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A Petri Net based Disassembly Sequence Planning Model with Precedence Operations

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분해우선작업을 가지는 페트리 넷 기반의 분해순서계획모델

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Abstract This paper presents a Petri Net (PN) based disassembly sequence planning model with precedence operations. All feasible disassembly sequences are generated by a disassembly tree and a disassembly sequence is determined using the disassembly precedence and disassembly value matrix, The precedence of disassembly operations is determined through a disassembly tree and the value of disassembly is induced by economic analysis in the end-of-life phase. To solve the disassembly sequence planning model with precedence operations, a heuristic algorithm based on PNs is developed. The developed algorithm generates and searches a partial reachability graph to arrive at an optimal or near-optimal disassembly sequence based on the firing sequence of transitions of the PN model. A refrigerator is shown as an example to demonstrate the effectiveness of proposed model.

Key Words : Disassembly Sequence Planning Model, Petri Net, Heuristic algorithm, Precedence Operations

요 약 본 논문에서는 분해우선작업을 가지는 페트리 넷 기반의 분해순서계획모델을 제안한다. 모든 가능한 분해순서는 분해트리에 의해 생성되고, 분해우선순위와 분해가치 행렬을 이용하여 분해순서를 결정한다. 분해작업의 우선순위는 분해트리를 통하여 결정하고 분해작업의 가치는 제품의 마지막 수명단계의 경제적 분석에 의해 유도된다. 분해우선작업을 가지는 분해계획모델을 해결하기 위하여, 본 연구에서는 페트리 넷 기반의 휴리스틱 알고리듬을 개발한다. 개발된 알고리듬은 페트리 넷 모델의 전이순서에 기반을 두어 도달할 수 있는 모든 그래프의 노드를 탐색하여 최적의 혹은 근사최적의 분해순서를 생성한다. 본 연구에서는 냉장고를 대상으로 제안모델의 유효성을 입증한다.

1. Introduction

Increased public consciousness of environmental issues has led to a growing concern with the environmental implications of product designs, manufacturing processes and recycling. This concern has also led to many countries imposing stricter legislation such as product "take-back" laws in Europe and the "recyclability" laws in Japan and placing responsibility for the environmentally safe disposal of products at the end of their life on the primary manufacturers. The increasing shortage of landfill space and the expanding regulation of waste are all combining significantly to drive up the costs of waste disposal significantly in the next few years. Therefore, research on the disassembly methodology for recovery is required for the end-of-life (EOL) phase of products.

A disassembly process is one whereby the components of a product are removed for the purpose of accessing other components for maintenance, replacement or repair. Recently, all the components in an assembly may be disassembled for recycling purposes. A disassembly sequence consists of the tasks which begin with a product

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to be disassembled and terminates in a state where all of the parts of interest are a partial and complete disassembly. Usually disassembly of a product can be performed to explore all possible options of performing disassembly that will ensure the maximization of the return and promote specific design characteristics that will facilitate the ease of disassembly.

There are many disassembly problems which are likely to be NP-complete and various researchers have studied. The issue of determining disassembly configurations that achieve an optimal trade-off between disassembly costs and the gains from reusing or recycling the items has been studied. Johnson and Wang [1] address the problem of determining disassembly sequences that maximize economic benefit. They adopt a cost framework and propose a number of rules for deciding whether to disassemble or dispose of each component. Johnson and Wang also suggest an approach to the disassembly sequence problem. Li. et al. [2] develop a mathematical programming model of the disassembly sequence problem and solve it using simulated annealing. Recently, Lambert and Gupta [3] addressed the problem of demand driven disassembly using a tree network model while Kongar and Gupta [4] used goal programming to address such problems. Seo et al. [5] proposed a genetic algorithm for generating optimal disassembly sequences considering both economical and environmental factors.

In this paper, we propose a different methodology to solve the disassembly sequence generation problem. The Petri Net(PN) based approach for an optimal disassembly sequence is proposed. Using the disassembly precedence and value matrix, a disassembly sequence is generated by PNs. The value of disassembly is induced by economic analysis in the EOL phase. The PN based model proposed is to capture the precedence relations of the disassembly process thereby skipping the conversion step. In addition, the proposed model can easily handle partial sequencing by appropriately specifying the initial and final markings. The model has the flexibility to reduce the search space and explores the markings of the PN used a heuristic function which provides optimal or near-optimal solutions.

