

## **Design for additive manufacturing: Simplification of product architecture by part consolidation for the lifecycle**

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### **Abstract**

Additive manufacturing (AM) can support the fabrication of the complex design and generate new design opportunities for improving products. To identify and leverage these opportunities, design studies in early product design stages are required. Since part consolidation is one of AM design potentials in conceptual and embodiment design stages, this study proposes a design method to reconceptualize existing product design in the context of part consolidation. Function requirements and physical relations between existing parts are used to investigate AM design potential and identify candidates for consolidation. After identification of consolidation candidates, function sharing between parts and modules is checked because they have high possibilities to be consolidated if they share the same functions. Furthermore, AM design potential is identified to help designers add value in part design. In order to support designers, it is required to link AM design potential to the part candidates in order to explore AM design benefits. A case study with motorcycles is performed to demonstrate the proposed method. The AM design potential for the case study contains the lifecycle considerations related to fuel savings due to lightweight, and simplified and less expensive assembly operations due to simplified product architecture by part consolidation.

### **Introduction**

The evolution of AM has been made by AM materials and technologies. The growth of AM is driven by market needs, such as increasing demand of a customized product, manufacturing time and cost reductions, and shorter product development process [1]. The objective of Design for Additive Manufacturing (DFAM) has focused on both maximizing product performance [2] and alleviating manufacturing constraints of AM to improve manufacturability [1] in order to take advantages of AM.

In order to explore AM benefits, DFAM research has been studied in various design stages. In conceptual and embodiment design stages, previous studies provided a framework to guide designers to generate new design for AM and identify AM potential [3]. Function structure was determined based on product requirements and then both economic and technical feasibilities were considered to evaluate new design [3]. In detailed design, design optimization has been mainly concerned to improve performance, such as topology optimization and application of cellular structure [4, 5]. Although the optimized part design has high shape complexity, AM can fabricate the optimized part design. Accordingly, DFAM in detailed design has been researched to add values in the part design and provide motivations of adopting AM in industry. However, AM processes also have manufacturing constraints. Accordingly, benchmark studies have been performed to alleviate AM process constraints by providing design rules [6, 7]. Furthermore, DFAM has been focused on optimizing build orientation to control support structure generation and redesigning parts to avoid support structure generation [8].

In these product design stages, design considerations, such as product, sustainability, and business considerations, should be considered as early as possible to leverage AM design potential. The product consideration is to improve

assembly operations by applying DFAM so that part consolidation and multi-part mechanisms without further secondary assembly operations are main considerations [9]. The sustainability consideration is to reduce harmful environmental impact by analyzing lifecycle of AM printed parts and then redesigning the parts for enhancing reusability and recyclability. Business consideration is to understand various costs from AM processes before adopting AM.

Therefore, the scope of this study is for conceptual and embodiment design stages, which are less considered in previous studies. Since part consolidation (PC) is one of the best AM design benefits by integrating multiple parts and assembly interfaces including moving mechanisms, this study provides a design method to reconceptualize existing product designs in the context of PC. The reconceptualization aims to add value in product design and identify design opportunities for PC when adopting AM. The proposed method consists of three steps. Firstly, function diagram is identified to analyze functional and physical structures of existing product. Secondly, important functions and function flows in the function diagram are selected to prioritize functions and flows. Lastly, parts with high important function and selected functional flows are selected and then grouped as candidates for consolidation. For generating new design concepts, physical relations among parts and function sharing between parts and modules are considered to group parts into larger modules for consolidation. The parts in the modules can be candidates for PC. Furthermore, AM design potential has been identified to support designers to leverage AM benefits while reconceptualizing the selected parts and modules. A case study of reconceptualizing existing motorcycle architectures as a novel electric motorcycle that are fully printed by AM is performed to demonstrate the usefulness of the proposed method.

