

EVALUATING DESIGN FOR UPGRADABILITY AT THE CONCEPTUAL DESIGN STAGE

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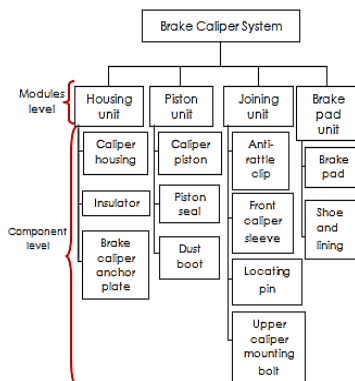
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Graphical abstract



Abstract

It is necessary to have an alternative approach in handling end of life vehicle (ELV) other than disposal, due to its adverse impact to the environment. Remanufacturing is the process that can retain the values of used products when they reached the end of their useful life. Product upgradability for multiple lifecycle products (MLPs) is one of the promising methods that can enhance a product's life and also maintain its value. The focus of this study is to make a pre-assessment on a selected automotive component in order to examine its design conceptualisation for purposes of upgradability. This is to ensure that the product meets the design characteristics of upgradability to accommodate and strive for the generational changes in view of extending the life of the product. Quality Function Deployment (QFD) was used to represent the requirements of a product in terms of physical and functional model at three levels namely Engineering Metric (EM), Component and Structure. Data from QFD is crucial in providing the details of the product for the purpose of developing a new design of the brake caliper model that can has ease-of-upgrade features through the remanufacturing process. A systematic approach for future study is proposed with the aim of developing a formulation through modeling and optimization in order to obtain the optimized upgradable product design.

Keywords: Brake caliper; design for upgradability; multiple lifecycle products; QFD

Abstrak

Pendekatan alternatif yang sesuai untuk pemuliharaan kenderaan yang mencapai akhir hayat adalah perlu bagi memastikan ianya tidak memberi impak negatif terhadap alam sekitar. Proses pembuatan semula merupakan suatu proses yang mengekalkan nilai produk terpakai apabila menghampiri hayat akhir produk tersebut. Penaiktarafan produk bagi kitar hayat berbilang merupakan salah satu strategi pembuatan semula yang berupaya melanjutkan jangka hayat produk dan mengekalkan nilai produk tersebut. Fokus kajian ini adalah untuk membuat penilaian awal terhadap komponen automotif yang terpilih dan mengkaji perangkaan konseptualnya untuk tujuan penaiktarafan. Ciri-ciri reka bentuk untuk penaiktarafan produk juga dapat dikenalpasti bagi menghadapi perubahan sepanjang jangka hayat produk tersebut. Penggunaan Fungsi Kualiti (QFD) telah digunakan bagi mewakili keperluan produk dalam domain fungsi dan fizikal untuk tiga tahap iaitu Metrik Kejuruteraan, Komponen dan Struktur. Data yang diperolehi dari QFD ini adalah penting dalam memberikan maklumat bertujuan untuk membangunkan rekabentuk model angkup brek yang baru yang mempunyai ciri-ciri mudah dinaiktaraf melalui proses pembuatan semula. Pendekatan sistematik bagi

kajian akan datang juga dicadangkan dengan objektif untuk menghasilkan formulasi melalui kaedah permodelan dan pengoptimuman untuk mendapatkan rekabentuk produk dengan ciri peningkatarafan yang optimum.

Kata kunci: Angkup brek; reka bentuk untuk peningkatarafan; produk kitar hayat berbilang; QFD

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1.0 INTRODUCTION

End-of-Life Vehicle (ELV) management is vital in ensuring that used products do not adversely affect the environment when they reach end-of-life. ELV recovery options are disposal, reuse, remanufacturing and recycle. Remanufacturing activity was one of the better and promising methods that can help in retaining the values of used products. Remanufacturing activity involves assembly and disassembly of parts which may become complex if there is no systematic and proper planning by the manufacturers and designers at the early stage of product design. This will certainly impacted sustainability efforts in terms of economic, social and the environment.

Despite an increasing awareness on the benefits of remanufacturing, the implementation of this recovery strategy in the country is still at the initiation stage. In-line with the National Automotive Policy (NAP) 2014, Malaysia Automotive Remanufacturing Roadmap was introduced by the government to promote remanufacturing activities in the country as one of the alternative to preserve used automotive components or parts [1]. The main challenge faced by the remanufacturer is on the quality of a remanufactured part that is always being disputed by the user and also manufacturer [2]. The product design upgrade through remanufacturing may be an attractive feature to implement remanufacturing and enhancing the remanufacturability of a product.

