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Integrating customer requirements into customized product configuration design based on Kano's model

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Abstract

Owing to the increasing concerns about customer needs in the current competitive market, the identification and incorporation of customer requirements (CRs) into product configuration designs have raised the interest of both researchers and practitioners. Most of the design methodologies focus on explicit technical domains to define CRs into specific design parameters directly. However, the CRs are so complicated that they are usually expressed in vague, ambiguous language containing uncertain information and are not in the form of well-defined specifications of product attributes and components. Kano's model provides a qualitative way to classify CRs accurately. However, research contributions are seldom found in terms of quantitatively integrating Kano's model with product designs. This paper identifies a novel approach based on the quantification of Kano's model for integrating CRs into product engineering characteristics. Kano's model is quantified by identifying the relationships between the CRs and customer satisfaction to link the requirements mapping phase and product configuration design phase. The quantitative results derived from Kano's model are formulated as the multi-objective functions in a mixed non-linear programming model to identify the product configuration solution. For illustrative purposes, an example associated with the configuration design of a material-forming configuration production line is presented to demonstrate the capability of the proposed model.

Keywords Customer requirements · Product configuration · Product design · Kano's model

Introduction

Product requirements and available information are crucial factors for business success and competitive advantage (He et al. 2006). Requirement management is one of the most important activities that help designers to structure and manage requirements from idea generation to product commercialization in the phases of new product development. The success of product design requires multifaceted customer requirements (CRs), such as technical features, price/revenue streams, and various regulation compliances, as well as the customers' subjective and qualitative perceptions (Wang and Tseng 2011; Montalto et al. 2018; Zhang et al. 2016). In particular, CRs are derived from different perspectives of the product lifecycle, including issues such as manufacturing, reliability, maintainability and environmental safety (Papinniemi et al. 2014; Lou et al. 2018). When dealing with the complexity of CRs involved in product development from concept to detailed design, the process is not standardized. There are some steps that cannot be skipped, but frequently, some steps have to be rearranged and revised (Violante et al. 2015). Furthermore, according to (Tseng and Jiao 1998), CRs have the tendency to be vague, fuzzy, and difficult to manage because they are usually expressed in ambiguous language and not in the form of well-defined specifications of attributes and components (Wang and Tseng 2015). Thus, the understanding and fulfillment of diversified CRs have been recognized as an urgent challenge to companies across industries (Jiao and Chen 2006).

Extensive literature on the subject has been produced to characterize, understand, and elicit CRs in product design domains, such as product configuration, conjoint analysis, and Kansei engineering (Chen and Wang 2008; Zhou et al. 2013). Nowadays, Quality Function Deployment

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(QFD) (Hauser 1988) is widely recognized as an effective approach to pursuing customer satisfaction for guiding the design of a product (Matzler and Hinterhuber 1998; Cristiano et al. 2001; Chen and Chuang 2008; Nahm et al. 2013; Zare Mehrjerdi 2010a). However, most of these methodologies depend heavily on the customers' explicit specification of the attributes, which are generally obtained by translating the customer feelings—normally expressed on ordinal scales—into a numerical scale. This artificial encoding can lead to errors or inconsistencies in the evaluation (Franceschini et al. 2015) and customers may find the process unpleasant or even stressful (Huffman and Kahn 1998; Schwartz 2004).

From the designer's perspective, there may be problems when integrating CRs and relationships in the customer domain into functional requirements (Jiao and Chen 2006). In cases where the customers have not yet obtained a tangible product in the customization process and are not familiar with the domain knowledge, explicit linkages among the CRs and the detailed technical specifications may not be feasible (Risdiyono and Koomsap 2013; Wang and Tseng 2014). However, the elicitation process for configurator-based CRs requires customers to express their needs in the specific design parameter domain rather than the customer domain. Only well-defined attributes and components can be specified by the cross-functional design team. Sometimes, the customer cannot relate the requirements for the detailed design parameters, creating difficulty in the configuring process. Thus, the explicit elicitation of customer expectations and perceptions of product functions or features for engineeringcharacteristics (ECs) plays a leading role in realizing customer satisfaction. This means that specific configuration processes are needed for realizing the horizontal movement between requirements structures and design product structures, such as functional, as described in Fig. 1. Therefore, there is a need to discover new ways to characterize CRs for tangible product design.

Consequently, the kinds of challenges are probably met and coped with when requirements are integrated into product configuration design:

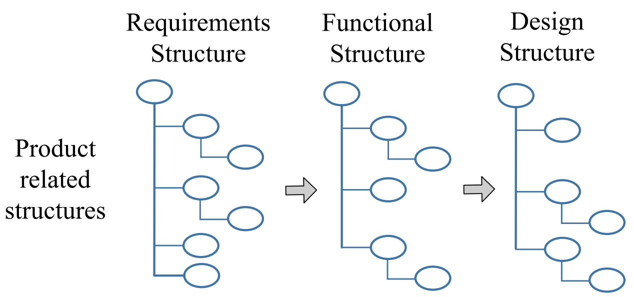

Fig. 1 Product-related structure integration. Adapted from Papinniemi et al. (2014)

1. Integrating CRs into product design without explicitly linking the elicitation of customer requirements in the customer domain and construction of specific design parameters in the technical domains.
2. Specific configuration processes, such as functional and design processes, are needed in product specific domains from a design perspective.

This study defines an alternative approach to overcoming the above-mentioned issues. Considering the difficulty in building a deterministic solution to address the proposed process, we applied Kano's model to incorporate vague CRs into product functional configuration and further translate them into the engineering characteristics (ECs) for design in order to enhance the effectiveness of the requirements management. Different product ECs can be composed of a number of components with distinct attribute levels. In detail, ECs are associated with critical part characteristics. The critical part is characterized by engineering functionality expressed in terms of the discrete level of attributes. ECs related to CRs can be identified by the cross-functional team (Franceschini et al. 2015). Thus, according to the customer satisfaction measurement of product ECs related to different CRs, the identification and evaluation of design schemes can be integrated into production configurations.

There are three main parts to this paper. First, the CRs are elucidated, quantified, and analyzed, where the expected perception performance or technical attributes of product ECs are defined and categorized according to Kano's model in the requirement structure. Second, target performance values are defined as the levels of fulfilment of ECs by the evaluation process. Third, the optimal product configuration solution can be generated by using a multi-objective programming to recommend the optimal configuration scheme to customers.

The remainder of this paper is organized as follows. "Literature review" section presents a brief review of the relevant literature on the integration of CR into product design, product configuration design, and Kano's model. "Overview of the proposed approach " and "A novel approach to integrating CRs into product design" sections respectively summarize and explain a novel approach that integrates Kano's model into product design. Section Case study discusses a case study that demonstrates how the proposed approach can be applied.

Literature review

Integration of CRs into production design

It is significant to integrate CRs into effective product design strategies to satisfy demand (Dou et al. 2017).

Numerous studies have been carried out on product design configuration. To elicit a customer's unarticulated needs, some configurator design approaches have been proposed in engineering design to emphasize the importance of customer involvement in product design (Aldanondo and Vareilles 2008; Aquino Shluzas and Leifer 2014; Zhou et al. 2013; Yang and Jiang 2019). Zhou et al. (2008) employed an optimization approach to customer-driven product configuration, which was established as the foundation for targeting a diversity of customer needs. To further increase customer satisfaction, Wang (2013) incorporated customer satisfaction factors into product configuration. Chan et al. (2011) proposed a method based on genetic programming (GP) to generate models for relating customer satisfaction to engineering requirements. Jiang et al. (2013) proposed a rough set and particle swarm optimization-based adaptive neuro-fuzzy inference systems for improving the accuracy of customer satisfaction modeling for product design. To meet different personalized requirements, Wang and Tseng (2015) used product variants as the class label to divide product variants into different categories according to a Naïve Bayesian approach. Merle et al. (2010) proposed the consumer-perceived value tool to measure different customers' perceived benefits related to mass-customized products. However, if product design is examined only from the perspective of the customer, the design may be divorced from design principles and basic paradigms or may even contradict the manufacturer's product design strategy. Therefore, some studies guide and optimize product design from the view of the manufacturer or professional designer (Dou et al. 2017).

