行政院國家科學委員會專題研究計畫 成果報告

綠色環保供應鍊之多目標主規劃排程問題研究
研究成果報告(精簡版)

計 畫 類 別 ： 個別型
計 畫 編 號 ： NSC 95-2416-H-002-054-
執 行 期 間 ： 95 年 08 月 01 日至 96 年 07 月 31 日
執 行 單 位 ： 國立臺灣大學資訊管理學系暨研究所

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處 理 方 式 ： 本計畫可公開查詢

中 華 民 國 96 年 10 月 30 日

行政院國家科學委員會補助專題研究計畫 ☑ 成 果 報 告
□期中進度報告

綠色環保供應鍊之多目標主規劃排程問題研究

A Master Planning Algorithm for the Supply Chain with Recycling Activities

計畫類別：☑ 個別型計畫 □ 整合型計畫
計畫編號：NSC 95－2416－ H －002－054－
執行期間：2006 年 8 月 1 日至 2007 年 7 月 31 日

計畫主持人：陳靜枝
共同主持人：
計畫參與人員：

成果報告類型(依經費核定清單規定繳交)：☑精簡報告 □完整報告

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執行單位：國立臺灣大學資訊管理學系暨研究所

2007 年 10 月 30 日

綠色環保供應鍊之多目標主規劃排程問題研究

A Master Planning Algorithm for the Supply Chain with Recycling Activities

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摘要

在競爭激烈的商業環境中，如何整合供應鏈內成員彼此間的政策及行為，以達到整體供應鏈利益的最大化，為目前大多供應鏈管理所探討的問題。而對於供應鏈的定義，隨著全球對環保議題的重視，已經從傳統自供應商至顧客端的範圍，擴大為自供應商至顧客端，再經過回收處理後提供製造商重新利用的過程。本研究即為考量回收機制之主規劃排程研究，以達到整體供應鏈最佳化為目的。本研究屬於先進規劃排程中之主規劃排程，規劃供應鏈中期的採購、生產與配銷計畫。研究中考量多個最終產品、規劃多期、有多張需求、產品結構具有共同料之特性，再加上回收規費的設定及產品回收流程，以間斷時間模式進行整體供應鏈的規劃。本研究對於此規劃問題提出一多目標模型為：以最小化總需求延遲成本滿足顧客需求為首要考量；當延遲成本獲得最佳解之後，再以最小化總生產、處理、運輸、存貨成本與回收規費為目標。在本研究中，規費的罰則為影響整體供應鏈成本的重要因素，法令設定的規費高低也會影響製造商等相關供應鏈成員的行為。因此規劃時必須同時考量變動成本與回收規費之間的變化關係，才能使整體供應鏈最佳化。本研究之規劃問題若以混合整數線性規劃模型求解，在問題規模龐大時，需要花費大量時間求解或完全無法求得解答。因此本研究提出一啟發性演算法，使得本研究問題能在有效率的時間下，得到一趨近最佳解之可行解決方案。本研究啟發性演算法之流程為：先進行規劃排程之前置作業，接著進行需求排序，完成後依照排序結果開始為每張需求做規劃。規劃之步驟為設定網路連結成本，尋找需求微調的機會，尋找最小成本之生產路徑，分配產能，增加存貨，以及調整網路結構等。以上規劃步驟重覆進行直到所有需求規劃完成為止。最後，本研究建立一規劃排程系統，並進行情境分析之實例討論，以驗證本演算法實為一可行且高效率之規劃求解選擇。

關鍵字：供應鏈管理、先進規劃排程、主規劃排程、啟發式演算法、多目標最佳化、回收流程、回收規費

ABSTRACT

This study focuses on solving the master planning problem for green supply chains by considering product structures with multiple final products using recycling processes and recycled components. This study proposes a heuristic algorithm, called the Recycling Penalty Avoidance Algorithm (RPAA), to efficiently and effectively solve the master planning problem. RPAA transforms what is, due to the recycling process, a closed-loop supply chain network into an open-loop network. This algorithm sorts demands according to the needed final products, due dates, shared capacities, and target recycling ratio, to name several possible criteria, and then plans the demands individually, using a minimum cost production tree. To avoid recycling penalties, RPAA activates a plan-ahead mechanism to find enough recycled components in upcoming demands to meet the target recycling ratio. To show the effectiveness and efficiency of

RPAA, a prototype was constructed and tested. Complexity and computational analysis were used to demonstrate the algorithm's power.

Keywords: Master Planning with Recycle Process and Recycle Penalty, Green Supply Chain Management, Advanced Planning and Scheduling, Heuristic Algorithm, Multiple-goal Optimization

1. INTRODUCTION

With concern about environmental issues growing over the past decade, the diverse partners in supply chain operations play a more and more important role in "greening" the supply chain. This evolution in green supply chain operations is part of the move away from reactive approaches that mostly seek to comply with regulations, towards more far-reaching approaches that proactively seek to create value with recycling in order to increase competitiveness. This view of the recycling process changes the perspective from "greening as a burden" to "greening as a potential source of competitiveness" [3].

Governments often play an important role in enforcing the environmental legislation regulating the different partners in a supply chain operation. For instance, the European Union has issued regulations for electrical and electronic equipment (WEEE), for used cars, and for depleted batteries [2]. In many European countries, manufacturers or producers are required to collect worn out or depleted products from their customers for possible recycling, while in most Asian countries, this is the job of the government [5]. Large companies with international brands, such as IBM, Hewlett-Packard, Xerox, BMW, and Duracell, have also actively participated in the greening of supply chain operations [1].