Product upgradability for multiple life cycles is one of the remanufacturing alternatives that help to prolong product's life. Based on this initiative, Design for Upgradability (DFU) was introduced to helps the designer in planning for ELV during the early stage of product design. DFU provides a solution to extend the life of products through performance and function changes [3]. The functions were improved at each life cycle and thus, enhancing the features of a product [4]. The implementation of multiple life cycle products is an added advantage to manufacturers as it helps to prolong the life and sustainability of the product. Through DFU, the design of the product will be continuously upgraded according to the trend and customer's demand at each generation of the product.

Developing multiple lifecycle products as one of the strategy in remanufacturing, is now gaining

significance among the industry such as Caterpillar Inc. The design upgrade can be accomplished through remanufacturing activity since the process involved in remanufacturing can adapt with evolving technical and customer requirement [5]. Therefore, it is important to develop a well upgrade plan for a product in each life cycle. The design characteristics need to be first identified to ensure that the upgradability's solution can be achieved which is the combination of physical, functional and architectural features.

The objective of this study is to make pre-assessment to evaluate the upgradability of the component based on the functional and physical requirements that can be accommodated for generational changes in the future. A pre-assessment will be conducted at the conceptual design stage in which the QFD design tool will be used to represent the requirements of a product. A brake caliper was chosen as case study in which its potential in establishing design upgrade was to be measured.

2.0 DESIGN FOR UPGRADABILITY (DFU) AND OTHER RELATED CONCEPTS

DFU provides a systematic plan for the designers and manufacturers to develop an upgrade plan of a product at the early stages of the design process. The upgrade plan is important to be developed in order to retain the product's values and also can help in reducing the impact towards environment. The design alternative of MLPs in DFU is able to enhance the remanufacturing features by providing the opportunity for upgrading in each lifecycle of a product in order to accommodate with customer demands and latest trend. Umeda *et al.* [6] also stress that product modularity is one of important element that need to be considered in the product upgradability to extend and improve product's life. Besides, the technological continuous changes also can be accomplished through MLPs without the need for any design changes in other modules [7].

The terms upgrade sometimes can be confusing due to its wide range of applications such as software upgrade, maintenance upgrade and hardware upgrade. The integration of DFU with the design process is necessary to ensure that the design

upgrade plan can be initiated at the early stages of the design process. The aim is to extend the product's service life through remanufacturing [3]. From the developed plan, the designer can decide in preserving the product's platform with several options either by exchanging components or by adding components or modifying the product structure [8]. The platform or base frame will be updated in certain time range where the features of product will be improved either in terms of performance or functionality. In addition, the modular design can help to increase the configuration of products and the technological choices as well. Therefore, this modular upgrade is able to offer more product variety throughout the time which also helps in reducing the material usage and workload [7].

2.1 Multiple Lifecycle Products (MLPs)

Multiple lifecycle products were introduced to facilitate the extension of product's life by considering its functional and performance characteristics for each generation or lifecycle where it is in-line with the strategies of product design upgrade. MLPs can be defined as a product that has potential to be preserved or recovered multiple times in order to increase the value of product within certain period [5]. MLPs is also able to help in supporting the remanufacturing activity by providing the resources for ability to be applied in closed loop manufacturing system [9]. It means that this MLPs is able to help in recovering product with a value from different types and returns over time.

Existing research recognizes a new approach for MLPs which is Design for Multiple Lifecycle (DfML) which maximize the utility of the resources used in developing a product by integrating the features that can help to prolong the life of the product [10]. Those features include assemblability and disassemblability, durability and accessibility, modularity, simplicity, utilization of standard parts and socio-cultural consideration.

2.2 Design Upgrade Plan Method

The upgrade plan also indicates the upgrade period that need to be considered at the early stages of

design process. It is to ensure that the upgradable products are capable to function within a certain time period and can satisfy customer's requirements. Matsuda and Shimomura [11] propose a five stages upgrade plan which include 1) Choosing the target product 2) Building a component database 3) Matching the demand and structure 4) Determining the design solution 5) Evaluating the upgrade product line up. Based on these five stages, the customer voices play important roles in determining the value parameter to be translated into design parameter. This design parameter will be a new specification that requires improvement to be made to a product. Ke Xing [3] also agrees that the future trends and customer demands need to be considered in design upgrade plan method to adapt to the next generation life cycle of product.