Developed in Japan during the 1960s (Li et al. 2009), QFD (Kogure and Akao 1983) is widely recognized as an effective manufacturing approach to customer-driven design and has been used for several years in the manufacturing industry to pursue customer satisfaction (Cristiano et al. 2001; Chan and Wu 2002; Zare Mehrjerdi 2010b; Chen and Huang 2011; Geum et al. 2012; Jia and Bai 2011; Zare Mehrjerdi 2010a). A house of quality (HOQ) is a conceptual map used by a cross-functional team to identify the CRs and the best way to develop systems (Karlsson 1997; Akao and Mazur 2003; IEEE International Engineering Management Conference Vancouver 1996). Ji et al. (2014) integrated Kano's model into QFD to optimize product design and provide a better classification of CRs. Ginting et al. (2018) collected and analyzed a number of relevant scientific publications for an in-depth analysis of the results, advantages, and drawbacks of QFD methodology. However, the importance of each CR is assumed to be expressed on a cardinal scale (interval or ratio scales) in the construction of HOQ, which is a major challenge to understanding CRs accurately.

Product design

Product configuration is a special case of design activity, i.e., selecting components from a predefined component library and connecting these components according to customer requirements (Tseng et al. 2005). Numerous scholars have researched product configuration optimization methods from different aspects involving different optimization objectives, such as product performance, cost, and task time. Roger Jiao et al. (2007) summarized the related topics, including fundamental issues and definitions, product portfolio, product family positioning, and platform-based product family design, and key technologies in the configuration optimization of products. For the introduction of fuzziness to capture the subjective nature of the design for the configuration process, Ostrosi and Tié Bi (2010) used multiple fuzzy models to propose possible physical solutions to configure a product. Yao and Yu (2018) proposed a product configuration approach based on online data. However, most of the optimization targets considered in the above configuration optimization schemes do not involve multiple objectives. Considering only single certainty requirements is unrealistic, so multiple discrete design requirement values should be considered for the improvement of performance by the integration of CRs into product design.

Kano's model

Kano's model (Kano et al. 1984), which studies the nature of CRs, provides a better classification of CRs because of the convenience of classifying CRs according to surveydata. Customer preferences are classified into three main types (Fig. 2) by the priority of the attributes and how they affect customer satisfaction:

1. Must-be (M): must-be attributes are expected by the customers, who take them for granted if their expectations are fulfilled but are dissatisfied if a product does not meet their expectations adequately.
2. One-dimensional (O): customer satisfaction has a positive and linear correlation with one-dimensional preferences.
3. Attractive attributes (A): attractive attributes are usually unexpected, meaning that their presence leads to greater than proportional customer satisfaction but their absence would not cause dissatisfaction (Wang and Ji 2010).

In addition to the categories of M, O, and A, CRs can also be classified into three other categories: indifferent (I), reverse (R), and questionable (Q). (I) denotes the customer's indifference to a particular attribute of a product, whereas (R) denotes the customer's dislike of the attribute and (Q) denotes the customer's expectation as having not been met by the attribute.

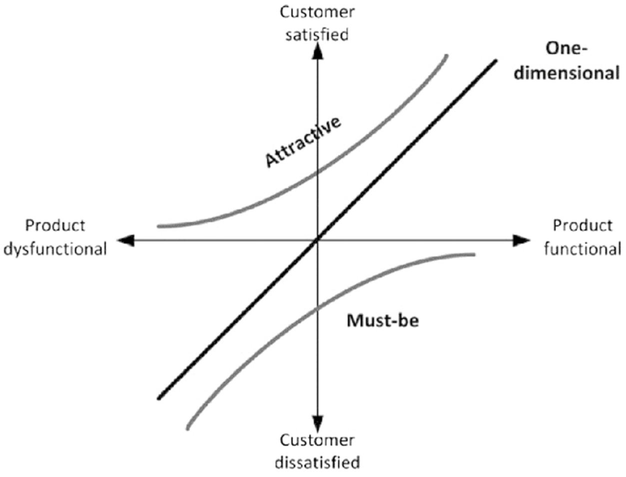

Fig. 2 Kano's diagram (Kano et al. 1984)

Several studies integrate Kano's model into product design and use it to optimize the design by recognizing and analyzing the potential factors influencing customer satisfaction (Chen and Chuang 2008). To fulfill the goal of market-oriented product development, customer satisfaction should be well incorporated into the decision-making process of product configuration. Wang (2013) presented a hybrid framework to address two critical issues in new product development: customer satisfaction and product configuration.

Kano's model, which focuses on the classification method and the qualitative descriptions of various relationship curves, provides only a qualitative way to recognize the diverse relationships between CR fulfillment and customer satisfaction (Ji et al. 2014). Lin et al. (2017) proposed a novel method for quantitatively assessing quality attributes to determine classification criteria and fit nonlinear relationships between quality attributes and customer satisfaction. Wang and Ji (2010) demonstrated a better understanding of CRs from an analysis of Kano's traditional model in a quantitative manner by showing that the proposed approach performed well not only in terms of mapping the relationship between CRs and customer satisfaction accurately but also a more comprehensive transformation in both the customer requirement domain and specific design constraint domain. İlbahar (2018) classified mobile phone design features in the direction of user perception and expectation by using a fuzzy version of Kano's Model.

Overview of the proposed approach

The goal of this research is to incorporate the specific CRs into product functional configuration and further translate them into the product design solution to enhance the effectiveness of the configuration of personalized manufacturing requirement.

Figure 3 illustrates the overall system architecture, which is divided into three stages: quantitative analysis of customer requirements phase, construction of product functional hierarchical structures phase, and integration of Kano's model into product configuration optimization phase.

Quantitative analysis of CRs phase

Kano's model has made it possible to utilize the degree of customer satisfaction for understanding the voices of the customers (Wang and Ji 2010). The quantitative analysis is applied to further identify the functional relationships between CRs concerning product performance and customer satisfaction. The quantitative analysis of the customer requirements phase consists of three steps:

1. Requirements elicitation and analysis. Through focus groups, individual interviews, and other techniques, the voices of the customers were questioned and recorded. Product function or performance requirements representing CRs was generated, from which a successful functional structure can follow.
2. Developing and administering Kano's questionnaires. Based on the requirements elicitation and analysis, a Kano's questionnaire concerning the product design was developed accordingly. Participants were required to express their feelings of whether they liked, needed, felt neutral about, could live with or disliked in both functional and dysfunctional conditions of the acquired CRs. The Kano's questionnaire was then distributed to their customers.
3. Applying Kano's quantitative analysis to process survey results. The functions or performance requirements were classified into different Kano categories by using the two coefficients proposed by Berger (Berger et al. 1993) and by further quantitative analysis (Wang and Ji 2010) of the different attributes or categories by applying Kano's model to recognizing the diverse relationships between the fulfillment levels of the CRs and customer satisfaction.

