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Optimization Models for Deriving Optimum Target of Key Characteristics

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The aim of this research is to develop optimization models in deriving optimum target of key characteristic (KC). There are two kinds of product KCs introduced in this paper, namely performance and dimension product KC. The performance product KC target values must be determined by balancing customer and designer utilities subject to design cost and time provided by a company. The KCs of a product can be visualized using a KC flow-down which shows the hierarchical structure of the product. The flow-down may consist of many levels from product KC to process KC. Using axiomatic design as a methodology to map the flow-down, we conclude that product KC, assembly-components KC, and process KC are in functional domain, physical domain, and process domain respectively. In this paper, the objective function of the model for deriving optimum product KC target is to minimize utility gap between customer and designer subject to design cost and time. The assembly-component KCs have to be derived considering the product KC targets. In the absence of product KC target, the objective function of the model is to maximize the desired effect or minimizing the undesired effect. In the existence of product KC target, the objective function of the model is to attain the target considering technical constraints of the product. We use a shaft design problem as a numerical example to show the implementation of the models.

Keywords: Key characteristics; optimum target; optimization model.

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1. Introduction

Key characteristic (KC) is defined as product, sub assembly, component, or process features which will significantly affect final cost, performance, or safety of a product if it deviates from its nominal values.[1] There are two issues concerning the KCs of a product. The first issue is how to identify and prioritize the KCs. The issue is important since there are so many KCs in a product and a company has to decide which KCs have to be controlled during the production process. The second issue concerns with the determination of KC target value and its tolerance. There are two approaches in identifying KCs of a product: bottom-up and top-down approach.[2] Bottom-up approach is applied to a product which is in production stage. The objective of this approach is to maintain product quality and solve the quality problems. Production areas with high scrap and rework can be used as a starting point in identifying the KCs. The selected processes are then monitored and controlled to maintain and improve product quality. Top-down approach is conducted in early design stage, applied to new design, redesign, or new technology development. This approach starts with translating customer requirement (CR) into functional requirement (FR). The FR of a product has a close relationship with product performances. According to Murthy and Osteras,[3] product performance is a measure of the functional aspects of a product. Wiktorsson *et al.*[4] also pointed that a FR must be defined by product performance.

After the translation process of CR into FR, a designer has to determine the KCs, a subset of FRs, and set the target. Those KCs are called product KCs. Afterwards, the designer has to map the FR onto design parameter (DP) of the product and determine the target value. The DP will be used as a physical solution to the FR and finally the DP must be mapped onto the process variable (PV). The mapping process between FR and DP is important since it relates the product performance to the physical characteristics of a product. Component KCs and process KCs must be determined as a subset of DPs and PVs respectively. All the KCs of a product can be visualized in a hierarchical structure called KC flow-down which is also termed as variation flow-down in Ref. 5. A flow-down may consist of many levels from product KCs on the top level to process KCs on the lowest level. Product KC can be identified by function, tolerance chain, and assembly.[5] When a product KC is identified by the function, then the KC is non-geometric and must be defined by product performance, and when a KC is identified by tolerance chain then the KC is geometric and must be defined dimensionally. Either product KC is defined by function or tolerance chain, both represent the FRs of a product. Hence, there are two kinds of product KCs, namely performance and dimensional KCs. Power of an engine and weight of an aircraft component are examples for performance KCs, while gap and clearance are examples of dimensional KCs.

In this research, we attempt to develop optimization models to determine the target value of a KC to aid a designer in making decisions concerning the second issue of KC. The product KC target has to be determined prior to the other lower levels of KC in the KC flow-down. In determining the target value of geometrical product KC, the designer only considers the functional aspect of a mechanism which is delivered by the KC. For example, in setting the clearance of an assembly which consists of a shaft and bearing, the designer has to set a tight clearance to the mechanism to ensure the assembly works properly. The performance product KC has to be set by the designer considering the target value of competitor products since it is related to customer preference and product value. After obtaining optimum product KC target values, the designer has to determine the assembly-component KC target values. The target value of an assembly- component KC is related to the mechanical element design which has three general characteristics[6]: (1) the attainment of product KC target value, (2) every mechanical element has undesired effects such as deflection, stress, weight, and cost, and (3) every mechanical element is defined by its material and geometrical specification. In the context of this research, the geometrical specification is assembly-component KC target values which must be obtained using an optimization model. In the absence of designer preference on product KC target value, then in general there are two objective functions commonly used in the model which are minimization of undesired effect and maximization of desired effect such as power in designing an internal combustion engine. In the existence of the preference, the objective function of the model is the attainment of the KC target values.

