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DESIGN FOR OPTIMAL END-OF-LIFE SCENARIO VIA PRODUCT-EMBEDDED DISASSEMBLY

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ABSTRACT

This paper presents a computational method for designing products with a built-in disassembly means that can be triggered by the removal of one or a few fasteners at the end of the product lives. Given component geometries, the method simultaneously determines the spatial configuration of components, locators and fasteners, and the end-of-life (EOL) treatments of components and subassemblies, such that the product can be disassembled for the maxim profit and minimum environmental impact through recycling and reuse via domino-like "self-disassembly" process. As an extension of our previous work, the present method incorporates EOL treatments of disassembled components and subassemblies as additional decision variables, and the Life Cycle Assessments (LCA) focusing on EOL treatments as a means to evaluate environmental impacts. A multi-objective genetic algorithm is utilized to search for Pareto optimal designs in terms of 1) satisfaction of the distance specification among components, 2) efficient use of locators on components, 3) profit of EOL scenario, and 4) environmental impact of EOL scenario. The method is applied to a simplified model of Power Mac G4 cube® for demonstration.

INTRODUCTION

Economic feasibility of an end-of-life (EOL) scenario of a product is determined by the interaction among disassembly cost, revenue from the EOL treatments of the disassembled components, and the regulatory requirements on products, components and materials. While meeting regulatory requirements is obligatory regardless of economic feasibility, EOL decision making is often governed by economical considerations [1]. Even if a component has high recycling/reuse value or high environmental impact, for instance, it may not be economically justifiable to retrieve it if doing so requires excessive disassembly cost. Since the cost of manual disassembly depends largely on the number of fasteners to be removed and of components to be reached, grabbed, and handled during disassembly, it is highly desirable to locate such high-valued or high-impact components within a product enclosure, such that they can be retrieved by removing less number of fasteners and components.

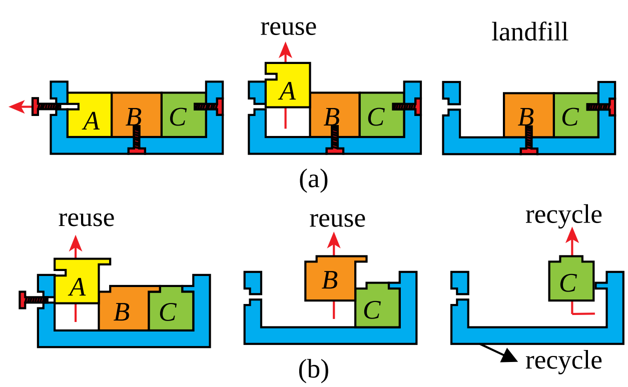

Figure 1. (a) Conventional assembly (b) assembly with embedded disassembly.

As a solution to this problem, we have previously introduced a concept of product-embedded disassembly [2, 3], where components are spatially arranged within a product enclosure such that they can be reached and removed in an optimal sequence. In order to minimize the number of fasteners, the relative motions of components are constrained, wherever possible, by locators (*eg*., catches, lugs, tracks and bosses) integrated to components.

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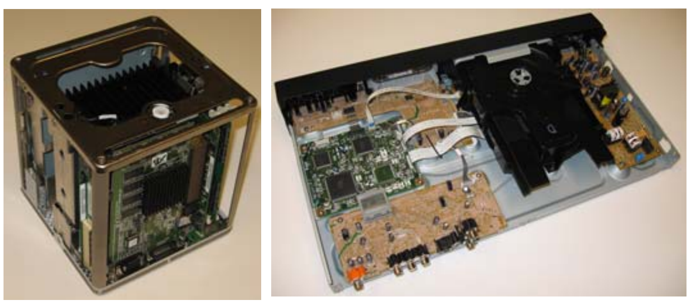
Figure 1 illustrates the concept of product-embedded disassembly as compare to the conventional disassembly. In the conventional assembly (Figure 1 (a)), components A, B and C are fixed with three fasteners. With high labor cost for removing fasteners (as often the case in developed countries), only A may be economically disassembled and reused, with the remainder sent to landfill. This end-of-life (EOL) scenario (*i.e.,* disassemble and reuse A, and landfill the remainder) is obviously not ideal both from economical and environmental viewpoints. In the assembly with embedded disassembly (Figure 1 (b)), on the other hand, the motions of B and C are constrained by the locators on components. As such, the removal of the fastener to A (called a trigger fastener) activates the domino-like self-disassembly pathway A→B→C. Since no additional fasteners need to be removed, B and C can also be disassembled, allowing the recycle/reuse of all components and the case. This EOL scenario (*i.e.,* disassemble all components, reuse A and B, and recyle C and the case) is economically and environmentally far better than the one for the conventional assembly.



(a) (b)

Figure 2. Example products suited for product-embedded disassembly, (a) desktop computer (b) DVD player.

The concept of product-embedded disassembly can be applied to a wide variety of products, since it requires no special tools, materials, or actuators to implement. It is particularly well suited for electrical products assembled of functionally modularized components, whose spatial configurations within the enclosure have some flexibility. Figure 2 shows examples of such products. A desktop computer in Figure 2 (a) is assembled of functionally distinct components such as a motherboard, a hard drive, and a power unit, arranged to fit within a tight enclosure. The components are, however, not completely packed due to the need of the air passage for cooling and the accessibility for upgrade and repair. Thanks to this extra space and electrical connections among components, the spatial configurations of the components have a certain degree of flexibility. A DVD player in Figure 2 (b) even shows roomier component arrangements, due to the consumers' tendency to prefer large sizes in home theater appliances. Since designing products with single "disassembly button" may cause safety concerns, the method will, in practice, be best utilized as an inspiration to the designer during the early stage configuration design and critical components can be independently fastened with a secure, conventional means.

The concept, however, may be unsuitable to the products that allow very little freedom in component arrangements. Examples include mobile IT products such as cell phones, laptop computers, MP3 players, due to their extremely tight packaging requirements and mostly layer-by-layer assembly.

This paper presents an extension of our previous work [2, 3], where the problem was posed as optimization of the arrangements of components, locators and fasteners, to merely maximize the profit of disassembly. In [2, 3], the profits of components via EOL treatments are considered as constant and given as inputs to the problem. Although one should always assume the most profitable EOL treatments (or non-treatments) for maximizing overall profit, it is well known that this would not be always optimal for minimizing environmental impacts. In order to examine a trade-off between the overall profit and the environmental impacts of EOL scenarios, the present work newly incorporates the EOL treatments of disassembled components and subassemblies as additional decision variables, and the Life Cycle Assessments (LCA) focusing on EOL treatments as a means to evaluate environmental impacts. A multi-objective genetic algorithm [4, 5] is utilized to search for Pareto optimal designs in terms of 1) satisfaction of the distance specification among components, 2) efficient use of locators on components, 3) profit of the EOL scenario of the product, and 4) environmental impact of EOL scenario obtained by LCA. The method is applied to a simplified model of Power Mac G4 cube® for demonstration.

