Disassembly Sequence Analysis for Environmentally Conscious Design and Manufacturing

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Abstract

Environmentally conscious design and manufacturing (ECDM) is becoming a very important issue in the manufacturing community. Adequate product reuse and recycling can greatly reduce waste generation, thus increasing product environmental compatibility. Design for disassembly analysis is a building block of the ECDM system. It is able to design or redesign products so that a higher percentage of the component parts can be reused or recycled. In this study, an economic model of disassembly analysis is formulated and integrated with an object oriented product model. Due to the nonlinear and combinatorial characteristics of the problem, a simulated annealing algorithm is employed to find the economically optimal sequences that yield the maximum return value, and to advise where the disassembly operation should stop. It shows the potential of analyzing the environmental friendliness of material selection, assembly configuration, and fastening methods. The proposed method is illustrated with a water pump assembly example.

1 Introduction

Now, more than ever, business is beginning to view environmental compliance as a management mandate. In fact, government initiatives are making stricter regulations for environment friendly products and technology. Impending German legislation requires that manufacturers take responsibility for the
disposal of their products. In the UK, firms are so far affected in the realm of process clean-up but will encounter stricter regulations soon [5]. Instead of cleaning up after the waste has been generated, reducing waste generation has become a more promising way of preventing environmental deterioration. Environmentally conscious design and manufacturing (ECDM) is a concept for designing a product with environmental compatibility. As such, manufacturing processes that produce hazardous waste and scrap are abolished or improved. The benefits of ECDM include safer and cleaner factories, worker protection, reduced future costs for disposal, reduced environmental and health risks, improved product quality at lower cost, better public image and higher productivity [8].

ECDM should be applied to every stage of the product life cycle. The product life cycle generally consists of raw material, procurement, manufacturing, service, and retirement. At the end of product service it is not preferable just to dispose the entire product. There are always parts that can be reused or recycled. Nonetheless, some hazardous materials may need to be dealt with before they can be disposed. In the future, the design of motor vehicles, domestic appliances and many other engineering products will have greater accountability for safe product disposal. This makes disassembly a very important stage in the product life cycle.

In the disassembly stage, parts are separated and sorted based on their environmental characteristics: reuse, recycle, treatment, or disposal. Environment protection regulations are forcing the engineers to design products for the ease of reuse and recycling. Therefore, design for disassembly might be employed as a measure of design efficiency with respect to environmental friendliness. It is most likely that design for disassembly will be a major challenge for designers in the year to come [2].

2 Related Research

In the ECDM literature, a number of studies have been reported on design for disassembly analysis. Simon [5] categorized the items removed during disassembly into a hierarchy based on their possible destinations. From top down, the hierarchy consists of re-use, re-manufacture, recycle to high grade material, recycle to low grade material, incinerate for energy content, and dump in landfill site. A high level means that much of the investment on raw materials, labor and energy in the component is conserved. One strategy of disassembly is to remove the most valuable parts first and stop disassembly when the marginal return on the operation becomes unfavorable. Simon argued that this can be done by proper product design. In this case, since disassembly costs are proportional
to the time taken and the percentage of components removed, it may only be economic to partially disassemble the product. The process terminates at the point of maximum return and the remainder of the product may be shredded for magnetic separation of its ferrous metal content. Finally, the low value remnants are simply landfilled. As landfill costs increase, this tips the balance in favor of further disassembly to separate and recycle a higher portion of the product.

For design for serviceability, Dewhurst [2] developed a cost model for the recycling process. He used a power-law type curve to emulate material reclamation value versus disassembly time. The cost of disassembly is proportional to the disassembly time. The labor rate is a constant. The disposal cost is assumed to decrease steadily as the disassembly goes on. This is based on an assumed steady cleanup of the residual mass of a product as material types are separated. Therefore, Dewhurst obtained three continuous equations based on disassembly time. From these three equations, he found the point at which the disassembly should stop.

It is true that with proper design one can always disassemble a product to gain the highest reclaim value. However, Simon’s model implicitly assumes that a best disassembly sequence can always be found, yet how it is found is not discussed in Simon’s or Dewhurst’s model.

For disassembly sequence, there is a belief that it is the reverse of the corresponding assembly sequence. Based on this assumption, some researchers studied the assembly sequences by decomposing an assembly configuration. Yet assembly sequencing and disassembly sequencing are very complex nonlinear problems when the precedence among them is taken into account. Currently, automated disassembly sequencing is successful only for very simple cases [1]. And it is not always true that one can obtain a disassembly sequence by reversing its assembly sequence.

