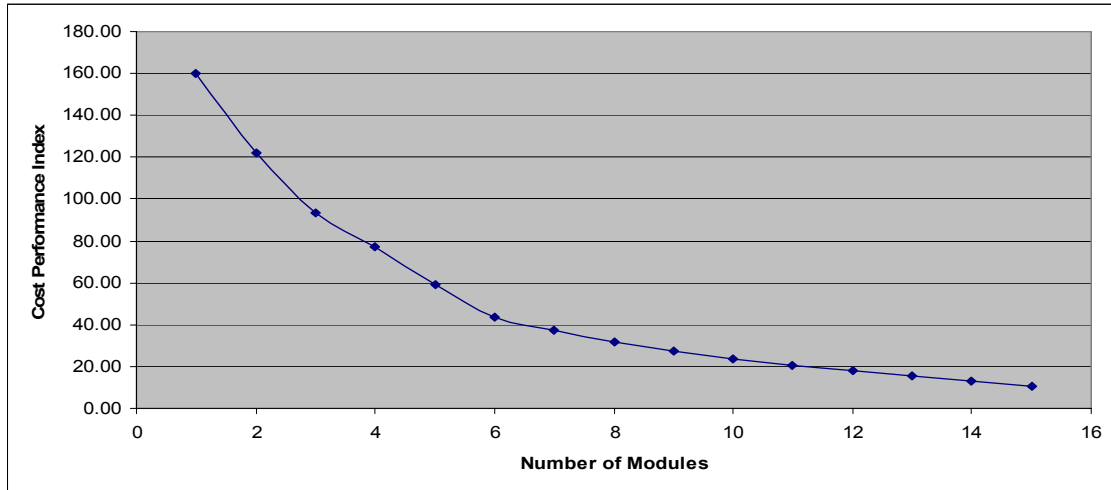


Figure 7: Sensitivity plot of cost performance index versus number of modules

Figure 7 shows that the CPI decreases exponentially when the number of modules increases; also, the curve does not have any point of inflexion, meaning that it is not possible to predict the optimal number of modules, if CPI is chosen as the single objective for optimization. This is because the current model is limited to component level modularization and does not consider the overall assembly cost in the calculation procedure for cost of modularization. Moreover, in case of QPI, the optimal number of modules for a given coffeemaker case study is found to be six, because with more or fewer number of modules the objective function value (QPI) decreases (Figure 8).