### Literature review

PC is a promising design approach to take advantages of AM in conceptual and embodiment design stages. Once parts for the consolidation are decided, design optimization methods for the parts can be applied to achieve multiple design objectives. Accordingly, previous studies of part consolidation have focused on part identification for PC. Another reason why the part identification receives attention is the limitation of the build chamber size of AM machines. AM cannot fabricate an entire product consisting of various parts with different sizes and materials but fabricate a part or module that have smaller than the size of the build chamber. Accordingly, identification of part candidates for PC is necessary. Accordingly, Yang, et al. [10], Yang and Zhao [11], Yang, et al. [12] developed rule-based design methods for design feasibility to identify the part candidates. The rules aim to reflect AM machine limitations, such as material availability and part size limitation, assembly considerations by checking relative motion between parts, and maintenance frequency. It would result in feasible sets of parts for PC. However, the rule-based methods have less considered how to utilize AM design potential and (re)design existing design as new design when adopting AM. In order to consider AM design potential, Lindemann, et al. [13] provided a design methodology to consider the design feasibility and identify AM design potential, such as part complexity and part consolidation possibility. The design methodology helps assess the part candidates based on criteria for design feasibility and AM design potential and then select parts with the biggest design benefits for AM. Furthermore, it provides a process of redesigning selected parts based on function diagram but does not clearly describe the redesign process for generating new design. On the other hands, Kumke, et al. [14] proposed new opportunistic DFAM method which aims to support designers to leverage AM design potential. The DFAM method provided classification of AM design potential to understand interrelations between design potentials by using terms *levers* and *value propositions*. The levers are several types of design freedom given by AM, while the value propositions are detailed benefits of the levers for customer as shown in Figure 1. The interdependencies between the levers and the value propositions in the classification help identify promising design ideas based on existing product and new product design requirements.

## AM design potential

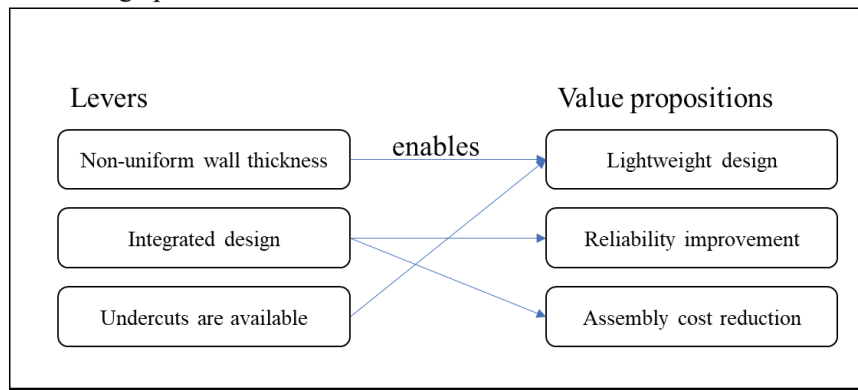


Figure 1 Classification of AM design potential (reproduced from [14])

From previous studies about PC, although many studies have dealt with functional analysis to understand functional and physical relationships between parts in order to decide design boundaries for PC, main contributions of them are identification of part candidates for consolidation rather than redesigning existing design to new design or generating new design by taking advantages of AM. Few studies have introduced finding AM enabled solutions which is related to redesign and new design in the conceptual and embodiment design stages. It would be critical for DFAM to guide designers to generate new design concepts or reconceptualize existing design as new design by incorporating the designers and various AM design potential. Therefore, this study proposed a design method to focus on redesign and new design in the early design stage.

### Part consolidation method by reconceptualization

In this study, a design method is proposed to support part consolidation in the conceptual and embodiment design stages. The objective of the proposed design method is to guide designers to reconceptualize existing product designs that only AM can achieve in the context of part consolidations. The proposed design method helps integrate selected parts, modules, and functions that are candidates for PC due to AM unique capabilities. This study provides three steps as shown in Figure 2.

