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Value-Based Product Structure Evaluation for Disassembly

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Abstract

Designing for the ease of End Of Life (EOL) disassembly is an important design function. The product structure that is the spatial relationships between the parts of the product and the value distribution over them plays an important role in determining the ease and profitability of disassembly. This paper presents a conceptual methodology to determine the effect of the spatial precedence on the desired value precedence of the product. The methodology introduces a digraph called the bureau graph to model this relationship between the spatial and value precedence structures. Based on this modeling indices are derived that provide a holistic evaluation of the product structure and also help determine the bottle necks and weak points of the product structure to aid the designer. This approach is explained for the family of unidirectional, fixed precedence assemblies.

1. Introduction

Disassembly is an essential part of the product life cycle that facilitates the application of various benign End Of Life (EOL) strategies such as material recycling, remanufacture, reuse and safe disposal on the product.

The importance of the effect of the *product structure* in determining a product's disassemblability has been extensively noted by researchers. Luttropp [1] provided some elementary classifications of product structures based on their disassembly characteristics. Jovane et al [2] have developed a fuzzy-logic based design evaluation methodology that uses a number of indices to evaluate the product structure along the optimum sequence. Feldmann et al [3] proposed indices like the *separation potential* and *extraction potential* to determine the weak points in the product structure. Simon et al [4] and Ishii et al [5] identified desirable characteristics like increased parallelism in the product structure for better disassembly. However there hasn't been much research done to determine the explicit effects of product structure on disassembly. In this paper a simplified approach that could help the designer reason about the effect of product structure on disassembly for certain classes of products is presented.

2. Product Structure Analysis

2.1. Motivation

One of the ways in which EOL disassembly differs from being merely a reversal of the assembly process is the profit motivation involved. This implies that disassembly could be selective and carried out only till it is profitable to do so. Thus disassembly is carried till the maximum return , *U*, is obtained as given by the following expression [2]:

$$U = \frac{R - C_d - C_p - C_f}{t} \qquad (1)$$

where,

R = Cumulative revenue or value of parts disassembled
C_d = Cost of disposal of remaining assembly
C_p = Cumulative labor cost
C_f = Fixed costs
t = Cumulative time

This maximum value of *U* is sensitive to the sequence in which the disassembly is carried out and there exists an optimal sequence for which the highest value of *U* is obtained at which point the disassembly is halted. So, the objective of designing for EOL disassembly is primarily to increase the value of *U* as obtained from the optimal sequence. From Equation (1) it can be seen that one of the important ways of achieving this objective is by enabling the removal of the highest value parts at the earliest [4][6].

The effect of the product structure on this means of increasing *U* is the issue addressed in this paper. Product structure is a very broad term and could encompass a variety of interpretations. In this paper product structure is defined to be *"the spatial relationships of the parts with respect to each other in* *the assembly and the value distribution over the product thereof*" where fasteners are also considered to be parts.

2.2. Terminology

Before proceeding any further some of the terms used in the paper are defined:

Disassembly Dividend and Quotients: The entity on which the disassembly operation is being performed is called the "*dividend*". The entities that are removed from the dividend during the disassembly operation in question are called the "*quotients*". Refer to Figure 1

Atomic moiety (A-moiety)*:* A quotient that requires no further disassembly, according to the disassembly plan, is called an *atomic moiety* (A-moiety). An A-moiety might thus be a single part, subassembly, clump or fastener.

Radical moiety (R-moiety): This is a quotient that requires independent disassembly after removal. It would thus become the dividend later on in the disassembly process. By definition the main assembly on removal of a quotient is regarded as an R-moiety till it becomes the dividend again for subsequent disassembly operations.

2.3. Value Precedence (VP)

The primary effect of product structure on the disassembly of a product is that it constrains the removal of the quotients with respect to each other by forming a precedence relationship between the parts. From now on this shall be referred to as *spatial precedence* (SP). For a given product structure and SP three important disassembly sequences can be identified.

Desired Value Precedence (DVP)

This is the ideal sequence where the disassembly quotients are disassembled in the descending order of their values unaffected by the spatial constraints making this the most desirable sequence.