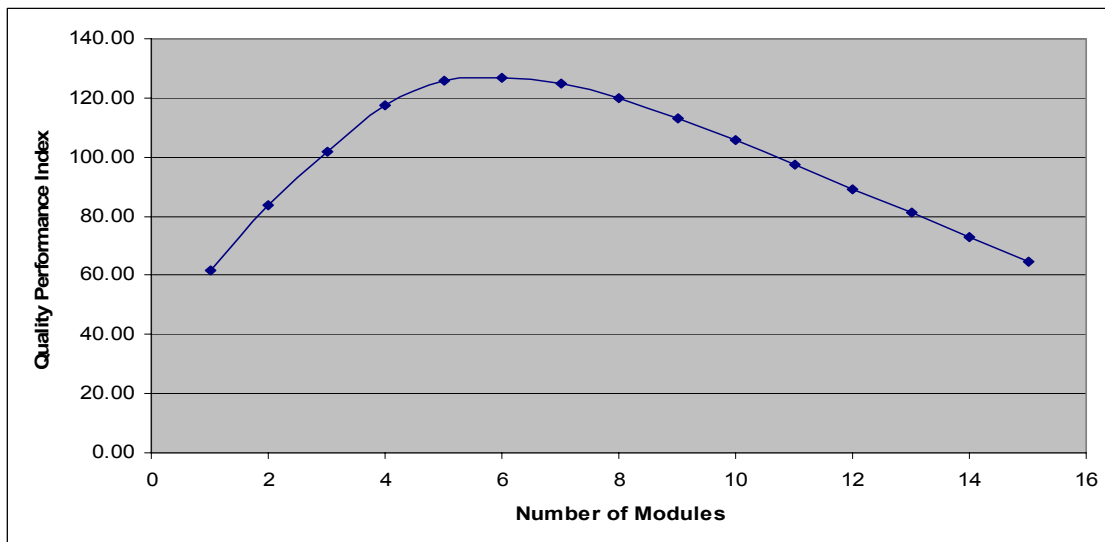


Figure 8: Sensitivity plot of quality performance index versus number of modules

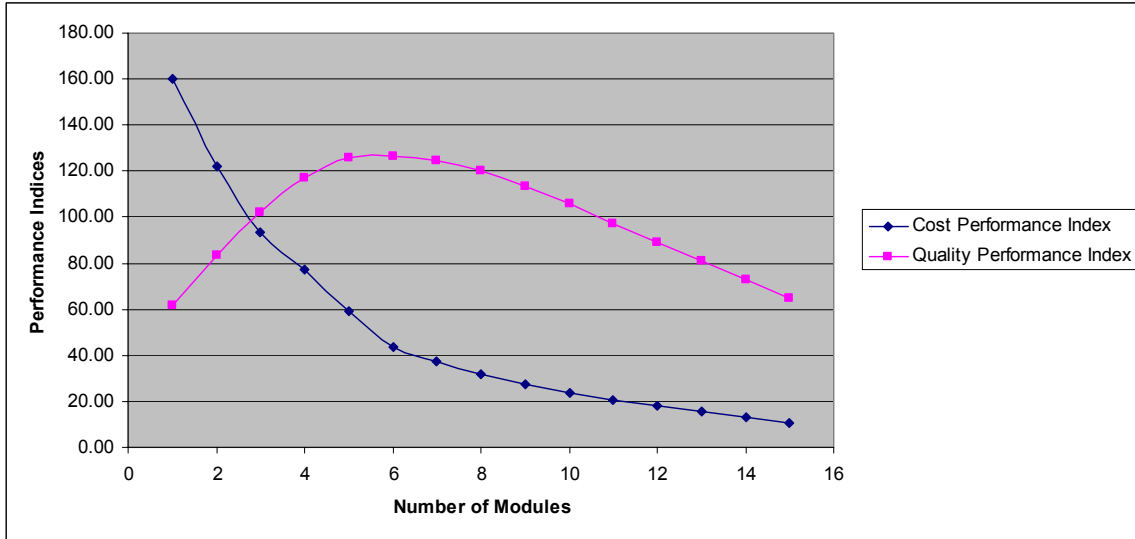


Figure 9: Modular architecture performance measure curves for Mr. Coffee coffeemaker

The optimal number of modules may vary when more than one performance criterion are taken into consideration. For example, in the proposed model we are considering two objectives, QPI and CPI. The sensitivity plots for QPI and CPI versus number of modules are superimposed in Figure 9. The plots can be considered as the modular architecture performance measure curves for the given case study because using those plots an engineer can define his or her own design priority. The optimal number of modules also depends upon the aspiration levels targeted for the various objectives by the designer. For instance, what is the priority-quality or cost? If the designer wishes to develop high quality products with little regard for product cost, then for the given case study the optimal number of modules identified at conceptual stage is six.

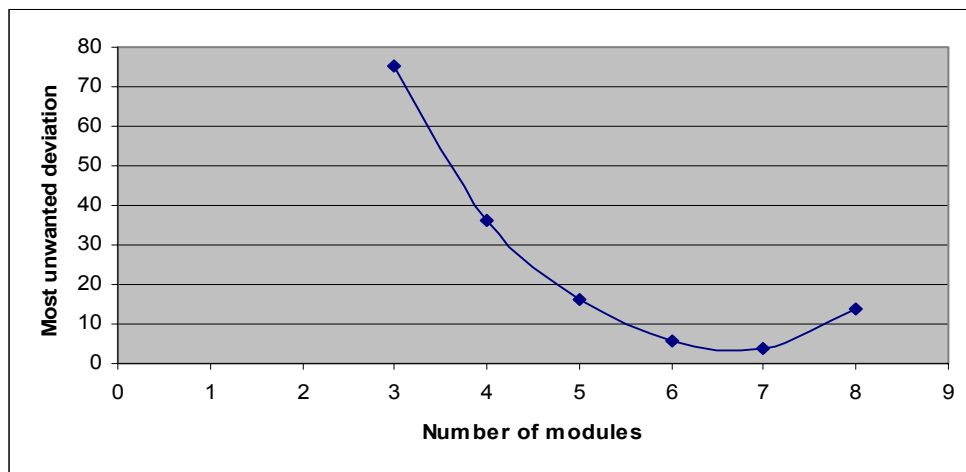


Figure 10: Sensitivity plot of most unwanted deviation versus number of modules

On the other hand, if cost is equally important, then the optimal number of modules would be seven as shown in Figure 10. The graph shows a sensitivity analysis of most unwanted deviation (objective function for Chebychev's goal programming model) versus number of modules. For this scenario of equal priority, the optimal modules and their associated components for the coffeemaker are as shown below (Figure 11):

- Module 1- Water reservoir, one way valve, water intake cover, top surface
- Module 2- Heating element, hot water tube, cold water tube, aluminum tube
- Module 3- Warming plate, bottom mounting, bottom cover
- Module 4- Cables, connectors, indicator light, switch
- Module 5- Sensors
- Module 6- Dripping surface, brew basket, exit valve
- Module 7- Decanter, handle, decanter cover

4.4 Comparison with other modularization approach

The Mr. Coffee coffeemaker has also been used as a case study by other researchers. We compare the results from the proposed methodology with the "module heuristics" developed by Stone et al (2000) and given in Otto and Wood (2001). These authors used three heuristics based on functional flow patterns such as "dominant flow", "branching flow", and "conversion-transmission flow" to identify the modules.

