Optimal Positioning of Product Components to Facilitate Ease-of-Repair

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Abstract

Design for ease-of-repair facilitates the reuse of products for multiple lifecycles through reducing the cost and time of repair processes. Due to existing technical and economic considerations, a fully repairable design may not be preferred by manufacturers and may not be requested by consumers. In this paper, an optimization framework is developed to determine the optimal configuration of components with the aim of minimizing the weighted mean-time-to-repair subject to constraints such as components’ connection criteria, reparability needs, and disassembly sequence. The findings can be incorporated into the early product design phase to increase consumers’ willingness to repair as well as the expected profit of recovery activities.

Keywords
Design for ease-of-repair, integer linear programming, repairability, product reuse

1. Introduction

Tons of electronic waste is discarded every year, although much of it can be reused if they are being repaired and upgraded. Surveying consumers’ attitudes towards repairing broken devices shows that consumers have a significant propensity for repair activities [1], but some reasons may discourage them. Among all these reasons, it seems that consumers’ repair decisions are most markedly affected by the cost of repair services [2]. As discussed in [2], people prefer to spend a limited budget on repairing a product over its lifespan. Repair services costs consist of two main parts: (1) spare parts; and (2) labor. The latter is basically related to time spent in repairing a broken device, and the repair time itself is related to the degree of repairability of a design. Hence, improving repairability would benefit both consumers and enterprises interested in remanufacturing End-of-Use/Life (EOU/L) products.

To call a product ‘repairable’, several factors—including the availability of spare parts, repair tools, and repair information—should be considered, rather than just assessing the teardown process. Factors such as access to repair information may significantly affect repair operations if they are performed by independent repair technicians who may not have access to repair guidelines easily. Repair processes, however, might be time-consuming for original manufacturers if components of a design are not effectively configured meaning that original manufacturers should take a specific number of steps to repair a broken product even if other established factors are controlled.
Throughout the literature, there are papers that have addressed the design for sustainable concerns (e.g., design for remanufacturing [3], recycling [4], and energy efficiency [5]). Hence, we focus more on the literature related to the design for ease-of-repair concept to draw conclusions concerning the potential research gap. Design for repairability is a promising solution to extend the lifespan of products by making the repair process economic and reasonably time-consuming.

For the last two decades, there have been attempts to study the disassembly planning problem for End-of-Use/Life products. As an early attempt to study the disassembly problem, Lambert [6] proposed an optimization model based on possible sub-assembly sequences to maximize net revenue. In this study and most of the subsequent studies, however, the repairability of a design is assumed to be fixed, and optimizing disassembly sequences has been targeted by applying different models under a different set of constraints [7,8].

Coulibaly et al. [9] developed an indicator by using a CAD 3D model and technical features of components (e.g., reliability) to measure repairability of a product at the early design stage. In another study, Gupta et al. [10] used a digraph to evaluate repairability of a system by comparing the actual and perfect design architectures. The comparison method is based on a set of repairability features. Here, a question may arise: ‘How to optimize design architecture of a product such that its repairability would be at maximum possible level?’ The term ‘possible’ refers to the set of technical constraints. Recently, Kobayashi et al. [11] applied the genetic algorithm to optimize the architecture of a design—including components layout and fastening methods—in order to facilitate removal procedures of high-value components from the product. In our paper, we develop a mathematical framework to optimally position a set of components by considering technical bi-lateral relationships between components and their chance of failure. In [11], extracting embedded values from EOU/L products is targeted, however, we aim at extending the lifespan of a product by considering the chance of failure of all components. As another difference, we also assume the distance between every pair of connected components. Finally, we proposed an integer linear programing model. This model is flexible enough to be extended for including more technical criteria and constraints. Optimally-positioned components can reduce the total expected repair effort, and consequently, remanufacturing workload.

A qualitative approach for assessing the repairability of a design has been developed by iFixit.com experts. iFixit.com is a wiki-based website hosting the repair manuals for different types of products, specifically consumer electronics such as mobile phones. A list of major and minor criteria is used to determine the repairability level of a particular device. The major criteria include the availability of repair information, ease of battery detachment, nonexclusive repair tools requirement, straight-forward disassembly process, and uncomplicated reassembly process. Unpacked layout of components, separable screen and display glass, lowest amount of adhesive, short disassembly process (less than half an hour), no need for heating element, minimum use of different types of screws (fewer than three different types), minimum use of fragile ribbon cables, having less than 30 screws, modular design, and finally replaceability of critical components (e.g., screen and battery) are counted as minor criteria. Although the proposed assessment method is accurate, it is not likely to be mathematically feasible. Considering all the constraints may complicate the optimization model. Furthermore, sharing the repair information with independent repair businesses seems to be a strategic decision. Hence, it may not be acceptable for original manufacturers since they may lose the potential repair demand.

