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An Approach to Combine House of Quality and Finite Element Method in Redesigning of Rotary Shaft Multi-Spindle Wheel Nutrunner Machine

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Abstract: An engineering-to-order company has developed multi-spindle wheel nutrunner machines for automotive wheel mounting. The rotating shaft component that supports that machine has experienced compressive and twisting stress during operation, resulting in damage not only to the shaft but also some parts attached to the wheel. This study uses the house of quality (HOQ) and finite element method (FEM) approaches to redesign the rotary shaft to meet quality standards for its engineers, as customers, in a systematic way by using qualitative data from interviews, documents, and questionnaires provided by five rotary shaft engineering experts. Based on the importance levels of technical specifications obtained from the HOQ results, two rotary shaft redesign models for the redesigned models 1 and 2 obtain the maximum von Mises stress from the virtual testing using FEM analysis of 277.5 MPa and 111.8 MPa, respectively, which are below the company standard maximum yield strength of 470 MPa. Hence, using the company's minimum safety factor, the redesigned model 2 is chosen for the improved version of rotary shaft design.

Keywords: Redesign, House of Quality, Finite Element, solidworks, rotary shaft.

Introduction

A design activity refers to the practice of applying technology to suit the needs and desires of customers by creating and implementing new products and processes [1]. For engineering product design to be successful, a solid foundation and engineering knowledge are necessary [2]. Design errors will lead to machine failures often followed by unpredicted situations which can be dangerous. Hence, in the event of an error arising in the design, it becomes imperative to undertake a redesign process that incorporates multiple facets of the design in order to yield a design with high standard quality.

In this case, this research aims to use a case in an engineering-to-order (ETO) company that can design and manufacture custom-built equipment or machinery rapidly for other companies. One such piece of equipment manufactured by the company is the nut-runner multi-spindle wheel machine, which serves as a tool for mounting wheels in the automobile industry. According to observation data collected in March 2021, the multi-spindle wheel nutrunner machine designed by a company collapsed during client operations. After careful examinations, experts from both companies have found that during engine operation, the overall machine assembly produces transition movements from the idle to the running states, inducing swinging motions and giving additional mechanical stress to the rotary shaft in the form of compressive and torsional forces.

Moreover, the original design of the rotating shaft according to data given by engineering experts from the company is intended to withstand tensile forces only without design capabilities to resist bending or flexural loads from the swing motions. Hence, the primary contributor to the failure of the rotary shaft is a design flaw. The damage had a significant impact on the company operations, with equipment downtime costing customers hundreds of millions of rupiah. Damage to the nutrunner multi-spindle wheel machine is extremely risky for operators since it increases the risk of workplace accidents. Based on these issues, the company has decided to redesign the rotary shaft components in order to guarantee that the outcomes of the rotary shaft redesign are safe and capable of long-term usage in their customer operations.

Many earlier researches have investigated a mechanical part or equipment redesign [3-16] where the house of Quality (HOQ) technique has generally been employed, as in the following studies [17-18] and [19-24]. HOQ itself is a set of methods for identifying consumer demands ("customer wants"), which are then transformed into attributes ("how") that can be understood by every member of the design team when creating product designs [25]. HOQ is the first step of the quality function deployment [26] (QFD) approach which it is a planning matrix used to determine how the companhy serves the needs of its customers [27]. This research uses HOQ to identify the engineering expert's requirements during the redesign processes related to technical aspects and non-technical ones such as production cost. In this case, the engineers are customers with their preference requirement for the product, i.e., the rotary shaft.

In some circumstances, the HOQ method must be used with other methods to meet the objectives of research analysis. The HOQ approach was unable to conduct material and structural tests on the design outcomes in this investigation. Thus, this research aims to conduct so-called virtual testing by using the finite element method (FEM) because this approach provides solutions to technical problems in machine element designs, such as force analysis in the form of strength, strain, stress, and vibration analysis [28]. The FEM approach is used to address engineering issues that cannot be solved in real terms or with exact solutions, as well as to solve analytical problems [29]. Several studies related to FEM can be found at [30].

Thus, this study aims to redesign the rotary shaft using the HOQ technique supporting by FEM running on the Solidworks software tools. The integration of the HOQ with FEM is novel and intended to produce the best decision during the rotary shaft redesigns that meets client and safety requirements.

