Development of an end-of-life vehicle recovery model using system dynamics and future research needs

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Abstract. The implementation of end-of-life vehicle (ELV) recovery policy in Malaysia has led vehicle manufacturers to look at different ways to improve design and development of vehicles. Nowadays, it is crucial to incorporate end-of-life (EOL) design strategies into the vehicle design in order to enhance the effectiveness of the ELV recovery network. Although recent studies have shown that product design has a significant effect on the product recovery rate, there is a lack of studies on how EOL design strategies affects the effectiveness of ELV recovery, particularly when there are dynamic changes in the behaviour of the product recovery network. Thus, in this study, we developed a preliminary model based on the system dynamics approach in order to predict the effectiveness of ELV recovery in response to dynamic changes of various factors (including EOL design strategies) in the business environment. We developed this model based on preliminary data that we had gathered from unstructured interviews with the key stakeholders of ELV management in Malaysia. We believe that our model will greatly benefit product designers in incorporating the appropriate EOL design strategies in order to boost ELV recovery effectiveness in Malaysia.

1. Introduction
It is known that the disposal of end-of-life vehicles (ELVs) creates hazardous wastes and toxic emissions. The dramatic increase in the number of vehicle ownership throughout the world has led to a significant increase in global fuel demands, material requirements, and carbon emissions [1]. The results of a survey on 27 European countries in 2012 revealed that ELVs contribute to 6,230,000 tonnes of wastes, of which the highest amount of ELV wastes was generated in France (1,229,096 tonnes), followed by United Kingdom (1,129,392 tonnes) and Italy (874,887 tonnes) [2]. In 2012, 84.1 million vehicles were manufactured in order to fulfil consumer demands, with China, United States of America and Japan being the countries with the highest statistics of vehicle production and usage [3]. Malaysia was ranked as the third country in Asia in terms of the highest vehicle production and sales in 2013. According to Amelia et al. [4], most of the vehicle sales in Malaysia was dominated by local manufacturers (i.e. PROTON and PERODUA), and both of these manufacturers use new parts in vehicle design and development. However, owing to the detrimental impact of vehicle production, usage and wastes on the environment, it is more crucial than ever for manufacturers to be proactive in tackling sustainability issues in order to improve the quality of life of the people while simultaneously...
reduce environmental impact. Hence, the sustainable manufacturing concept was introduced to assist manufacturers to achieve this purpose [5]. Sustainable manufacturing is implemented throughout the product life cycle, beginning from the acquisition of raw materials until the end of life (retirement) of the product, taking into consideration the levels, processes, and systems involved in manufacturing [6]. In general, the product life cycle consists of four stages: (1) pre-manufacturing, (2) manufacturing, (3) use, and (4) post-use.

Product recovery elements are an essential part of the cradle-to-cradle philosophy, in which wastes recovered at the product end of life are used as the raw materials to manufacture new products. According to Jawahir et al. [6], the term ‘recover’ refers to the activity of collecting EOL products for subsequent post-use activities. According to these researchers, the main goal of redesign, remanufacturing, reuse, recover, recycle and reduce (i.e. the so-called 6R concept) is to reduce wastes, particularly at the product end of life. The product design stage appears to be a critical stage to incorporate EOL design strategies into the product which will facilitate product recovery after the product has reached its end of life [7]. Nowadays, manufacturers should implement the product recovery concept in order to boost their environmental image, which in turn, gives them a competitive edge, considering that consumers are becoming more environmentally conscious. By implementing the product recovery concept, new products can be launched into the market while conserving natural resources, maximizing the consumption of materials and minimizing wastes [6]. It is evident here that the product design plays a crucial role in incorporating product recovery strategies into the product.

There are many challenges in incorporating product recovery strategies (or rather, EOL design strategies) in vehicle design in Malaysia. The concept of ELV recovery is relatively new in this country due to several barriers which hinder its effective implementation. At present, it is a norm for manufacturers in Malaysia to use new parts in manufacturing new products [4]. In addition, there is a lack of knowledge in eco-design [8] as well as ELV management. There are no reliable statistics on the number of ELVs that have been recovered in Malaysia to date [9]. Furthermore, there is a lack of a proper ELV management system [10]. It is found in a recent study [11] that most local manufacturers do not consider design for environment and design for disassembly as part of their strategy to reduce the environmental impact of their products. All of these issues need to be addressed and hence, there is a critical need to understand how EOL design strategies can contribute towards a positive environmental impact of products, specifically ELVs.