RELATED WORK

Design for Disassembly

Design for disassembly (DFD) is a class of design method and guidelines to enhance the ease of disassembly for product maintenance and/or EOL treatments such as recycling and reuse [6-8]. As in the case of design for assembly (DFA), the estimation of disassembly time has been a central focus of the research on DFD [9, 10], since it is a major driver of disassembly cost and consequently, the economic feasibility of the EOL scenarios that require disassembly [11]. Recently, Desai *et al.* [12] developed a scoring system, where factors associated with disassembly time such as disassembly force, the requirement of tools and the accessibility of fasteners are considered. Sodhi *et al*. [13] focused on the impact of unfastening actions on disassembly cost and constructed U-effort model that helps designers to select fasteners for easy disassembly.

While these works help identify problems in existing assemblies and suggest local redesigns to improve the ease of disassembly, they do not address the improvement of an entire disassembly processes by the global changes in the component, locator, and fastener configurations, as addressed in this paper.

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Disassembly Sequence Planning

Disassembly sequence planning (DSP) aims at generating feasible disassembly sequences for a given assembly, where the feasibility is checked by the existence of collision-free motions to disassemble components. Since the problem is NP-complete, the past researches have focused on efficient heuristic algorithms to approximately solve the problem. Based on assembly sequence planning [14-18], algorithms for disassembly sequence generation have been developed [19-21]. More recent works are geared towards DSP with special attention to reuse, recycling, remanufacturing, and maintenance [22-26]. Chung *et al*. [27] modified the wave propagation method [23] to solve DSP, by considering both disassemblability of components and accessibility of fasteners. Kuo [28] found the most profitable EOL scenario of electromechanical products by examining all feasible disassembly sequences. Seo *et al.* [29] considered both economical and environmental costs to obtain the optimal disassembly sequence.

These works, however, only address the generation and optimization of the disassembly sequences for products with a pre-specified component layout. Since the accessibility of a component heavily depends on the spatial configuration of its surrounding components, this would seriously limit the opportunity for optimizing an entire assembly. In addition, these works do not address the design of locator and fastener configurations, which also have a profound impact on the feasibility and quality of a disassembly sequence.

Configuration Design Problem

While rarely discussed in the context of disassembly, the design of spatial configuration of given shapes has been an active research area by itself. Among the most popular flavors is bin packing problem (BPP), where the total volume (or area for 2D problem) occupied by the given shapes is minimized. Since this problem is also NP-complete, heuristic methods are commonly used. Corcoran and Wainwright [30] solved a 3D BPP with genetic algorithm (GA). Kolli *et al*. [31] used multi-resolution quad trees and simulated annealing to solve a 2D BPP using. Jain and Gea [32] solved a packing problem of 2D shapes represented by pixels. Fadel *et al*. [33] used virtual rubber band to solve a 3D BBP. As a variant of BPP, the layout design problem has been also widely studied. Fujita *et al.* [34] solved a 2D plant layout design problem by simulated annealing and the generalized reduced gradient (GRG) method. Grangeon *et al*. [35] addressed a 3D layout design of a steel sheet manufacturing workshop. Grignon and Fadel [36] presented a 3D layout design problem considering static and dynamic balance, maintainability and volume.

These works, however, do not address the integration with DSP as addressed in this paper.

Life Cycle Assessment

Life cycle assessment (LCA) has been widely used as a tool to estimate the environmental impacts of an EOL scenario of various products [37,38] including computers [39-41]. Since the optimal EOL scenario should be economically feasible as well as environmentally sound, LCA is often integrated with cost analysis. Goggin *et al*. [42] constructed a model for determining the recovery of a product, components and materials, where EOL scenarios are evaluated from economical and environmental perspectives. Kuo *et al.* [43] integrated LCA into Quality Function Development (QFD) to achieve the best balance between customer satisfaction and environmental impact. In our previous work [44], we compared the optimal EOL scenarios of a coffee maker in Aachen, Germany and in Ann Arbor, MI, and concluded the optimal EOL scenario varied greatly depending on the local recycling/reuse infrastructures and regulatory requirements.

These works, however, merely address the evaluation and optimization of the environmental impact of a given product, and do not address the design of component, locator, and fastener configuration as addressed in this paper.

METHOD

The method can be summarized as the following optimization problem:

- **Given:** geometries, weights, materials, and recycle and reuse values of each component, contact and distance specifications among components, locator library, and possible EOL treatments and associated scenarios.
- **Find:** spatial configuration of components and locators, EOL treatments of disassembled components and subassemblies.
- **Subject to:** no overlap among components, no unfixed components prior to disassembly, satisfaction of contact specification, assembleability of components.
- **Minimizing:** violation of distance specification, redundant use of locators, and environmental impact of EOL scenario.
- **Maximizing:** profit of EOL scenario.

Since the optimization problem has four objectives, a multi-objective genetic algorithm (MOGA) [4, 5] is utilized to obtain Pareto optimal solutions.

Inputs

There are four (4) categories of inputs for the problem as listed below:

- **Component information:** This includes the geometries, weights, materials and reuse values of components. Due to the efficiency in checking contacts [45] and the simplicity in modifying geometries, the component geometry is represented by voxels.
- **Contact and distance specifications:** The contact specification specifies the required adjacencies among the component, such as CPU and a heat sink in a computer. The distance specification specifies the relative importance

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(weight) of minimizing the distances between each pair of the components, *eg.*, for wire connections. Figure 3 shows an example.

- **Locator library:** This is a set of locator features that can be added on each component to constrain its relative motion. Types of locators in the library depend on the application domain. Figure 4 shows schematics of locators commonly found on sheet metal or injection-molded components in computer assemblies [46]. Note screws are regarded as a special type of locators, and slot can only be used with two circuit boards.
- **Possible EOL treatments and scenarios:** An EOL scenario is a sequence of events, such as disassembly, cleaning, and refurbishing, before a component receives an EOL treatment such as recycle and reuse. The EOL treatments available to each component and the associated scenarios leading to each treatment must be given as input. Figure 5 shows an example of EOL treatments (reuse, recycle, or landfill) and the associated EOL scenarios represented as a flow chart.