Many researches have been conducted in the field of KC. Thornton[1] developed a mathematical framework for the KC process in determining the KC priority. Yang[7] developed a KCs model for quality assurance in supply chain. The research emphasizes that the coordination in supply chain is important to maintain and improve the product quality. The need of coordination is more important when product specifications are defined. Du *et al.*[8] designed a product KCs management system to allow a collaborative process among various departments and disciplines in produt development activities. They suggest the web services technology to integrate the application. Du *et al.*[9] developed a KC extraction method in product concept design. The method is based on CR matrix and the results of customer evaluation to their own similar product and best product. The method cannot be used to relate the preference of customers with the product KC value. Rosyidi *et al.*[10] developed a utility-based optimization model for deriving the optimum target of product KCs. The model is developed using information derived from Quality Function Deployment (QFD) matrices, i.e. technical competitive assessment and cost factor. The objective function of the model is to minimize the gap between customer and designer utilities subject to design cost and time. The optimum targets obtained from the model will balance the customer and designer of interest in determining the targets.

Yadav and Goel[11] developed an optimization model to determine assembly-component KC target values using target cascading process. The model is then applied to a product of an automotive industry. In the application, the target value of vehicle-level is determined first. The customer satisfaction is used as an objective of the company. The relationship between customer satisfaction and target value of vehicle-level is assumed to be linear and derived using linear regression. The target value of vehicle-level is then decomposed into target value of system, sub system, and component. Since the customer satisfaction is set as the ultimate objective function and the relationship between customer satisfaction and target value of vehicle-level is assumed to be linear, then in order to satisfy the customer, the manufacturer has to set the target value of vehicle-level at its highest value for larger-the-better characteristics and lowest value in lower-the-better characteristics. Hence, the cost to deliver the value will be prohibitively high. Stelmack *et al.*[12] used an interactive multidisciplinary design as a framework to optimize KC target value of an airplane brake component. The framework is characterized by the simultaneous use of discrete and continuous decision variables. Information about the design space is obtained by the designer through system analysis. The information is then used to develop response surface approximation to the design space. The objective function in the design of the component is weight minimization since it is a crucial factor in the airplane design. Campanile[13] also used weight minimization as the objective function in a hinge design. Szykman[14] developed a computational predictive model to predict design attribute values based on available information in early design stage. The aim of the research is to anticipate the dependency of design process to an experienced designer, and gives the new designer a knowledge which can be used to help in finding a solution and improving the design. References 12–14 did not consider the performance product KC target value in optimizing the assembly-component KC. It will result in a higher or lower product KC than that expected by customer, and hence will raise the design and production cost.

In this research, we extend the model in Ref. 10 to include the determination of assembly-component KC target value. The product KC target value will be obtained using the model in Ref. 10. The assembly-component KC target is then determined based on the optimum product KC target value. The rest of this paper is organized as follows: Sec. 2 describes the problem solving approach and modeling. In Sec. 3, we provide a numerical example and analysis using shaft design problem, and conclusions and directions for the next research are drawn in the last section.