Subramani and Dewhurst [6] developed the concept of a disassembly diagram that can be used, along with a search and bound computer algorithm, to generate an optimum disassembly sequence for identified target parts. This work was for establishing procedures to be used for assessing servicing costs at the earliest stages of product design. The disassembly sequence was meant to retrieve a specified part in an assembly. In another study, Laperrière and ElMaraghy [3] developed a method that combined assembly sequencing and various aspects of disassembly.

In summary, most of the reported studies focused on the development of economic models of disassembly operation. Very few addressed the issue of disassembly sequence generation. To support the real world disassembly analysis, a comprehensive economic model with the mechanism of generating an optimal disassembly sequence needs to be developed. The study presented in this paper
explores the disassembly economic model coupled with a procedure for generating optimal disassembly sequences. The model takes into account of the major factors in disassembly, such as primary cost drivers and precedence relationships among the parts to be disassembled. This integrated method yields the maximum return value and advises where the disassembly operations should stop. It also has potential capabilities of analyzing the environmental friendliness of product material selection, assembly configuration, and fastening methods.

3 Economic Model of Disassembly Operations
3.1 Product Model

A prerequisite to developing a realistic economic model for disassembly processes is an appropriate product assembly model. Many assembly models exist in literature. Liu [4] developed an object-oriented STEP based product model for assembly evaluation, motivated by the international standard for product data exchange. Based on his work, an extended assembly model is developed for this study. In this model, parts and joints are two major classes of objects. The “part” objects are used to represent the components in an assembly. The “joint” objects are used to represent the relationships among the component parts. Object parts and object joints construct an assembly network model (Figure 1).

![Figure 1: Assembly model based on parts and joints.](image)

In this assembly network model, the nodes represent parts, while the links represent joints which show the relationships between parts. Note that a joint may connect more than two parts, and a part may have many joints connected to it.

3.2 Precedence Relationships in an Assembly

Another important issue in assembly is the precedence. There are two ways to interpret the precedence, one of which is that the precedence can be viewed as a relationship among parts. In this sense, a part cannot be assembled or disassembled before certain other parts. The other way of interpretation is that
the precedence can be viewed as the relationship among joints. Here, a joint
cannot be fixed or broken before certain other joints. Because of the part-joint
relationship, these two ways of interpretation can be converted into each other.
In this study, precedence among joints is used in formulating the model, since
fixing or breaking a joint is directly related to human efforts.

3.3 Disassembly Economics

At the end of its service, a product may be disassembled for reclaimed parts, re-
used, re-manufactured, recycled to high grade material, recycled to low grade
material, incinerate for energy content, or landfilled [5]. In this study, every part
that will not be disposed of is assigned a reclaim value. The part that will be
disposed of is assigned a disposal cost. To disassemble a product, the joints need
to be broken. Hence, each joint is associated a labor cost to break it.

Assume that a product has \(m\) parts and \(n\) joints. In terms of reclaim value
and cost, the disassembly related product information can be expressed as
follows:

\[
A = \{ P, J, V_r, C_d, C_l \};
\]

where: \(P = \{ P_1, P_2, ..., P_m \}\), part set; \(J = \{ J_1, J_2, ..., J_n \}\), joint set;
\(V_r = \{ V_{r1}, V_{r2}, ..., V_{rm} \}\), reclaim values of parts; \(C_d = \{ C_{d1}, C_{d2}, ..., C_{dm} \}\), disposal
costs of parts;
\(C_l = \{ C_{l1}, C_{l2}, ..., C_{ln} \}\), disassembly costs of joints; \(V_r, C_d, \) and \(C_l\) are all non-
negative.

In the case when \(V_r > 0\), the part can be reused and recycled, and the part
will not be disposed of; thus, the disposal cost is zero. Therefore, the equivalent
reclaim profit value is \(V_r + C_d\). If \(V_r = 0\), even if the part is released from the
assembly, it must be disposed of and the disposal cost will be \(C_d\).

In a disassembly operation, suppose \(p\) joints are broken and among the
released parts, \(q\) parts have a positive value, then the net profit will be:

\[
P_{V_{net}} = \sum_{i=1}^{q} V_r - \sum_{j=1}^{n} C_j - \sum_{r=q+1}^{m} C_d\] (1)

Equation 1 can be rewritten as:

\[
P_{V_{net}} = \sum_{i=1}^{q} (V_r + C_d) - \sum_{j=1}^{n} C_j - C_{d0}\] (2)

where \(C_{d0}\) is the initial disposal cost of the entire assembly.