Last but not least, it is likely that a modular design has higher repairability than a non-modular one [12]. The main purpose of studies that address design modularity is to optimally design modules of product families according to manufacturers’ and consumers’ preferences such as cost and quality [13]. Using the idea behind the modular design, our suggested model can be divided into two steps: (1) positioning components of each module; and (2) positioning modules of a product.

The rest of this paper is organized as follows: In Section 2, the design problem is explained. Next, an integer linear programming model is developed as a mathematical representative for the conceptual problem. A numerical example is presented in Section 4 to illustrate how to apply the proposed model. Finally, the study is concluded in Section 5 and some insights are provided for the early phase of a product design.

2. Problem Description

Consider a product that consists of $N$ components. Without loss of generality, we assume that the components can be positioned in $M$ different layers such that Layer 1 is the outermost layer from the center of the product. In addition, Layer 1 has the largest capacity for positioning components. It may not be possible to position a component in every single layer because of some technical limitations. Therefore, a set of feasible layers should be determined for every component. These components, of course, have functional and technical relationships with each other meaning that a failed component should be disconnected from all connected components. Figure 1 represents an example of the described model.
Any component may fail at any time, however, with a different failure rate. It is assumed that a product will be restored to its working condition when a failed component is replaced with a new one. The most repairable design is formed when components with a high chance of failure are positioned in upper layers in order to be more accessible. On the other hand, a component should be positioned as close as possible to its connected components. Meeting these two criteria, the time to replace a failed component would be at a minimum amount. Here, the question is how to minimize the total repair efforts by considering all mentioned technical constraints. In the next section, the problem is represented as an optimization model to find optimal positions of components.

3. Integer Linear Programming Formulation

A non-linear integer programming model is utilized to analytically describe the problem. Equations (1-4) represent the developed mathematical model. Let’s introduce the set of parameters, variables, constraints, and objective function. In this model, it is assumed that a product has $N$ components and $M$ layers. $\lambda_i$ represents the relative failure rate of component $i$. The relationships between components are represented by matrix $R$ such that $r_{ij}$ equals one if Components $i$ and $j$ are connected to each other. $V_k$ stands for the available capacity of Layer $k$ ($k=1,\ldots,M$). Here, available space might be a good example for the capacity constraint. The needed capacity for Component $i$ is represented by $v_i$. Positions of components are the variables in this model. $x_{ik}$ is one if Component $i$ is positioned at Layer $k$, and otherwise is zero.

Equation (2) presents the first constraint. According to this constraint, a component can be positioned in only one layer, ultimately. The second constraint is the capacity constraint (Equation (2)). The total capacity of all positioned components in Layer $k$ cannot exceed the available capacity of this layer. Finally, the objective function is defined in a way that the total repair effort is minimized. Assume that Components $i$ and $j$ are positioned at Layers $k$ and $l$, respectively ($x_{ik}$ and $x_{jl}$ are equal to one). Also, $r_{ij}$ is equal to one if Components $i$ and $j$ have a relationship. Thus, these components should be disconnected if one of the components is failed. Here, the amount of repair effort is quantified for the case of Component $i$’s failure. Given the failure rate of Component $i$, $\lambda_i [k-l]+\max (k, l)$ represents the expected repair effort for Component $i$ considering its relationship with Component $j$. $|k-l|$ is a measure of closeness, and $\max(k, l)$ represents the amount of repair effort needed to access the furthest component from Layer 1. Considering all possible configurations of components, the total expected repair effort can be calculated by Equation (1).

$$
\text{minimize } \sum_{i \in N} \sum_{k \in M} \sum_{j \in N} \sum_{l \in M} \left[ \lambda_i x_{ik} x_{jl} (|k-l|+\max (k, l)-1) \right] r_{ij} \\
\text{subject to } \sum_{k \in M} x_{ik} = 1, \quad i \in N, \\
\sum_{i \in N} v_i x_{ik} \leq V_k, \quad k \in M, \\
x_{ik} \in \{0,1\}, \quad i \in N, k \in M.
$$

We need to take one step further to obtain the minimum value of the objective function and optimal positions of components. A new variable, $z_{iklj}$ is defined in order to linearize the above-defined model. Then, the product of $x_{ik}$
and $x_{ij}$ is replaced by $z_{ikl}$, and three additional constraints are added to the model, which are represented by Equations (8-10). In the next section, the solution procedure is illustrated with a numerical example.

$$\min \sum_{i \in N} \sum_{k \in M_i} \sum_{j \in H_k} \sum_{l \in M_j} \lambda_{ijkl} \left( |k-l| + \max (l,k) - 1 \right) r_{ij}$$

subject to

$$\sum_{i \in N} x_{ik} = 1, \quad i \in N, \quad (5)$$

$$\sum_{i \in N} v_i x_{ik} \leq V_k, \quad k \in M, \quad (6)$$

$$z_{ikl} \leq x_{ik}, \quad i \in N, k \in M_i, j \in N, l \in M_j, i \neq j, \quad (7)$$

$$z_{ikl} \leq x_{jl}, \quad i \in N, k \in M_i, j \in N, l \in M_j, i \neq j, \quad (8)$$

$$z_{ikl} \geq x_{ik} + x_{jl} - 1, \quad i \in N, k \in M_i, j \in N, l \in M_j, i \neq j, \quad (9)$$

$$z_{ij} \in \{0,1\}, \quad x_{ij} \in \{0,1\}, \quad i, j \in N, k, l \in M, i \neq j. \quad (10)$$