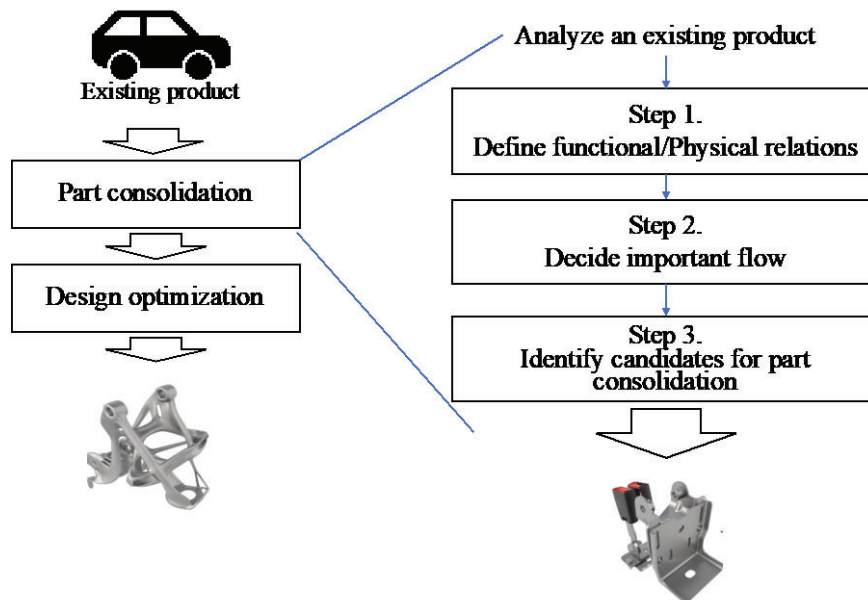


Figure 2 A process of part consolidation method

## Step 1. Define functional/physical relations

Firstly, the functional diagram of existing product is identified as fundamental information in this study. The function diagram has function elements, functional flows, and physical chunk. Main functions of the existing product can be decomposed into functional elements in Figure 3. The functional elements will be used to identify parts that share same function as candidates for PC in this study. Functional flows consist of material, signal, and energy flows between the functional elements so that they represent function types of the relations. It is important to group function elements to figure out physical chunk. Physical chunk is the design solutions to the functional elements. In other words, the functional elements can be matched with possible solutions which are concepts of parts, modules or systems. For example, as shown in Figure 4, function ‘store energy’ can be divided into specific functional elements and then matched with possible solutions like battery or fuel cell for ‘store electrical energy.’

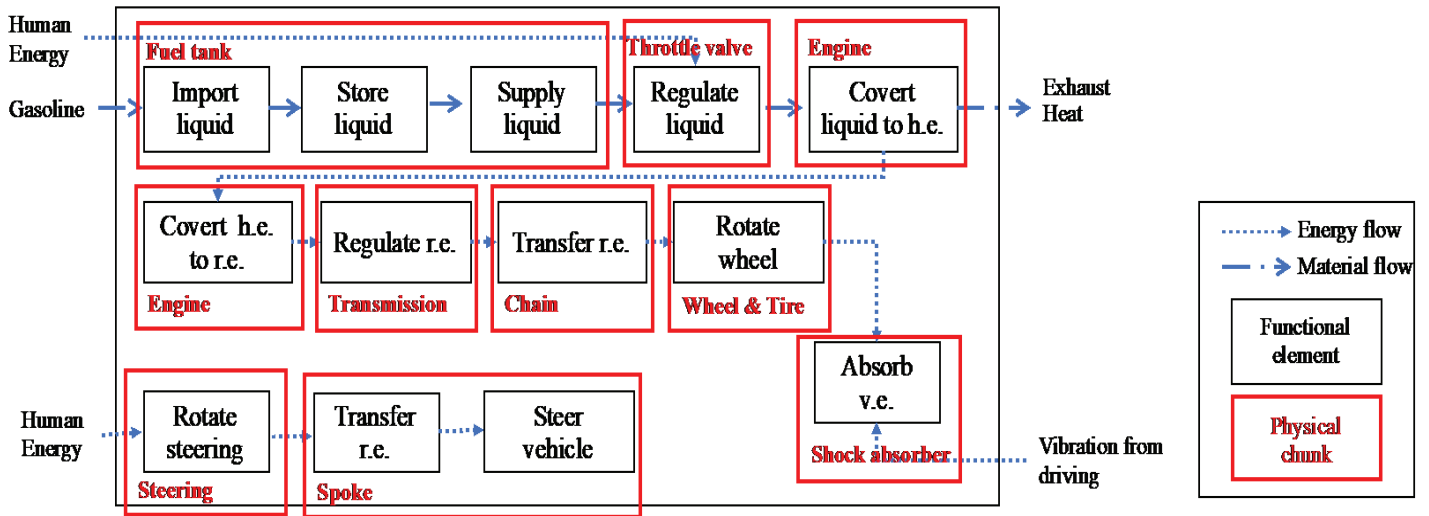


Figure 3 Function diagram of a motorcycle

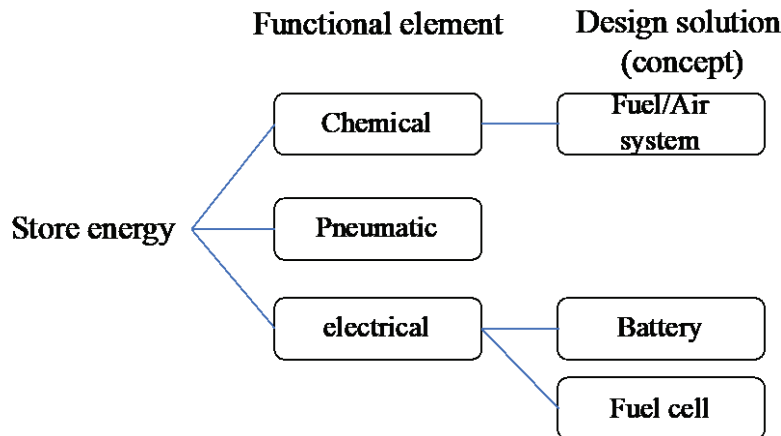


Figure 4 Function hierarchy [15]