The objective of the disassembly is to find the maximum value of \(P_{V_{net}}\)
and indicate where the disassembly operation should stop. In Equation 2, \(C_{d0}\) is a
constant for every product. Therefore, the optimization problem is transformed
into:
\[ P V_{net} = \sum (V_i + C_d) - \sum C_i \]  

(3)

Apparently, when there are no precedence constraints among the joints, one can always break the joint with the highest respective profit value first and stop wherever the \( PV_{net} \) starts to drop. In the worst case, disassembly can only start with the joint associated the least equivalent profit. Figure 2 shows these two extreme conditions. In reality, the best case can never be reached because of the precedent constraints. There exists a set of feasible disassembly sequences (those indicated by the dashed lines in Figure 2) between the best and worst conditions.

Figure 2: Extreme cases vs. real cases of disassembly operations.

For each feasible sequence, there is a maximum \( PV_{net} \) which indicates where the operation should stop for the sequence. The overall optimum is the best one among all those feasible sequences given. For economical disassembly, it is desired that the global optimum solution which yields the maximum profit is found. It is the designer’s responsibility to design a product with a precedence relationship which gives the largest possible \( PV_{net} \). Therefore the disassembly planning problem can be formulated as the following optimization model:

\[
\begin{align*}
\text{Max} \quad & PV_{net} = \sum (V_i + C_d) - \sum C_i - \sum C_{dis} \\
\text{s.t.} \quad & \text{Precedence among joints} \\
& \text{Constraints on reclaim values} \\
& \text{Constraints on disassembly costs} \\
& \text{Constraints on disposal costs}
\end{align*}
\]

4 Solution Algorithm

As it turns out, the above optimization problem can be very complex to be solved. The number of possible sequences for an assembly with \( n \) joints would be \( n! \) if precedents were not taken into consideration. Precedent constraints among joints reduce the number of feasible sequences. Yet the number is still very large for a relatively complex product. On the other hand, even if a precedence
network among the joints can be easily developed, the evaluation of each node with respect to profit and cost would be very difficult. This is because the evaluation is associated not only with joints, but also with the parts which are released depending on the sequence in which the joints are broken. Due to the nonlinear and combinatorial characteristics of the objective function and constraints, no existing network algorithms have been found to be successful for this class of problems. In this study, a stochastic optimization algorithm - simulated annealing (SA) is employed to solve the disassembly optimization problem.

4.1 Simulated Annealing Algorithm for Optimal Sequencing in Disassembly Analysis

In the early 1980s, the simulated annealing technique was introduced and it has been employed in many application areas such as VLSI layout, traveling salesman problem, and image processing with proven effectiveness [7]. SA, as the name implies, simulates the physical annealing process in which the temperature of an object is lowered very slowly in order to reach a lowest energy particle configuration from a high energy particle configuration where the particles are randomly arranged. The mathematical foundation of SA can be found in [7]. SA can not guarantee reaching the global optimal solution. However, it provides a promising method for finding satisfactory solutions for combinatorial optimization problems [7][9]. The following sections describe the application of SA algorithm to the disassembly planning problem.

To perform a disassembly analysis, the objective function needs to be evaluated over all disassembly sequences that conform to the precedence among the joints. Each of these sequences is a configuration in SA. For the disassembly problem, a configuration is easy to determine. However, it is difficult to determine a neighborhood move. Normally, a neighborhood move is preferred to be switching from one point to another in the domain without any intermediate feasible solution in between. For continuous variable optimization problems, a neighborhood move is similar to a random walk with bias. In other words, the determination of a neighborhood move involves the selection of a direction along which a move is made, and the determination of a step size which decides how far a new solution is away from the current one. In sequencing problem, a solution is a sequence of tasks to be performed. No criteria exist to measure the difference between sequences. Intuitively, three methods are tested to find a good neighborhood move.

For an assembly with $n$ joints to be broken, the three alternatives for neighborhood moves are:
1. Randomly generate the first sequence. At the \(ith\) iteration of the algorithm, exchange \(J_i\) and \(J_{i+1}\) (\(J_i\), \(ith\) joint. \(1 \leq i < n\)); at the \(nth\) iteration exchange \(J_n\) and \(J_1\).

2. At each iteration, randomly generate two numbers \(i\) and \(j\) within the range from \(1\) to \(n\). Exchange \(J_i\) and \(J_j\).

3. At every iteration, randomly generate one number \(i\) within the range from \(1\) to \(n\). Exchange \(J_i\) and \(J_{i+1}\); if \(i = n\), exchange \(J_i\) and \(J_1\).