Developing an upgrade plan is the first step in the implementation of DFU. As mentioned earlier, DFU is able to facilitate the designer in integrating the upgrade features of product at the early stages and throughout the product design process. Umemori and Kondoh [12] who developed upgrade design method for upgradable product noted that the future uncertainty in DFU may incur loss to the company if long term planning is not conducted properly. Due to this factor, it is important to make product evaluation before proceed to the next stage in implementing product design upgrade. The next section will discuss on the pre-assessment of a product to ensure that it can be designed as an upgradable product. Brake caliper is used as case study to demonstrate how design for adaptability is applied.

Figure 1 shows the proposed steps for design upgrade plan in order to achieve the optimal upgradable product design. This study focused on the evaluation of the selected component prior to the development of the Design of Master Model. The evaluation of the product is very crucial because the product data will be required when making assumptions at the upgrade planning phase to accommodate future changes for the next lifecycle. The findings from this case study should be able to provide information and knowledge to be adapted and matched with the real model that will be accomplished for the future work.

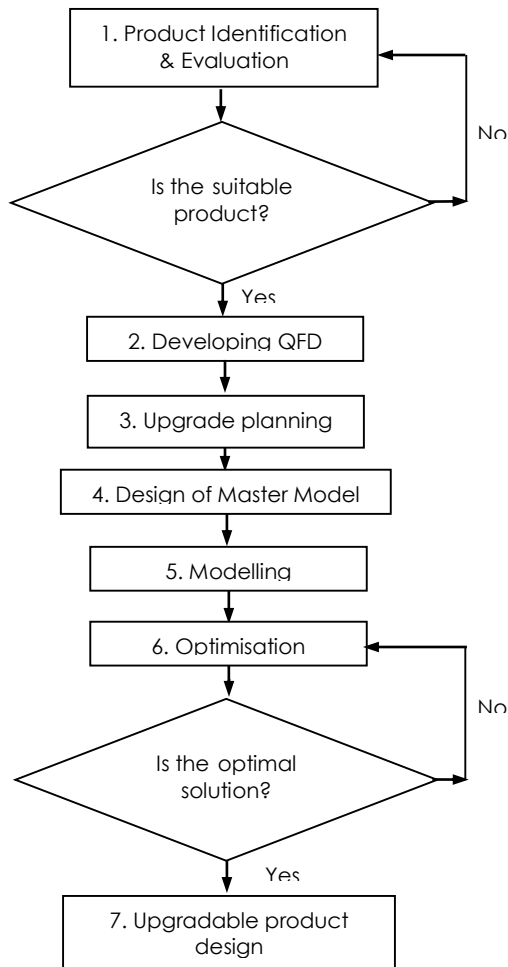


Figure 1 Proposed method in determining the optimal upgradable product design

3.0 CASE STUDY: BRAKE CALIPER

The remanufacturing activities of brake calipers have gained significant attention among OEM such as Hella-Pagid GmbH and TRW Automotive. A brake caliper has attractive features that are suitable for remanufacturing. The features include non-complex automotive component, ease of disassembly and reassembly of parts, small number of parts and also the availability of the caliper core that can be used for a long period of life cycle. The returned core of brake caliper must meet OEM's requirement to ensure that the quality of product can be retained as original product. Schuck [13] stressed that the caliper will be inspected as soon as possible and will be scrapped if it does not meet their requirements.

Several guidelines were provided by OEMs for customer to check their brake caliper before returning them back to the manufacturers [14]. Figure 2 shows the assembly structure of brake caliper where the main casing and anchor plate of brake caliper were usually returned to the manufacturer for inspection before it can proceed for remanufacturing purpose.

Components that have wear and tear properties like piston seal and dust boot must be replaced with the new parts.



Figure 2 Brake caliper assembly

(Source: http://www.brakewarehouse.com/brake_calipers.asp)

It is observed that the implementation of product upgrade is still limited for brake calipers even though its remanufacturing activities were widely accomplished by the manufacturers. Improving the life span of a brake caliper is important in term of safety for the user which is not only limited to the replacing of new caliper, but the whole part of caliper must be serviced when replacment of caliper pads were accomplished [13]. The replacement of a brake caliper is not only due to the worn pads but also other factors such as caliper hardware wear out, non retracting piston and also noise emitted from brake pads. This study was intended to introduce a design upgrade method through DFU for a brake caliper based on its remanufacturability and also the design upgrade alternatives to enhance the functional features of a brake caliper throughout the upgrading time. Product evaluation through product conceptualisation will be the focus of this study in order to assess the upgradability potential of a brake caliper. The next section will discuss the pre-assessment of brake calipers as the initial stage for developing the DFU for brake calipers.