2. Problem Solving Approach and Modeling

The problem solving approach of this research is shown in Fig. 1. The approach starts with the house of quality (HOQ) to translate CRs into FRs. The mapping process of FRs onto DPs and DPs onto PVs may be carried out using Axiomatic Design.[15] After the mapping process, the designer must determine a subset of FRs, DPs, and PVs to become product, assembly-component, and process KCs respectively. The designer then develops a KC flow-down to show the relationship between consecutive KCs levels and define the transfer functions between them. Model 1 is used to derive product KCs target values using HOQ matrices. The output of the

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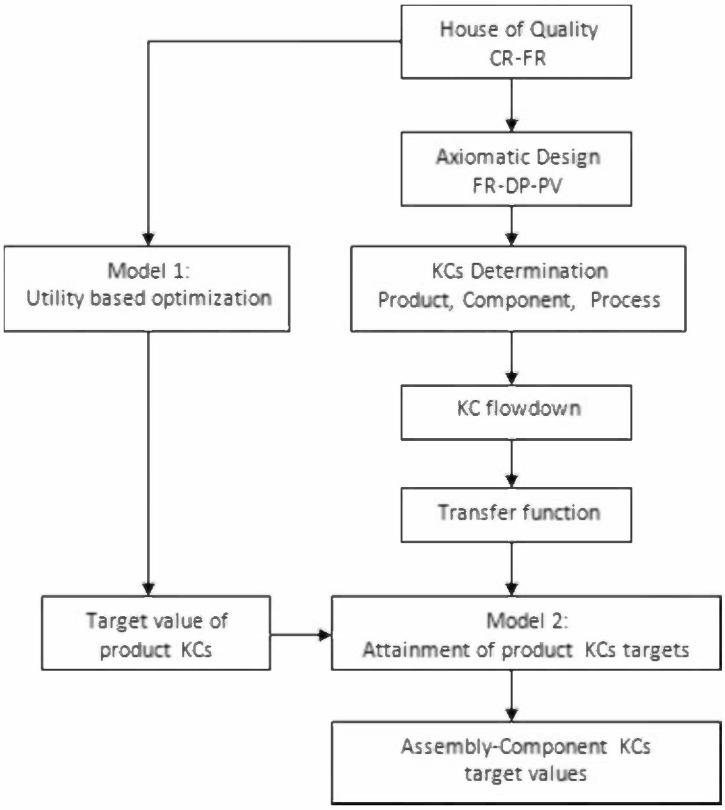

Fig. 1. Problem solving approach.

model is the optimum product KCs target values. These values along with the transfer functions are then used by the designer to develop Model 2 to obtain optimum assembly-component KC target values.

As noted in Sec. 1, KCs of a product can be visualized hierarchically using a diagram called KC flow-down. Figure 2 shows a mathematical representation of KC flow-down. In the figure, x_{jk} denotes the target value of jth KC at level k. Level 1 in the figure represents the array of product KC and the lowest level represents the array of process KCs. We assumed that the lowest level of the flow-down is component KC.

Based on mathematical representation of KC flow-down in Fig. 2, and the assumption that each KC is dimensionally dependent, all product KCs can be expressed in terms of assembly-component KC. Equation (1) shows product KC which expressed as a function of jth assembly-component KC. In the equation, x_{j1} and x_{j2} denote the jth level 1 and level 2 KCs in the flow-down respectively. In general, the relationship between two consecutive levels of KC can be shown in Eq. (2). The equation shows level k KC can be expressed as a function of level

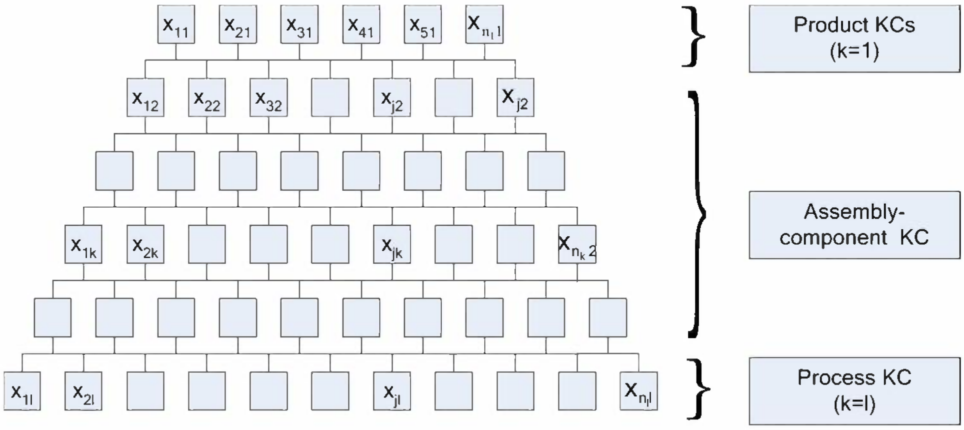

Fig. 2. Mathematical representation of KC flow-down.