According to these heuristics, the authors suggested six unique modules for the Mr. Coffee coffeemaker case study. However, as we have seen in the previous section, this study has shown that the optimal number of modules for the given case study is seven, considering quality and cost as performance measures of its modular architecture. Therefore, the proposed multi-objective optimization not only provides more design resolution and opportunity for more modules but also has the following additional advantages over the heuristic approach:

- 1) Certainly the "module heuristics" provide a strong basis for modularizing the product, yet the construction of a functional base structure showing all the flows is quite complex and tedious. In contrast, the decomposition analysis in the proposed methodology is relatively straightforward.
- 2) The results from the three "module heuristics" may lead to a situation where two modules embody the same function. In the coffeemaker example, the function '*dissipate thermal energy*' falls under "coffee containment module" and "thermal energy module." In such cases, the designer has to carry out further analysis to identify the unique modules (Otto and Wood, 2001). On the other hand, such a situation does not arise in the proposed optimization approach. Each component is associated with only one module based on some objective criteria. Unlike the heuristics, the proposed method helps us to determine the optimal number of modules for a given architecture. This information may eventually be very useful in formulating a product complexity reduction strategy.

	Water Reservoir	One way valve	Water Intake cover	Top Surface	Dripping Surface	Heating Element	Hot water Tube	Cold water tube	Alumium Tube	Warming plate	Bottom Mounting	Bottom Cover	Cable	Connectors	Sensors	Brew Basket	Exit Valve	Indicator Light	Switch	Decanter	Handle	Decanter Cover	Total
Water Reservoir	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
One way valve	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Water Intake cover	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Top Surface	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Dripping Surface	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Heating Element	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Hot water Tube	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Cold water tube	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Alumium Tube	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Warming plate	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Bottom Mounting	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Bottom Cover	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Cable	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Connectors	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Sensors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Brew Basket	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Exit Valve	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Indicator Light	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Switch	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Decanter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Handle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Decanter Cover	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1

Figure 11: Optimal assignment of components to various clusters or modules when cost and quality have equal priority

- 3) The proposed model allows the design engineer to define his/her priority, such as higher quality or most economical product in the marketplace. The priorities can be defined by proper selection of aspiration levels in the goal-programming model.
- 4) Conceptually, the proposed multi-objective optimization model can also be used for any performance criteria, such as maximizing the functional interaction between the components within a module.

Similarly, in our previous work (Nepal et al., 2005), we have considered cost as only one objective function for modularizing the product architecture. Therefore, as stipulated, it was not possible to determine the optimal number of modules. Even the configurations of modules are different in the previous approach from the proposed multi-objective approach. The modules identified from the proposed method provides designers with more resolution in terms of their design needs. For example, all the electrical components are in one module and their design requirements will obviously be very similar. This will help to formulate independent yet integrated product development teams and assign them tasks that can be carried out concurrently.

4.5 Naming of modules

There are no universal rules developed so far for naming the modules. Past researchers have mostly used functional naming conventions (Pimmler and Eppinger, 1994; Stone et al., 2000). This paper follows a sort of hybrid (functional and physical) naming convention to arrive at the name of modules. For example, from the optimization model solution we found that all electrical components are grouped into one cluster; thus we name the cluster the electrical supply module. The complete list of modules and their names for the coffeemaker case are as follows:

- Module 1- Water Containment module
- Module 2- Valve and Tube module
- Module 3- Mounting or base module
- Module 4- Electrical supply module
- Module 5- Intelligent Component (sensors) module
- Module 6- Brewing Compartment module
- Module 7- Decanter module

5. Conclusions and Implications for Further Research

This paper has enhanced the existing work in the area of design for quality by integrating with modular design concepts. Conceptually, the paper has used modular design theory to optimize product quality by considering the underlying principles of axiomatic design and robust design in conjunction with the perceived product quality. A fuzzy theory-based structured procedure has been presented to analyze the component interactions and measure the performance of product architecture at the conceptual stage by decomposing it into various candidate modules.

The paper has considered two criteria for product modularization: minimization of modularization costs and maximization of overall product quality. The quality and cost both are measured in terms of dimensionless quantities known as quality performance index and cost performance index. The Chebychev's goal programming model was proposed to solve the multi-objective optimization problem for product modularization. A coffeemaker case study has been presented to demonstrate the proof of concept of the proposed methodology. The final results obtained after sensitivity analysis showed that the multi-objective optimization approach not

only determined the optimal number of modules but also provided an opportunity for more modularity as compared to the heuristic approach. Further, the identified modules are intuitive and offer more design resolution for the formulation of an independent product design and allow the development team to work concurrently on different tasks.

In this paper an attempt has been made to simplify the implementation of the proposed framework by providing a set of structured and well guided steps. Majorities of steps such as optimization, sensitivity analysis, and fuzzy logic model can be programmed to improve the usability of the framework. The automation of steps further enhances the capability of the framework for repeated applications without requiring much of modifications.

It should be noted that this research has focused on product architecture for developing higher quality products at the conceptual stage. In actual case, few additional factors may also play significant roles in ensuring better quality. Those factors include the right material, the right manufacturing process, and the right quality control techniques at the production stage. The other issues like product safety, design standards and codes are equally important for building a quality product. Therefore, in future, all these factors should also be considered in order to get a complete DFQ solution.

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