## Step 2. Decide important flows

Secondly, important flows are selected from the functional flows. It aims to identify functions or physical chunks that are closely linked by the same functional flows. When there are many parts in a product with multiple functions, the function diagram would be complex. Function elements can be connected by various functional flows between other elements. Accordingly, identifying the most important functions and flows is helpful to screen the elements to select candidates for PC. When selecting different important flow, the candidates for PC will differ. For example, when a material flow is selected as an important flow in Figure 3 for changing energy source of motorcycle from gasoline to electricity, five functions from ‘import liquid’ to ‘convert liquid to heat energy (h.e.)’ are selected. When selecting energy flow starting from human energy, three functions ‘rotate steering’, ‘transfer rotational energy (r.e.)’, and ‘steer vehicle’ are selected as candidates for PC.

### Step 3. Identify candidates for part consolidation

Lastly, functions and parts that are linked to the importance flows are grouped into modules for PC. The functions and parts in modules have high possibility to be integrated, which is groups of candidates for PC. When integrating them, especially the parts, function sharing between the parts are considered to facilitate decision making for designers. If parts on the same important flow have common functions, the common functions can be shared by consolidating the parts.

After that, design values that are inherited by AM should be added into the candidates. Adding design values is a starting point of reconceptualization by exploring AM benefits. However, due to the inexperience of AM, designers would face limitation of creating novel design and facilitating AM unique capabilities. Accordingly, these design values are necessarily identified to support designers to add design values in three different levels as shown in Figure 5. Design values in product level can contain mass customization, performance improvement, and production improvement. The values in the product level can be more specified into manufacturing level and part level. Design values in manufacturing level can deal with production efficiency and supply chain benefits, while values in part level focus on design benefits from high design freedom by AM, such as lightweight structure. If more specific design values are listed and visualized, designers can utilize more diverse AM capability for design.

