Design for Optimal End-of-Life via Product-Embedded Disassembly

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Abstract

This paper presents a method for designing products that disassemble via a domino-like “self-disassembly” process triggered by the removal of a few fasteners. Given component geometries, the method optimizes the spatial configurations of components, locators and fasteners, and the end-of-life (EOL) treatments of components and subassemblies for maximum profit and minimum environmental impact. Extending our previous work, it incorporates the end-of-life (EOL) treatments of components as additional decision variables, and Life Cycle Assessments (LCA) for evaluating environmental impact. A multi-objective genetic algorithm is utilized to search for Pareto optimal design alternatives. An example on Power Mac G4 cube® is discussed.

Keywords

Design for disassembly, configuration design, disassembly sequence planning, life cycle assessments

1 INTRODUCTION

Economic feasibility of an 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.

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 the sequence for the optimal EOL scenario. 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.

As an illustration, consider two assemblies in Figures 1 (a) and 1 (b). In Figure 1 (a), three components *A*, *B* and *C* are fixed to a case with three fasteners, whereas in Figure 1 (b), the motions of components *B* and *C* are constrained by the locators integral to the components and the case. With a high labour cost for removing fasteners, only component *A* in Figure 1 (a) can be disassembled for reuse and recycle, with the reminder sent to landfill. For the assembly in Figure 1 (b), on the other hand, the removal of the fastener fixing component *A* activates the domino-like self-disassembly process of *A*, *B*, and then *C*. Since no additional fasteners need to be removed, components B and C can also be disassembled, allowing the recycle/reuse of all components as well as the case.

This paper presents an extension of our previous work [2, 3] on the computational method for designing the products with such embedded disassembly means, where the problem was posed as optimization of the arrangements of components, locators and fasteners, to 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 impact. In order to examine a trade-off between the overall profit and the environmental impact of disassembly, the present work newly incorporates the end-of-life treatments of disassembled components and subassemblies as additional decision variables, and the Life Cycle Assessments (LCA) as a means to evaluate environmental impact. A multi-objective genetic algorithm [4] 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 obtained by LCA. The method is applied to a simplified model of Power Mac G4 cube® for demonstration.

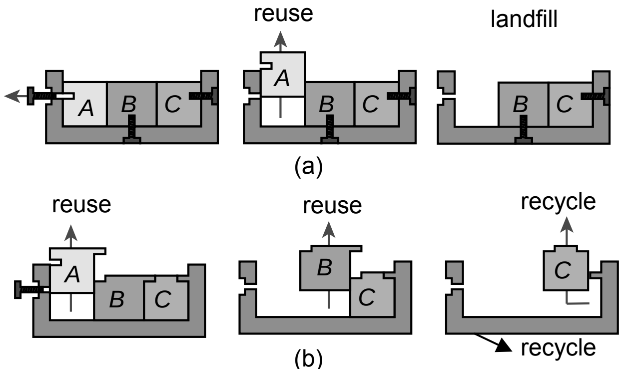


Figure 1: (a) conventional assembly (b) assembly with embedded disassembly.

2 RELATED WORK

2.1 Design for disassembly, configuration design, and disassembly sequence planning

The present work belongs to the area of design for assembly, and relates to the areas of configuration design, disassembly sequence planning. The previous works on design for disassembly [5] address local deign modification for the ease of disassembly, but not the global rearrangement and redesign of components for an optimal disassembly sequence addressed in this paper.

The global rearrangement of components within a product enclosure and the optimization of disassembly sequence are separately addressed in the previous works on configuration design [6] and disassembly sequence planning [7]. These works, however, do not integrate these two issues as done in the present work.

The detailed reviews of these areas can be found in [2, 3] and hence is omitted due to the space limit.

2.2 Life cycle assessment

LCA has been used as a tool for optimizing EOL decisions of products. Caudill [8] has proposed a multi-life cycle assessment (MLCA) approach to evaluate a product as it passes through several use phases. Rose and Stevels [9] created an EOL metric to evaluate product reuse, recycle, disposal, service, and remanufacturing. Hula *et al*. [10] proposed a methodology to determine the optimal EOL scenario through the evaluation of feasible disassembly sequences. They compared the results in Aachen, Germany and Ann Arbor, MI, and reported that the optimal EOL scenario varied greatly depending on the local recycling/reuse infrastructures and regulatory requirements.