In this study, we propose a preliminary model for ELV recovery in Malaysia based on the system dynamics approach in order to gain a better understanding on the impact of EOL design strategies (particularly design for reuse, design for remanufacturing, and design for recycling) on ELV recovery effectiveness. We believe that our model will greatly facilitate product designers in the automotive industry to predict the ELV recovery effectiveness when there are dynamic changes in the behaviour of the ELV recovery system.

2. Literature review

At present, there is a large number of studies published in the literature related to the application of system dynamics (SD) in analysing EOL design strategies, and several key works in this field are summarized in table 1.
Table 1. Summary of key works related to the application of SD in analysing EOL design strategies.

| Field of study | EOL design strategy | Key findings of the study | Limitations of the study | Reference |
|----------------|---------------------|---------------------------|--------------------------|-----------|
|                | Refurbishing        | • In general, closed-loop supply chain policies require a well-calibrated return rate for various different types of products.  
• A sustainable return policy increases sales significantly.  
• Product design as well as social awareness and acceptance of refurbished products are critical for aftermarket activities. | The study is only focused on cost benefit scenario and analysis. | [12] |
|                | Policy              | • Increasing the number of remanufacturers is greatly beneficial during the initial stages of industrial development.  
• There is a need for recycling subsidy for insufficient cores. | The case study is only carried out for auto parts in China.  
• The authors assumed that 100% of the recycling subsidy fee goes to the recyclers. | [13] |
|                | Recycling and remanufacturing | • Auto recyclers and operators who are able to adapt their premises and workforce are more likely to remain longer in the business. | The study is focused only on three areas: (1) premises, (2) workforce, and (3) sourcing of ELVs. | [14] |
|                | Recycling           | • The authors are able to correctly model the workflow in and between the different phases of processes. | The study is focused on the engineering design process. | [15] |
|                | Sustainable manufacturing | | | [16] |
| Legislation | Recycling and disposal | 
| --- | --- | 
| • Legislation has a significant effect on the sum of waste disposal. | • The case study is carried out on waste electrical and electronic equipment (WEEE) and refrigerators. | [17] |
| • Delays in legislation are not considered in the activities of the closed-loop supply chain. |  |  |

| Reducing, reuse and disposal | Recycling and disposal | 
| --- | --- | 
| • Levying tax on used car exports will facilitate control of used car exports and promote economic opportunities for manufacturers, remanufacturers, recyclers, consumers and the Government of Japan. | • The study is limited only to the automotive industry in Japan. | [18] |
| • The study does not address the joint effect of refurbished and recycled products towards sustainability. |  |  |

| Recycling | Materials | 
| --- | --- | 
| • The recovery rate is influenced by the material composition of the vehicle. | • The recovery rate is influenced by the material composition of the vehicle. | [19] |
| • It is expected that the amount of shredder residue per vehicle will continue to rise over the years. |  |  |

| Recycle | Recycling | 
| --- | --- | 
| • Product design affects product 'mineralogy', recycling of cars, and the recycling rate. | This study is limited to wrought and cast aluminium steel, copper, as well as remainder materials including organic fraction. | [20] |

Design for product recovery has a long history, as evidenced from the number of key works related to EOL design strategies shown in table 1. In general, the design strategies can be classified as policy, design processes, legislation and materials. However, based on our literature survey, none of these studies are focused on improving the ELV recovery effectiveness. In addition, there are only a few studies focused on simultaneous implementation of multiple EOL design strategies (e.g. reuse, recycling and remanufacturing) [13, 18–19, 21–24]. Even though [25] considered all of these strategies, their study is centred on searching for an optimal solution and they did not use dynamic and stochastic approaches such as SD. Based on the results of our literature survey, we perceived that it is crucial to develop a model for ELV recovery in Malaysia. We envisioned that our model will assist product designers in the automotive industry in Malaysia to predict ELV recovery effectiveness, taking into consideration the dynamic changes of interrelated factors involved in ELV recovery. This
model will indeed be useful since it can be used by product designers to assess how the EOL design strategies (particularly design for reuse, design for remanufacturing, and design for recycling) affects ELV recovery effectiveness during the early stages of product design and development. We used the SD approach to develop our model.