Methods

Overview of the Proposed Method

This study was carried out with the goal of determining the success of the rotary shaft redesign. The evaluative approach is a methodology employed to assess the trial process during the product development phase [31]. Fieldwork conducted at the destination company, which is situated in the Jababeka II industrial district in Cikarang, Bekasi Regency, in order to collect research data. The data that has been collected consists of both primary and secondary data.

Data Collection

For primary data, interviews were performed with engineering experts as customers from the company including the head of engineering department who invented the rotary shaft design of the nutrunner multi-spindle wheel machine. Many detail information regarding how participants interpret phenomena or circumstances will be collected through interviews [31]. The interview went into great detail on the customer voices, the current state of the machine, issues, and the anticipated developments in the nut-runner multi-spindle wheel machine. Thus, our interviews are used to gauge customer satisfaction and expectations on the initial design of the damaged rotary shaft. The data is utilized as a basis for analysis and assessment in order to facilitate the development of a redesigned rotary shaft. The Likert scale was employed to construct the questionnaire, and a panel of five experts was selected as study participants. These experts were chosen based on their comprehensive knowledge of rotary shafts and their ability to reflect the voice of the consumer effectively. The process of determining the wants and needs of consumers for a product or service is known as voice of the customer (VOC)[24].

On the other hand, secondary data was collected from the company in the form of physical reports, images, or videos. Documentations were gathered on machine damage reports, material specifications, and detailed dimensions of the rotary shaft of the multi-spindle wheel nutrunner machine. These specification will serve as a guideline for redesigning the rotary shaft.

House of Quality (HOQ)

All the data was then processed in order to construct our HOQ by translating the voice of dedicated customers into product ideas with specified design goals [32]. The process of preparing our HOQ involves several steps namely the identification of customer needs, the creation of a planning matrix, the development of a technical response, the establishment of a relationship matrix, the analysis of technical correlation, and the construction of a technical matrix [33] [20].

Customer Needs

Consumer needs, often referred to in a more specific way as the voice of the customer (VOC), is simply qualitative data representing customer interest, demand, and needs, which can be discovered through in-depth interviews with knowledgeable sources [15]. Based on Garvin's eight quality dimension functions [34] the customer demands attribute data is assembled into bespoke customer requirements. This practice is implemented in order to enhance the measurability of the development and design of the rotary shaft in terms of both its quality and performance.

Planning Matrix

When analyzing client demands or translating those needs into a plan that can satisfy those needs, a planning matrix is utilized. This matrix will determine performance values of the rotary shaft based on the amount of satisfaction filled in by respondents, as well as the value of customer expectations for a characteristic based on an appraisal of its importance.

Performance Value

Calculating performance value based on the assessment of customer needs attributes on the customer satisfaction level questionnaire. The calculation of the performance value can be determined using (1)and (2) by several steps defined as follow [35]:

a. First, calculate the total value of satisfaction level using (1)

$$\text{Total } Score = (E1 \times 1) + (E2 \times 2) + (E3 \times 3) + (E4 \times 4) + (E5 \times 5) \tag{1}$$

b. Then, divide the total score by the number of respondents using (2)

$$\text{Performance Score} = \frac{Total\ Score}{Number\ of\ Respondents} \tag{2}$$

Expected Value

Following the computation of the performance value, the expected value is determined by evaluating the characteristics of the customer requirements as indicated by the customer interest level questionnaire. These are the steps involved in calculating the performance value as show on (3) and (4) as

a. Calculating first the total value of the importance level using (3)

$$\text{Total } Score = (E1 \times 1) + (E2 \times 2) + (E3 \times 3) + (E4 \times 4) + (E5 \times 5) \tag{3}$$

b. Then, divide the total score by the number of respondents, as shown in Equation 4ividing the total score by the number of respondents as show in equation 4, i.e.

$$\text{Expected Value} = \frac{Total\ Score}{Number\ of\ Respondents} \tag{4}$$

Notation:
$E1$: Number of respondents answering "Very Not Important"
$E2$: Number of respondents answering "Not Important"
$E3$: Number of respondents answering "Neutral"
$E4$: Number of respondents answering "Important"
$E5$: Number of respondents answering "Very Important"

Technical Specification

Technical specifications are the company's response to client needs, and the specifications here are the outcome of translating customer requirements into a more technical language [36].