Best Value Precedence (BVP)

This is the sequence where the quotients are removed considering the spatial precedence constraints but neglecting the disassembly costs. So, it would be the sequence along which an idealized return U_i is maximized assuming unit time is taken for all disassembly operations. Therefore U_i, can be expressed as:

$$U_i = \frac{R - C_d - t'}{t'} \tag{2}$$

where

t' = Cumulative number of quotients removed till that instant

Therefore this represents the highest yielding sequence for given SP of the product.

Actual Value Precedence (AVP)

This is the optimal sequence that maximizes U as given in Equation 1, obtained by taking into consideration all the actual costs involved in performing the disassembly. An example of these three sequences is shown in Figure 2.

2.4. Similarity measures

The similarity between the DVP and the BVP is a measure of the suitability of the product architecture to meet the objective of removing the high valued quotients as early as possible. It is the extent to which the spatial precedence facilitates the occurrence of the desired value precedence. In the same vein, the similarity between the BVP and AVP gives a measure of the extent of distortion that the cost effects have on the BVP where a greater similarity indicates lower distortions and vice versa. It is to be noted that these cost distortions do not refer to the absolute cost of disassembly but to the factors that could cause the AVP to veer away from the BVP like accessibility constraints, ergonomic factors and so on. Thus the knowledge of the similarity between the DVP, BVP and AVP could serve as an intuitive guide to the strategy to be considered while designing for disassembly.

Let $S_{d/b}$ be the similarity measure between the DVP and the BVP and let $S_{b/a}$ be the similarity between the BVP and the AVP. So the possible strategies for different scenarios could be:

High $S_{d/b}$, High $S_{b/a}$ – Product structure is near ideal from the VP perspective and cost distortions are minimal. So the strategy would be to carry out minor design revisions to reduce costs rather than major changes to the product architecture.

High $S_{d/b}$, Low $S_{b/a}$ – Product structure is near ideal but large distortions due to cost effects. This would imply the need for major directed design changes to reduce these effects without major changes in the product architecture.

Low $S_{d/b}$, High $S_{b/a}$ – Cost distortions are minimal but the product structure is far from ideal. So the designer would have to consider making significant changes to the product structure.

Low $S_{d/b}$, Low $S_{b/a}$ – Product structure is far from ideal and cost distortions are large. Major changes in the product structure are desirable to improve the disassembly potential of the product.

3. Value-based evaluation

3.1. Rationale

The question then arises as to how to calculate these similarity measures. Rather than actually determining the different sequences, a method to reason indirectly about the magnitudes of $S_{d/b}$ and $S_{b/a}$ has been developed. In this paper the discussion has been restricted to the relationship between $S_{d/b}$ and the SP for a simple class of assemblies.

This basic rationale of this methodology can be explained as follows. Let every potential quotient possess a "desire" to be disassembled that is proportional to its value. So, if the disassembly of a quotient, *G*, is preceded by another quotient, *J*, with a lower "desire" then *G* "petitions" *J* to move out of the way with an intensity proportional to the differences in values or "desires". So, the presence of a petition between two quotients indicates a mismatch between the spatial and the value precedence priorities of the two quotients. So for a product where $S_{d/b}$ is maximum there would therefore be no petitions. Therefore the approach here is to analyze the number and magnitude of the petitions as they could serve as an indirect way of estimating $S_{d/b}$. This idea of value dependency due to spatial constraints is not novel [2],[3] but the scope of the analysis here differs from earlier approaches.

3.2. Assumptions

To illustrate the methodology a simple class of unidirectional assemblies is considered. The other assumptions made are:

- The quotients are removed sequentially
- Only non-destructive disassembly is performed
- Each disassembly operation with the exception of the last one result in the formation of only one R-moiety and one A-moiety. This implies sequential disassembly with no consideration of the independent disassembly of the subassemblies after removal from the main assembly.
- The product is entirely disassemblable in a single direction and the quotients have a fixed precedence.