Construction of product functional hierarchical structures phase

For mapping the functional structures and integration of the customer's requirement, an analysis of the product composition is first adopted to find the ECs and instantiated parts that have interactive relationships with the specific performance. As shown in Fig. 3, $\left\{C_1, C_2, \dots C_j \dots, C_J\right\}$ denotes the CRs for a product. $\left\{E_1, E_2, \dots E_i \dots, E_I\right\}$ represents the ECs of the product.x_j denotes the functional evaluation index for a product

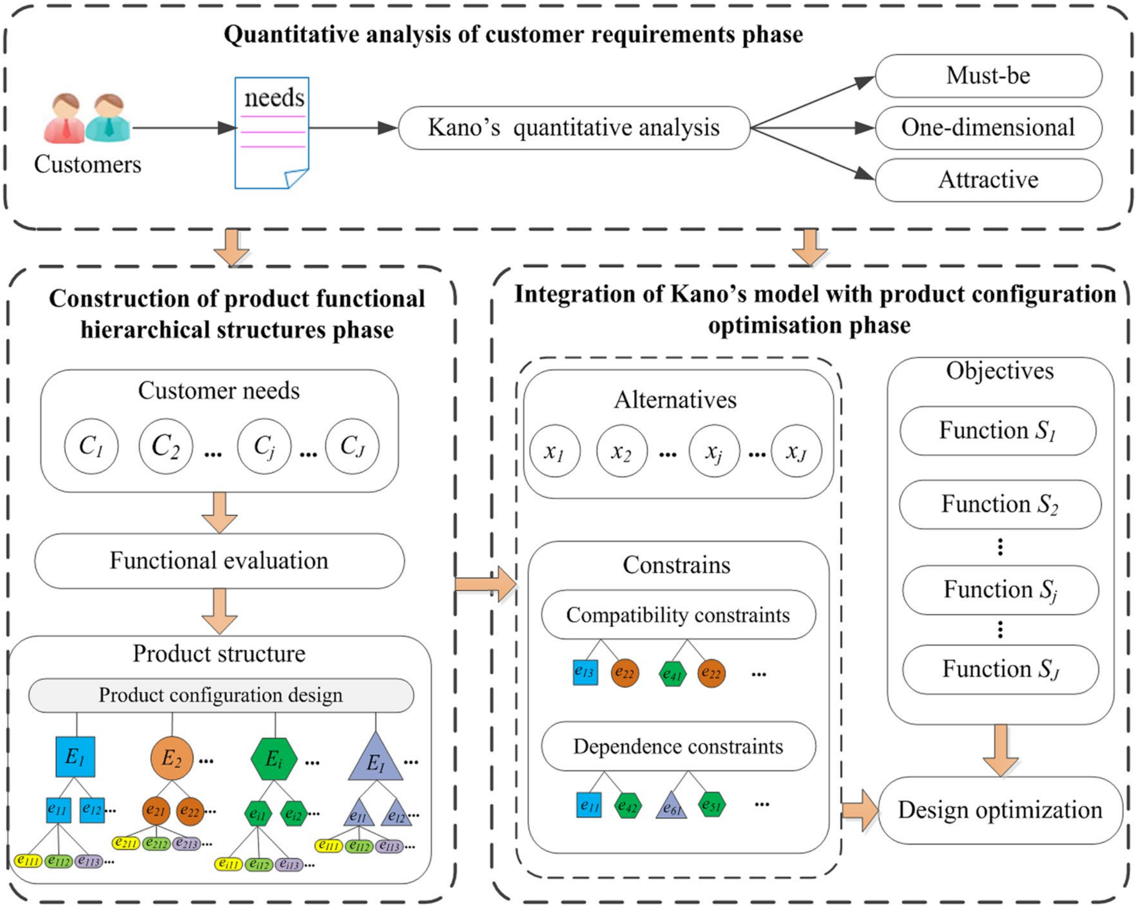

Fig. 3 Overview of system architecture

based on the jth CR. S_j denotes the objective functions in the mixed non-linear programming model.

The performance indicator x_j is used to measure the overall performance of a product consisting of specific ECs and instantiated parts, which reflects the performance fulfillment degree of different CRs. Using the analytic hierarchy process (AHP) method, the functional priority values of the components can be assigned, and so, the performance index of a product can be derived by the normalization combination of the priority values of the ECs and instantiated parts. Thus, the functional hierarchical structures are established and a qualitative description of the product configuration is generated for the next step of the optimal product configuration solution.

Integration of Kano's model with product configuration optimization phase

Based on the retrieval of the requirement categories from the Kano quantitative analysis, the estimation of the relationship functions between customer satisfaction and the fulfillment of the CRs (S–CR) can be defined and regarded as the objective function. The constraints in Fig. 3 specify the extra boundary conditions for the level of fulfilment of certain ECs. Thus, the optimal product configuration solution can be generated by using multi-objective programming.

A novel approach to integrating CRs into product design

Quantification of CRs based on Kano's model

By analyzing the results of the customer questionnaires, the model categorizes the different CRs into three main types: must-be, one-dimensional, and attractive attributes. Using the classification'sresults, the proposed quantitative analysis (Wang and Ji 2010) of Kano's model is then applied to identifying the relationship functions for different CRs in order to recognize clearly the diverse relationships between the fulfillment levels of the CRs and customer satisfaction. The process of identifying the quantified functions is listed as follows:

1. Calculating customer satisfaction (CS) and customer dissatisfaction (DS) values. To reflect the average extent of CS, Berger (Berger et al. 1993) proposed a method to calculate two coefficients, which are the CS index and the DS index, i.e., the percentages of customers that expressed satisfaction and dissatisfaction, respectively, with the fulfillment of the product requirements. To calculate the CS value, the number of all satisfied attributes (attractive and one-dimensional) are summed up and divided by the sum of the attractive attributes (f_A), one-dimensional attributes (f_O), must-be attributes (f_M), and indifferent attributes (f_I), as expressed in Eq. (1). Similarly, the DS value for CR is calculated by summing all the dissatisfied attributes (one-dimensional and must-be) and dividing the sum by the sum of f_A, f_O, f_M, and f_I, as expressed in Eq. (2):
$$CS = \left(f_A + f_O\right) / \left(f_A + f_O + f_M + f_I\right) \tag{1}$$
$$DS = -\left(f_O + f_M\right) / \left(f_A + f_O + f_M + f_I\right) \tag{2}$$
where f_A, f_O, f_M, and f_I stand for the attractive, one-dimensional, must-be, and indifferent columns.
2. Plotting the relationship curves. To define the *CS* and *DS* together with their corresponding quantified levels of fulfillment for specific CRs, the level of customer satisfaction is assumed to be 1 if the CRs are completely fulfilled or 0 for complete non-fulfillment (Wang and Ji 2010). According to this assumption, the CS and DS points are defined. At the CS point of the ith customer requirement CR_i, which is expressed as $(1, CS_i)$, is the level of CS_i where CR_i is fully fulfilled. The DS_i point of the CR_i, which is expressed as $(0, DS_i)$, is the extent of the customer DS_i at which the CR_i is fully unsatisfied. The relationship curves of the different categories (attractive attribute, one-dimensional, and must-be attributes) follow the shapes of the exponential curves (Fig. 2) that pass through the *CS* and *DS* points and can be plotted as shown in Fig. 4.
3. Identifying relationship functions. The above diagram shows that the relationships between customer satisfaction and CRs fulfillment (S–CR) can be approximately quantified by an appropriate function. Generally speaking, the S–CR relationship function can be expressed as $S = f(x, a, b)$, where S denotes the degree of customer satisfaction and x, ranging from 0 to 1, denotes the fulfillment level of CRs concerning the product performance.

For the one-dimensional CRs, the relationship can be unambiguously quantified, since, for any two distinct points, there is one and only one line that crosses the points. The function is then $S_o = a_1 x + b_1$, where a_1 is the slope and b_1 is the DS value when the CR value equals 0. Accordingly, given $(1, CS_o)$ and $(0, DS_o)$, the parameters are $a_1 = CS_o - DS_o$ and $b_1 = DS_i$. The S–CR curve of the attractive attributes is capable of being approximated by an exponential function $S_A = a_2 e^x + b_2$, where a_2 is a parameter for tuning the slope and b_2 is for adjusting the vertical level. Given the CS and DS points, the two parameters can be estimated by $a_2 = \frac{CS_A - DS_A}{e-1}$ and $b_2 = -\frac{CS_A - eDS_A}{e-1}$, respectively. Similarly, the S–CR curve of the must-be attributes can be estimated by an exponential function,$S_M = a_3 e^{-x} + b_3$, where $a_3 = -\frac{e(CS_M - DS_M)}{e-1}$ and $b_3 = \frac{eCS_M - DS_M}{e-1}$. Thus, the relationship functions of the product performance and customer satisfaction for the different categories can be calculated asfollows.