Due the recent increase in abandoned computers, more works are found on LCA of computers. Williams *et al.* [11] consider three different EOL options for computers: reselling to secondary markets, upgrading of key components, and recycling to recover materials. Life cycle energy use is evaluated for the quantitative assessment of life cycle, and the results indicate the effectiveness of reselling and upgrading from an environmental viewpoint. Aanstoos *et al.* [12] construct a model to estimate the energy impact of an EOL computer disposition process, where recycling, cannibalization and refurbishing are considered as the main streams in EOL computer disposition. Other LCA approaches on computers can be found in [13].

These works, however, merely evaluate the environmental impact of existing designs, and do not address the optimal design of assemblies as in this paper.

3 METHOD

The method can be summarized as the following optimization problem:

- **Given:** geometries, weights, materials and reuse values of components, contact and distance specifications, locator library, and EOL scenarios
- **Find:** spatial configuration of components and locators
- **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, environmental impact
- **Maximizing:** profit of EOL treatments

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

3.1 Inputs

There four (4) categories of inputs for the problem: 1) the geometries (represented as voxels [3]), weights, materials and reuse values of components, 2) the contact and distance specifications among the components, 3) the library of feasible locator types, and 4) the possible EOL scenarios of each component.

The contact specification specifies the *required* adjacencies among the component, such as the CPU and a heat sink. The distance specification specifies the relative importance (weight) of minimizing the distances between each pair of the components, *eg.*, for wire connections.

The locator library is a set of locator types that can be added on each component to constrain its relative motion. The types of locators in the library depend on the application domain. Figure 2 shows six locators typical for computer assemblies [3], which are used for the case study. Note that slot can be used only between two circuit boards.

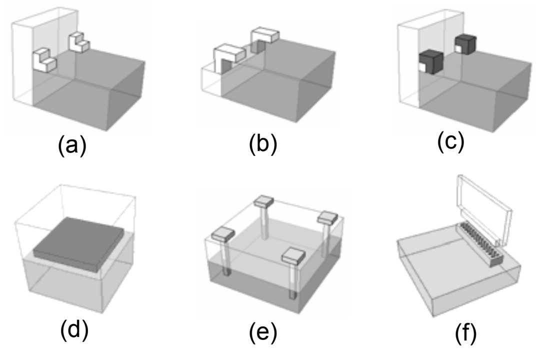


Figure 2: Locator library for the case study: (a) catch, (b) lug, (c) track, (d) boss, (e) screw, and (f) slot.

The EOL scenarios are the sequences of events a component must go through in order to receive EOL treatments (reuse, recycle, or landfill). In the case study, the possible EOL scenarios are assumed same for all components and defined as:

- A subassembly can either be further disassembled, shredded, or land filled.
- A disassembled component can be either refurbished, shredded, or land filled.
- A refurbished component is reused.
- A shredded component is recycled.

3.2 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:

$$\mathbf{x} = (x_0, x_1, \ldots., x_{n-1}) \tag{1}$$

$$x_i = (t_i, r_i, d_i,);\ \ i = 0, 1, \ldots\ n\text{-}1 \tag{2}$$

$$t_i, d_i \in \{0, \pm c, \pm 2c, \pm 3c, \ldots\} \tag{3}$$

$$r_i \in \{-90^{\circ}, 0^{\circ}, 90^{\circ}, 180^{\circ}\} \tag{4}$$

where n is the number of components in the assembly, t_i and r_i are the vectors of the translational and rotational motions of component i with respect to the global reference frame, and $d_i = (d_0, d_1, \ldots, d_{f\text{-}1})$ is a vector of the offset values of the faces of component i in their normal directions, and c is the length of the sides of a voxel. Note that the dimensional changes are considered only for the components whose dimensions are assumed unfixed.

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

$$\mathbf{y} = (y_0, y_1, \ldots, y_{m\text{-}1}) \tag{5}$$

where $m = n\,(n\text{-}1)/2$ is the number of pairs of components in the assembly, and y_i (i = 0, 1, … m-1) is a vector containing the information on the motion constraints between the i-th pair of components and the configuration of locator that realizes them. The detailed description of the locator vector is found in [2].

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

$$\boldsymbol{z} = (z_0, z_1, \ldots, z_{n-1}) \tag{6}$$

$$z_i \in E_i \tag{7}$$

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.

3.3 Constraints

There are four (4) constraints for the problem:

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

while constraint 1 is for physical feasibility of a configuration, constraints 2 and 3 are for product function. Constraint 4 is for ensuring all components, weather they are to be disassembled or not, can be assembled when the product is first put together.