3.3. Bureau Graph (B-graph)

A representation of the petition schema is introduced called the *Bureau* graph or *B*-graph. This name was chosen due to the similarity of this situation to the hierarchy in a red-tape ridden office with a number of departments, each sending memoranda to the other for the performance of a task.

Each arc going from node *i* to node *j* is defined by a 3-tuple $<p_{ij}, q_{ij}, m_{ij}>$. The nodes or vertices represent the potential quotients and are defined by a 3-tuple <V, R, D>. These node and arc attributes are defined below:

V_i = Value of the ith quotient
V_{max} = Value of the highest value quotient
V_{min} = Value of the lowest value quotient
p_{ij} = Petition from *i* to *j* if
$[(V_i > V_j) \wedge (i \text{ is preceded by } j)]$
$= (V_i - V_j) / (V_{max} - V_{min})$
R_i = Cumulative petitions or *requests* incoming to the ith node

$$R_i = \sum_{n=1}^{k} p_{ni}$$

where *k* = Number of petitions made to quotient *i*
D_i = Cumulative petitions or *demands* being made by the ith node

$$D_i = \sum_{n=1}^{m} p_{in}$$

where *m* =Number of petitions made by quotient *i*
q_{ij} = Request intensity = (p_{ij} / Rj)
m_{ij} = Demand intensity = (p_{ij} / Di)
Refer to Figure 3 for an unattributed example from Yan et al[8] of a bureau graph.

The derivation of the request and demands attributes can be summarized as follows using the adjacency matrix representation of the graphs:

1. Obtain the adjacency matrix, **A**, for the precedence digraph.
2. Determine the "reachability" matrix, **RM**, for the precedence digraph using the relation [7]

$$\mathbf{RM} = B\,[\mathbf{A} + \mathbf{A}^2 + \ldots.. + \mathbf{A}^{n-2} + \mathbf{A}^{n-1}]$$

   where *n* is the number of moieties to be disassembled and B(**X**) is defined as the matrix whose entries are 1 if $x_{ij} > 0$ and 0 otherwise.
3. Determine the adjacency matrix, **AB**, for the *B*-graph from **RM** using the relation

$$ab_{ij} = 1 \text{ if } [(rm_{ij} = 1) \wedge (V_i > V_j)]$$
$$= 0 \text{ otherwise}$$

4. The petition matrix, **P**, is obtained from **AB** by setting:

$$p_{ij} = (V_i - V_j) / (V_{max} - V_{min}) \text{ if } [(ab_{ij} = 1) \wedge (V_{max} > V_{min})]$$
$$= 0 \text{ otherwise}$$

5. The *requests*, R, and *demands*, D, for each moiety, are obtained from **P** as:

$$R_i = \sum_{k=1}^{n} p_{ki}$$

$$D_i = \sum_{k=1}^{n} p_{ik}$$

where
i = Quotient number
n = Total number of quotients

4. Permeability of product structures

As mentioned earlier $S_{d/b}$ is closely linked with the number of petitions between the quotients. Based on these petition statistics the *permeability* (λ) of a product structure is determined. Permeability is a composite index of the VP – SP correlation as well as the “openness” of a product structure where openness refers to the degree of parallelism. Though the number of petitions alone without the information of the magnitude of the petitions would be incomplete in expressing the extent of similarity it serves as a good first cut indicator. Two measures of permeability are given below:

Value permeability, λ_v ($0 \le \lambda_v \le 1$)

This is a measure of the suitability of the SP for the given VP. A structure with a low value permeability would indicate that the high valued quotients are deep in the structure and vice versa. Thus the value permeability is very closely correlated to $S_{d/b}$.

$$\lambda_v = 1 - \frac{NP}{NP_{max}} = 1 - \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} ab_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} rm_{ij}}$$

NP = Number of petitions
NP_{max} = Maximum number of petitions possible for given SP of the product

Spatial permeability, λ_s ($0 \le \lambda_s \le 1$)