Relationship Matrix

The relationship or linkage scale assesses the extent to which customer's need is contingent upon a technical specification. The compilation of the relationship in the HOQ research was conducted in collaboration with professionals from the development and engineering teams to determine the precise relationship between the needs of each customer and the technical specifications.

Technical Correlation

The importance of absolute or measured importance is shown in a matrix called the technical matrix. The significance of measurement lies in its ability to quantify the magnitude of a technical specification that is given priority or becomes a matter of concern in relation to fulfilling customer needs. The following equations can be used to calculate the importance of measure/absolute importance and its percentage [37].

$$Importance\ of\ Measure = \sum(Importance \times Relationship\ Weight) \tag{5}$$

$$\%\ Importance\ of\ Measure = \frac{Importance\ of\ Measure}{\sum(Importance\ of\ Measure)} \times 100\% \tag{6}$$

Redesign with SolidWorks

In this study, all redesigned versions of the shaft were created with the Solidworks software. When performing design for mechanical components for machines either as a standalone part or in an ssembly, Solidworks is frequently used. It can be used in the form of a 2D view (drawing) for machining process drawings and can represent the shape of the component before the real shape (prototype) is made.

The development of a redesigned version in the Solidworks environment will generate several potential design choices based on the original rotary shaft design. The creation of the rotary shaft redesign model is conducted in collaboration with the company's engineering team. This is done to determine whether or not the redesign of the modeled rotary shaft can be implemented in the multi-spindle wheel nut-runner machine. The priority of technical specifications from the house of quality guides the development of a redesigned model, where the highest priority is the most important technical specification and demands greater attention in the redesign.

Finite Element Method (FEM)

Virtual testing for a mechanical design is a procedure conducted to observe, test, and verify the alterations, distortions, and flaws in the rotary shaft when exposed to loading early before physical tests [38]. The Solidworks FEM is capable of conducting such testing. The process of testing for the rotary shaft redesign model begins with several steps that have a significant impact on the level of validity of the simulation results. The steps for testing FEM in Solidworks are as follows:

Modeling

Modeling refers to the comprehensive set of procedures and stages required to model a virtual specimen or body for testing, wherein the ultimate outcome is a prepared model ready for simulation. The modeling requires the implementation of certain processes as follows [39]:
1) Choosing material type
2) Meshing model redesign
3) Defining necessary supports and loadings

Simulation

The static force analysis module in SolidWorks was used to conduct the test with outcomes of the von Mises stress and safety factor calculations. The following steps are taken to determine the von Mises stress and safety factor from the tests:
The von Mises stress
Failure criteria based on the von Mises stress imply that a fracture may occur in locations in the model where the von Mises stresses surpass the yield strength of the material [40]. This type of failure criteria based on stress values can be computed as in (7).

$$\sigma = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \tag{7}$$

Notation:
σ: $Von\ Mises\ Stress$ (N/mm^2 or MPa)
σ_1: Principal stress 1 (N/mm^2 or MPa)
σ_2: Principal stress 2 (N/mm^2 or MPa)
σ_3: Principal stress 3 (N/mm^2 or MPa)

Safety Factor
The safety factor is a critical parameter that must be satisfied in order for a modified model to be deemed safe for use [41]. The safety factor can be defined as the ratio between the yield strength, which represents the

highest stress that a material can withstand without permanent deformation, and the maximum von Mises stress that may be experienced. In our case, the minimal safety factor determined by the company for the rotary shaft of the multi-spindle wheel nutrunner machine is 2.1. The determination of the safety factor value in Solidworks employs the subsequent mathematical expression shown in Equation 8.

$$SF = \frac{\sigma_y}{\sigma_{max}} \tag{8}$$

Notation:
SF : $Safety\ Factor$ (ul)
σ_{max}: Maksimum $Von\ Mises$ (N/mm^2 or MPa)
σ_y : $Yield\ strength$ 1 (N/mm^2 or MPa)

Results and Discussions

House of Quality (HOQ)

Figure 1 shows the result from the HOQ method from eight customers provided by the company as mentioned before. According to the results, the technical specifications with the highest priority are the rotary shaft screw diameter of 55 mm, the rotary shaft safety factor, the diameter of the rotary shaft cylinder is 55 mm, and the yield strength of the material is 470 MPa. Additionally, the two highest importance values are given to shaft thread diameter and safety factor assessment, respectively, with 141 and 122 for our proposed designs which will be used to determine the best-improved shaft design.