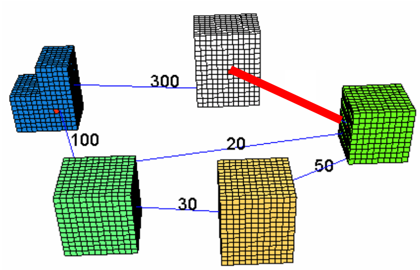

Figure 3. Example of contact specification (thick line) and distance specification (thin lines). Labels on thin lines indicate relative importance of minimizing distances.

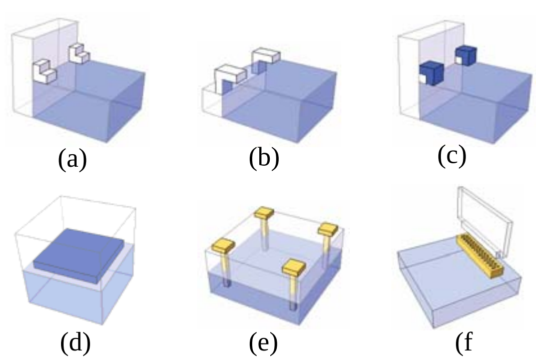

Figure 4. Graphical representation of typical locators for sheet metal or injection-molded components [46]: (a) catch, (b) lug, (c) track, (d) boss, (e) screw, (f) slot.

Design variables

There are three (3) design variables for the problem. The first design variable, *configuration vector*, represents the spatial configuration and dimensional change of each component:

$$\boldsymbol{x} = (x_0, x_1, \ldots, x_{n-1}) \quad (1)$$
$$x_i = (\boldsymbol{t}_i, \boldsymbol{r}_i, \boldsymbol{d}_i); \quad i = 0, 1, \ldots n\text{-}1 \quad (2)$$

$$\boldsymbol{t}_i \in \{0, \pm c, \pm 2c, \pm 3c, \ldots\}^3 \quad (3)$$
$$\boldsymbol{r}_i \in \{-90^{\circ}, 0^{\circ}, 90^{\circ}, 180^{\circ}\}^3 \quad (4)$$
$$\boldsymbol{d}_i \in \{0, \pm c, \pm 2c, \pm 3c, \ldots\}^f \quad (5)$$

where n is the number of components in the assembly, $\boldsymbol{t}_i$ and $\boldsymbol{r}_i$ are the vectors of the translational and rotational motions of component i with respect to the global reference frame, and $\boldsymbol{d}_i$ is a vector of the offset values of the f faces of component i in their normal directions, and c is the length of the sides of a voxel. Note that $\boldsymbol{d}_i$ is considered only for the components whose dimensions can be adjusted to allow the addition of certain locator features. For example, the components designed and manufactured in-house can have some flexibility in their dimensions, whereas off-the-shelf components cannot.

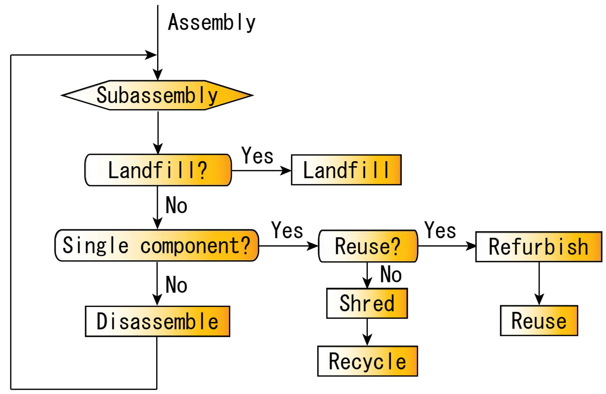

Figure 5. Flow chart of example EOL scenarios.

The second design variable, *locator vector*, represents the spatial configuration of the locators on each component:

$$\boldsymbol{y} = (\boldsymbol{y}_0, \boldsymbol{y}_1, \ldots, \boldsymbol{y}_{m-1}) \quad (6)$$
$$\boldsymbol{y}_i = (CD_i, p_i); \quad i = 0, \ldots, m\text{-}1 \quad (7)$$

where $m = n\,(n\text{-}1)/2$ is the number of pairs of components in the assembly, and $CD_i \subseteq \{-x, +x, -y, +y, -z, +z\}$ is a set of directions in which the motion of component c_0 in the i-th pair (c_0, c_1) is to be constrained, and p_i is a sequence of locators indicating their priority during the construction of the locator configuration.

The choice of locator for the i-th component pair is indirectly represented by CD_i and p_i, since the direct representation of locator id in the library would result in a large number of infeasible choices. The construction of locator configurations from a given $\boldsymbol{y}_i$ is not trivial since 1) multiple locator types can constrain the motion of c_0 as specified by CD_i, and 2) among such locator types, geometrically feasible locators depend on the relative locations of components c_0 and c_1. Figure 6 shows an example. In order to constrain the motion of c_0 in +z direction, a catch can be added to c_1 if c_0 is "below" c_1 as shown in Figure 6 (a). However, a catch cannot be used if c_0 is "above" c_1 as shown in Figures 6 (b) and (c), in which case boss (Figure 6 (b)) or track (Figure 6 (c)) needs to be used.

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Thus, the locator configuration of a component is dynamically constructed by testing locator types in the sequence of p_i. More details of the locator vector are found in [2].

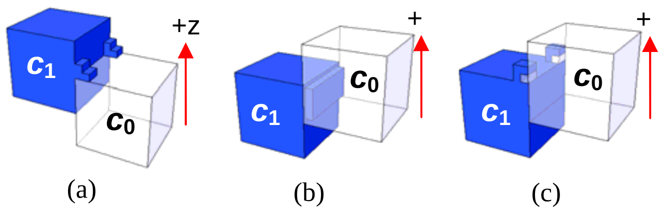

Figure 6. Construction of locator configuration.

The third design variable, *EOL vector*, represents the EOL treatments of components:

$$\boldsymbol{z} = (z_0, z_1, \ldots, z_{n-1}) \tag{8}$$
$$z_i \in E_i \tag{9}$$

where E_i is a set of feasible EOL treatments of component i. In the following case study, E_i = {recycle, reuse, landfill} for all components.

Constraints

There are four (4) constraints for the problem:

1. No overlap among components.
2. Satisfaction of contact specification.
3. No unfixed components prior to disassembly.
4. Assembleability of components.