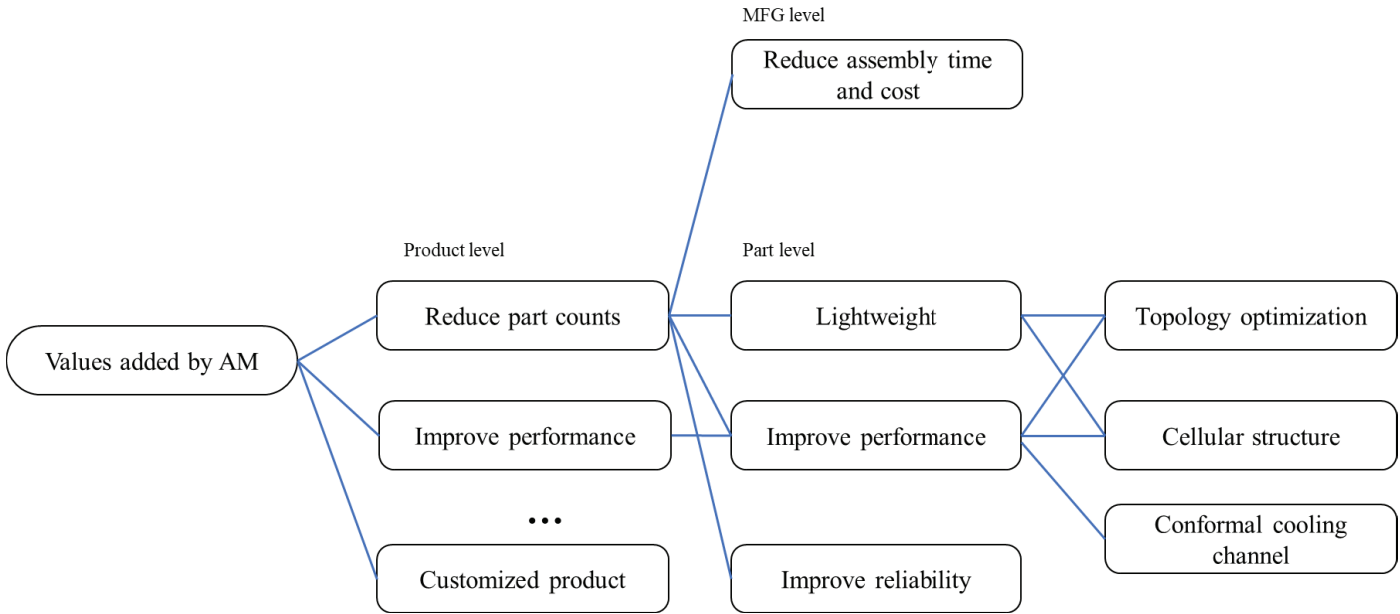


Figure 5 Design value structure that AM can provide

### Case study

A case study is performed to demonstrate the proposed design method on conventional motorcycle architectures by reconceptualizing the architecture to take advantage of novel function sharing and part consolidation opportunities in the conceptual design of AM fabricated electric motorcycles. New concept design of the electric motorcycle in Figure 6 (b), called as NERA, is printed by BigRep that is a large scale AM company [16]. The purpose of fabricating the NERA is to show AM fabrication capabilities. When designing the NERA, designers arranged core parts that are relevant functionally and then decided to leverage AM design potential and avoid manufacturing constraints [16]. The design process of the NERA has similarity with the proposed design method. Accordingly, this case study is performed to show how existing design of the motorcycle in Figure 6 (a) can be reconceptualized as new concept design of an electric motorcycle that will be fully fabricated by AM in Figure 6 (b).





Figure 6 Reconceptualizing from (a) existing motorcycle (Courtesy of Ducati) to (b) electric motorcycle that is fully printed by AM (Courtesy of BigRep)

### Step 1 Define functional/physical relationships

Main functions of the existing motorcycle are power generation for movement, steering direction, and vibration absorbing for comfort. Original complex function diagram can be simplified by only considering these main functions as shown in Figure 3. The function diagram can be represented more specifically by using part-function diagram in Figure 7. In the part-function diagram, main modules and parts are determined and the modules are connected by functional flows and physical relations.

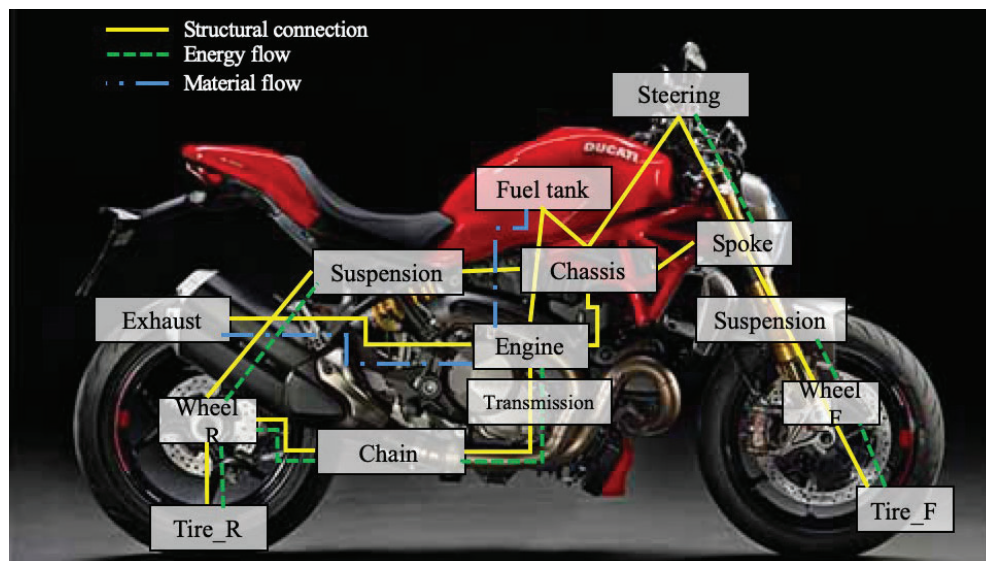


Figure 7 Part-function diagram of the existing motorcycle

### Step 2 Select important flow and Step 3 Identify candidates for part consolidation

Physical relations are selected as important flow to achieve part consolidation. As an example, parts related to steering the motorcycle, such as a wheel, tire, suspension, spoke, and steering handle, are selected based on their physical relations as shown in Figure 8. Additionally, functions of parts, such as 'rotate wheel' and 'steering the motorcycle,' are defined to check function sharing between parts. If functions are shared between parts, such as front wheel and tire with the same function 'rotate wheel,' then these parts can be worth integrating each other. By considering physical relations and function sharing, in this case, two groups are determined: the group with the wheel and tire, and the group with the suspension, spoke, and steering handle. It means that parts in each group have high chance to be consolidated by joining assembly interfaces.

After selecting part candidates and before reconceptualizing existing part candidates, designers should understand AM benefits in Figure 5 to add values in the existing design for reconceptualization. In this case, new design of the electric motorcycle, the NERA, takes advantages of mainly part count reduction and lightweight values. Accordingly, existing tire and wheel in the first group are consolidated and then reconceptualized by applying cellular structure as shown in Figure 8. It results in new concepts, which is airless tire and wheel. Parts in the second group from existing design are also reconceptualized by consolidating three parts into the forkless steering as shown in Figure 8.