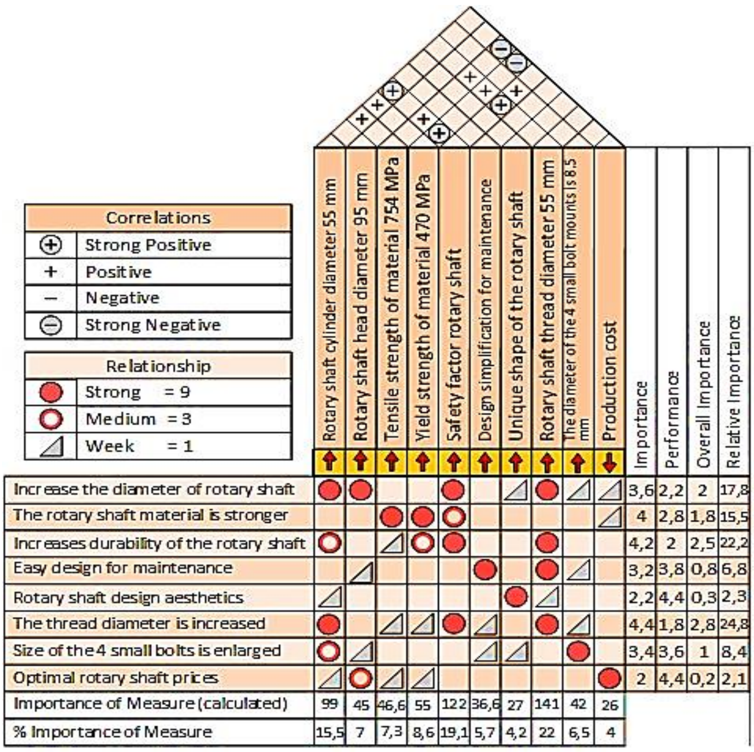


Figure 1. House of Quality of redesign rotary shaft

Meanwhile, Figure 2 presents the initial design of the rotary shaft, which has been found to perform poorly in the direction of combination loadings, which will be used to guide the development of the redesign model. This design has failed to withstand the combination loading direction due to the simplification in the previous design requirements, which considered only tensile stress as a critical aspect during operation.

The outcomes of the rotary shaft redesign using the HOQ are then shown in Figure 3. Additionally, Table 1 presents summaries of the proposed technical specifications for the redesign model from our HOQ in Figure 1. Thus, as the respondents who constructed our HOQ are considered experts, the authors can apply the result directly to proposed new designs without additional calculation, in particular for technical aspects regarding geometry and material used as input.

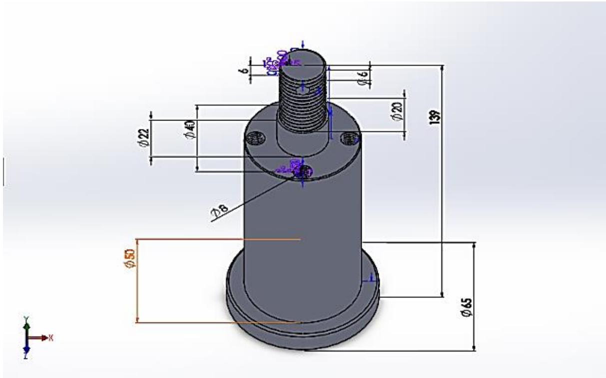
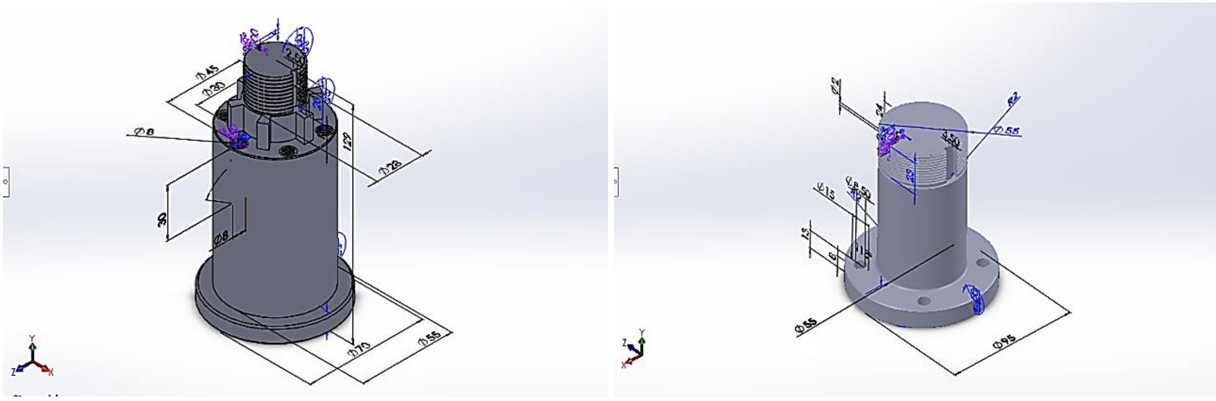