Since the constraints are all geometric in nature, the voxel representation of component geometry facilitates their efficient evaluation. Constraints 1-3 are checked solely based on the information in $\boldsymbol{x}$, since the locator configurations constructed from $\boldsymbol{y}$ generate no overlaps. For constrain 3, immobility of all possible subassemblies is examined. Constraint 4 is necessary to ensure all components, weather or not to be disassembled, can be assembled when the product is first put together. It requires the information both $\boldsymbol{x}$ and $\boldsymbol{y}$. Since checking this constraint requires simulation of assembly motions (assumed as the reverse of disassembly motions), it is done as a part of the evaluation of disassembly cost needed for one of the objective functions.

Objective functions

There are four (4) objective functions for the problem. The first objective function (to be minimized) is for the satisfaction of the distance specification, given as:

$$f_1(\boldsymbol{x}, \boldsymbol{y}) = \sum_i w_i d_i \tag{10}$$

where w_i is the weight of the importance of distance d_i between two designated voxels.

The second objective function (to be minimized) is for the efficient use of locators, given as:

$$f_2(\boldsymbol{x}, \boldsymbol{y}) = \sum_i mc_i \tag{11}$$

where mc_i is the manufacturing difficulty of the i-th locator in the assembly, which represents the increased difficulty in manufacturing components due to the addition of the i-th locator.

The third objective function (to be maximized) is the profit of the EOL scenario of the assembly specified by $\boldsymbol{x}$ and $\boldsymbol{y}$, given as:

$$f_3(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) = \sum_{i=0}^{n-1} p_i(z_i) - c^*(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) \tag{12}$$

In Equation 12, $p_i(z_i)$ is the profit of the i-th component from EOL treatment z_i, calculated by the LCA model described in the next section. Also in Equation 12, $c^*(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$ is the minimum disassembly cost the assembly under the EOL scenario required by $\boldsymbol{z}$:

$$c^*(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) = \min_{s \in S_{xyz}} c(s) \tag{13}$$

where S_{xyz} is the set of the *partial and total* disassembly sequences of the assembly specified by $\boldsymbol{x}$ and $\boldsymbol{y}$, for retrieving the components with z_i = reuse or recycle and the components with regulatory requirement, and $c(s)$ is the cost of disassembly sequence s. Since an assembly specified by $\boldsymbol{x}$ and $\boldsymbol{y}$ can be disassembled in multiple sequences, Equation 13 computes the minimum cost over S_{xyz}, which contains all disassembly sequences feasible to $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$, and their subsequences. Set S_{xyz} is represented as AND/OR graph [14], computed based on the 2-disassemblability criterion [19, 45] (component can be removed by up to two successive motions) as follows:

1. Push the assembly to stack Q and the AND/OR graph.
2. Pop a subassembly sa from Q.
3. If sa does not contains component with z_i = reuse or recycle and components with regulatory retrieval requirements, go to step 5.
4. For each subassembly $sb \subset sa$ that does not contain any fixed components, check the 2-disassemblability of sb from sa. If sb is 2-disassemblable, add sb and $sc = sa \backslash sb$ to the AND/OR graph. If sb and/or sc are composed of multiple components, push them to Q.
5. If $Q = \emptyset$, return. Otherwise go to step 2.

For efficiency, only translational motions are considered during the 2-disassembleabilty check in step 4.

Assuming manual handling, insertion and fastening as timed in [47], $c(s)$ is estimated based on the motions of the components and the numbers and accessibilities of the removed screws at each disassembly step. The accessibility of a removed screw is given as [2]:

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$$a_s = 1.0 + \omega_a / (aa + 0.01) \quad (14)$$

where ω_a is weight and aa is the area of the mounting face of the screw, accessible from outside of the product in its normal direction.

The forth objective function (to be minimized) is the environmental impact of the EOL scenario:

$$f_4(\boldsymbol{z}) = \sum_i e_i(z_i) \quad (15)$$

where $e_i(z_i)$ is the environmental impact of i-th component according to the EOL scenario for treatment z_i. The value of $e_i(z_i)$ is estimated by the LCA model described in the next section.

LCA model

The LCA model adopted in the following case study focuses on EOL treatments and assumes the EOL scenarios in Figure 5 for all components (reuse for some components only), and energy consumption as the indicator for environmental impact [44]. Accordingly, profit $p_i(z_i)$ in Equation 12 is defined as:

$$p_i(z_i) = \begin{cases} r_i^{reuse} - c_i^{trans} - c_i^{refurb} & \text{if } z_i = \text{reuse} \\ r_i^{recycle} - c_i^{trans} - c_i^{shred} & \text{if } z_i = \text{recycle} \\ -c_i^{trans} - c_i^{landfill} & \text{if } z_i = \text{landfill} \end{cases} \quad (16)$$

where r_i^{reuse} and $r_i^{recycle}$ are the revenues from reuse and recycle, respectively, and c_i^{trans}, c_i^{refurb}, c_i^{shred} and $c_i^{landfill}$ are the cost for transportation, refurbishment, shredding, and landfill, respectively. Similarly, energy consumption $e_i(z_i)$ in Equation 15 is defined as:

$$e_i(z_i) = \begin{cases} e_i^{reuse} + e_i^{trans} + e_i^{refurb} & \text{if } z_i = \text{reuse} \\ e_i^{recycle} + e_i^{trans} + e_i^{shred} & \text{if } z_i = \text{recycle} \\ e_i^{landfill} + e_i^{trans} & \text{if } z_i = \text{landfill} \end{cases} \quad (17)$$

where e_i^{reuse}, e_i^{trans}, $e_i^{recycle}$, e_i^{refurb}, e_i^{shred} and $e_i^{landfill}$ are the energy consumptions of reuse, transportation, recycle, refurbishment, shredding, and landfill, respectively.

Revenue from reuse r_i^{reuse} is the current market value of component i, if such markets exist. Energy consumption of reuse e_i^{reuse} is the negative of the energy recovered from reusing component i:

$$e_i^{reuse} = -\sum_j me_j^{intens} \cdot m_{ij} \quad (18)$$

where me_j^{intens} is the energy intensity of material j and m_{ij} is the weight of material j in component i. Reuse, if available, is usually the best EOL treatment for a component because of its high revenue and high energy recovery. The availability of the reuse option for a component, however, is infrastructure dependent, and even if available, the revenue from reuse can greatly fluctuate in the market and hence difficult to estimate *a priori*.

Revenue from recycle $r_i^{recycle}$ and energy consumption of recycle $e_i^{recycle}$ are also calculated based on the material composition of a component:

$$r_i^{recycle} = \sum_j mr_j^{recycle} \cdot m_{ij} \quad (19)$$

$$e_i^{recycle} = -\sum_j me_j^{recover} \cdot m_{ij} \quad (20)$$

where $mr_j^{recycle}$ and $me_j^{recover}$ are the material value and recovered energy of material j, respectively.