The function for the one-dimensional attributes is estimated by a linear function:

$$S_O = \left(CS_O - DS_O\right)x + DS_O. \tag{3}$$

The function for the attractive attributes is estimated by an exponential function:

$$S_A = \frac{CS_A - DS_A}{e-1} e^x - \frac{CS_A - eDS_A}{e-1}. \tag{4}$$

The function for the must-be attributes is estimated by an exponential function:

$$S_M = -\frac{e\left(CS_M - DS_M\right)}{e-1} e^{-x} + \frac{eCS_M - DS_M}{e-1}. \tag{5}$$

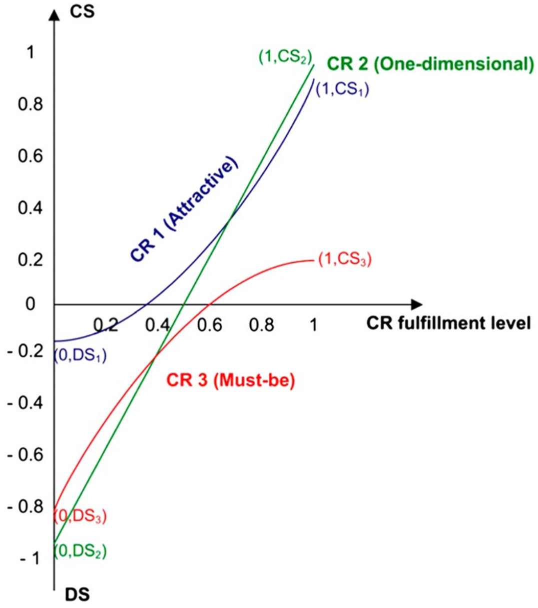

Fig. 4 Relationship curves of customer satisfaction and CR fulfillment. Adapted from Wang and Ji (2010)

An approach is proposed (Wang and Ji 2010) to extend Kano's model from qualitative descriptions to quantitative analysis in order to understand the specific CRs concerning diverse product performance in a more accurate manner.

Construction of product functional hierarchical structures phase

To utilize the customer's perceptions for supporting the product functional configuration, a hierarchical analysis of the product functional structure is conducted to obtain a better fulfillment of the CRs. The higher a customer's specific preference of a product, the more likely they are to choose a structure with the corresponding high-performance components. According to this understanding and how well the function of the components being able to achieve customer satisfaction, the optimum configuration of product modular instantiated components can be derived to optimize the product structure. Therefore, after the product structure composition is confirmed, a problem arises as to identifying the functional satisfaction evaluation of diverse product components in order to achieve customer satisfaction. This phase should be specified by the cross-functional design team to identify the well-defined attributes and components in a specific design parameter domain.

Analysis of product functional structure composition

The functional structure, which can serve as a central information pool, is a concept in the customer-oriented manufacturing management process ensuring that the voice of the customer is heard. The structure of a product includes the design scheme, which consists of specific components and technical design parameters. The functional structure is determined by the composition of the various ECs and modular instantiated components in accordance with a certain combination of rules; therefore, the constituent parts of the components directly determine the performance properties of the product. Other relevant product structures, including the design and manufacturing, are derived dynamically with the functional product structure.

Assuming that the product functional hierarchical structure is defined in such a way that the diverse performance properties of CRs are placed at the top of the hierarchy, the ECs of the product configuration structure are placed at the sublayer and the optional modular instantiated components related to the corresponding ECs are placed in descending order, as shown in Fig. 5. To satisfy the diversified needs of the market, a set of internal configurations are specially designed for the products, so that for each EC, a number of product components with similar functionalities but different levels of performances or features are fully replaceable. Thus, the key to product functional configuration is to choose an optimal combination of modular instantiated components by company designers to satisfy CRs and the corresponding product configuration constraints.

Functional evaluation of product structure composition

According to the differentiated performance preference for diverse instantiated components, there exists some performance indicator that links the level of fulfillment in CRs and distinct ECs with a product composition of special modular instantiated components. We first used the AHP (Saaty 1982) approach to assess the relative functional importance among different ECs and modular instantiated components concerning specific CRs, then finally determined the performance indicator of a product consisting of certain instantiated parts through a normalization method. Thus, the relational intensity between each pair of CRs and ECs is established by the designers as a relationship matrix, which indicates the degree of impact of an EC on the performance of a corresponding CR, embedded in the matrix. To maximize customer satisfaction, some more important modular instantiated components related to an EC can be selected for the product design.

Definition Aproduct is considered as consisting of a set of ECs $\left\{E_1, E_2, \ldots E_i \ldots, E_I\right\}$, where each variable E_i represents the ith EC of the product. E_i takes on values from its alternative modular instantiated components choice set $\varepsilon_i = \left\{e_{i1}, e_{i2}, \ldots e_{im_i} \ldots, e_{iM_i}\right\}$, where each variable e_{im_i} represents the m_ith alternative component of E_i and M_i is the alternative cardinality of E_i. A customer's performance requirements for a product are represented as a set of variables $\left\{C_1, C_2, \ldots C_j \ldots, C_J\right\}$, where each variable C_j represents the

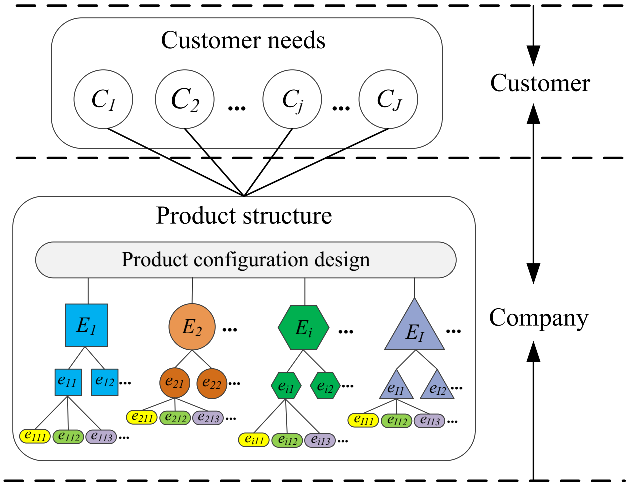

Fig. 5 The product functional hierarchical structure

jth CR, which can be the technical requirements or subjective requirements, such as a car's safety or appearance.

The mathematical formulation of the performance indicator of the CRs for a product can be expressed as follows:

1. The relative functional importance of modular instantiated components. After the identification of the product performance and the ECs, the pairwise comparison matrix among different ECs for each product performance according to the CRs is implemented separately according to the AHP method. Thus, the priority value of each EC related to different categories of CRs d_{ij}, which displays the relationship intensity between ECs and CRs, is determined. The absolute functional importance weight of each alternative component $w^j_{im_i}$ concerning the diverse CR is obtained as:

$$w^j_{im_i} = d_{ij} d^j_{im_i}, \tag{6}$$

   where d_{ij} represents the importance rating of the ith EC related to the jth CR and $\sum_{i=1}^{I} d_{ij} = 1$. $d^j_{im_i}$ represents the importance rating of the m_ith alternative component of E_i among the set ε_i concerning the specific customer requirement C_j and $\sum_{m_i=1}^{M_i} d^j_{im_i} = 1,\ (i = 1 \ldots I; j = 1 \ldots J)$. Based on $w^j_{im_i}$ from Eq. (6), the relative functional importance of the instantiated component concerning diverse CRs in terms of a percentage is obtained for prioritization.
2. Normalizing the functional values of modular instantiated components concerning different CRs. Due to technical constraints, a certain EC can choose one of the alternative modular instantiated components with several discrete values. Regarding the different CRs, the performance of the EC is positively proportional to its technical value of the alternative component, i.e., the higher the value of the alternative component, the better is the performance. The normalization method shown in Eq. (7) was developed for directly comparing and recognizing the proper alternative instantiated components for diverse ECs:

$$w^{j*}_{im_i} = w^j_{im_i} / w^j_{im_i,max}, \tag{7}$$

   where $w^j_{im_i,max}$ represents the relative maximum functional importance weight of the alternative component among set ε_i for specific EC; E_i related to customer requirement C_j.
3. The performance indicator of a product consisting of certain instantiated parts. The performance indicator indicates how well a product or component is capable of the performance fulfillment degree of different CRs. In this study, only one instance in the alternative components set can be selected and arranged. The performance indicator x_j of the product can be obtained by:

$$x_j = \frac{1}{I} \sum_{i=1}^{I} \sum_{m_i=1}^{M_i} b_{im_i} w^{j*}_{im_i}, \tag{8}$$

   where x_j denotes the functional evaluation index for a product based on the jth performance requirement. b_{im_i} denotes a binary decision variable. $w^{j*}_{im_i}$ represents normalized functional weight values among selected components $\sum_{m_i=1}^{M_i} b_{im_i} = 1,\ (i = 1 \ldots I)$. $b_{m_i} = \{0, 1\}$; $b_{im_i} = 1$ denotes the m_ith instantiated component and is selected to configure the products; otherwise, $b_{im_i} = 0$.