Figure 2. Initial rotary shaft design with dimension



(a) (b)

Figure 3. (a) Redesigned rotary shaft model 1, (b) redesigned rotary shaft Model 2

Table 1. Preliminary design and redesign model specifications

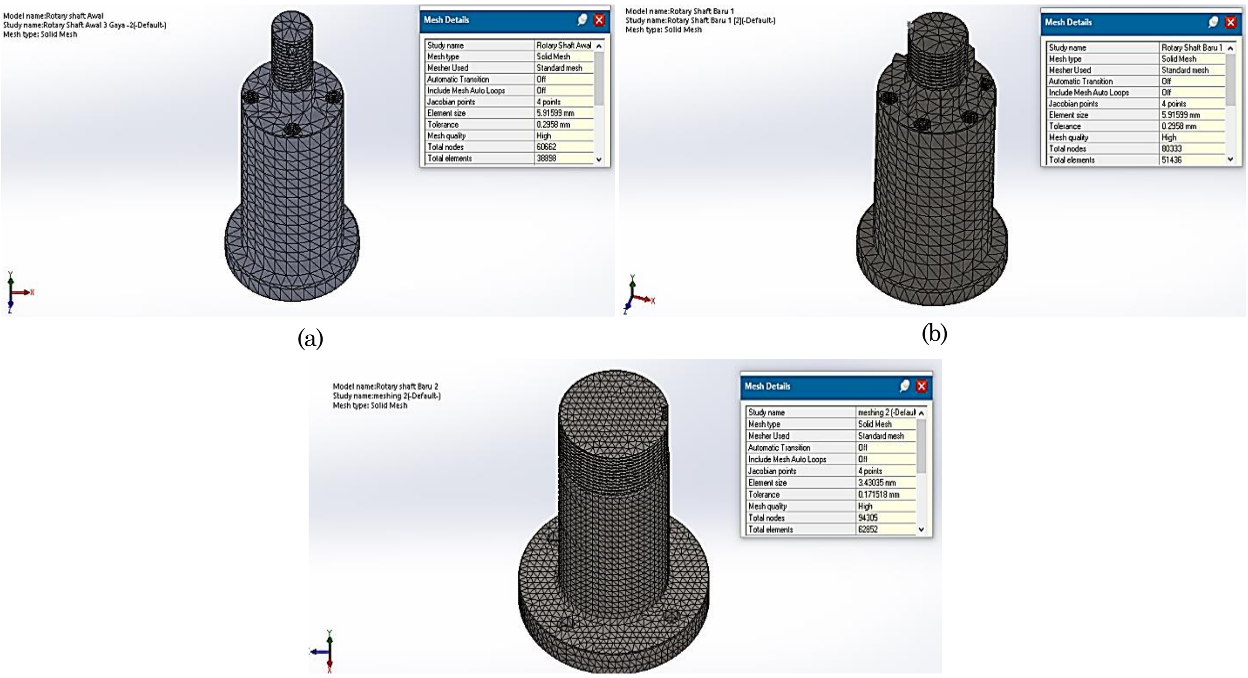
No	Specifications	Initial design	Redesign Model 1	Redesign Model 2	Units
1	Rotary shaft thread diameter	20	28	55	mm
2	Diameter of rotary shaft cylinder	50	55	55	mm
3	*Safety factor*	0.46	1.44	4.2	ul
4	*Yield strength*	400 (S50 C)	470 (VCN 150)	470 (VCN 150)	MPa
5	*Tensile strength*	630 (S50 C)	745 (VCN 150)	745 (VCN 150)	MPa
6	Diameter of rotary shaft head	65	70	95	mm
7	Mounting diameter screws	8	8	8.5	mm

Virtual Testing with FEM

For virtual testing, this study uses the mesh structure shown in Figure 4. Since the geometries in Figures 1-3 have irregularities due to holes and sharp corners, the only choice was to use tetrahedral elements. In this case, this study uses only one specific mesh for the three cases without considering automatic mesh refinement. We assume that the mesh configurations are enough to detect accurate stress responses as shown later.