The paper is organized as follows: The economic analysis is described in section 2. In section 3, a PN based modelling approach for disassembly sequence planning is presented. An application example is then provided in section 4. Finally, some conclusions are presented in section 5.

2. Economic Analysis

The economic equations for economic analysis are formulated in this section. The quantitative equations for the disassembly cost, the disposal cost and the recycling value are defined.

Notations:

RV_k : Recycling Value of part k (\$/g)

MV_k : Used Material Value of part k (\$/g)

W_k : Weight of part k (g)

CV_k : Disassembly Cost for part k (\$)

dt_k : Disassembly time for the kth part (hr)

CL : Disassembly Labor Cost (\$/hr)

CD_{p_k} : Disposal Cost for the kth part (\$/g)

TCD_p : Total Disposal Cost for m parts (\$/g)

$CD_{p_{current}}$: Current Disposal Rate (\$/g)

DV_k : Disassembly Value of part k (\$/g)

n : Total number of recycled parts

m : Total number of parts within product

d_1 : Total number of disassembled parts but disposed

d_2 : Total number of disposed parts without disassembly

Upon disassembly, a specific component k is defined as having an individual recycling value (RV_k) of:

$$RV_k = W_k \times MV_k \quad \cdots\cdots (1)$$

where MV_k represents the used material value of the kth component of a product.

The disassembly cost usually includes the disassembly time and the labor costs. The disassembly time depends on tool changes and the direction of movement changes. These changes often require additional resources. Tool changes need additional setup time, while direction changes can require more processing time. Another cost factor relates to the part characteristics which are hazardous, corrosive or fragile and so on.

The disassembly cost associated with removal of the k th component can be represented as:

$$CD_k = dt_k \times CL \quad (2)$$

where dt_k is the disassembly time for the kth component and CL is the labor cost.

The disposal cost associated with landfilling or incinerating of the kth component can be represented as:

$$CD_{p_k} = CD_{p_{current}} \times W_k \quad (3)$$

where $CD_{p_{current}}$ is the current disposal rate, e.g. the regular or special landfill and incineration cost, and W_k is the weight of the kth component.

Within the previously defined parameters, the disassembly value (DV) of recycling the kth component for material recycling can then be expressed as:

$$DV_k = RV_k - CD_k + CD_{p_k}(k = 1,2,...,n) \quad (4)$$

where CD_{p_k} is the savings from not paying the disposal cost of the kth component, and where CD_{p_k} is the disposal cost only, or the disposal cost plus the disassembly cost.

3. Petri Net based Modelling for Disassembly Sequence Planning

3.1 Petri Net

PNs consist of four primitive elements (tokens, places, transitions, and arcs) and the rules that govern their operation. Graphically, PNs are based on a vision of token moving around an abstract network. Tokens are conceptual entities; they appear as small solid dots and model the objects that move in a real network. Places are shown as circles and represent the locations where objects await processing or the conditions that objects are in. Transitions appear as bars or rectangles and represent processes, events, or activities. Arcs represent the paths of objects through the system. Arcs connect places to transitions and transitions to places; an arrowhead indicates the direction of the path. When an event or activity occurs, the transition is said to be fired, and is accompanied by changes in the markings of the system. Marking essentially represents the state of system, which has been modelled by the PNs.