After constructing and quantifying the functional hierarchical structures, the relationships between the fulfillment levels of the CRs and diverse product components can be generally measured as performance indicators, which can be developed to measure the optimum product configuration.

Integration of Kano's model with product configuration optimization

Design structuring is a critical activity that realizes the physical function of a product. The design structure includes the design scheme, which consists of several components and corresponding technical design parameters. Product design structures consist of a discrete level of critical components that serve as universal carriers and can realize different levels for ECs. The goal of product configuration optimization is to find feasible structure configuration solutions that satisfy CRs. The optimal product configuration solution can be generated by the multi-objective programming model.

Design optimization objectives

The design optimization objectives considered in the traditional configuration optimization schemes are mostly single. However, in product design for mass customization, a good configuration design typically involves multiple objectives, such as product performance, cost, and task time (Wei et al. 2014). All of the function or performance requirements can be classified into different Kano categories and further quantitative analysis as the optimization objectives in the configuration design phase.

To recognize the different Kano categories of the CRs by analyzing the results of the customer questionnaires, the proposed quantitative analysis of the S–CR relationship functions can be defined and regarded as the objective function in the multi-objective decision-making process. The customer satisfaction index S for all the variables in the set of CRs

$\left\{C_1, C_2, \dots C_j \dots, C_J\right\}$ are employed to measure the alternative configuration design scheme for a product. Thus, by integrating the S–CR relationship functions, the objective function (Eq. (11)) can be established.

$$\max S_j (j = 1, 2 \dots J) \tag{9}$$

$$\max S_j = \left(CS_j - DS_j\right)x_j + DS_j$$
$$\text{if } C_j \text{ denotes one-dimensional attributes}$$

$$\max S_j = \frac{CS_j - DS_j}{e-1}e^{x_j} - \frac{CS_j - eDS_j}{e-1}$$
$$\text{if } C_j \text{ denotes attractive attributes}$$

$$\max S_j = -\frac{e\left(CS_j - DS_j\right)}{e-1}e^{-x_j} + \frac{eCS_j - DS_j}{e-1}$$
$$\text{if } C_j \text{ denotes must-be attributes}$$

$$x_j = \frac{1}{I}\sum_{i=1}^{I}\sum_{m_i=1}^{M_i} b_{im_i} w_{im_i}^{j*} \tag{10}$$

$$\sum_{m_i=1}^{M_i} b_{im_i} = 1, (i = 1..I); b_{im_i} = \{0, 1\}, \tag{11}$$

where CS_j and DS_j denote the percentages of customers that expressed satisfaction and dissatisfaction, respectively, about the fulfillment of the product requirements. $w_{im_i}^{j*}$ represents the normalized functional weight values among the selected components; b_{im_i} denotes a binary decision variable. $b_{im_i} = 1$ denotes the m_ith instantiated component and is selected to configure the product; otherwise, $b_{im_i} = 0$.

Design constraints

Inproduct configuration, a product is considered as a modular architecture consisting of a set of function module instances that are not independent of each other but depend on each other in terms of existence, function, compatibility, etc. In this paper, several constraints among the module instances developed by the design phase are considered.

There are some components with different functions and parameters that are incompatible with each other. This means that some module instances cannot be applied simultaneously in one configuration scheme because of the compatibility constraints (Tang et al. 2017). Meanwhile, in some cases, the existence of a modular instantiated component relies on another component because of the dependence constraints. It is assumed that the modular instantiated component e_{ha} is not compatible with the component e_{hb} and component e_{kc} relies on the component e_{kd} such that they should be combined with each other to realize the function $\left(e_{ha}, e_{hb}, e_{kc}, e_{kc}\varepsilon_i = \left\{e_{i1}, e_{i2}, \dots e_{im_i} \dots, e_{iM_i}\right\}, (i = 1..I)\right)$The constraints can be described as follows:

$$b_{ha} + b_{hb} \leq 1 \tag{12}$$

$$b_{kc} - b_{kd} = 0 \tag{13}$$

$$\sum_{m_i=1}^{M_i} b_{im_i} = 1, (i = 1 \dots I); b_{im_i} = \{0, 1\} \tag{14}$$

Case study

Application example

In this section, a simplified customized design example of a Material-forming Configuration Production Line is used to illustrate the proposed configuration design process. The case is based on a project supported by Metal Forming Intelligent Machine Tools Co., Ltd. in China. The enterprise can design and manufacture various types of hydraulic machines, automobile interior parts molding, and product molding production lines based on specific requirements. The production-forming configuration line is often applied to the synthetic forming processes such as gluing, hot pressing, and blanking of the fibers, PVC, diaphragms, and other ultralight composite materials.

Details of the three-stages solution are discussed below.

This example begins with conducting Kano's customer survey and performing a traditional Kano analysis. There are five attributes that are to be specified by customers and correspond to the requirements: Qualified rate (C_1), Operating time (C_2), Automation assembly (C_3), Safety (C_4), and Cost (C_5). The survey receives responses from the customers of the company. According to their responses, Formulas (1–5) and Kano's classification (KC), the CS and DS values for each CR are obtained, then the S–CR relationship functions are estimated according to the proposed quantitative Kano analysis. The results are given in Table 1.

In the second phase, the product structure composition can be established and the functional evaluation can be quantified by considering the diverse CRs. The analysis of the product functional structure composition is conducted by an interdisciplinary team of engineers and designers. Figure 6 shows the general overview of the production line and the several simplified technical ECs ($E_1 - E_6$) belonging to the production line. The functional descriptions of the ECs are listed in Table 2.

Different users and industrial fields have different parameter standards for using the production-forming line. The optimal values of the line for the selected ECs are finally

Table 1 S–CR functions for CRs

CRs	KC	CS	DS	S–CR functions
Product quality (C_1)	M	0.37	−0.88	$S_1 = -\frac{1.25e}{e-1}e^{-x_1} + \frac{0.37e+0.88}{e-1}$
Operating time (C_2)	A	0.79	−0.39	$S_2 = \frac{1.18}{e-1}e^{x_2} - \frac{0.79+0.39e}{e-1}$
Automation assembly (C_3)	A	0.82	−0.4	$S_3 = \frac{1.22}{e-1}e^{x_3} - \frac{0.82+0.4e}{e-1}$
Safety (C_4)	M	0.33	−0.85	$S_4 = -\frac{1.18e}{e-1}e^{-x_4} + \frac{0.33e+0.85}{e-1}$
Cost (C_5)	O	0.71	−0.77	$S_5 = 1.48x_5 - 0.77$

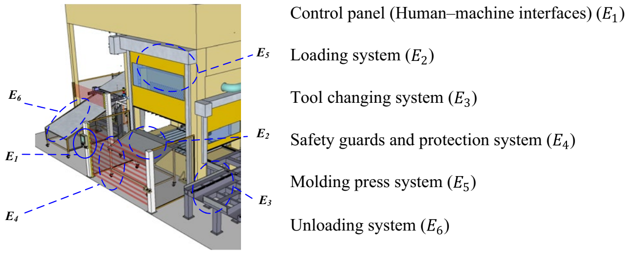

Fig. 6 Partial overview of the structural diagram of the material-forming configuration production line

determined by establishing an optimization model. The alternative numbers and the information about the parameters for the selected ECs are listed in Table 3.