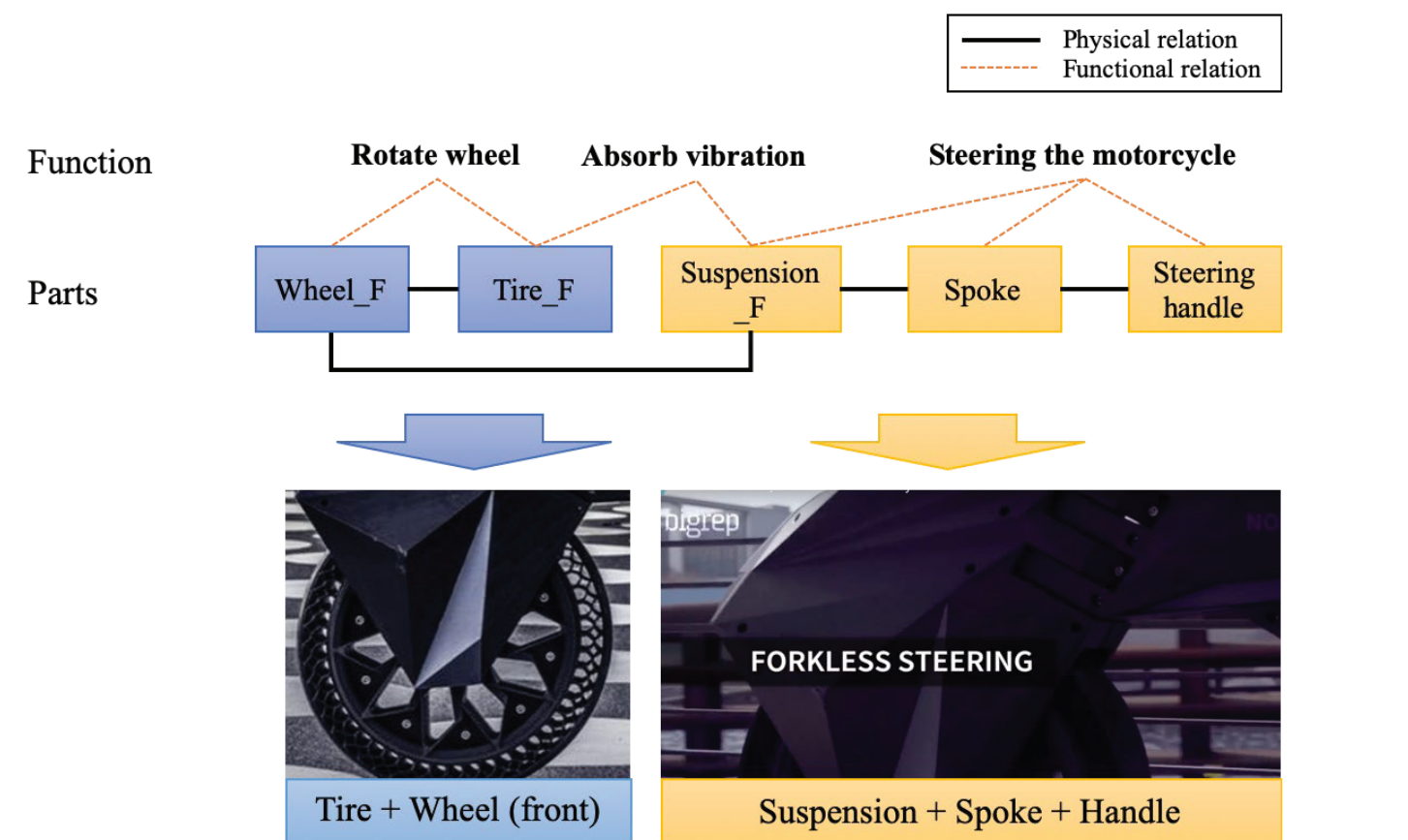


Figure 8 An example of part consolidation based on physical relations and function sharing

For integrating functions, energy flow has chosen as important flow in Figure 3. We focused on two functions of the existing motorcycle: ‘rotate wheel’ and ‘absorb vibration’ to add values for AM in Figure 9 (a). Then, parts that are related to these functions are determined such as rear wheel and tire, suspension, and chassis as shown in Figure 9 (a). Furthermore, it is checked whether any functions in these parts are shared. If the functions are shared, there is high possibility to integrate function. Therefore, we checked specific functions of suspension and chassis in Figure 9 (b). The chassis has multiple functions including ‘absorb vibration’, while the suspension has the only function ‘absorb vibration’. In this case, the function ‘absorb vibration’ is shared with two parts so that they can be redesigned by adding design values, such as cellular structure for lightweight structure, while consolidating each other. Finally, the proposed method shows possibility to help come up with novel body design of NERA by integrating same function from different parts. The novel body design has the bumper with cellular structure, instead of using the suspension, for absorbing vibration and making the motorcycle light.