As one observes in Figure 5, the initial design is predicted to have only one direction of critical stress, i.e. from the weight of an assembly of machine attached to the shaft. In fact, during actual operation, it has been found, according to information from engineers of the company, that major forces act in all directions, i.e., x, y, and z axes, in combination interactions due to swing movements, as indicated in Figure 6. By using the actual loadings, the result for the von Mises stress analysis in the initial design is presented in Figure 6, which surpasses the material yield strength almost twice, i.e., 877 MPa, in some locations.

On the other hand, the von Mises stress analysis conducted for the proposed redesigned models are presented in Figures 7 and 8. Here, the corresponding maximum von Mises stresses are given by 276 MPa and 112 MPa for the model 1 and 2, respectively. Both stress values are below the yield strength of the material given in Table 1. It is worth to note that we do not need to further refine the mesh because the finer mesh in both redesigned models shown in Figure 4 have produced lower maximum von Mises stress compared to the result from the initial design. A finer meshing configuration for the initial design will produced even higher stress than the stress values in Figure 6.



(a) (b) (c)

Figure 4. Meshing used for the initial design (a), proposed design 1 (b), and proposed design 2 (c)

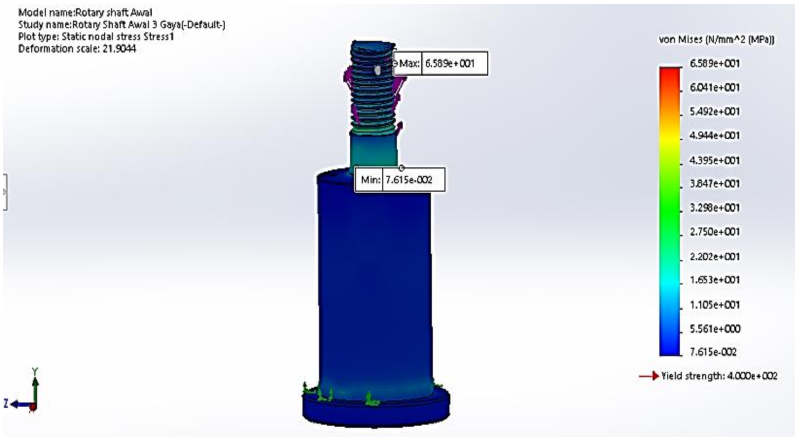


Figure 5. von Mises stress for rotary shaft in its initial design model with unidirectional loading from the machine weights

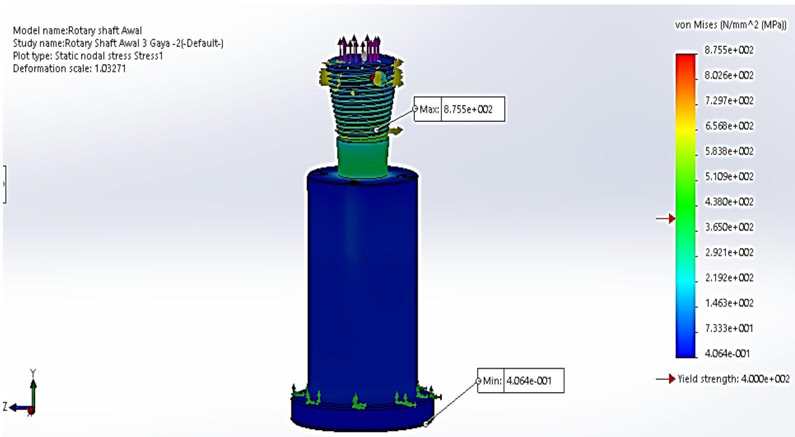


Figure 6. The von Mises stress for the same shaft in Figure 5 but now with the combination loadings from swing movements