3.1 Pre-assessment of Brake Caliper

It is necessary to conduct pre-assessment of a product to examine its suitability and compatibility to be designed as an upgradable product. The incorporation of design characteristics into this pre-assessment was crucial so that a well-planned design upgrade method can be developed. Martin and Ishii [16] in his study has accomplished a comprehensive study on the development of standardised and modularised product architectures as a guideline for Design for Variety. This Design for Variety encourages the designer to design a product by considering the generational changes in future. The proposed method in their research was applicable for the pre-assessment purpose in developing the design upgrade plan. Quality function deployment (QFD) is one of the design tools that represent the product's requirement at Conceptual Design Stage. Ke Xing [3]

in his work suggested three levels of product conceptualisation which are engineering metrics, component and architecture. These three levels provide the information and relation in defining the functional requirements, specifying design parameters and also enabling the product to be in two design domains which are functional and physical domain.

3.1.1 Engineering Metric Level

At this level, the measuring criterion was not limited to the performance of a product but also the information regarding the technologies related to product's functionality. In short, this level indicates the combination of discrete functional requirements, performance metrics and also related constraints contributed from customer's requirements [3]. The customer needs which are usually qualitative and vague will be interpreted in the form of engineering metrics that will be subsequently projected into corresponding components of a product specifically at the component level in matrix form. Table 1 shows the matrix form that represents the correlation between customer needs that are translated into engineering metrics for a brake caliper. There are several engineering metric identified by the customers such as thickness of brake pad [mm], temperature [°C] and cost [RM].

Table 1 Correlation between customer needs and engineering metrics

Customer Needs	Engineering Metrics					
	Thickness [mm]	Noise [dB]	Pressure [Pa]	Temperature [°C]	MTBF [hr]	Cost [RM]
1. Increase pad life (Reduce pad wear)	▲					
2. Reduce brake squeal		▲				
3. Maximize braking force			▲			
4. Cooling prevent heat fade				▲		
5. Reliable					▲	
6. Low cost						▲

▲ indicate the correlation between two elements

3.1.2 Component Level

The projection of functional domain into physical domain is accomplished at the component level in order to define the interaction between functional requirements with the physical design parameters [16]. The corresponding engineering metrics that correlate with the components are not specifically defined to one component but also could be

coupled with other components with different influences that will satisfy the functional requirement of the product as shown in Table 2. Based on the correlation at this level, the life cycle characteristics of the product can be featured as the properties and conditions of its constituents. For the upgrade purpose, the aim at this level is for the product to have its reflection of the technological and engineering properties of its component in terms of reuse and remanufacture [3].

Table 2 Correlation between engineering metrics and components of brake caliper

Engineering Metrics	Components					
	Caliper housing	Brake pads	Caliper piston	Piston seal	Insulator	Joining unit
Thickness, mm		▲				
Noise [dB]	▲	▲	▲			
Pressure [Pa]		▲	▲	▲		▲
Temperature, °C		▲			▲	
MTBF, hr	▲	▲	▲	▲		▲
Cost, RM	▲	▲	▲			

3.1.3 Structural Level

The scheme of which functional requirements are projected into physical components and then facilitated by the interaction between them is indicate as a product's architecture [17]. This architectural representation is able to help the implementation of product upgrade that may be combined with reuse or remanufacture in order to help extend product's life by measuring the fitness of its configuration for ease-of-upgrade [3]. The relationship and interconnection between a component and module can be established and also able to help in making decision for upgrading either to exchange the component or adding the component or modifying the structure. Figure 3 shows the brake caliper's exploded structures with the labeled component to represent the decomposition of brake caliper in two levels as shown in Figure 4. The functional requirements of a brake caliper defined in engineering metric levels are decomposed into a hierarchical form based on its non-separable functional modules according to their importance.

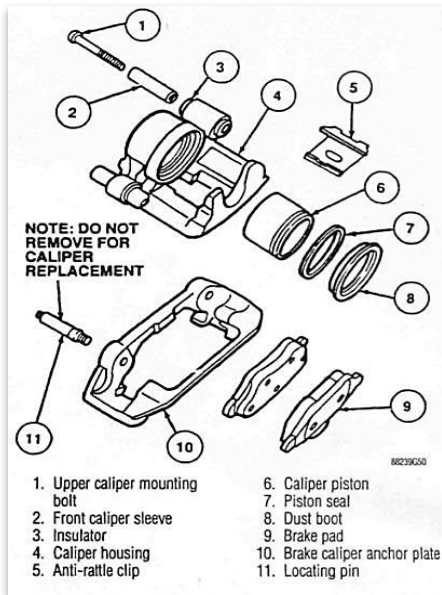


Figure 3 Exploded view of the front brake caliper

(Source: <http://diagrams.hissind.com/caliper-teardown-diagram/>)

