Assessment of modularity architecture for recovery process of electric vehicle in supporting sustainable design

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Abstract. The electric vehicle is one of the innovations to reduce the pollution of the vehicle. Nevertheless, it still has a problem, especially for disposal stage. In supporting product design and development strategy, which is the idea of sustainable design or problem solving of disposal stage, assessment of modularity architecture from electric vehicle in recovery process needs to be done. This research used Design Structure Matrix (DSM) approach to deciding interaction of components and assessment of modularity architecture using the calculation of value from 3 variables, namely Module Independence (MI), Module Similarity (MS), and Modularity for End of Life Stage (MEOL). The result of this research shows that existing design of electric vehicles has the architectural design which has a high value of modularity for recovery process on disposal stage. Accordingly, so it can be reused and recycled in component level or module without disassembly process to support the product that is environmentally friendly (sustainable design) and able reduce disassembly cost.

1. Introduction
The rising discussion of issues related to the concept of environmentally-sound industry encourages companies to improve environmental performance [1]. Moreover, the government provides strict regulations related to environmental issues so that the manufacturing industry is also required to comply with environmental regulations and produce environmentally friendly products [2–5]. Electric vehicles are made for purposes to reduce environment pollution by replacing the use of fossil energy into electrical energy. It does not produce exhausted gas and does have an impact on reducing environmental damage, but when viewed from the use of materials and recovery process, it does not necessarily have a good impact on the environment when the product has entered the disposal stage (cannot be used). Products that have complex architectures when they enter the disposal stage will have difficulty during disassembly processes, individual parts of the product will be difficult to reuse and may increase the likelihood of damage to parts [6]. Damaged and non-reusable products will then become waste which will have a negative impact on the environment. The complex architecture of the product recovery process will lead to difficulties in the disassembly stage, individual parts of the product will be difficult to reuse and may increase the likelihood of damage to parts [5,7]. Modular product design becomes one of the solutions to overcome difficulties during the disassembly process. The modular product can be the most critical factor in determining the preparation of product architecture [8,9]. Most of the design methods for modularity of product architecture from previous studies only consider the physical structure and function of the product architecture to improve the effectiveness of the manufacturing process. The backward approach is to sequence the disassembly
sequence of the disk drive product and then reassemble the modules which are considered optimal (Disassembly Sequence Structure Matrix) [10]. Other studies have added considerations to the purchasing function [11], from the life cycle aspect, manufacturing costs and interactions between components using Liason Network [12]. However, the use of such methods still has limitations in its ability to identify complex system elements such as in electric vehicle products. Approaches to the modular design of product architecture have been widely implemented, but the most thing to consider is only regarding function or physical relationship of product architecture [13,14].

2. Method
The object of this study used the product of electric vehicle X which has entered the disposal and recovery stage, shown in figure 1. This research was done by following the steps as follows:

a. Data collection. Data about components or parts of products, materials used, lifespan, and functions of each component.

b. Product Architecture Analysis. The linkages between the components to one another are represented using the design structure matrix (DSM) [15,16].

c. Identify Modular Drivers. This grouping stage is based on information on (a) the complexity of the relationship (categorized according to table 1. Its value is calculated using (1) and table 2). (b) the material similarity (value follows (2)), and (c) the lifespan of the component (its value refers to (3)).

![Figure 1. Product Design of Electric Vehicle X](image)

**Table 1. Definition of Interface Type [17]**

| Interface Type       | Definition                                                                 |
|----------------------|-----------------------------------------------------------------------------|
| Attachment (A)       | Structural connections between two components that require a type of connector |
| Spatial (S)          | Geometrical and locational constraints of a components                       |
| Transfer (T)         | Flow of materials or power between components                               |
| Control & Communication (C) | Relationship of signal or information flow is communicated or controlled by another component |
| Field (F)            | Interaction between two components in which one component can generate heat, vibration, or magnetic field |
| Power (P)            | Electrical connection between two components unlike communications and control interfaces |

$$\omega_{MCS} = \left[ \omega_i x (\# of 1's x 1) \right] + \left[ \omega_i x (\# of 2's x 2) \right] + \left[ \omega_i x (\# of 3's x 3) \right] + \left[ \omega_i x (\# of 4's x 4) \right] + \left[ \omega_i x (\# of 5's x 5) \right] + \left[ \omega_i x (\# of 6's x 6) \right]$$ (1)
with $\omega_i$ is weight value for each type of interface based on table below.