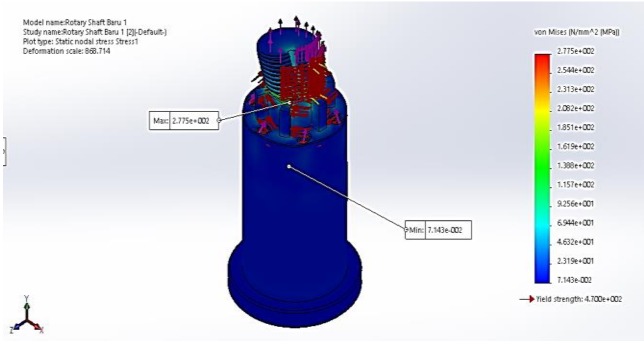


Figure 7. The von Mises stress for the redesign model 1

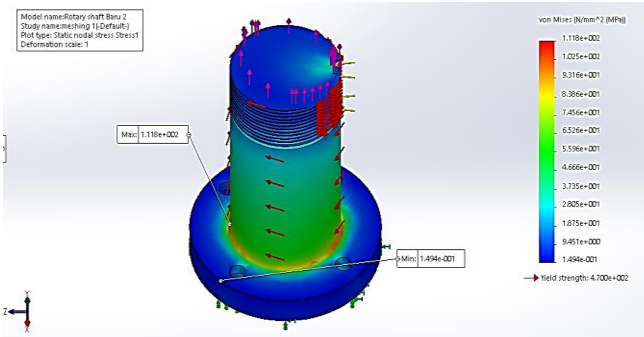


Figure 8. The von Mises stress for the redesign model 2

Table 2. The von Mises Stress obtained from the virtual testing on the initial and redesigned models of Rotary Shaft

Rotary Shaft		Yield Strength (MPa)	Von Mises Stress (MPa)
Initial Design	Single-Force	4.000e+002	6.589e+001
	Combination Force		8.755e+002
Redesign	Redesign Model 1	4.700e+002	2.775e+002
	Redesign Model 2		1.118e+002

Finally, we summarize the virtual testing results in Table 2 from both the initial design and the proposed redesigned models of rotary shaft. Initially, the shaft was subjected by design to a single force only as explained before, resulting in the maximum von Mises stress up to 65.89 MPa. Unfortunately, during its operational task, combination of forces due to swing movements led to the significantly higher von Mises stress level up to 875.5 MPa. Meanwhile, the von Mises stresses for the redesigned models presented in Table 2 indicate significant decrement with the lowest stress provided by the redesigned model 2. Compared such results and the HOQ results before, we suggest, the recommended redesign for the rotary shaft model is the model 2.

Safety Factor

The minimum safety factor of 2.1 is determined by the company for the rotary shaft. Consequently, the rotary shaft models having their safety factors less than 2.1 will be automatically rejected for further design steps. This study obtains the safety factors from the virtual testing for the initial design with single force, the initial design with combined forces, the redesigned model 1, and the redesigned model 2, as shown in Figures 8, 9, 10, and 11, respectively.

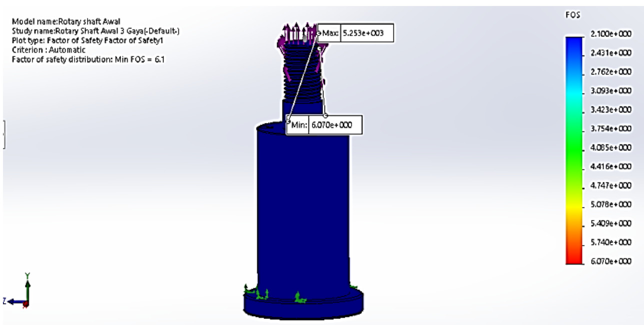


Figure 9. Safety factor for single force loading in the initial design model

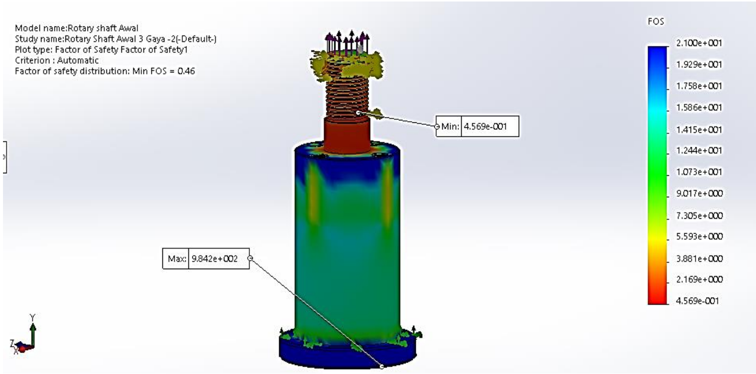


Figure 10. Safety factor for the combination of forces loading in the initial design model