4. Numerical Example
A numerical example is provided to show the application of the proposed model. In this example, optimal positions of eight components of a product are obtained. Equation (12) represents the relationships between each pair of components. Again, $r_{ij}=1$ means that Components $i$ and $j$ have a technical relationship. Here, this matrix can be multiplied by another one that shows the difficulty level to disconnect a pair of connected components. For example, a set of selected fastening methods can be compared with each other to assign them a relative difficulty-level score. Another way to incorporate the type of fasteners is to add a set of new variables to the model. We assume that a failed component is replaced with a new one, and then the product is restored to its working condition. Table 1 summarizes the parameters setting for this example. Among all components, Component A has the highest failure rate, however, Component D needs the highest capacity. On the other hand, Component C has the largest number of relationships with other components. There are several limitations on the possible positions for every component. For example, Component G can be only positioned at Layer 3. For example, the display screen of a phone should be positioned at the first layer. The total capacity of three layers is 420 units. However, the total required capacity of all components is 350 units. The rest of capacity is considered for the six existing connections between the components. In addition, we assume that all components have a cubical shape, which may not always be a true assumption. The remaining capacity may be considered as a possibility for upgrading the product in the future. Finally, a design should not be too packed such that it limits the performance of repair tools.

$$A \ B \ C \ D \ E \ F \ G \ H \n\begin{bmatrix}
A & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
B & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
C & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\
D & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
E & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\
F & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
G & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
H & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\
\end{bmatrix} \quad (12)$$
After solving the model, the optimal positions for components are $A \rightarrow 1$, $B \rightarrow 3$, $C \rightarrow 2$, $D \rightarrow 2$, $E \rightarrow 2$, $F \rightarrow 1$, $G \rightarrow 3$, and $H \rightarrow 1$. The optimal value of the objective function, $Z^*$, is 4.12. This unit of the objective function is the expected total repair effort per unit of time. The total capacity of positioned components in the first layer is 140 cm$^2$. This value for layer 2 and 3 is 135 and 75, respectively. The results of this model can be used to determine an optimized pricing strategy for repair services as well. Given optimal positions of components, the mean-repair-time values can be estimated. As a result, prices for repair services would be more appealing to consumers, and the total demand for repair services increases.

The size of the optimization problem depends on the number of components of a product. The problem for small devices like consumer electronics is not computationally expensive and finding optimal solutions is not hard. However, for large-size instances, heuristic algorithms can be employed.

### 5. Discussion and Concluding Remarks

In this paper, an integer linear programming model is developed to determine optimal positions of components in different layers of a product architecture, considering the minimum total expected repair effort. The basic idea behind the model is to maximize the level of accessibility to a set of components with a high chance of failure and a large number of relationships with other components. In the proposed model, two main constraints are included: a set of feasible layers is considered for every component, and a limited number of components can be positioned in each layer. A numerical example is used to illustrate the proposed model.

The purpose to improve repairability of a design might be misleading. First of all, improving repairability of a design may not be always aligned with manufacturers’ design policies. It is observed that manufacturers sometimes have to sacrifice the repairability of a design to achieve a higher technology competitiveness. Suppose that having more resolution on a curved-form display screen requires using special materials that increase crackability of the screen, and also increases the time of repair process due to the need for a specific repair tool. As a result, the repairability of product decreases, however, it increases the popularity of the smartphone because of the technical features. Second, we should consider whether a broken product is repaired by its original manufacturer or by independent remanufactures, repair shops, and consumers. Since the repairability of a product includes both design-related features as well as strategic policies such as sharing repair information and making spare parts available, a lower repairability does not necessarily mean that the repair process is complicated for original manufacturers as much as independent repair businesses. Repair information is not usually shared with users or independent repair technicians. Therefore, a repair process seems to be more complicated for someone who has limited access to the repair information. Without loss of generality, however, it makes sense that a device with a low degree of repairability is more time-consuming and hard-to-repair for manufacturers as well. Hence, considering these points in a design problem can be studied in the future.

In this model, we do not consider the type of connections between two components. Disassembling two components that are connected by a glue-based fastener is much more difficult than screw-based fasteners. Thus, the type of connection method can be added as a variable to the model. In this way, the model would be more realistic. Similar to the constraint on the feasible layers for each component, the set of feasible connection methods for each pair of components might be limited as well. There are, of course, other considerations in designing a product that should be considered. For example, design budget may limit the flexibility to select an ideal method connection for each pair of components. Therefore, the cost of design can be included in the model as an objective or constraint.

### References