| Interface | Weight | Interface | Weight | Interface | Weight | Interface | Weight |
|-----------|--------|-----------|--------|-----------|--------|-----------|--------|
| A         | 2.974  | SC        | 21.435 | ATC       | 64.025 | PCF       | 76.142 |
| S         | 1.795  | SF        | 22.843 | ATF       | 66.137 | TCP       | 75.598 |
| P         | 6.832  | SP        | 17.253 | ATP       | 57.752 | TF P      | 77.710 |
| C         | 8.923  | TC        | 36.735 | ACF       | 64.568 | ASTC      | 92.546 |
| T         | 9.445  | TF        | 38.143 | ACP       | 56.184 | ASTF      | 95.362 |
| F         | 9.627  | PF        | 32.916 | AFP       | 58.296 | ASTP      | 84.182 |
| AS        | 9.538  | CF        | 37.098 | STC       | 60.488 | ATCF      | 123.872|
| AT        | 24.838 | PC        | 31.508 | STF       | 62.600 | ATCP      | 112.692|
| AC        | 23.793 | AST       | 42.642 | STP       | 54.215 | ACFP      | 113.418|
| AF        | 25.201 | ASC       | 41.074 | SCF       | 61.032 | ASTCF     | 163.815|
| AP        | 19.611 | ASF       | 43.186 | SCP       | 52.647 | ASTCP     | 149.841|
| ST        | 22.480 | ASP       | 34.801 | SFP       | 54.759 | ASTCFP    | 237.568|

\[
\omega(v_i, v_j) = \begin{cases} 
1 & \text{if the same material is used in } i\text{th and } j\text{th components} \\
0.5 & \text{if similar materials are used} \\
0.3 & \text{else}
\end{cases}
\] (2)

\[
\omega(v_i, v_j) = \frac{\min \text{lifespan} (v_i, v_j)}{\max \text{lifespan} (v_i, v_j)}
\] (3)

d. Identification of Modular Architecture. After obtaining modules based on a modular driver then identify existing modular architecture of the electric vehicle X.

e. Evaluating Modular Architecture. Perform measurement Module Independence (MI) and Module Similarity (MS). Evaluation category of Modularity Architecture (MA) is based on MI and MS values, which is calculated using (4)-(7) and the category of MA shown in fig. 2.

\[MI = \frac{\sum_{i=1}^{N} \text{Intra-module interface complexity}_i}{\text{Total interface complexity}}\] (4)

\[MS = \frac{\sum_{i=1}^{N} \text{Max} (S_{ij})}{N}\] (5)

\[S_{ij} = \left[ \frac{S_{i1}}{n}, \frac{S_{i2}}{n}, \ldots, \frac{S_{iN}}{n} \right] = \sum_{j=1}^{N} S_{ij}\] (6)

\[MA = \begin{cases} 
A, & \text{if } MS \geq \theta_1, MI \geq \theta_2 \\
B, & \text{if } MS \geq \theta_1, MI < \theta_2 \\
C, & \text{if } MS < \theta_1, MI \geq \theta_2 \\
D, & \text{if } MS < \theta_1, MI < \theta_2
\end{cases}\] (7)

Value of $\Theta_1$ and $\Theta_2$ as the constant of the decision limits of the product architecture category is 0.5.

**Figure 2.** Category of Modularity Architecture (MA) [6]
3. Results and Discussions
DSM is used to represent inter-relationship between components. Based on DSM built adjacency matrix, then generate the relationship between module and component. In the electric vehicle models analyzed, there are 102 components (shown in table 3) grouped into 9 modules or clusters. Its Namely (a) Frame, (b) Front Left and Front Right Wheel, (c) Brake System, (d) Steering, (e) Seat, (f) Drive Train, (g) Electronic System, (h) Rear Left and Right Back, and (i) Body.

### Table 3. Component List of Electric Vehicle X

| No. | Part Name      | Part Name          | Part Name          | Part Name          | Part Name         | Part Name         |
|-----|----------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| 1   | Frame          | 27 Tire right      | 28 Shaft           | 29 Disk brake left | 30 Brake caliper left | 31 Disk brake right |
| 2   | a-arm upper left | 32 Brake caliper right | 33 Pedals gas   | 34 Pedals brake   | 35 Master rem   | 36 Wire brake |
| 3   | a-arm lower left | 37 Rack            | 38 Pinion          | 39 Housing rack & pinion | 40 Tie rod left     | 41 Tie rod right |
| 4   | a-arm upper right | 42 Bushing         | 43 Steering rod    | 44 Rolling bearing | 45 Housing bearing | 46 Steering wheel |
| 5   | a-arm lower right | 47 Seat            | 48 Motor brushless | 49 Adaptor sprocket diff | 50 Sprocket up     | 51 Sprocket low |
| 6   | Bushing left   | 52 Differential gears | 53 Adaptor sprocket diff | 54 Chain           | 55 Shaft          | 56 a-arm upper left |
| 7   | Bushing right  | 57 a-arm lower left | 58 a-arm upper right | 59 a-arm lower right | 60 Bushing left | 61 Bushing right |
| 8   | Push rod left  | 62 Spacer left     | 63 Spacer right    | 64 Push rod left   | 65 Push rod right | 66 Rocker arm left |
| 9   | Push rod right | 67 Rocker arm right | 68 Absorber left   | 69 Spring left     | 70 Absorber right | 71 Spring right |
| 10  | Rocker arm left | 72 Tie rod left    | 73 Tie rod right   | 74 Bushing left    | 75 Bushing right  | 76 Knuckle left  |
| 11  | Rocker arm right | 77 Knuckle right   | 78 Single row ball bearing left | 79 Single row ball bearing right | 80 Rim wheel left | 81 Rim wheel right |
| 12  | Absorber left  | 82 Tire left       | 83 Tire right      | 84 Disk brake left | 85 Brake caliper right | 86 Disk brake right |
| 13  | Spring left    | 87 Brake caliper right | 88 Battery pack   | 89 Shutdown circuit | 90 Sensor         | 91 Controller motor |
| 14  | Absorber right | 92 Vehicle control | 93 Dash board      | 94 DC to DC converter volt | 95 MCB           | 96 Contactor   |
| 15  | Spring right   | 97 Telemetric antenna receiver | 98 Telemetric antenna deliver | 99 Front body      | 100 Rear body    | 101 Left side  |
| 16  | Knuckle left   | 102 Right side     |                    |                    |                    |                    |
| 17  | Knuckle right  |                    |                    |                    |                    |                    |
| 18  | Bushing knuckle left |                    |                    |                    |                    |                    |
| 19  | Bushing knuckle right |                    |                    |                    |                    |                    |
| 20  | Spacer left    |                    |                    |                    |                    |                    |
| 21  | Spacer right   |                    |                    |                    |                    |                    |
| 22  | Rolling bearing left |                    |                    |                    |                    |                    |
| 23  | Rolling bearing right |                    |                    |                    |                    |                    |
| 24  | Rim wheel left |                    |                    |                    |                    |                    |
| 25  | Rim wheel right |                    |                    |                    |                    |                    |
| 26  | Tire left      |                    |                    |                    |                    |                    |