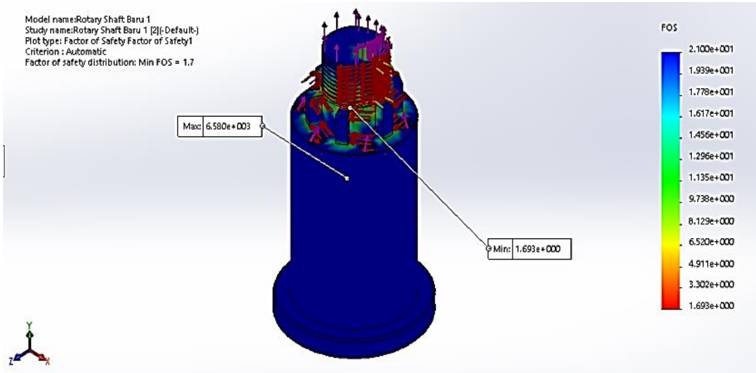


Figure 11. Safety factor for the combination of forces loading in the redesign Model 1

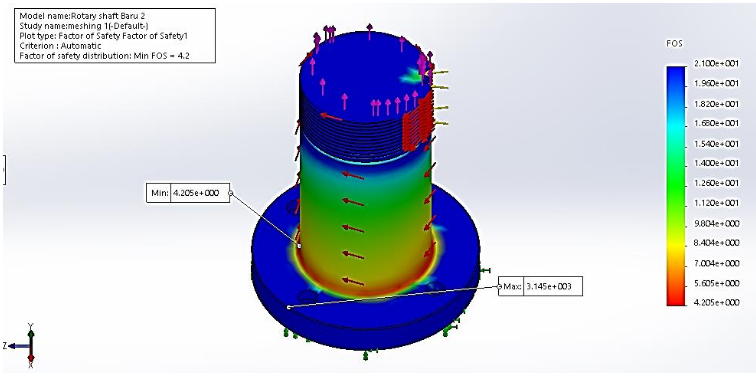


Figure 12. Safety factor for the combination of forces loading in the redesign Model 2

Table 3. Results of the safety factor from the virtual testing on the rotary shaft model

Rotary Shaft		Safety Factor	Standard Safety Factor
Initial design	Single force	6.070e+000	2.100e+000
	Combination force	4.569e-001	
Redesain	Redesign Model 1	1.693e+000	
	Redesign Model 2	4.205e+000	

Table 3 shows the summary of the safety factors obtained from FEM simulation in SolidWorks for the rotary shaft models in Figure 4 for the two loading scenarios. While the best safety factor is reached for the rotary shaft redesigned model 2, the initial design with the combination of forces produces the lowest safety factor. Hence, since the safety factor in the HOQ results in Figure 1 occupies the second highest importance, the rotary shaft redesign model 2 is again selected as the best alternative to the further redesign of the shaft.

Conclusions

The house of quality (HOQ) method and FEM analysis have been performed sequentially to improve the initial design of a rotary shaft used for multi-spindle wheel nut-runner machine for a company. The HOQ produces several technical responses or technical specifications with the two highest importance values related to rotary shaft thread diameter and safety factor. They are followed by the importance of rotary shaft cylinder diameter of 55 mm and yield strength of material 470 MPa. As a result, the redesign of the rotary shaft follows those of importance values resulting in two redesign models. This study, instead of using only standard discussion methods to determine redesigned parameters, actually demonstrates an integrated and systematic way to guarantee that our redesigned process will produce minimal errors at the end. Based on those of important values, analysis based on FEM is used to perform so-called virtual testing with respect to the initial design and the redesign models of the rotary shaft. The testing obtained that the technical specification given from the HOQ results can be used to develop the best redesign model for the rotary shaft, which can withstand the combination of forces during operation.

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