3.4 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:

$$f_1(\boldsymbol{x}, \boldsymbol{y}) = \sum_i w_i d_i \tag{8}$$

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:

$$f_2(\boldsymbol{x}, \boldsymbol{y}) = \sum_i mc_i \tag{9}$$

where mc_i is the manufacturing difficulty of the i-th locator in the assembly, which represents the relative manufacturing cost to add the i-th locator to a component.

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:

$$f_3(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) = \sum_{i=0}^{n-1} p_i(z_i) - c^*(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) \tag{10}$$

In the above, $p_i(z_i)$ is the profit of the i-th component from EOL treatment z_i and $c^*(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$ is the minimum disassembly cost the assembly under the EOL scenario required by $\boldsymbol{z}$:

$$c^*(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) = \min_{s \in S_{xyz}} c(s) \tag{11}$$

where:

- S_{xyz} is the set of the partial and total disassembly sequences of the assembly specified by $\boldsymbol{x}$ and $\boldsymbol{y}$ satisfying the 2-disassemlability criterion [14] (translation only), the disassembly of components with z_i = reuse or recycle, and regulatory requirements on component retrieval.
- $c(s)$ is the cost of disassembly sequence s, estimated based on the motions of the components and the numbers and accessibilities of the removed fasters at each disassembly step [5, 15].

The forth objective function (to be minimized) is the environmental impact of the EOL scenario, calculated as total energy consumption [10]:

$$f_4(\boldsymbol{z}) = \sum_i e_i(z_i) \tag{12}$$

where $e_i(z_i)$ is the energy consumption of the i-th component according to the EOL scenario.

According to the input EOL scenarios in section 3.1, profit $p_i(z_i)$ in Equation 10 is defined as:

$$p_i(z_i) = \begin{cases} r_i^{reuse} - c_i^{trans} - c_i^{refurb} & \text{if } z_i = \text{reuse} \\ r_i^{recycle} - c_i^{trans} - c_i^{shred} & \text{if } z_i = \text{recycle} \\ -c_i^{trans} - c_i^{landfill} & \text{if } z_i = \text{landfill} \end{cases} \tag{13}$$

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 $e_i(\boldsymbol{z}_i)$ in Equation 12 is defined as:

$$e_i(z_i) = \begin{cases} e_i^{reuse} + e_i^{trans} + e_i^{refurb} & \text{if } z_i = \text{reuse} \\ e_i^{recycle} + e_i^{trans} + e_i^{shred} & \text{if } z_i = \text{recycle} \\ e_i^{landfill} + e_i^{trans} & \text{if } z_i = \text{landfill} \end{cases} \tag{14}$$

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

4 CASE STUDY

The method is applied to Power Mac G4 Cube® manufactured by Apple Computer, Inc. (Figure 3). Ten (10) major components are chosen based on the expected contribution to the profit and the environmental impact. Figure 4 (a) shows the ten components and their primary liaisons, and Figure 4 (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 shown in Figure 2 is used in this case study, and the manufacturing difficulty of locators in the locator library is listed in Table 1.

locator	lug	track	catch	boss	screw	slot
mfg. cost	20	30	10	70	20	20

Table 1: Manufacturing difficulty of the locators in the locator library.

Table 2 shows the material composition [kg] of components *A-J* in Figure 4 (b). For components *C-F*, the material composition data in [17] is utilized. Table 3 shows the revenues, costs and energy consumptions used for calculating the profit and the environmental impact.

Component	Aluminium	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 2: Material composition [kg] of 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

Table 3: Revenue (r [\$]), cost (c [\$]) and energy consumption (e [MJ]) of components *A*-*J*.

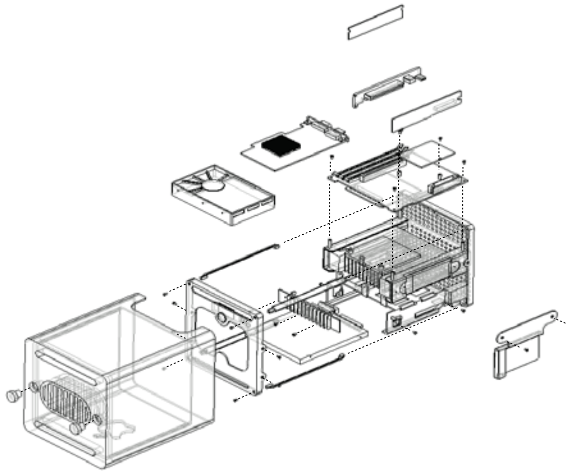
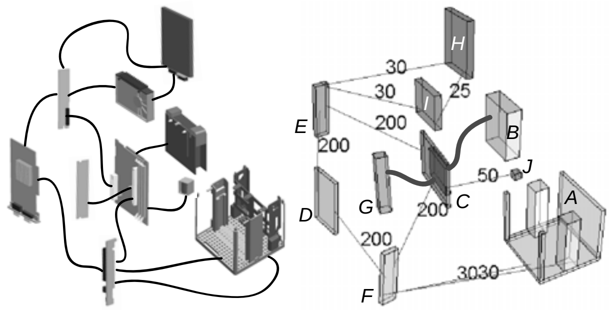


Figure 3: Assembly of Power Mac G4 Cube®.