As shown in Table 4, according to Formula (6), the correlation matrix between the instances and product performance are established according to the AHP method. Thus, the priority value of each EC and the absolute quantification functional importance weight of each alternative component concerning the diverse CR can be generated. The normalization information for all the alternatives obtained by Formula (7) is also provided in Table 4.

In the third phase, the model is formulated as a mixed integer non-linear programming model. By filtering the module instances that do not satisfy the selection constraints, the incompatibility and independency between candidate instances of each EC are obtained as follows:

$$b_{14} + b_{22} \leq 1$$

$$b_{23} + b_{41} \leq 1$$

$$b_{32} + b_{54} \leq 1$$

$$b_{43} + b_{62} \leq 1$$

$$b_{11} - b_{42} = 0$$

$$b_{51} - b_{61} = 0$$

A powerful modeling tool named LINGO was selected to solve the proposed model. The results of the alternative components configuration and corresponding CR fulfilments according to the proposed configuration scheme are summarized in Table 5 and Table 6. Regarding the diverse ECs, the corresponding component allocations results are also summarized in Table 5. The results of the EC fulfilments are presented in Table 6.

Discussion of results

The results of the alternative EC component configurations are shown in Table 5. Regarding the discrete alternative components with different technical values of parameters, the best compromise solution illustrates that the selected specific ECs not only satisfy the incompatibility and independency constraints but also their corresponding fulfilment

Table 2 Functional description of the ECs

ECs	Functional description of the ECs
Control panel (E_1)	The control panel is a key component of the human–machine interface, which is equipped with signal lights of different colors and operations to identify machine faults
Loading system (E_2)	The loading system feeds raw materials into the molding press machine
Tool changing system (E_3)	An adjustable tool system that can be changed with a vertical guiding control to satisfy different thicknesses and materials of the products
Safety guards and protection system (E_4)	To ensure the personal safety of the operators, the press machine is protected by light curtains, fences, or an automatic PVC sliding door
Molding press system (E_5)	By changing the process parameters, the forming loads and completeness of the die patterns with concave and convex shapes can be set in the molding press system
Unloading system (E_6)	Materials can be discharged equably and continuously to the downstream unit according to the unloading conveying system's requirements

Table 3 The list of ECs of component attributes and their alternative component choices

ECs	Alternative component choices			
	A1	A2	A3	A4
Control panel (E_1)	12″ tactile color touchscreen	10″ tactile touchscreen	10″ tactile touchscreen with a keyed mode change switch	7″ tactile monochrome screen with signal lights
Loading system (E_2)	Loading table with adjustable rotary wheels	Loading table with mechanical clamps	Loading table with adjustable guides	Loading table with position sensors
Tool changing system (E_3)	Tools are loaded onto the table by a forklift	1 × 20T—Stroke 4000 mm with automatic clamping	2 × 20T—Stroke 4000 mm with automatic clamping	2 × 20T—Stroke 4500 mm with automatic clamping
Safety guards and protection system (E_4)	Sliding doors	Light curtains and safety switches	Access door equipped with safety lock	Fence
Molding press system (E_5)	Max. press technical 7000KN level	Max. press technical 5000KN level	Max. press technical 4000KN level	Max. press technical 3000KN level
Unloading system (E_6)	Automatic mode I	Automatic mode II	Automatic mode III	Manual mode

Table 4 The priority values and normalizations of alternative component choices

CRs	ECs		A1	A2	A3	A4
C_j	E_i	d_{ij}	$d_{im_i}^j$	$d_{im_i}^j$	$d_{im_i}^j$	$d_{im_i}^j$
C_1	E_1	0.23	0.35 ($w_{11}^{1*}=1$)	0.24 ($w_{12}^{1*}=0.69$)	0.21 ($w_{13}^{1*}=0.6$)	0.20 ($w_{14}^{1*}=0.57$)
	E_2	0.09	0.18 ($w_{21}^{1*}=0.51$)	0.35 ($w_{22}^{1*}=1$)	0.14 ($w_{23}^{1*}=0.4$)	0.33 ($w_{24}^{1*}=0.94$)
	E_3	0.17	0.18 ($w_{31}^{1*}=0.58$)	0.31 ($w_{32}^{1*}=1$)	0.31 ($w_{33}^{1*}=1$)	0.20 ($w_{34}^{1*}=0.65$)
	E_4	0.05	0.25 ($w_{41}^{1*}=1$)	0.25 ($w_{42}^{1*}=1.00$)	0.25 ($w_{43}^{1*}=1$)	0.25 ($w_{44}^{1*}=1$)
	E_5	0.38	0.25 ($w_{51}^{1*}=0.86$)	0.23 ($w_{52}^{1*}=0.79$)	0.23 ($w_{53}^{1*}=0.79$)	0.29 ($w_{54}^{1*}=1$)
	E_6	0.08	0.5 ($w_{61}^{1*}=1$)	0.14 ($w_{62}^{1*}=0.28$)	0.19 ($w_{63}^{1*}=0.38$)	0.17 ($w_{64}^{1*}=0.34$)
C_2	E_1	0.06	0.3 ($w_{11}^{2*}=0.86$)	0.35 ($w_{12}^{2*}=1$)	0.16 ($w_{13}^{2*}=0.46$)	0.19 ($w_{14}^{2*}=0.54$)
	E_2	0.15	0.35 ($w_{21}^{2*}=1$)	0.2 ($w_{22}^{2*}=0.57$)	0.21 ($w_{23}^{2*}=0.6$)	0.24 ($w_{24}^{2*}=0.69$)
	E_3	0.24	0.33 ($w_{31}^{2*}=1$)	0.25 ($w_{32}^{2*}=0.76$)	0.11 ($w_{33}^{2*}=0.33$)	0.31 ($w_{34}^{2*}=0.94$)
	E_4	0.08	0.17 ($w_{41}^{2*}=0.43$)	0.32 ($w_{42}^{2*}=0.8$)	0.4 ($w_{43}^{2*}=1$)	0.11 ($w_{44}^{2*}=0.28$)
	E_5	0.31	0.38 ($w_{51}^{2*}=1$)	0.28 ($w_{52}^{2*}=0.74$)	0.2 ($w_{53}^{2*}=0.53$)	0.14 ($w_{54}^{2*}=0.37$)
	E_6	0.16	0.31 ($w_{61}^{2*}=1$)	0.29 ($w_{62}^{2*}=0.94$)	0.25 ($w_{63}^{2*}=0.81$)	0.15 ($w_{64}^{2*}=0.48$)
C_3	E_1	0.35	0.29 ($w_{11}^{3*}=0.94$)	0.2 ($w_{12}^{3*}=0.65$)	0.31 ($w_{13}^{3*}=1$)	0.20 ($w_{14}^{3*}=0.65$)
	E_2	0.13	0.3 ($w_{21}^{3*}=0.86$)	0.19 ($w_{22}^{3*}=0.54$)	0.16 ($w_{23}^{3*}=0.46$)	0.35 ($w_{24}^{3*}=1$)
	E_3	0.22	0.31 ($w_{31}^{3*}=1$)	0.21 ($w_{32}^{3*}=0.68$)	0.24 ($w_{33}^{3*}=0.77$)	0.24 ($w_{34}^{3*}=0.77$)
	E_4	0.06	0.4 ($w_{41}^{3*}=1$)	0.35 ($w_{42}^{3*}=0.88$)	0.16 ($w_{43}^{3*}=0.4$)	0.09 ($w_{44}^{3*}=0.23$)
	E_5	0.1	0.27 ($w_{51}^{3*}=1$)	0.27 ($w_{52}^{3*}=1$)	0.21 ($w_{53}^{3*}=0.78$)	0.25 ($w_{54}^{3*}=0.93$)
	E_6	0.14	0.29 ($w_{61}^{3*}=0.67$)	0.43 ($w_{62}^{3*}=1$)	0.21 ($w_{63}^{3*}=0.49$)	0.07 ($w_{64}^{3*}=0.16$)
C_4	E_1	0.05	0.32 ($w_{11}^{4*}=0.87$)	0.2 ($w_{12}^{4*}=0.54$)	0.37 ($w_{13}^{4*}=1$)	0.11 ($w_{14}^{4*}=0.3$)
	E_2	0.17	0.2 ($w_{21}^{4*}=0.54$)	0.12 ($w_{22}^{4*}=0.32$)	0.37 ($w_{23}^{4*}=1$)	0.31 ($w_{24}^{4*}=0.84$)
	E_3	0.13	0.21 ($w_{31}^{4*}=0.64$)	0.22 ($w_{32}^{4*}=0.67$)	0.33 ($w_{33}^{4*}=1$)	0.24 ($w_{34}^{4*}=0.73$)
	E_4	0.34	0.31 ($w_{41}^{4*}=1$)	0.31 ($w_{42}^{4*}=1$)	0.24 ($w_{43}^{4*}=0.77$)	0.14 ($w_{44}^{4*}=0.45$)
	E_5	0.18	0.29 ($w_{51}^{4*}=1$)	0.25 ($w_{52}^{4*}=0.86$)	0.23 ($w_{53}^{4*}=0.79$)	0.23 ($w_{54}^{4*}=0.79$)
	E_6	0.14	0.33 ($w_{61}^{4*}=1$)	0.31 ($w_{62}^{4*}=0.94$)	0.3 ($w_{63}^{4*}=0.91$)	0.06 ($w_{64}^{4*}=0.18$)
C_5	E_1	0.07	0.24 ($w_{11}^{5*}=0.73$)	0.21 ($w_{12}^{5*}=0.64$)	0.33 ($w_{13}^{5*}=1$)	0.22 ($w_{14}^{5*}=0.67$)
	E_2	0.12	0.3 ($w_{21}^{5*}=1$)	0.16 ($w_{22}^{5*}=0.53$)	0.3 ($w_{23}^{5*}=1$)	0.24 ($w_{24}^{5*}=0.8$)
	E_3	0.22	0.26 ($w_{31}^{5*}=0.81$)	0.19 ($w_{32}^{5*}=0.59$)	0.23 ($w_{33}^{5*}=0.72$)	0.32 ($w_{34}^{5*}=1$)
	E_4	0.06	0.11 ($w_{41}^{5*}=0.3$)	0.33 ($w_{42}^{5*}=0.89$)	0.19 ($w_{43}^{5*}=0.51$)	0.37 ($w_{44}^{5*}=1$)
	E_5	0.35	0.3 ($w_{51}^{5*}=0.81$)	0.16 ($w_{52}^{5*}=0.43$)	0.17 ($w_{53}^{5*}=0.46$)	0.37 ($w_{54}^{5*}=1$)
	E_6	0.17	0.51 ($w_{61}^{5*}=1$)	0.14 ($w_{62}^{5*}=0.28$)	0.17 ($w_{63}^{5*}=0.33$)	0.18 ($w_{64}^{5*}=0.35$)