### Table 4. Interface Matrix Steering

| Part | 41 | 42 | 43 | 44 | 45 |
|------|----|----|----|----|----|
| 41   |    | S(2) |    |    |    |
| 42   | S(2) |    |    |    |    |
| 43   |    | S |    |    |    |
| 44   | S | S |    |    |    |
| 45   | S |    |    |    |    |

### Table 5. Adjacency Matrix Interface Complexity Steering

| Part | 41 | 42 | 43 | 44 | 45 |
|------|----|----|----|----|----|
| 41   |    | 3.590 |    |    |    |
| 42   | S(2) |    |    |    |    |
| 43   |    | 1.795 |    |    |    |
| 44   | S |    | 1.795 |    |    |
| 45   | S |    |    | 1.795 |    |
Table 6. Adjacency Matrix Similarity
Material Steering

| Part | 41 | 42 | 43 | 44 | 45 |
|------|----|----|----|----|----|
| 41   |    | 1.00 |    | 0.50 | 0.30 |
| 42   | 1.00 |    |    |    |    |
| 43   | 0.50 |    |    |    |    |
| 44   | 0.30 |    |    |    |    |
| 45   |    |    |    |    |    |

Table 7. Adjacency Matrix Similarity Lifespan
Steering

| Part | 41 | 42 | 43 | 44 | 45 |
|------|----|----|----|----|----|
| 41   |    | 0.188 |    | 0.188 | 0.250 |
| 42   | 0.188 |    |    |    |    |
| 43   | 0.188 |    |    |    |    |
| 44   | 0.188 |    |    |    |    |
| 45   | 0.250 |    |    |    |    |

For example, the interface form of the matrix in the steering module can be seen in table 4, while the adjacency matrix of the steering module for complexity, material similarity and lifespan can be seen in tables 5, 6 and 7 respectively.

Table 8. Modularity Architecture on Existing Design

| Architecture | MI | MS Material | MS Lifespan | MEOL |
|--------------|----|-------------|-------------|------|
| Existing Design | 0.685 | 0.718 | 0.696 | 0.700 |

Based on table 8, the value is then plotted into four regions based on the Module Independence (MI) and Module Similarity (MS) values as shown in fig. 3. The decision point of modular architecture category is determined based on two thresholds $\Theta_1, \Theta_2 = (0.5, 0.5)$. The threshold value is flexible depending on the design strategy including customer demand for product or module recovery, the quality of the recovery product, or the cost of recovery and profit [15]. Therefore, based on fig. 3, the existing design of electric vehicle X has been classified Eco-Modular architecture, it has seen from the MI and MS values of the material and lifespan that is above 0.5.

![Category of Modularity Product Architecture](image)

Based on the classification of architectural type of existing design of electric, vehicle X consists of 9 modules in one product. It can be said that the design can be recycled and reused without further disassembly process at component level or module. The value of modularity product architecture at the end of life or MEOL stage also shows that the architectural design of electric vehicle X product is relatively high at 0.7. This value is obtained because each value of MI, MSMaterial and MSLifespan is above 0.5. The highest value contribution is obtained from the value of MSMaterial and MSLifespan whose equation contains the variable N or the number of modules in the product. The number of modules in the product in the calculation of Modular Similarity both material and lifespan becomes the divisor in the calculation to enable an effect on the high value of MEOL.
4. Conclusion
The modular design of the architecture in electric vehicles X has been classified as an eco-modular architecture with an $M_{EOL}$ value of 0.7 so that for recovery process in the disposal stage of the product the electric vehicle can be reused and recycled without further disassembly processes at the component level or modules so as to support sustainable design, and able to reduce the cost of disassembly.

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