$(k+1)$ KC. Using the equation, all of the KCs target of a product can be obtained sequentially.

$$x_{j1} = f(x_{j2}), \tag{1}$$

$$x_{jk} = f(x_{j(k+1)}). \tag{2}$$

We develop two models to determine KC target values. The first model (Model 1) is a utility-based optimization model to derive product KC target value, and the second model (Model 2) is used to derive assembly-component KC target values based on the output of Model 1. In Model 1, utility function is used to represent customer and designer attitudes towards product KC target values on design cost and time respectively. For larger the better characteristics, customer utility function will increase monotonically since customer expects a larger value, while designer utility function will decrease monotonically since larger product KC target needs larger design cost and time. For example, in an engine design, the customers will expect larger power and result in higher design cost and time. Conversely, for lower the better characteristics customers expect lower product KC target value. It will result in monotonically decreasing utility function for customers and since lower product KC target needs larger design cost and time the designer utility function will increase monotonically. Customer and designer utilities will go in the opposite way for each characteristic which enables us to integrate their utility functions into one objective function, namely minimizing utility gap between customer and designer. The product KC target value obtained from the model will balance customer and designer interests in making decisions about the target value and will be used as the target in deriving assembly-component KCs. In the existence of the preference, the objective function of Model 2 is to attain the product KC target.

2.1. *Model for deriving optimum product KC target value (Model 1)*

Performance product KC has to be determined not only considering the preference and product value in the view of the customer but also the manufacturer (designer) view on cost and time in the design process under budget and time limitations. In this research, we use the model in Ref. 10 to determine the performance product KC. In general, the model can be expressed as follows:

$$\text{Minimize} \sum_{j=1}^{m} w_j |U_j^k(x_{j1}) - U_j^d(z_{rj})|, \tag{3}$$

subject to

$$z_{rj} = f(x_{j1}), \tag{4}$$

$$\sum_{j=1}^{m} z_{rj} \le z_r^{\max}, \tag{5}$$

$$x_{j1}^l \le x_{j1} \le x_{j1}^u, \tag{6}$$

$$\sum_{j=1}^{m} w_j = 1. \tag{7}$$

Equation (3) is the objective function of the model to minimize utility gap between the customer and the designer. In the equation, w_j denotes the weight of the jth product KC which can be obtained from HOQ matrices. The customer utility is denoted by U_j^k which expressed in terms of performance product KC(x_{j1}), while the designer utility is denoted by U_j^d which is expressed in terms of design cost and time. The design cost and time is denoted by z_{rj}, where the index $r = 1$ represents the cost and $r = 2$ represents the time. The designer and customer utility functions can be derived by asking a series of questions to elicit their attitudes toward the risk in making decisions about KC target values. Equation (4) expresses the design cost and time as a function of product KC. It is used to substitute the design cost and time of designer utility into the performance product KC. The design cost and time represent the unit cost and time needed to design and develop the product KC. Equation (4) can be derived from historical data using regression method. Equation (5) ensures the total design cost and time are within the budget and time provided in designing the product. In the equation, $z_r^{\max}$ denotes maximum cost for $r = 1$ and time for $r = 2$ provided by the company in designing and developing product KC. Equation (6) is the feasible solution space of the KC. This can be determined using the technical quantitative assessment matrix in HOQ.[10] Equation (7) ensures that the total weight used in the objective function equals to one.