Table 5 Results of alternative component configurations

ECs	Selected EC options	EC technical parameter values
Control panel (E_1)	e_{11}	12″ tactile color touchscreen
Loading system (E_2)	e_{24}	Loading table with position sensors
Tool changing system (E_3)	e_{34}	2x20T - Stroke 4500 mm with automatic clamping
Safety guards and protection system (E_4)	e_{42}	Light curtains and safety switches
Molding press system (E_5)	e_{51}	Max. press technical 7000KN level
Unloading system (E_6)	e_{61}	Automatic mode I

Table 6 The results of CR fulfillment level and customer satisfaction level

CRs	CR fulfillment level (x_j)	Customer satisfaction level (S_j)
Product quality (C_1)	0.9084	0.3002
Operating time (C_2)	0.8804	0.5795
Automation assembly (C_3)	0.9620	0.5958
Safety (C_4)	0.9051	0.2616
Cost (C_5)	0.8717	0.5201

levels. The solution provides more practical information for product design. The results of CR fulfilment level (x_j) and individual CS (S_j) achieved by each CR are shown in Table 6. All the CRs have achieved fulfilment levels of more than 0.87 with limited incompatibility and independence for diverse ECs. The results of the CS level (S_j) by each CR are achieved as (0.300, 0.580, 0.596, 0.262, 0.520). Under the constraints, C_3 has achieved the maximum fulfilment levels and the CR fulfilment levels for C_3 are also the highest, demonstrating that all the selected EC options have high performance for the optimization features and realize a relatively higher level of customer satisfaction.

The full CR fulfillment level (x_j) in this context is close to 1 while the customer satisfaction level (S_j) is not high because CS in the proposed model is defined as the CS value from the quantified Kano model, which is more objective than the traditional approach, in which the high fulfilment of a certain CR cannot guarantee high customer satisfaction with that CR. According to the practice, the customers may simply not need some ECs.

In addition to recognizing the different features of the CRs to achieve a high level of fulfillment, it is also of vital importance to note the different features of the ECs. Regarding the corresponding EC allocations presented in Table 5, the results illustrate that the production lines are highly automated and equipped with automatic controls, which provide more practical information for the customized product configuration design. Regarding certain ECs, such as the loading system (E_2), the detailed configurations are a loading table with position sensors, which can improve the reliability of the system with automatic monitoring equipment.

Re-engineering assessment stage

The relationship between the CR and the engineering design in the configuration system architecture should be further measured. As shown in Fig. 3, our methodology introduces a three-step approach to integrate CRs into product design to map the interactive relationship between CRs, functional structure and specific performance. However, this method also has a limitation because the CRs elicited from Kano's model will restrain the design from optimization when realizing customer satisfaction. To further explore the threshold point between product configuration and other variant design, we examine the obstacles where customer's personalized demand exceeds the configurable design. In this way the threshold point of integration between CRs and engineering design requirements as well as capability can be found. Finally, the configurable range can be confirmed and shifted the recommended product configuration to a new variant design.

The performance of product configuration scheme should meet the CRs, that is, the performance evaluation indicator should be as far as possible greater than the minimum configuration requirements, while maximizing CRs. There are two key indicators:

1. The performance indicator of a product consisting of certain instantiated parts.

$$x_j = \frac{1}{I}\sum_{i=1}^{I}\sum_{m_i=1}^{M_i} b_{im_i} w_{im_i}^{j*}$$

2. The customer satisfaction for three types attributes (one-dimensional, attractive, must-be attributes).

$$\mathrm{S}_j \quad (j = 1, 2 \ldots J)$$

For each S_j, the threshold point between product configuration and variant design can be described as follows:

$$if\ S_j > DS_j\ and\ x_j > \sigma,\ (j = 1, 2 \ldots J);\ x_j = \frac{1}{I}\sum_{i=1}^{I}\sum_{m_i=1}^{M_i} b_{im_i} w_{im_i}^{j*}$$

$$\sum_{m_i=1}^{M_i} b_{im_i} = 1, (i = 1..I); b_{im_i} = \{0, 1\}$$

Otherwise, for must-be attributes, if $S_M < DS_M$, deformation design is required; for one-dimensional attributes, if $S_O < DS_O$, deformation design is required; for attractive attributes, if $S_A \langle DS_A\, and\, x_j \rangle \sigma$, deformation design is not required; if $S_A < DS_A\, and\, x_j < \sigma$, deformation design is required. Where σ denotes a given threshold, which can be determined based on empirical values or specified by the customer or designers.

As shown in Table 7, all the customer satisfaction level is greater than 0 and also greater than the minimum satisfaction level (DS). The CRs of the three types attributes for the final product configuration design meet specified conditions in this case. Therefore, we set the alternative EC component configurations are $e_{11}, e_{24}, e_{34}, e_{42}, e_{51}, e_{61}$.

If the customer satisfaction conditions for three types attributes are not met, the original selected product components should be re-evaluated and then replaced by the better one. By analyzing the results of product configuration generated from the quantification of Kano's model, we can conclude that the capability and effectiveness of the proposed model.

Further analysis of the proposed method

Performance comparison

The way of defining the CS from Kano's model in the proposed method is more objective than that in the traditional approach because the customer cannot translate the requirements into the form of well-defined specifications to product attributes and components. Extensive research has been conducted on the Kano's model and it has been modified into different approaches as well. In this section, the proposed approach is compared with an existing one (Violante et al. 2015), which provide a framework for supporting the customization of the available CR management solution.