2.1. Causal loop diagrams

The SD concept was introduced by Jay Wright Forrester. This technique involves creating a causal loop diagram, which is a pictorial representation of the cause and effect of the system. This diagram is developed based on the development of stock and flow. In this study, we developed the causal loop diagram by identifying the variables of the ELV recovery system from literature survey. Figure 1 shows an example of a causal loop diagram, which shows how an automotive recycling programme affects the workforce of the automotive recycling industry [14]. The cause and effect of this causal loop diagram is described briefly as follows:

The starting point of this causal loop diagram is ‘Business turnover’, which increases (↑) the ‘Workforce size’ of auto recyclers, which in turn, increases (↑) the ‘Labour cost’. The increase in ‘Labour cost’ decreases (↓) ‘Business profits’ while at the same time increases (↑) ‘Optimized operations’. The increase in ‘Optimized operations’ increases (↑) the ‘Workforce skill level’, which in turn, increases (↑) the ‘Workforce efficiency’. The increase in ‘Workforce efficiency’ increases (↑) the ‘Workforce size’.

![Figure 1. Example of a causal loop diagram for workforce dynamics [14]](image)

In this study, we created causal loop diagrams for ELVs and reusable parts, as shown in figure 2, respectively. We extracted the variables to construct the causal loop diagrams after reviewing the works of [26] and [27].

There are two primary loops in figure 2(a), which are described as follows:

1. ‘Dismantling activities’ will decrease (↓) ‘ELVs’, which will increase (↑) the ‘Operation cost’. The increase in ‘Operation cost’ (↑) will reduce (↓) the ‘Number of ELV parts removed’, which will reduce (↓) ‘Recycling activities’. The decrease in ‘Recycling activities’ will increase (↑) ‘ELVs’.

2. The increase in ‘Operation cost’ will reduce (↓) ‘ELV management’, which will increase (↑) ‘Car imports’. The increase in ‘Car imports’ will increase (↑) ‘Disposal cost’, which in turn reduces (↓) the ‘Number of participating firms’ and consequently decreases (↓) ‘ELV management’. The decrease in ‘ELV management’ will increase (↑) ‘ELVs’.

The causal loop diagram shown in figure 2(b) is described as follows: An increase in the ‘Value of reusable parts’ will increase (↑) the ‘Profits gained from reusable parts’, which leads to an increase (↑) in the ‘Collection of parts’. The increase in the ‘Collection of parts’ will decrease (↓) the ‘Demand for products from original equipment manufacturers’, which consequently increases (↑) the ‘Demand for reusable parts’ and ‘Value of reusable parts’. The increase in the ‘Value of reusable parts’ will also promote (↑) the ‘Number of remanufacturers’, which will eventually increase (↑) the ‘Demand for reusable parts’.
The relationship between figure 2(a) and figure 2(b) can be established by connecting the effect of ‘Demand for reusable parts’ on ‘Recycling activities’. We expected that there will be an increase in recycling activities when there is an increase in the demand for reusable parts. This in turn, will boost effectiveness of the ELV recovery system in Malaysia. However, we perceived that it is not possible to achieve this goal without incorporating design for environment strategies during the early stages of product design and development. Selecting the appropriate EOL design strategies is a challenging task since product designers need to anticipate the long-term environmental impact of the product. Moreover, this task is influenced by a combination of factors which include policies stipulated by the local government and international authorities. Thus, careful planning is needed in order to select the appropriate EOL design strategies to be incorporated into the product.