2.2. *Model for deriving assembly-component KC target value (Model 2)*

The objective function of Model 2 is to attain product KC target value. As noted in Sec. 1, in the absence of product KC target value, there are two objective functions which are minimization of undesired effect and maximization of the desired effect. Those objective functions will result in lower or higher product KC target value than that expected by the customers. To avoid this result, the designer has to set the product KC target value using Model 1 and find the assembly-component KC target values based on the optimum result of Model 1. The objective function of Model 2 can be expressed in Eq. (8). In that equation, x^*_{jk} denotes the optimal product KC target value, while $f(x_{j(k+1)})$ denotes the transfer function which relates the product KC target value with assembly-component KC target value. The transfer function can be derived analytically using the law of nature. Due to the complexity of the problem, the designer may also use design of experiment or simulation to derive the function. Computer Aided Engineering (CAE) may also be used as a powerful tool in deriving the function.[11] In general, the constraints of Model 2 can be expressed in the form of equality and inequality constraints as expressed in Eqs. (9) and (10) respectively.[16] Those equations represent the formula for dimensional and tolerance chain and the design requirements among level $(k+1)$ KCs. Equation (11) defines the feasible solution space.

$$\text{Minimize } |f(x_{j(k+1)}) - x^*_{jk}|, \tag{8}$$

$$g(x_{j(k+1)}) = 0, \tag{9}$$

$$h(x_{j(k+1)}) \le 0, \tag{10}$$

$$x^l_{j(k+1)} \le x_{j(k+1)} \le x^u_{j(k+1)}. \tag{11}$$

3. Numerical Example and Analysis

Figure 3 shows a diagram for numerical example which is adapted from Ref. 17. The figure shows a motor with two loads at point A and B which take the power of 30 and 20 kW respectively. Hence, the motor generates a power of 50 kW at the

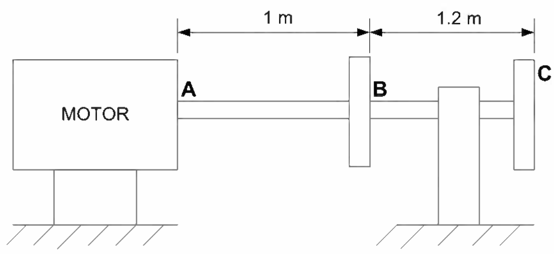

Fig. 3. Shaft design diagram.

frequency of 10 Hz or 600 rpm. The constraints and design specifications used in this paper are as follows:

(1) safety factor for the shaft is 1.5,
(2) total angle of twist in the shaft, φ is less than 0.075 radian,
(3) the shaft is hollowed,
(4) the maximum outer radius of the shaft is 0.05 m,
(5) the minimum thickness of the shaft (outer radius-inner radius) is 0.075 m,
(6) the materials used for the shaft is high strength steel (ASTM-A242). Table 1 shows parameters of the material.

In this numerical example, the product KC is the weight of the shaft. The target value of the product KC can be obtained using Model 1. We assume that the utility functions of the designer and customer have exponential shapes since it is the widely used utility functions as noted by Yang *et al.*[18] We also assume that the range of the shaft weight of the competitor products is 3.979–14.935 kg. This range is used to derive the customer and designer utility functions and the feasible solution of the model as generally expressed by Eq. (6). Customer utility function may be derived using a survey by asking the customer about their attitudes concerning the product KC target value. Utility function of the designer may be derived by asking them about their attitudes concerning the design cost in delivering product KC target value. Customer and designer utility functions which are used for the numerical example can be seen in Eqs. (12) and (13) respectively. The relationship between cost of product development and the target value of product KC can be derived using historical data and assumed to be linear as expressed in Eq. (14). The maximum cost in developing the product is assumed to be IDR 7,000,000. Equation (14) is then substituted into Eq. (13) to result in Eq. (15). Figure 4 shows the graphical representation of customer and designer utility functions. The model for determining product KC target can be expressed in Eq. (16). The optimal solution of the model is 10.128 kg. This value is then used as the target value that must be attained by Model 2.

$$U^k = 1.25(1 - e^{-2.194+0.1469x_{11}}), \tag{12}$$

$$U^d = 2.25(1 - e^{-0.86+0.00001073z}), \tag{13}$$

$$z = -50000x_{11} + 1000000, \tag{14}$$

$$U^d = 2.25(1 - e^{-0.86+0.000010/3(-5000x_{11}+1000000)}). \tag{15}$$

Table 1. Parameters of the material.