Since few data is available for the refurbishment of components, the cost for refurbishment is simply assumed as:

$$c_i^{refurb} = 0.5 \cdot r_i^{reuse} \quad (21)$$

Based on the data on desktop computers [40], energy consumption for refurbishment e_i^{refurb} is estimated as:

$$e_i^{refurb} = 1.106 \cdot m_i \quad (22)$$

where m_i is the weight of the i-th component.

Cost and energy consumption of transportation c_i^{trans} and e_i^{trans} are estimated as [44]:

$$c_i^{trans} = \Delta c_i^{trans} \cdot D_i \cdot m_i \quad (22)$$
$$e_i^{trans} = \Delta e_i^{trans} \cdot D_i \cdot m_i \quad (23)$$

where Δc_i^{trans} =2.07e-4 [\$/kg·km], Δe_i^{trans} =1.17e-3 [MJ/kg·km], and D_i is the travel distance. Similarly, costs and energy consumptions for shredding and landfill c_i^{shred} , $c_i^{landfill}$, e_i^{shred} and $e_i^{landfill}$ are calculated as [44]:

$$c_i^{shred} = \Delta c_i^{shred} \cdot m_i \quad (24)$$
$$e_i^{shred} = \Delta e_i^{shred} \cdot m_i \quad (25)$$
$$c_i^{landfill} = \Delta c_i^{landfill} \cdot m_i \quad (26)$$
$$e_i^{landfill} = \Delta e_i^{landfill} \cdot m_i \quad (27)$$

where Δc_i^{shred} = 0.12 [\$/kg·km], Δe_i^{shred} = 1.0 [MJ/kg·km], $\Delta c_i^{landfill}$ = 0.02 [\$/kg·km] and $\Delta e_i^{landfill}$ = 20000 [MJ/kg·km].

Optimization algorithm

Since the problem is essentially a “double loop” of two NP-complete problems (disassembly sequence planning within a 3D layout problem), it should be solved by a heuristic algorithm. Since design variables $\boldsymbol{x}$, $\boldsymbol{y}$, $\boldsymbol{z}$ are discrete ($\boldsymbol{x}$ is a discrete variable since geometry is represented as voxels) and there are four objectives, a multi-objective genetic algorithm [4,5] is utilized to obtain Pareto optimal design alternatives. A

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multi-objective genetic algorithm is an extension of the conventional (single-objective) genetic algorithms that do not require multiple objectives to be aggregated to one value, for example, as a weighted sum. Instead of static aggregates such as a weighted sum, it dynamically determine an aggregate of multiple objective values of a solution based on its relative quality in the current population, typically as the degree to which the solution dominates others in the current population.

A chromosome, a representation of design variables in genetic algorithms, is a simple list of the 3 design variables:

$$c = (\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) \tag{28}$$

Since the information in $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$ are linked to the geometry of a candidate design, the conventional one point or multiple point crossover for linear chromosomes are ineffective in preserving high-quality building blocks. Accordingly, a geometry-based crossover operation is used as in [2].

CASE STUDY

Problem

The method is applied to a model of Power Mac G4 Cube® manufactured by Apple Computer, Inc. (Figure 7). Ten (10) major components are chosen based on the expected contribution to profit and environmental impact. Figure 8 (a) shows the ten components and their primary liaisons, and Figure 8 (b) shows the voxel representation of their simplified geometry and the contact (thick lines) and distance (thin lines with weights) specifications. The contacts between component *B* (heat sink) and *C* (CPU), and *C* (circuit board) and *G* (memory) are required due to their importance to the product function. Component *A* (case) is considered as fixed in the global reference frame. Component *J* (battery) needs to be retrieved due to regulatory requirements. The locator library in Figure 4 is assumed for all components. The relative manufacturing difficulty of locators in the library is listed in Table 1.

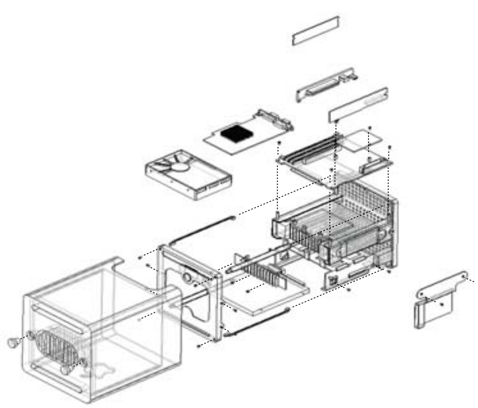

Figure 7. Assembly of Power Mac G4 Cube®.

Table 2 shows the material composition m_{ij} of components *A*-*J* in Figure 8 (b). For components *C*-*F*, the material composition data in [48] is utilized. Table 3 shows energy intensity me_j^{intens}, recovered energy me_j^{recove}, and material values $mr_j^{recycle}$ [41,44]. Considering Apple Computer's Electronic Recycling Program in United States and Canada [49], the EOL Power Mac G4 Cubes® are assumed to be transported to one of two facilities in United States (Worcester, MA and Gilroy, CA) for reuse, recycle, and landfill. The average distance between the collection point and the facility is estimated as D_i = 1000 km for all components. It is assumed that 40 ton tracks are used for transportation. Based on this assumption, Table 4 shows the revenues, costs and energy consumptions of components *A*-*J* calculated using Equations 18-27. Revenue from reuse r_i^{reuse} reflects current values in the PC reuse markets in the United States [50, 51]. Note that reuse option is not available to components *A* (frame) and *B* (heat sink).

Table 1. Relative manufacturing difficulty of the locators in the locator library in Figure 4

Locator	Lug	Track	Catch	Boss	Screw	Slot
Mfg. difficulty	20	30	10	70	20	20

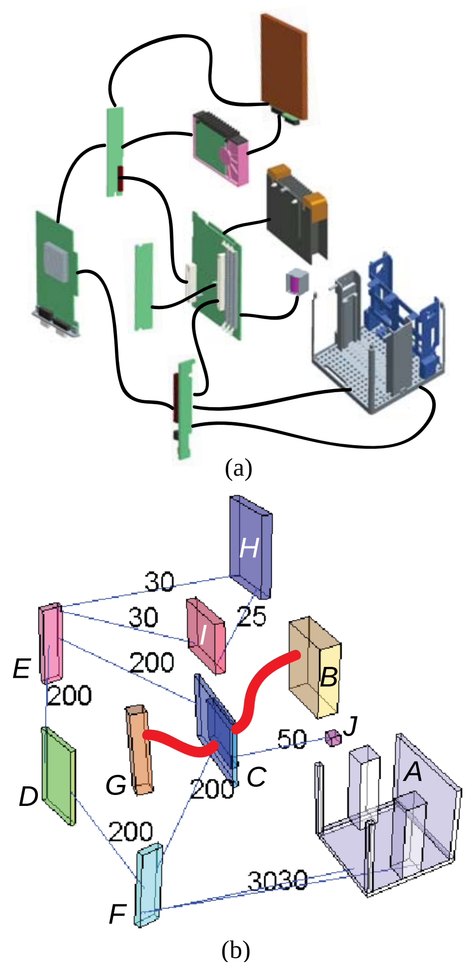

Figure 8. (a) ten major components and their primary liaisons, and (b) contact and distance specifications.