To identify the CRs and to list the product features in order of importance to customers, the *Tontini's* (Tontini 2007) integration method has been used in the paper. In the original method, the importance column in the matrix for CR is replaced by the result of the following equation:

$$Tontinis'\ Factor = Max(|CS|;|DS|)$$

where CS and DS are the satisfaction and dissatisfaction indexes. The adjustment factor is the higher absolute value of CS or DS, putting more weight on the requirements that bring more satisfaction when present or that bring more dissatisfaction when absent. In this case, excitement, performance and basic requirements will be taken into consideration depending on the degree of satisfaction or dissatisfaction that they could bring to customers.

The *Tontini's* integration method uses only the CS and DS information to realize the quantitative analysis of CRs. Table 8 illustrates the relative weight for CRs. Each of the relative weight in this context is close to 0.2. Although the *Tontini's* integration method is used for the quantitative analysis of the Kano's model, the classification of CRs in basic Kano's model (one-dimensional attributes; attractive attributes; must-be attributes) are impaired because the distinction of the weight value are very close (0.21;0.19;0.20;0.21;0.19).

Furthermore, to estimate the relationship between CRs and product specifications features, another questionnaire has been proposed and submitted to users to define the priority values for the components. After the priority values of diverseproduct components for the CRs have been derived, the personalised productrecommendation can be generated to the customers through single or multi-objective decision-making. By this way, the decision-making among multiple CRs will recommend the optimal alternative components with higher weighted sum of multiple priority values. For example, if we use the priority values of diverse product components for the CRs shown in Table 4, the final decision-making objective can be formulated as (the constrains are the same as in the original case study using proposed model):

$$\text{Max } 0.21x_1 + 0.19x_2 + 0.2x_3 + 0.21x_4 + 0.19x_5$$

$$x_j = \frac{1}{I}\sum_{i=1}^{I}\sum_{m_i=1}^{M_i} b_{im_i} w_{im_i}^{j*} (j = 1 \ldots 5)$$

$$\sum_{m_i=1}^{M_i} b_{im_i} = 1, (i = 1..I);\ b_{im_i} = \{0, 1\}$$

The comparison results of the alternative EC component configurations are shown in Table 9. The selected

Table 7 The results of customer satisfaction level

CRs	Maximum satisfaction level (CS)	Minimum satisfaction level (DS)	Customer satisfaction level (S_j)
Product quality (C_1)	0.37	−0.88	0.3002
Operating time (C_2)	0.79	−0.39	0.5795
Automation assembly (C_3)	0.82	−0.4	0.5958
Safety (C_4)	0.33	−0.85	0.2616
Cost (C_5)	0.71	−0.77	0.5201

EC options are $e_{11}, e_{24}, e_{34}, e_{42}, e_{51}, e_{61}$ when using the proposed method, while the options are $e_{13}, e_{23}, e_{33}, e_{42}, e_{54}, e_{64}$ when using Tontini's integration method, respectively. The detailed performance of the CR fulfillment level is summarized in Table 10. Comparing the performance of the proposed quantification of Kano's model and the Tontini's integration method, it can be inferred that the CR fulfillment level of Product quality (C_1) brings a promotion of about 20% when integrating the CRs into the multi-objective functions in a mixed non-linear programming model, and the other CRs ($C_2 - C_5$) derived from the proposed model are also better than the Tontini's integration method.

Qualitative analysis of the objective confirmation

The traditional methodologies depend heavily on the customer's explicit specifications of the attributes by formulating the CRs with a quantitative weight to define the relative importance. The results obtained by translating the customer's feelings—normally expressed on ordinal scales—into a numerical scale. This artificial encoding can lead to errors or inconsistencies in the evaluation.

For example, the correspondence analysis and interactive relationship between the CRs, product specific performance of the components can be done directly through multi-attribute decision making method. Therefore, the personalised product configuration can be generated through single objective decision-makingwith directly obtaining the weight of the CRs (similar with the final decision-making objective formulated in "Performance comparison" section).

Numerous literatures regarded time, quality and cost as the objective functions of decision-making in the context of configuration of product. In customer-driven product design, one of the critical challenges is that how to understand CRs and how to associate CRs with CS are not explained clearly (there are more than the CRs of time, quality and cost). Traditional customer survey methods are usually adopted in product design to collect CRs and determine their degree of importance. Moreover, the CRs are so complicated that they are usually expressed in ambiguous language and contain uncertain information. The detailed methods on how to collect customer data are not clearly defined. Due to these

Table 8 The relative weight for CRs using Tontini's integration method

CRs	KC	CS	DS	Tontini's Factor	Relative weight
Product quality (C_1)	M	0.37	−0.88	0.88	0.21
Operating time (C_2)	A	0.79	−0.39	0.79	0.19
Automation assembly (C_3)	A	0.82	−0.4	0.82	0.20
Safety (C_4)	M	0.33	−0.85	0.85	0.21
Cost (C_5)	O	0.71	−0.77	0.77	0.19

Table 9 Comparison Results of alternative component configurations

ECs	Selected EC options using proposed method	Selected EC options using Tontini's integration method
Control panel (E_1)	e_{11}	e_{13}
Loading system (E_2)	e_{24}	e_{23}
Tool changing system (E_3)	e_{34}	e_{33}
Safety guards and protection system (E_4)	e_{42}	e_{42}
Molding press system (E_5)	e_{51}	e_{54}
Unloading system (E_6)	e_{61}	e_{64}

Table 10 Comparison results of CR fulfillment level

CRs	CR fulfillment level using proposed method	CR fulfillment level using Tontini's integration method
Product quality (C_1)	0.908	0.700
Operating time (C_2)	0.880	0.586
Automation assembly (C_3)	0.962	0.674
Safety (C_4)	0.905	0.829
Cost (C_5)	0.872	0.841

reasons, Kano's model is quantified by identifying the relationship between customer needs and customer satisfaction is more reasonable.

Conclusion

Owing to the complexity of requirements, the CRs are usually expressed in vague, ambiguous language and contain uncertain information rather than well-defined specifications of attributes and components. Kano's model provides a qualitative way to classify customer needs accurately. However, Kano's model provides only a qualitative way to recognize the diverse relationships between CR fulfillment and customer satisfaction. Moreover, few research contributions are found in terms of integrating Kano's model quantitatively with product design. Therefore, we provide a novel perspective for product configuration design through three phases: quantitative analysis of customer requirements phase, construction of product functional hierarchical structures phase, and integration of Kano's model with product configuration optimization phase.

This paper has presented and discussed the multi-objective optimization method of product configuration design schemes by quantitatively integrating Kano's model into product design for the above issues. Based on the proposed product design technology, the three-phase multi-objective optimization mathematical model of product configuration is built by taking the CRs as the objective functions. At first, Kano's model was quantified by identifying the relationship between the needs and satisfaction of the customer to link the processes of customer requirements mapping and product configuration design. The quantitative results from Kano's model are then constructed as the multi-objectives in the optimization mathematical model of product configuration. As a result, the optimal solution is acquired and offers a foundation for balancing the multi-objectives with limited incompatibility and independence for diverse ECs. Finally, an illustrative case associated with the product configuration design of a material-forming configuration production line is presented to demonstrate the availability of the proposed model.

Integrating customer requirements into customization product configuration design based on the quantitative Kano model not only avoids heavily depending on the explicit translation of the customer specification of the product features but also helps companies recognize important CRs that have a great impact on CS and avoid the mistake of putting excessive effort into CRs with little care. The quantitative configuration process also improves the assessment of the performance of a product.

Future work can be done on the improvement of the configuration design process and quantitative analysis of Kano's model according to a data-driven customer requirements analysis in order to determine the function of the relationship. Moreover, improvements can be made to the traditional requirements management analysis, especially integrating requirements management with the product lifecycle management systems in the case of a company in the automotive industry. Finally, more case studies on product design problems should be conducted to test the applicability of the proposed approach.

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