Revenue from reuse r_i^{reuse} reflects current values in the PC reuse markets in the United States [18, 19]. Energy consumption of reuse e_i^{reuse} is the recovered energy due to reuse, given as the negative of the sum of the energy intensities for the component materials in the *i*-th component. Revenue from recycle $r_i^{recycle}$ and energy consumption for recycle $e_i^{recycle}$ are calculated based on this material composition with the material information in Table 4 [10, 13]. Since few data is available for the refurbishment of components, we simply assume the cost for refurbishment $c_i^{refurb} = 0.5 \cdot r_i^{reuse}$. Energy consumption for refurbishment e_i^{refurb} is estimated based on [12].

Considering Apple Computer's Electronic Recycling Program in United States and Canada [16], 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.



(a) (b)

Figure 4: (a) ten major components and their primary liaisons, (b) contact and distance specifications.

The average distance between the collection points of the EOL computers and the facility is estimated as 1000 km. Using this distance, cost and energy consumption for transportation c_i^{trans} and e_i^{trans} are calculated for all EOL treatments according to the equations and parameters in [10]. Similarly, costs and energy consumptions for transportation, shredding and landfill c_i^{shred} , $c_i^{landfill}$, e_i^{shred} and $e_i^{landfill}$ are calculated using the data in [10].

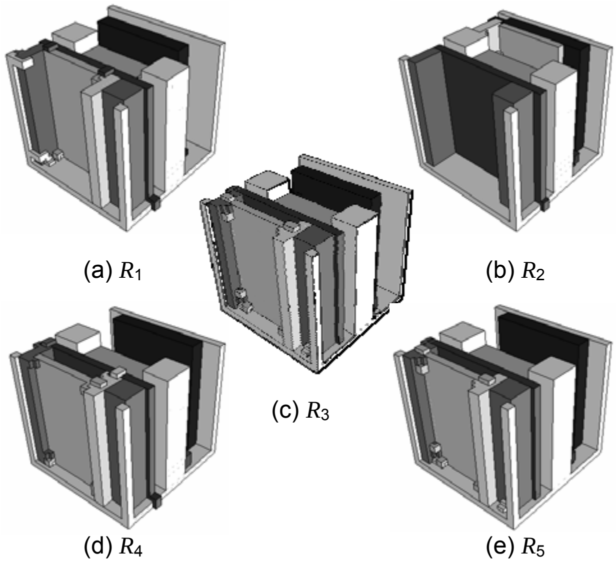
After running multi-objective genetic algorithm [4] for approximately 240 hours (10 days) with a standard PC (numbers of population and generation are 100 and 300), thirty-seven (37) Pareto optimal solutions are obtained as design alternatives. Figure 5 shows five representative designs R_1, R_2, R_3, R_4 and R_5. Their objective function values are listed in Table 5 and also plotted on a spider web diagram in Figure 6. The 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 other objectives, whereas R_5 is a balanced result in all four objectives.

Material	Energy intensity [MJ/kg]	Recovered energy [MJ/kg]	Material value [$/kg]
Aluminium	2.1e2	1.4e2	0.98
Steel	59	19	0.22
Cupper	94	85	1.2
Gold	8.4e4	7.5e4	1.7e4
Silver	1.6e3	1.4e3	2.7e2
Tin	2.3e2	2.0e2	6.2
Lead	54	48	1.0
Cobalt	8.0e4	6.0e4	38
Lithium	1.5e3	1.0e3	7.5

Table 4: Material information [10]. The underlined values are estimations due to the lack of published data.

	f_1 (dist.spec.)	f_2 (mfg. cost)	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	374.71	35592
R_4	6884	1210	-130.78	-741
R_5	38292	840	373.24	-647

Table 5: Objective function values for R_1 – R_5.


(a) R_1

(b) R_2

(c) R_3

(d) R_4

(e) R_5

Figure 5: Representative Pareto designs, (a) R_1, (b) R_2, (c) R_3, (d) R_4 and (e) R_5.