Parameters of material ASTM-A242	
Density	7860 kg/m^3
Ultimate strength	480 MPa
Yield shear strength	210 MPa
Modulus of elasticity	200 GPa

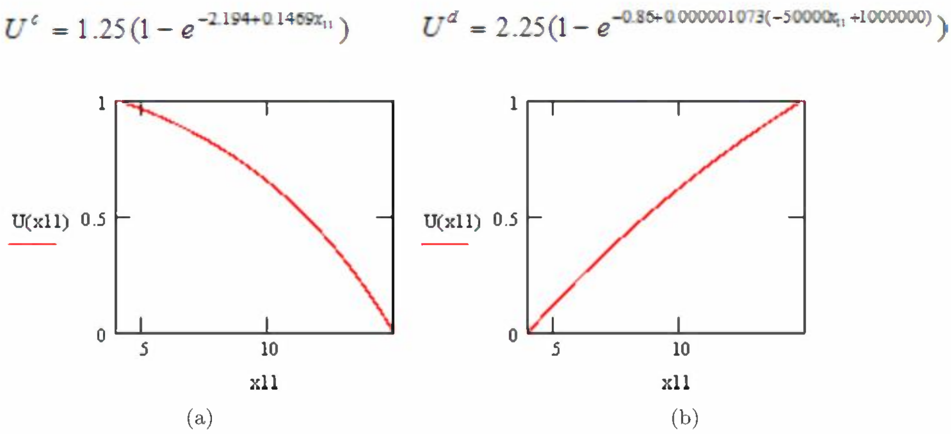

Fig. 4. (a) Customer utility function and (b) designer utility function.

The product KC can be expressed in the term of assembly-component KC, i.e. shaft outer and inner radius. Those radii are the decision variables of Model 2, while shaft length and material density are model parameters. Equation (17) is the transfer function which can be derived analytically to relate the product KC, i.e. shaft weight to assembly-component KC. In the equation, x_{12} and x_{22} denote outer and inner radius of the shaft respectively, L denotes the total length of the shaft, and ρ is the material density. The torque that works on the shaft can be expressed in terms of power (Watt) and the turning velocity (rpm). Equation (18) can be used to express the torque on segments AB and BC. In the equation, P denotes the power and f denotes the turning frequency of the shaft. For example, using Eq. (18) the torque in the segment AB in Fig. 2 is 796 Nm, and on the segment BC is 318 Nm.

Minimize

$$|1.25(1 - e^{-2.194+0.1469x_{11}}) - 2.25(1 - e^{-0.86-0.00001073(-500000x_{11}+1000000)})|$$

subject to

$$3.79 \leq x_{11} \leq 14.935$$

$$-50000x_{11} + 1000000 \leq 7000000, \tag{16}$$

$$\pi(x_{12}^2 - x_{22}^2)L\rho, \tag{17}$$

$$T = \frac{60P}{2\pi f}. \tag{18}$$

The torque will result in shear stress (τ), and angle of twist or deformation angle (φ) to the shaft.[19] For safety reasons, the shear stress of the shaft must not exceed the allowable stress which can be calculated by Eq. (19). In the equation, S_y denotes the yield strength of material while the safety factor is denoted by q. Equation (20) expresses the relationship between torque and component KC (outer and inner radius of the shaft, x_{12} and x_{22}). The angle of twist value depends on segment length (L), modulus elasticity of the material (G), and polar moment of inertia (J) as can be seen in Eq. (21). The polar moment of inertia of the shaft can be obtained using Eq. (22).