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Table 2. Material composition [kg] of components A-J in Figure 8.

Component	Aluminum	Steel	Cupper	Gold	Silver	Tin	Lead	Cobalt	Lithium	Total
A (frame)	1.2	0	0	0	0	0	0	0	0	1.2
B (heat sink)	0.6	0	0	0	0	0	0	0	0	0.60
C (circuit board)	1.5e-2	0	4.8e-2	7.5e-5	3.0e-4	9.0e-3	6.0e-3	0	0	0.30
D (circuit board)	1.0e-2	0	3.2e-2	5.0e-5	2.0e-4	6.0e-3	4.0e-3	0	0	0.20
E (circuit board)	4.0e-3	0	1.3e-2	2.0e-5	8.0e-5	2.4e-3	1.6e-3	0	0	8.0e-2
F (circuit board)	5.0e-3	0	1.6e-2	2.5e-5	1.0e-4	3.0e-3	2.0e-3	0	0	0.10
G (memory)	2.0e-3	0	6.4e-3	2.0e-5	4.0e-5	1.2e-3	8.0e-4	0	0	4.0e-2
H (CD drive)	0.25	0.25	0	0	0	0	0	0	0	0.50
I (HD drive)	0.10	0.36	6.4e-3	1.0e-5	4.0e-5	1.2e-3	8.0e-4	0	0	0.50
J (battery)	8.0e-5	0	1.4e-3	0	0	0	0	3.3e-3	4.0e-3	2.0e-3

Table 3. Material information [41, 44]. Underlined values are estimations due to the lack of published data.

Material	me_j^{intens}[MJ/kg]	me_j^{recove}[MJ/kg]	$mr_j^{recycle}$ [$/kg]
Aluminum	2.1e2	1.4e2	0.98
Steel	59	19	0.22
Cupper	94	85	1.2
Gold	8.4e4	<u>7.5e4</u>	1.7e4
Silver	1.6e3	<u>1.4e3</u>	2.7e2
Tin	2.3e2	2.0e2	6.2
Lead	54	48	1.0
Cobalt	8.0e4	<u>6.0e4</u>	38
Lithium	<u>1.5e3</u>	<u>1.0e3</u>	7.5

Results

After running multi-objective genetic algorithm for approximately 240 hours (10 days) with a standard PC (number of population and generation are 100 and 300), thirty seven (37) Pareto optimal designs are obtained as design alternatives. Since the number of objective functions is four, the resulting 4-dimensional space is projected on to six 2-dimensional spaces in Figure 9 (a)-(f). Figure 10 shows five representative designs R_1, R_2, R_3, R_4 and R_5. Their objective function values are listed in Table 5 and also plotted on a bar chart in Figure 11. As seen in Figure 9, designs R_1, R_2, R_3 and R_4 are the best results only considering an objective function f_1, f_2, f_3 and f_4 regardless of the other objective function values, whereas R_5 is a balanced result in all four objectives.

The spatial configurations of R_3 and R_5 are quite similar, with noticeable differences in the EOL treatments. Figures 12 and 13 show one of the optimal disassembly sequences of R_3 and R_5 with the EOL treatments of components, respectively. Design R_3 (design biased for profit) uses three screws, one of which is used between components *A* and *B*. Since components *A* and *B* have no reuse options, and recycling them is less economical than landfilling due to high labor cost for removing screws, they are not disassembled and simply discarded altogether for higher profit. On the other hand, components *A* and *B* are disassembled and recycled in R_5 (balanced design for all objectives) to reduce environmental impact at the expense of higher disassembly cost (lower profit).

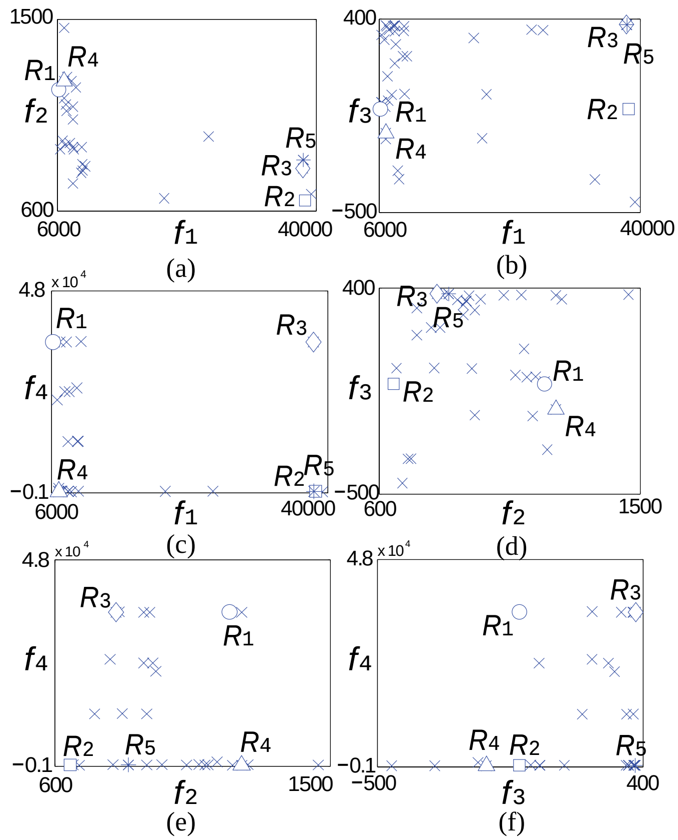

Figure 9. Distribution of Pareto optimal designs in six 2-dimensional spaces (a)-(f).

As stated in the previous section, reuse, if available, is usually the best EOL treatment for a component because of its high revenue and high energy recovery. For the components without reuse option, the choice between recycle and landfill depends on the ease of disassembly, as seen in these results. If the disassembly cost is low enough that recycling the component is more profitable than landfilling it, recycle becomes the most profitable EOL treatment. Otherwise, there is a trade-off between the profit and the environmental impact, which is found in the Pareto optimal designs.