This is an index evaluating the suitability of the SP in general for any VP and is closely related to the openness of the structure. Though this index does not consider the value precedence information it measures the sensitivity of the SP structure to a possible change in values of the different quotients by considering the worst case scenario. A high spatial permeability would indicate a greater indifference of the structure to value changes, in principle. This is an important consideration for EOL disassembly as the product designed today would reach its end of life many years in the future making the value estimates very uncertain [9],[10]. The spatial permeability is given by:

$$\lambda_g = \frac{NP_{worst} - NP_{max}}{NP_{worst} - NP_{best}} = \frac{n(n-1)/2 - \sum_{i=1}^{n}\sum_{j=1}^{n} rm_{ij}}{(n-1)(n-2)/2}$$

NP_{worst} = Maximum number of petitions possible in a structure with n quotients. This is equal to the number of edges in a completely connected graph with n vertices, $K_n = n(n-1)/2$
NP_{best} = Minimum number of petitions possible in a structure with n quotients which is equal to $(n-1)$

As can be seen a product could have a very high value permeability while having an alarmingly low spatial permeability and vice versa. So both the permeability criteria need to be considered before any conclusion is reached about the optimality of the product structure. The permeability measures are holistic measures evaluating the overall product structure. However it is important to detect the actual “weak” points in the structure to be of maximum use to the designer.

5. “Weak” point identification

The information contained in the *B*-graph can be used to good effect to detect the “weak” points in the product structure from the disassembly perspective. This is can be demonstrated using the example shown in Figure 3(a). The spatial precedence and bureau graphs for the product are shown in Figure 3(b) and (c) respectively. The petition matrix, **P**, is determined using the procedure detailed in section 3.3. The values in the dotted row and column are the requests and demands for each quotient respectively.

$$\boldsymbol{P} = \left[\begin{array}{ccccccc:c}
0 & 0.25 & 0.33 & 0.08 & 0 & 0 & 0 & 0.66 \\
0 & 0 & 0.08 & 0 & 0 & 0 & 0 & 0.08 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.75 & 0.83 & 0.58 & 0 & 0 & 0 & 2.16 \\
0 & 0.58 & 0.66 & 0.41 & 0 & 0 & 0 & 1.65 \\
0 & 0.91 & 1 & 0.75 & 0.16 & 0.33 & 0 & 3.15 \\
\hdashline
0 & 2.49 & 2.9 & 1.82 & 0.16 & 0.33 & 0 & 0
\end{array}\right]$$

A plot of the demands against requests for every quotient can help identify the “problematic” quotients. For the example being considered, the plot is shown in Figure .The quotients having a high request and/or demand lie in the outer regions and are the ones having large effects on $S_{d/b}$. For the example product, quotients a large fraction of the quotients– quotients 2, 3, 4, 5 and

7 – meet this criteria indicating a poor structure from the disassembly perspective. This inference is also borne out by the low value and spatial permeability of the structure, $\lambda_v = 0.25$ and $\lambda_r = 0.06$ respectively. Also, though not shown here, the request and demand intensities can then be used to identify the specific spatial relationships that need to be examined by the designer.

Thus the *B*-graph serves as a very convenient tool to perform both a holistic as well as a quotient specific analysis.

6. Discussion and Conclusions

In this paper, a quantitative method for value-based evaluation of product structures from the disassembly perspective analysis has been presented. This is based on the important realization that the value precedence is as much a part of the product structure as the spatial precedence. A graph to capture the relationship between the value precedence and the spatial precedence called the *Bureau* graph is presented. Also the concept of permeability is proposed that relates the value precedence relationships to the openness of the product structure and provides a holistic evaluation of the product structure. The fact that this value based evaluation only requires basic information on the spatial precedence and values of the quotients makes it a convenient tool to analyze disassembly considerations during the conceptual design stages.

However, the abstract and simplistic nature of the approach can only provides hints to the designer and a final decision would depends on the consideration of the cost and other factors affecting disassembly like specific fasteners, tools used and so on. The extension of the methodology to understand cost distortions or $S_{b/a}$ needs to be addressed to provide the full picture. Further the consideration of only fixed precedence unidirectional assemblies and 100%disassembly was a major simplification and the extension of the value precedence principles to other kind of assemblies needs to be addressed.