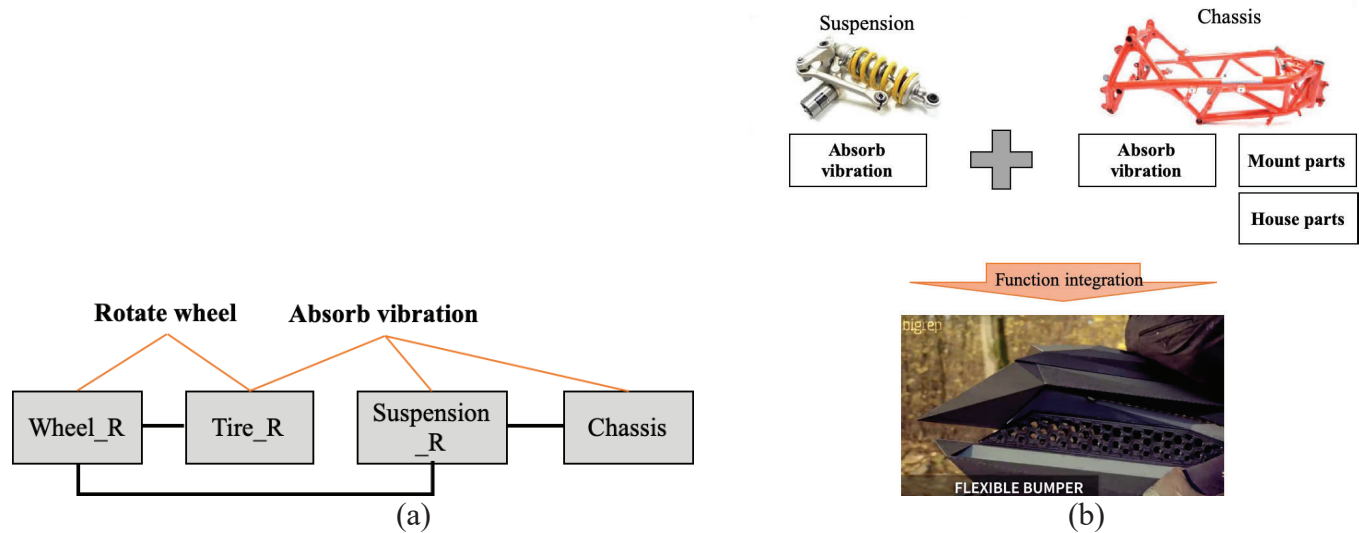
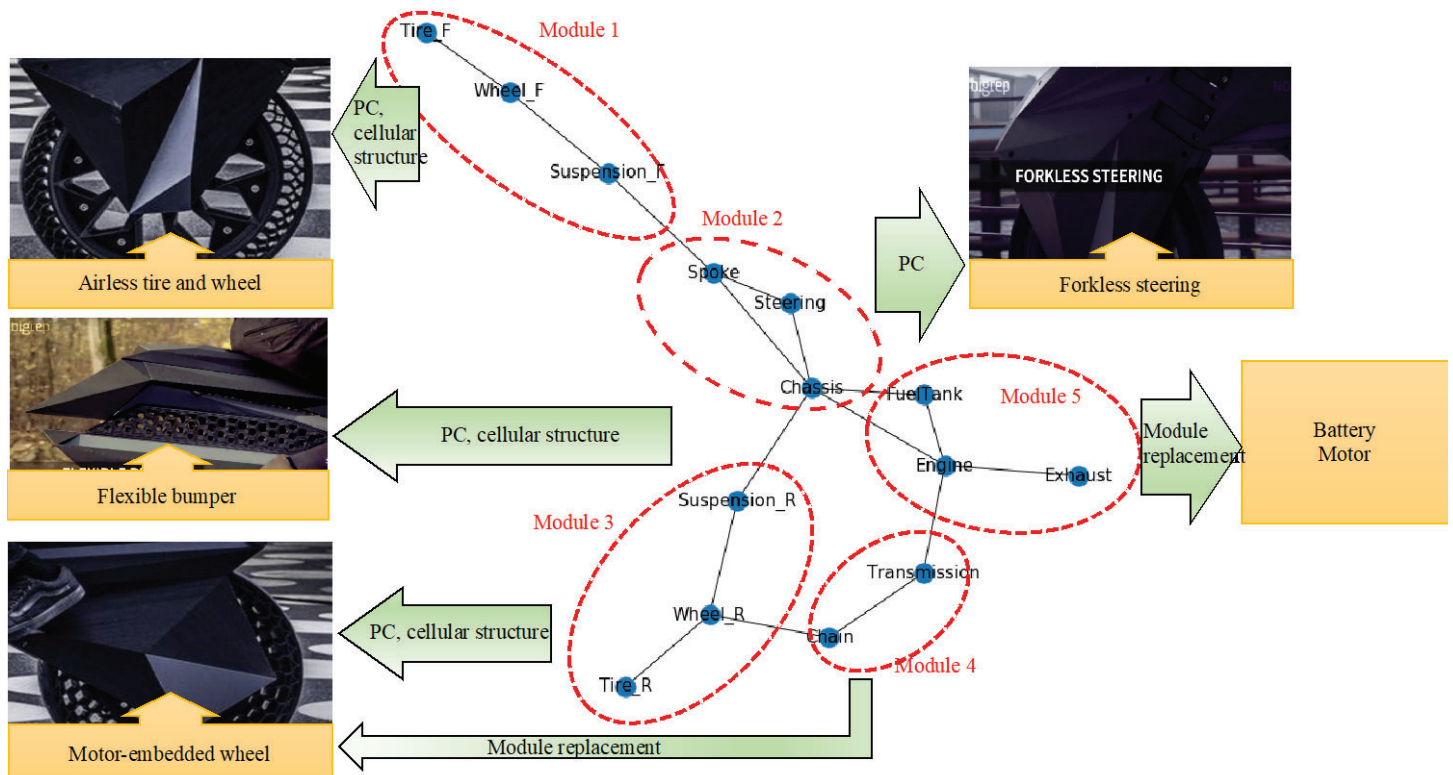