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Table 4. revenue (*r* [\$]), cost (*c* [\$]) and energy consumption (*e* [MJ]) of the major components *A-J*.

	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*
r_i^{reuse}	N/A	N/A	3.5e2	80	1.3e2	39	57	40	60	5.0
$r_i^{recycle}$	1.2	0.60	1.5	1.0	0.39	0.49	0.36	0.30	0.37	0.12
c_i^{trans}	0.25	0.12	6.2e-2	4.1e-2	1.7e-2	2.1e-2	8.3e-3	0.10	0.10	4.1e-3
c_i^{refurb}	N/A	N/A	1.8e2	40	65	20	29	20	30	2.5
c_i^{shred}	0.14	7.2e-2	3.6e-2	2.4e-2	9.6e-3	1.2e-2	4.8e-3	6.0e-2	6.0e-2	2.4e-3
$c_i^{landfill}$	2.4e-2	1.2e-2	6.0e-3	4.0e-3	1.6e-3	2.0e-3	8.0e-4	1.0e-2	1.0e-2	4.0e-4
e_i^{reuse}	-2.6e2	-1.3e2	-17	-12	-4.5	-5.6	-3.1	-68	-45	-2.6e2
e_i^{trans}	1.4	0.70	0.35	0.23	9.4e-2	0.12	4.7e-2	0.59	0.59	2.3e-2
e_i^{refurb}	2.7	1.3	0.66	0.44	0.18	0.22	8.8e-2	1.1	1.1	4.4e-2
e_i^{rcycle}	-170	-84	-14	-9.5	-3.8	-4.8	-2.7	-40	-23	-2.0e2
e_i^{shred}	1.2	0.60	0.30	0.20	8.0e-2	0.10	4.0e-2	0.50	0.50	2.0e-2
$e_i^{landfill}$	2.4e4	1.2e4	6.0e3	4.0e3	1.6e3	2.0e3	8.0e2	1.0e4	1.0e4	4.0e2

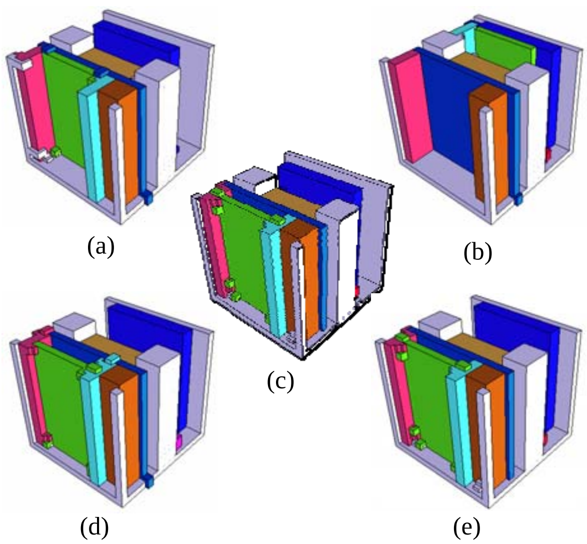

Figure 10. Representative Pareto designs: (a) R_1**, (b)** R_2**, (c)** R_3**, (d)** R_4 **and (e)** R_5**.**

Table 5. Objective function values of R_1, R_2, R_3, R_4 **and** R_5

	f_1 (dist.spec.)	f_2 (mfg. diff.)	f_3 (profit)	f_4 (env. impact)
R_1	6175	1170	-19.30	35627
R_2	38496	650	-19.34	-642
R_3	38227	800	374.72	35593
R_4	6884	1210	-130.79	-741
R_5	38299	840	373.24	-647

Oftentimes such trade-off among alternative designs can hint opportunities for further design improvements. For example, the examination of the differences between R_3 and R_5 suggests the possibility of replacing the screws between *A* and *B* by slot-like locators (which are not available for *A* and *B* in the locator library) for higher profit and lower environmental impact.

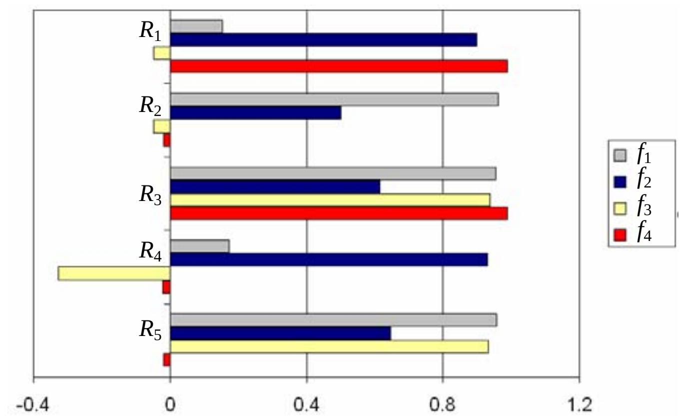

Figure 11. Objective function values of R_1, R_2, R_3, R_4 **and** R_5 **(scaled as** f_1 **: 1/40000,** f_2 **: 1/1300,** f_3 **: 1/400,** f_4 **: 1/36000).**

SUMMARY AND FUTURE WORK

This paper presented an extension of our previous work on a computational method for product-embedded disassembly, which newly incorporates EOL treatments of disassembled components and subassemblies as additional decision variables, and LCA focusing on EOL treatments as a means to evaluate environmental impacts. The method was successfully applied to a realistic example of a desktop computer assembly, and a set of Pareto optimal solutions is obtained as design alternatives.

Future work includes the adoption of more detailed LCA covering entire product life including the production and use phases, the development of more efficient optimization algorithm, the study on the effect of embedded disassembly on assembly, and the derivation of the generalizable design rules through the comparison of the optimization results with the existing designs of other product types.