$$\tau_{\text{all}} = \frac{S_y}{q}, \tag{19}$$

$$\tau_{\max} = \frac{Tx_{12}}{J}, \tag{20}$$

$$\varphi = \frac{TL}{GJ}, \tag{21}$$

$$J = \frac{\pi}{2}(x_{12}^4 - x_{22}^4), \tag{22}$$

The model for deriving the component KC target value of the shaft design problem using the attainment of product KC as the objective function can be expressed in Eqs. (23)–(27). The objective function of Model 2 for the numerical example is to attain the optimal product KC target value obtained from Model 1 which can be expressed as in Eq. (23). Since there are two working torques in the shaft, the largest torque will determine the minimum radius. Equation (24) is the constraint for limiting the shaft thickness. Equation (25) determines the maximum outer radius of the shaft. Equation (26) ensures that the angle of twist in shaft does not exceed the maximum value. The equation is obtained by substituting Eq. (22) into Eq. (21). Equation (27) ensures that the maximum shear stress of the shaft does not exceed the allowable shear stress determined by Eq. (19). Equation (27) is obtained from substitution of Eq. (22) into (20).

$$\text{Minimize } |\pi(x_{12}^2 - x_{22}^2)L\rho - 10.1561| \tag{23}$$

subject to

$$x_{12} - x_{22} \leq 0.0075, \tag{24}$$

$$x_{12} \leq 0.05, \tag{25}$$

$$\frac{2(T_{AB}L_{AB} + T_{BC}L_{BC})}{G\pi(x_{12}^4 - x_{22}^4)} \leq 0.075, \tag{26}$$

$$\frac{2T_{AB}x_{12}}{\pi(x_{12}^4 - x_{22}^4)} \leq 1.4 \times 10^8. \tag{27}$$

The model will be compared to the weight minimization problem in which no customer and designer preference concern the weight of the shaft. The solution of the optimization models can be seen in Table 2. The second column of the table shows the solutions of Model 2, while the solution of the model using weight minimization as the objective function is shown in the third column. The model to minimize the weight results in larger radius but thinner wall than the model developed in this paper. The weight target can be attained by the model since the

Table 2. Optimization results.

KC	Attaining Product KC Target Value	Weight Minimization
x_{12}	15.66 mm	15.765 mm
x_{22}	7.62 mm	8.265 mm
Weight	10.128 kg	9.870 kg

target is in the range of the feasible solution. If the product KC target is beyond the range of the feasible solution due to less than lower bound of the range in lower the better characteristics, or more than upper bound of the range then the designer has two choices: (1) forcing the model to attain the target value by changing the parameters of the model, or (2) designing the product according to the current parameters of the model. The designer decision will depend on the consequences of the attaining target of product KC to the cost of the design. For example, changing the product KC target value of the numerical example to 8 kg will result in the objective function of 1.786 kg. It means that the product KC target value cannot be attained by the model since the target is located below the minimum value of the model. In this case, if designer needs to attain the target, he must change the minimum wall thickness parameter to 0.0025 m. Optimizing the model as it is without changing the parameter will result in a cheaper and easier design than attaining the product KC target. The consequence of such a decision is that the product will lose an opportunity to deliver higher value for the customers.

4. Conclusions

This paper developed optimization models for determining KC target values. For product KC target values, the objective function is to minimize utility gap between customer and designer considering cost and time provided by company in designing a product. The customer utility function is defined based on competitor products target values while the designer function is defined based on design cost and time. The objective functions for assembly-component KC will depend on the existence of designer preference on product KC targets. In the absence of the preference, there will be two objective functions: minimization of undesired effects and maximization of desired effects. In the existence of the preference, the objective function is to attain product KC target values. In certain conditions where product KC target values cannot be attained as the values are beyond the objective function of the model, the designer has two choices: optimize the model as it is, or change the parameters of design constraints to attain product KC targets. Both choices have consequences. The first choice will result in cheaper and easier design process with the consequence of the product will lose an opportunity to deliver higher value to customers. Conversely, the second choice will result in a higher product value in consequence of more expensive design. The designer has to consider both consequences in deciding the product and assembly-component KC target values.

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