In this study, the neighborhood move is generated using the third method, because it preserves the stochastic nature of SA, and has the ability to cover the entire feasible region.

Another important component of the SA algorithm is the cooling schedule. The starting temperature and the schedule of lowering the temperature should be carefully controlled in order to obtain optimum solutions. The simulated annealing process is terminated when one of the following conditions holds: (1) the temperature reaches the freezing temperature, a very small \(T\), (2) no significant changes at the last \(N_t\) consecutive temperature levels, and (3) the objective function has been evaluated for a certain number of times, say \(N_t\).

The simulated annealing algorithm for disassembly analysis is described as follows.

\begin{verbatim}
Begin with an initial feasible sequence \(S_0\) (\(S_0 = \{J_1, J_2, J_3, \ldots, J_n\}\)) at temperature \(t\)
Evaluate the objective function
Repeat
   Perform the following loop \(M\) times
      Set \(i = 1\)
      Repeat
         Pick a neighborhood configuration \(S'\) of \(S\)
         If the new solution does not fall in the feasible region (violate the precedence conditions)
            Go back to generate a new move
         Else
            Set \(\delta = (f(S') - f(S)) / f(S)\)
            If \(\delta \geq 0\) (uphill move)
               Set \(S' = S\)
            Else (downhill move)
               Set \(S' = S\) with the probability \(e^\frac{\delta}{T}\)
         Set \(i = i + 1\)
      Until \(i = n\)
   Lower \(t\)
Until one of the terminating conditions is true
Return \(S\)
\end{verbatim}

5 An Example
A water pump assembly is employed to demonstrate the methodology presented in the previous sections. Figure 3 shows the pictorial view of this product. The parts in this water pump assembly are also listed.

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<th>Part No.</th>
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<td>1</td>
<td>Square headed bolt</td>
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<td>Outside cap</td>
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<td>2</td>
<td>Intake flange</td>
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<td>4</td>
<td>Pump body</td>
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<td>5</td>
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<td>Pump plunger</td>
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<td>Cotter pin</td>
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<td>Electric strap</td>
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Figure 3: Pictorial view of the water pump assembly.

An assembly network is developed for this product and is shown in Figure 4.

Figure 4: Assembly network of the water pump.

The precedence relationships among joints are described as follows:

- \( J6 \) can not be broken unless \( J5 \) has been broken.
- \( J5 \) can not be broken unless \( J7 \) has been broken.

A joint-part matrix is established to structure the joint-part relationships. The reclaim value and disposal cost of each part, and the labor cost of breaking each joint are also shown in the matrix in Table 1. In this matrix, if a part is related to a joint, “1” is marked. The parts are shown column-wise and the joints are shown row-wise.

Table 1: Joint-part matrix

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</table>
The simulated annealing algorithm is implemented in C++ and the product model is represented in an object oriented structure. Because of its nature, SA can find more than one optimal solutions. Three of the optimal solutions for the water pump assembly are shown in Table 2. They all gave the same objective function (Equation 3) value, 46.5.

<table>
<thead>
<tr>
<th>No.</th>
<th>Sequence Obtained</th>
<th>Obj. Func. Value (cost unit)</th>
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<tbody>
<tr>
<td>1</td>
<td>(2,1,4,3,9,7,5,8,6)</td>
<td>46.5</td>
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<tr>
<td>2</td>
<td>(1,4,9,3,2,7,8,5,6)</td>
<td>46.5</td>
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<tr>
<td>3</td>
<td>(9,3,1,2,4,7,5,6,8)</td>
<td>46.5</td>
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</table>

The value changes along with the number of the joints broken for these three solutions are labeled in (a), (b), and (c) in Figure 5, respectively. In the figures, Series 1 represents the accumulated equivalent value \(V_r + C_d\) of the parts released when certain joints are broken, Series 2 represents the accumulated disassembly cost of joints, and Series 3 is the net profit. The figures shows that the net profits in all these three solutions start to drop after the fifth joint has been broken. This suggests where the disassembly operations should terminate. For the first sequence, the operation should stop after Joint 9 has been broken. For the second one, it should stop at Joint 2. And for the third one, it should stop at Joint 4.
6 Conclusion

In this study, a comprehensive economic model for disassembly analysis is formulated and built upon an object oriented assembly model. A simulated annealing algorithm is employed to find the optimal sequences that yield the maximum return value and to determine where the disassembly operation should stop. This method also provides the potential capabilities of analyzing the environmental friendliness of selecting product materials, assembly configuration, and fastening methods. Future study will focus on these areas in environmentally conscious manufacturing.

References