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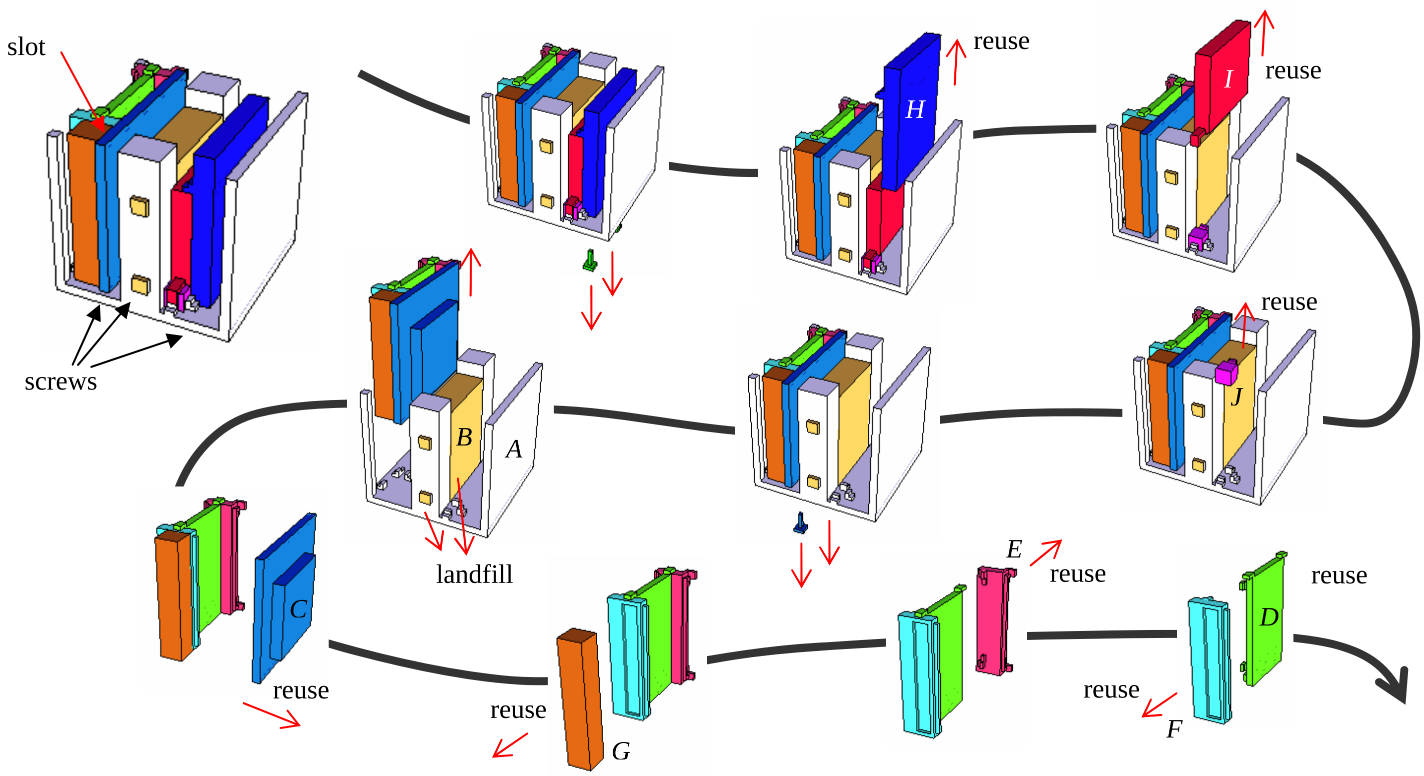

Figure 12. Optimal disassembly sequence of R_3 with the optimal EOL treatments of components.

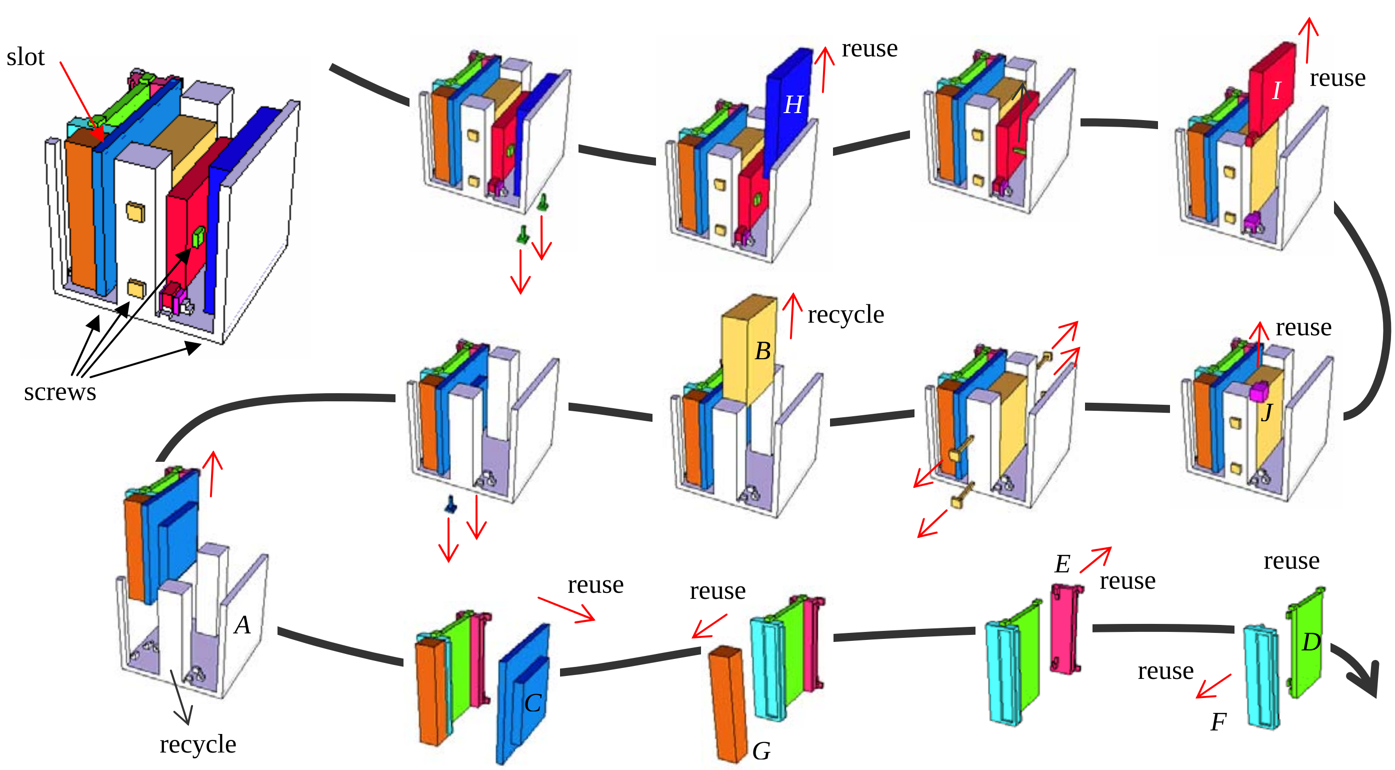

Figure 13. Optimal disassembly sequence of R_5 with the optimal EOL treatments of components.

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