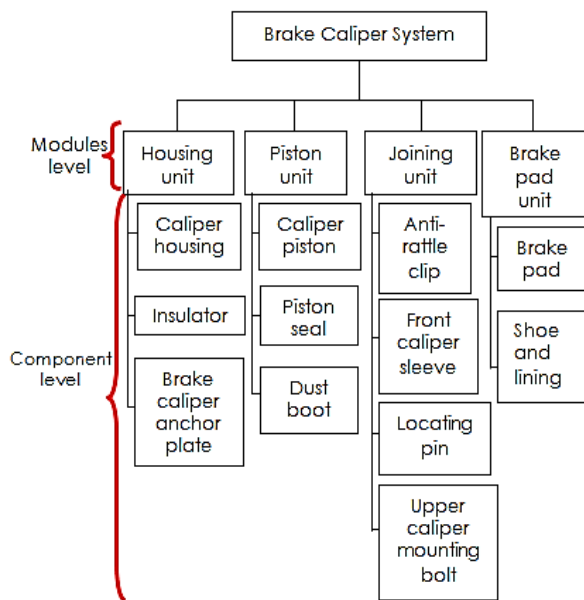


Figure 4 Hierarchical form of brake caliper's structure

3.2 Design Upgrade Consideration on Brake Caliper

As the QFD is developed to provide the details of a product in terms of its physical and functional domain, the upgrade plan will then be accomplished in the next step. The main focus of this study is to observe the upgradability potential of a brake caliper by representing the requirements of the product at the Conceptual Design Stage through QFD. This section will address the considerations in producing an upgradable design solution through modeling and optimisation.

The upgrade plan of a product requires a comprehensive study on the life cycle of the brake

caliper in order to estimate the occurrence and uncertainties in the future or for the next life cycle [5, 18]. Zhao *et al.* [5] in their study had explained on the need for varying lifecycles due to decrease in performance at the end of each lifecycle or generation of a product. For the case of a brake caliper, its life is usually measured in terms of the mileage of a car. Assumptions must be made for a specified planning horizon and the right decision on either to reuse or upgrade the product at one lifecycle must be made to ensure that the decision does not affect factors such as cost, environment and performance [5].

In addition, the modeling and optimization approach proposed in this study is aimed at developing a brake caliper with higher system's upgradability than its current design. Some suggestions on the implementation of DFU for a brake caliper specifically for this study as such:

- The upgrade is mainly on the system upgrade which focus on the performance of the product to have more power and reliable brake caliper
- The module structure is easy to disassemble and assemble, as well as interchangeable
- The design can be fixed or used for various car models to ensure availability of the product in the market
- The brake caliper is able to operate with the same performance after its first lifecycle or generation

Other than the above, other improvements can be made or considered based on customer requirements as stated in Table 1. Further analysis will need to be carried out in order to fulfill those requirements based on the planning horizon. It is necessary to understand that product upgradability is not only based on the function or trends, but also to produce a higher systems performance to ensure that it can strive for each lifecycle or generation in view of upgrading and reuse in the future.

4.0 CONCLUSION

This study has proposed an evaluation method for a product to be designed as an upgradable product which will ensure that it can accommodate generational changes and has ease-of-upgrade features in the future. The application of QFD that helps in conceptualizing the product presents the interaction between the functional domain and physical domain by considering the performance requirement, functional features and also physical design parameters of the product. The architecture of a brake was discussed to examine the modularity features of the product and thus, give brake caliper an advantage as one of the multiple lifecycle products through the design upgrade method. Further improvements will be required in this study to ensure its feasibility for the DFU application namely:

- (a) Conducting a background study on specific models of brake calipers which include market study, technological trends and the average period of brake caliper's usage. It is important to have these kinds of data to relate with the functional and physical requirements of a brake caliper in order to measure its potential for upgrade.
- (b) Consideration on the operational features of a brake caliper which suits the kinetic application for upgrade purpose as one of the characteristics that have to be measured for a product's performance.
- (c) Developing a systematic approach for DFU based on the planning for a certain range of upgrade period through modelling and optimisation.

This paper has discussed the approach in evaluating DFU on a selected automotive component starting with a pre-assessment or evaluation of a product at the conceptualisation stage. With a proper planning on design upgrades, the life of a product can be extended and that will directly contribute towards product and environmental sustainability.

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