Figure 9 Novel body design from function integration: (a) function sharing between parts, (b) function integration

To sum up this case study, parts of conventional product are grouped into five modules in Figure 10 based on function sharing and selection of important flows. Since design team of the NERA aims to take advantage of part consolidation and lightweight structure, designers redesign the parts in the modules as new concepts for the NERA by considering these specific design benefits, such as ‘reduce assembly time and cost’, ‘improve reliability’, ‘lightweight’, and ‘improve performance’ as shown in Figure 5. As shown in Figure 10, modules 1 and 2 are redesigned to airless tire and wheel and forkless steering by adding design values such as cellular structure for lightweight as described in Figure 8. For the same reason, modules 3 and 4 are redesigned as motor-embedded wheel. Since module 4 is related to engine, it is replaced to the motor and then consolidated with module 3. Module 5 related to engine should be replaced to battery and motor for the NERA. Novel body design in Figure 9 and Figure 10 is derived from function sharing between suspension and chassis. Since the novel body design contains cellular structure that has function of absorbing vibration, the original suspension is not required for the NERA.





Overall, adding the design values for adopting AM in conceptual and embodiment design stages is critical because it can influence the lifecycle of a product. By adding design value for the lightweight and consolidating parts for part count reduction, the reconceptualized design would reflect the lifecycle consideration potentially. Due to lightweight structure, less material is consumed in manufacturing phase and fuel can be saved in use phase of the lifecycle of the NERA. The part count reduction by PC has an impact on simplified and less expensive assembly operations in manufacturing phase and facilitating disassembly operation because of less disassembly joints in the end-of-life phase.

### **Concluding remarks**

Part consolidation is one of the best ways to explore and take advantages of AM. This study provides a design method to support part consolidation when adopting AM. Especially, in order to explore AM capabilities in product design, the proposed method focused on the reconceptualization of existing design towards new design that only AM can fabricate. For the reconceptualization, physical and functional relations are utilized to group parts into modules. Parts in the modules are considered as candidates for part consolidation. After selecting parts for the consolidation, the possible design values from AM are identified to help designers explore AM benefits during part consolidation. This study contributes to guiding designers to create new design by identifying candidates for part consolidation and reconceptualizing existing design in conceptual and embodiment design stages.

Future work will be to model the function diagram in ontology and develop semantic network for AM design potential. It will allow easy identification of both function sharing between parts in the function diagram and AM design potential to generate promising AM design. Since the AM design potential such as part consolidation and lightweight structure has an impact on the lifecycle, the lifecycle considerations will be more studied and implemented in the conceptual and embodiment design stages.

### **Acknowledgement**

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