The spatial configurations of R_3 and R_5 are quite similar, with noticeable differences in the EOL treatments. Figures 7 and 8 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 recycling components *A* and *B* is less economical than landfilling them due to high labour 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).

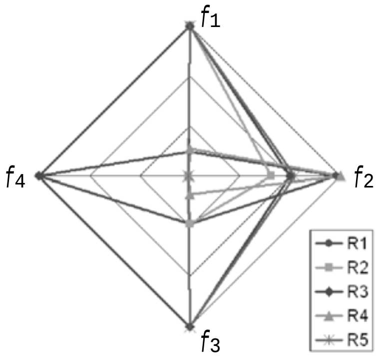


Figure 6: Spider web diagram for objective function values of R_1, R_2, R_3, R_4 and R_5.

As seen in Table 3, reuse is naturally the best EOL treatment of 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. To illustrate the situation, the reuse option for components *A* and *B* are assumed not available in this case study. For those components without the reuse option, the choice between recycle or landfill depends on the ease of disassembly. If the disassembly cost is low enough that recycling the component is more profitable than landfilling it, recycle becomes the optimal EOL treatment. Otherwise, there is a trade-off between the profit and the environmental impact, which is found in the Pareto optimal designs.

At times, 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.

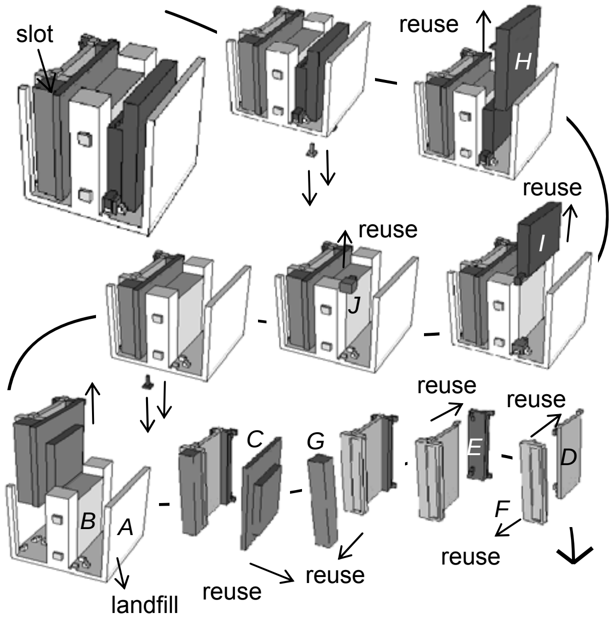


Figure 7: Optimal disassembly sequence of R_3 with the EOL treatments

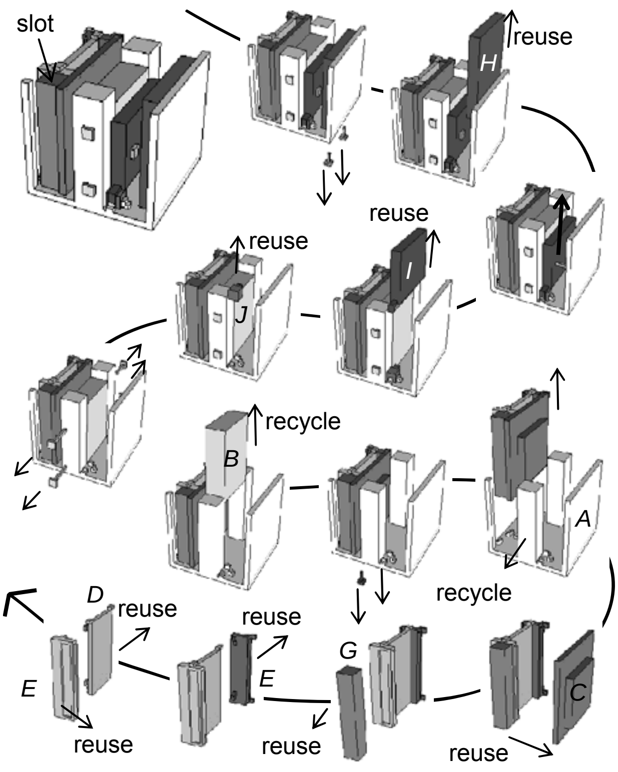


Figure 8. Optimal disassembly sequence of R_5 with the EOL treatments.

5 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 as a means to evaluate environmental impact. 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 more detailed LCA with accurate data, the development of more efficient optimization algorithm, and application to other product types.

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