7. Acknowledgements

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Figure 1. Disassembly dividend and quotients

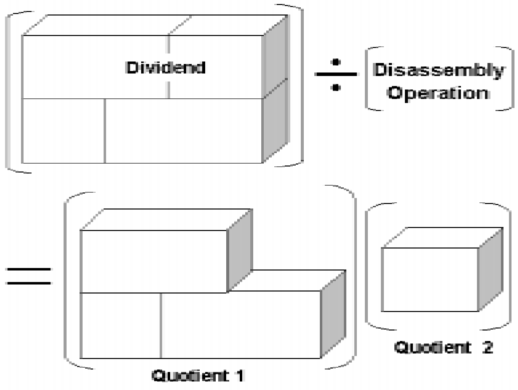


Figure 2. Value Precedence comparisons

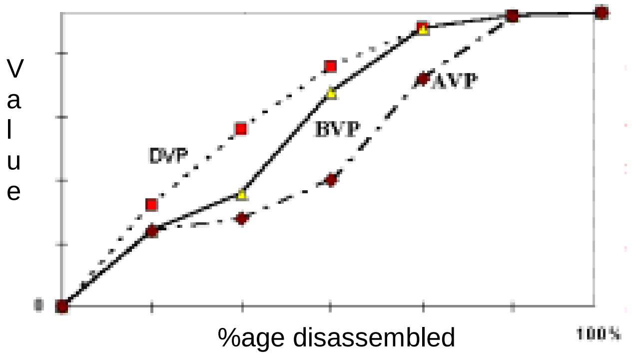
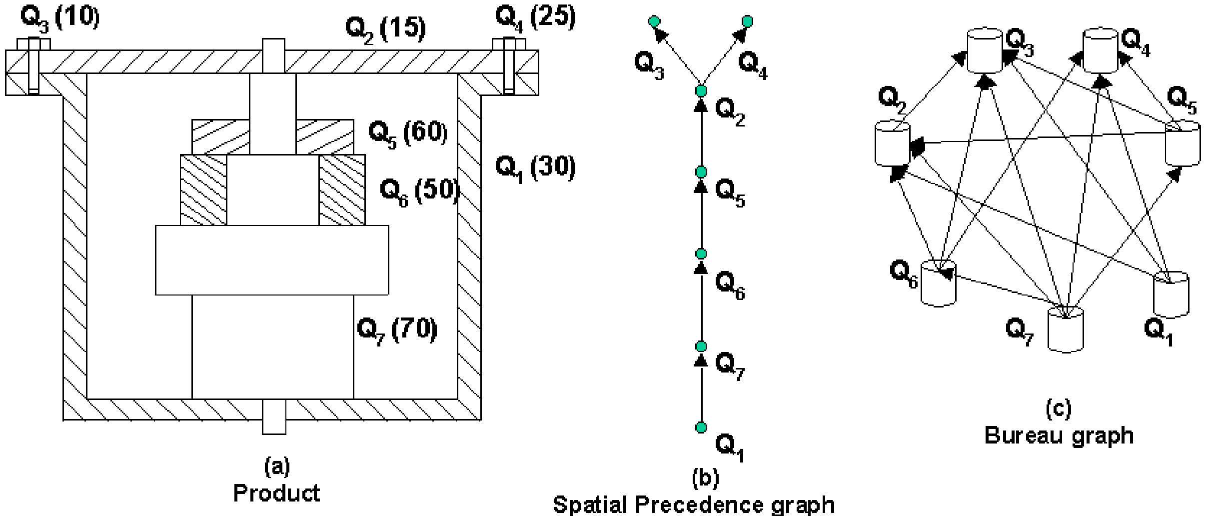


Figure 3. Spatial precedence and bureau graphs

(Quotient values [8] in brackets)



(a) Product

(b) Spatial Precedence graph

(c) Bureau graph

Figure 4. Plot of Demand against Request for each quotient