For modelling the disassembly process, a representation capable of envisioning all feasible disassembly sequences is introduced and the PN for disassembly (denoted as PND) is defined as follows. A PND is defined as five-tuple such as $PND = (P, T, I, O, m_0)$ is an acyclic PN where $P = (p_1, p_2, \cdots, p_n)$ is a finite set of places, $n \geq 0$. The final product or root is denoted by p_1, which has no input arc. A set of places called parts is denoted by p_{end}, each of which has no output arcs; $T = (t_1, t_2, \cdots, t_m)$ is a finite set of transitions, $m \geq 0$. They denote the decision-making steps and each transition has at most one input arc and at least two output arcs; The set of places and the set of transitions are disjoint, $P \cap T = \varnothing$; $I: T \to P^{\infty}$ is the input function, a mapping from transitions to bags of places; $O: T \to P^{\infty}$ is the output function, a mapping from transitions to bags of places; The initial marking is $m_0(p_1) = 1$ and $m_0(p) = 0,\ \forall p \in P - \{p_1\}$; The terminal marking is $m_f(p_1) = 1,\ \forall p \in P_{end}$ and $m_f(p) = 0,\ \forall p \in P - P_{end}$ and no transition is enabled.

3.2 The Proposed Algorithm to Generate Optimal Disassembly Sequence Planning

Once the PN model of the system is constructed, all possible characteristics of the system can be completely tracked by the reachability graph. The change in the markings of the PN describes the evolution of the disassembly system. An optimal sequence is obtained by generating the reachability graph and finding the optimal path from the initial marking to the final marking. The path is a trace of the firing sequence of transitions of the PN model. Even for a simple PN, the reachability graph may be too large to generate in its entirety. Instead of generating the entire reachability graph, a heuristic search algorithm is employed. Depending on the heuristic functions used, this algorithm generates the necessary portion of the reachability graph to find an optimal or near optimal path.

The algorithm proposed in this section is a modified version of graph search algorithm A^* [6]. The proposed algorithm unravels the reachability graph from the initial marking to the final marking through a restricted search procedure. The optimal sequence is constructed by linking the final marking to the initial marking.

The stepwise procedure for the proposed algorithm is shown as follows:

Step 1. Put the initial marking m_0 in the temporary list.

Step 2. If the temporary list is empty then terminate with failure.

Step 3. Remove the first marking m from the temporary list and put m in the list of markings that constitute the optimal sequence.

Step 4. If m is the final marking, then construct the optimal path from the initial marking to the final marking and terminate.

Step 5. Find the enabled transitions of the marking m.

Step 6. Generate the next marking, or the successor for each enabled transitions and set the pointers from the next markings to m. Compute $p(m^*)$ for every successor m^*.

Step 7. For every successor m^* of m, do the following:

Step 7-1. If m^* is already on the temporary list then direct its pointer yielding the highest $p(m^*)$.

Step 7-2. Calculate $h(m^*)$ and $c(m^*)$ and put m^* in the temporary list .

Step 8. Reorder the list in the decreasing order of the function $c(m)$.

Step 9. Go to step 2.

The proposed algorithm has two lists. The one is the temporary list consisting of markings (m) and figuratively it consists of the list of enabled transitions. The other is the list of markings that constitute the optimal sequence, i.e. the order in which transitions should be fired to obtain the optimal or near-optimal sequence. The temporary list maintains the markings that are generated but not yet explored. These markings form the frontier of the reachability graph. The reachability graph expands by exploring this frontier outward from the initial marking until it touches the final marking. Hence, the proposed algorithm does not generate the whole reachability graph but rather proceeds by engendering the reachability graph layer by layer until it finds an optimal or near-optimal path to the final marking.

The proposed algorithm uses a function of marking m:

$$c(m) = p(m) + h(m) \quad \cdots\cdots (5)$$

The term c(m) is an estimate of the profit gained during disassembly operation from the initial marking to the final marking along an optimal path that goes through the current marking m. The term $p(m)$ is the current highest profit obtained from the initial marking to the current marking m. The term $h(m)$ is an estimate of the profit from the marking m to final marking along the optimal path that goes through the marking m. It always finds an optimal sequence if $h(m)$ satisfies the following condition [6]:

$$0 \le h(m) \le h'(m), \forall m \quad \cdots\cdots (6)$$

where $h'(m)$ is the profit of the optimal path from m to the final marking.