3. Proposed model
There are various factors that need to be considered when selecting a suitable EOL design strategy. In this case, we need to consider the types of EOL design strategies available for ELVs, as well as identify the key performance indicators, and select endogenous and exogenous variables. This task is complicated by the fact that these factors are interrelated, and changing one factor may have significant effect on other factors within the product recovery network as well as ELV recovery effectiveness. For example, if the product designer selects design for reuse as the EOL design strategy, the product will have a specific recovery chain once it has reached its end of life. This recovery chain will affect other chains in the product recovery network such as economic growth for automotive spare part dealers as well as competition between remanufactured parts and those manufactured by original equipment manufacturers. Even though the ELV recovery scenario appears simple, it is actually complex in nature because of a variety of interrelated factors, and each of these factors may change because of market trends, which will have impact the ELV recovery effectiveness as a whole.
Figure 3 shows an example of the elements of design strategies. In this example, there are four design strategies, namely, design by original equipment manufacturers (OEM design), design for reuse (D.F.Reu), design for remanufacturing (D.F.Rem.) and design for recycling (D.F.Rec.). Each of these design strategies consist of two elements: (1) materials, and (2) operation cost. These elements are set up by the product designers during the early stages of product design and development to suit each design strategy. These elements have their own cause and effect towards the design strategies, as indicated by the shaded cells. This cause and effect will also affect other chains in the recovery network such as automotive spare part dealers, remanufacturers and recyclers. For instance, figure 4 shows the plot of a basic stock and flow analysis, which indicates how monthly recovery improvement affects the recovery effectiveness. We assumed here that the recovery activities improve at a rate of 6% per month. After one year, the recovery effectiveness is 72% instead of 0% at the start of the year. However, it shall be noted that this stock and flow analysis is carried out based on our understanding on the current ELV recovery scenario in Malaysia using the SD approach. For this reason, we implemented SD to link the EOL design strategies and ELV recovery factors in order to evaluate and predict the ELV recovery effectiveness. We believe that this technique is suitable to evaluate the impact of EOL design strategies on ELV recovery effectiveness based on the interrelationship between factors, as shown in figure 5. However, we still need to assess the reliability and capability of this model by taking into account the key performance ELV recovery indicators, controlled and uncontrolled factors, as well as design strategy elements (i.e. designer’s policy).

Figure 4. Basic stock and flow analysis

Based on our preliminary analysis, the recovery effectiveness plunges to −948% if the number of parts disposed per month is 84%, as shown in figure 5. Hence, we anticipate that incorporating EOL design strategies during the early stages of product design and development will enhance recovery effectiveness, as shown in figure 4. However, we need to conduct a critical assessment of the factors
involved to ensure that our model is representative of the actual ELV recovery scenario in Malaysia. It shall be highlighted that we developed this initial model based on literature survey as well as preliminary data that we gathered from unstructured interviews with the key stakeholders involved in ELV management in Malaysia. Our model is still incomplete, which is why a number of elements in the model are indicated by a question mark or hashtag, as shown in figure 5. At present, we have not yet obtained information regarding the data for reuse, data for recycling, compatibility data, collection of parts, collection compatibility rate, materials used, level of contamination from fasteners, availability of economical reprocessing, and market value of materials. We need to further refine our model in order to determine the best EOL strategies that should be implemented by product designers in order to enhance the effectiveness of ELV recovery in Malaysia, taking into account other factors such as stakeholders, economic factors and infrastructures.

Figure 5. Our preliminary model for ELV recovery in Malaysia

4. Conclusion
At present, ELV management is still relatively new in Malaysia due to several barriers which hinder its effective implementation including lack of knowledge on eco-design and other EOL design strategies such as design for reuse, design for remanufacturing, and design for recycling. Hence, it is imperative to gain a better understanding on how EOL design strategies contribute towards a positive environmental impact for ELVs. In order to fulfil this need, we propose a preliminary model for ELV recovery based on the system dynamics approach in order to understand the impact of different EOL design strategies (specifically design for reuse, design for remanufacturing, and design for recycling) on the effectiveness of ELV recovery in Malaysia.

We also present a brief review of studies pertaining to the application of system dynamics in analysing EOL design strategies. Selecting a suitable EOL design strategy to enhance ELV recovery effectiveness is a challenging task since the ELV recovery system involves a large number of factors with complex interrelationships that are subject to changes in market trends. Therefore, predicting the recovery effectiveness in such uncertainties is crucial in order to improve the current ELV management system in Malaysia. Our model offers a potential solution whereby product designers can analyse changing trends in the automotive industry from a holistic point of view. This tool will be beneficial for product designers to enhance the recovery effectiveness of ELVs in Malaysia.

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