Each arc of the reachability graph corresponds to a firing of a transition and has a corresponding disassembly value associated with it. The disassembly value associated with the arc is given by the following equation:

$$\tau(m, m') = [DV_{i,j}] \quad \cdots\cdots (7)$$

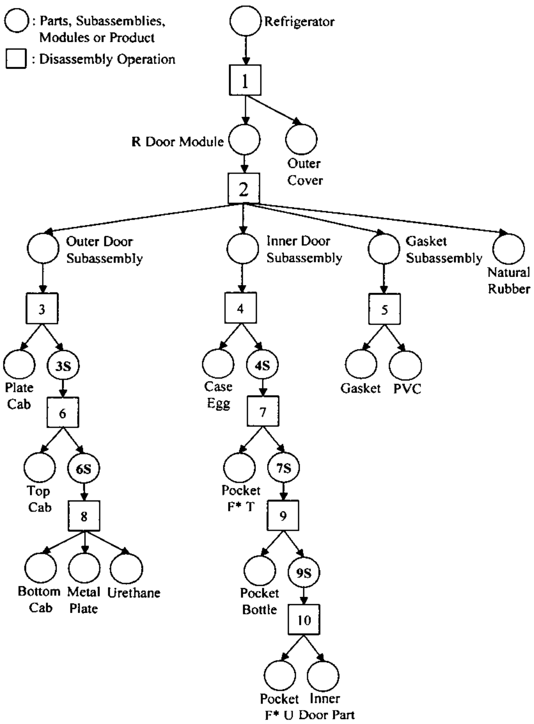
where i is the last transition fired and j is the transition which is fired during the movement of reachability graph from m to m^*.

The function τ links the PN model with the DVM and forms the basis of optimization. The function p is actually the summation of τ from the initial marking to the current marking m. The value of $c(m)$ represents the optimum profit when m reaches the final marking.

4. Application Example

4.1 Identification of Disassembly Operations

To explain and validate the disassembly operation sequences generated from the PN based approach, we use the R(refrigerated) Door module of a refrigerator as an example. The disassembly operations to be done on the disassembly tree (DT) are labeled as O_1, O_2, ..., O_n (O: Operation). The disassembly operations and the precedence of disassembly are shown in Figure 1, along with the constraints considered.

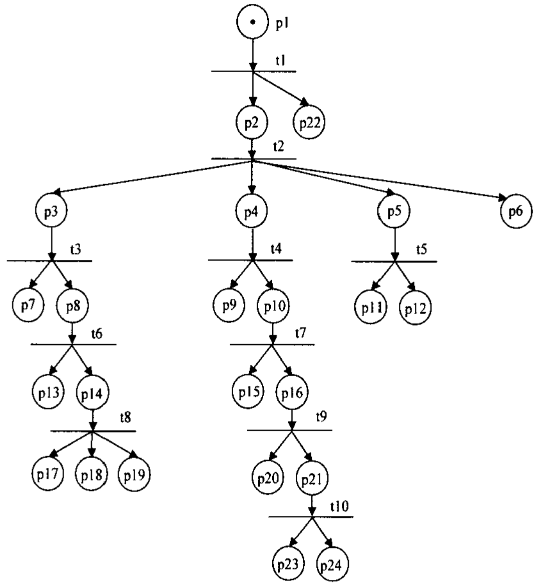


[Fig. 1] DT representation of the R DOOR module

From the precedence graph, the disassembly precedence and value matrix is generated for each pair of disassembly operations based on the values corresponding to the disassembly cost, the recycling value and the disposal cost. The PN associated with the DT of the R Door module is shown in Figure 2. The DT depicted in Figure 1 imposes the following precedence constraint: $O_1 \rightarrow O_2 \rightarrow (O_3, O_4, O_5)$, $O_3 \rightarrow O_8$ and $O_6 \rightarrow O_8$. This precedence constraint is handled easily by the PND model through the sequence in which the transitions are fired.

4.2 Disassembly Value Formation

The disassembly sequence is generated by optimizing the disassembly process that will simultaneously minimize the disassembly cost



[Fig. 2] The PN model for the R DOOR module

and maximize the material revenue to be recycled. Meanwhile, generating a disassembly sequence based on either disassembly costs or material values alone cannot be optimal.

For this reason, the disassembly value index is introduced in order to generate an optimal disassembly sequence in the demanufacturing phase. The DVs are obtained by the data of disassembling R DOOR modules of some refrigerators of the same size and company.

The optimal disassembly sequence is generated by the DV and DV_{ij} represents the disassembly value of the changeover between the disassembly operations i and j. The DV matrix (DVM) D, shown in Figure 3, would include all possible disassembly operations and changeover values, which will be the same in each operation of the matrix. Figure 3 for DVs is obtained by the data of disassembling R DOOR modules of 20 refrigerators of the same size and company. The RVs are reflected in purchasing cost of used material. The main factors of the disassembly time are tool changes and the characteristics of released parts. The RVs and CDs are examined by the maximum, minimum and mean. The CD_{p_k} is fixed by incineration cost such as \$0.3 per kilogram.

$$D = [DV_{ij}] = \begin{array}{c} \text{Disassembly} \\ \text{Operation} \end{array} \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \end{array} \overset{\text{Disassembly Operation}}{\begin{array}{cccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \end{array}} \atop \begin{bmatrix} - & 23 & -15 & 6 & 14 & -12 & 5 & 85 & 4 & 13 \\ -13 & - & -15 & 6 & 14 & -12 & 5 & 85 & 4 & 13 \\ -13 & 23 & - & 6 & 14 & -12 & 5 & 85 & 4 & 13 \\ -13 & 23 & -15 & - & 14 & -12 & 5 & 85 & 4 & 13 \\ -13 & 23 & -15 & 6 & - & -12 & 5 & 85 & 4 & 13 \\ -13 & 23 & -15 & 6 & 14 & - & 5 & 85 & 4 & 13 \\ -13 & 23 & -15 & 6 & 14 & -12 & - & 85 & 4 & 13 \\ -13 & 23 & -15 & 6 & 14 & -12 & 5 & - & 4 & 13 \\ -13 & 23 & -15 & 6 & 14 & -12 & 5 & 85 & - & 13 \\ -13 & 23 & -15 & 6 & 14 & -12 & 5 & 85 & 4 & - \end{bmatrix}$$

[Fig. 3] DVM formation of the R DOOR module

4.3 Experimental Results

The proposed algorithm is coded in the C++ programming language and run on the system with Pentium Ⅳ processor. We have used the final DT, its PN model and DVM of R Door module as an example to illustrate our proposed methodology. The result obtained by applying the proposed algorithm is shown in Table 1.

[Table 1] The result obtained by applying the proposed algorithm

No. of iterations	No. of marking explored	Overall profit	Sequence of transition fired (Optimal sequence)
12	21	\$1.10	t_1-t_2-t_3-t_6-t_8-t_5-t_{10}-t_4-t_7-t_9 (1-2-3-6-8-5-10-4-7-9)

Table 1 shows that the optimal sequence for this example is O_1 - O_2 - O_3 - O_6 - O_8 - O_5 - O_{10} - O_4 - O_7 - O_9 satisfied with precedence constraints and the total disassembly value is \$ 1.10. With respect to the R Door disassembly of a refrigerator, the final DV is estimated to be \$1.10. In other words, the present R Door design of a refrigerator is expected to be economically feasible with respect to the disassembly for recycling.

5. Conclusion

This paper explored a systematic procedure for determining the economic level of product disassembly and the corresponding sequence of disassembly operations. This procedure has been divided into two phases: First, the economic analysis of disassembly operations was performed and DVM were formed. Secondly, it has presented a simple and effective disassembly sequence generation methodology using the PN model by correlating the different cost indices, DVM with the firing of transitions to achieve an optimal or near optimal disassembly sequence. It is important to point out that disassembly sequence generation is a computationally complex problem and the PN based approach effectively treats this problem with less computational effort. There are some of the distinguished characteristics of the proposed approach are as follows: i) Once a complete model of the system is constructed, the proposed algorithm uses this PN model to search a partial reachability graph and finds a globally optimal or near-optimal disassembly sequence; ii) The formulation explicitly and easily handles the important characteristics of disassembly systems, such as precedence relations; iii) By setting the initial and the final markings appropriately, partial sequencing can be handled without any modification to the model.

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