The diverse partners in green supply chain operations have many different and sometimes conflicting objectives. The conflict between these different objectives makes optimizing green supply chain operations very difficult, if not impossible [4]. The objective of this study is to provide a method for generating an optimal production plan that will satisfy all demands while minimizing delay penalties, recycling penalties, and the costs of production, transportation, inventory holding, and the recycling process itself—all while respecting capacity limitations, recycling requirements, and demand deadlines. This method will help manufacturers reach their objective: mass production with a sufficient quantity of recycled materials to avoid recycling penalties.

Most of the studies related to the planning problems consider heuristic approaches to solving the planning and scheduling problems in a supply chain operation, and this study does not break with that approach. Our algorithm aims to provide feasible and sometimes optimal, solutions to MP problems with recycling processes both effectively and efficiently. The recycling process changes the supply chain network structure from an open loop to a closed loop and changes the product structure from a tree configuration to a loop. Dealing with a loop in the product structure would be a great challenge for algorithms using shortest path and backward planning mechanisms. Our algorithm adds this type of recycling process to the MP problem, but breaks the loop structure that this process causes, thus making the problem easier to deal with.

2. PROBLEM DESCRIPTION

When integrating a recycling process into a supply chain operation, the product structure is changed from a tree configuration to a loop configuration and the supply chain structure is changed from an open loop to a closed loop. This article introduces a method for generating an optimal production plan that will not only satisfy all demands, but will also minimize delay penalties, recycling penalties, and the costs of production, transportation, inventory holding, and the recycling processes itself—while continuing to respect capacity limitations, recycling requirements, and demand deadlines.

In a master planning problem with a recycling process, there are two possible product structures, depending on the type of Bill-of-Materials (BOM): a manufacturing BOM or a recycling BOM. (Figure 1 shows the two product structures, PO5 and PO6, representing a manufacturing BOM and a recycling BOM, respectively.) In addition, the supply chain network with a recycling process can be divided into two segments: the product manufacturing supply chain and the used-product reverse supply chain. (Figure 2 shows the two segments of a close-loop supply chain network for two final products, PO5 and PO6.)

When solving master planning problems for green supply chain operations, recycling penalties and recycling patterns are the two major difficulties that must be dealt with. The Environmental Protection Agencies (EPA) of various governments (e.g., Japan, the European Union, the USA) have issued regulations concerning the percentage of recycled components that manufacturers must use when producing their products. To avoid recycling penalties, manufacturers of a given final product must use enough recycled components to meet the target ratio.

Recycling penalties can be fixed or variable. Fixed recycling penalties are charged to manufacturer once for each period when the target recycling ratio has not been met. Variable recycling penalties are calculated for each unit under the target recycling ratio, with the variable recycling penalty per unit multiplied by the quantity of units under the target ratio, where the under-target quantity is the demand quantity multiplied by the target recycling ratio minus the actual reuse quantity.

In this study, the recycling pattern is modeled using a multinomial distribution. Assuming that, once a product is sold, its recycling time will follow a multinomial distribution with the total number of recycling periods equal to n, the probability that the product will be recycled in period t is pt, where $\sum_{t=1}^{n} p_t$ = 1. Given this assumption, the average number of recycled components used in each period is based on the sales in previous periods, and thus is known and constant.

Apart from the recycling penalty and the recycling pattern, the following information are also needed to understand how the heuristic algorithm functions.

(1) It is assumed that the planning time horizon is cut into different intervals, called “time buckets.” Furthermore, items are assumed to be received at the beginning of a time bucket and delivered at the end of that time bucket.

(2) It is assumed that multiple final products are made or transferred in a given supply chain network. The structures of these final products are presented in the form of product tree graphs with both manufacturing and recycling BOMs, in which nodes represent products and links represent parent-and-child relationships (Figure 1).

(3) A directed graph, G(V, L), is used to represent a green supply chain network. The nodes in G(V, L) stand for facilities that produce, process, store, sell, collect, disassemble, and reprocess products and the links stand for logistical connections between two nodes.

(4) Each demand includes the products, quantities, deadlines, and delay penalties per unit time bucket. It is assumed that the demands are divisible, which means that each demand can be filled by several different combinations of supply chain partners.

Though this planning problem can be formulated as a Mixed Integer Programming (MIP) model, difficulties arise when trying to solve the MIP model due to the number of constraints and variables involved. Therefore, a heuristic algorithm, called the Recycling Penalty Avoidance Algorithm (RPAA), is proposed to efficiently and effectively solve this planning problem.

3. RECYCLE PENALTY AVOIDANCE ALGORITHM (RPAA)

The difficulties of solving a planning problem for supply chains with a recycling process lie first in determining when to use the recycled components and how many of them to use, and second in allocating the appropriate amount of the fixed recycling fee to each item when the manufacturer is penalized. Planning for a supply chain with a recycling process implies multiple objectives: (1) minimizing delay penalties; (2) minimizing fixed and variable recycling penalties; and (3) minimizing the costs of production, transportation, inventory holding, and the recycling process. The heuristic master planning (MP) algorithm proposed in this study for supply chains with a recycling process is by nature a greedy algorithm. It is designed to plan the demands one by one without backtracking, meaning that the plans for the current demand cannot affect the plans for previous demands. Our algorithm uses a flexible search method that allows demands to be programmed with other demands, ahead of the deadline, if this would help to avoid a recycling penalty, and thus is called the Recycling Penalty Avoidance Algorithm (RPAA).

To facilitate the explanation of RPAA, two important terms related to production tree selection should be defined first.

- The minimum cost production tree—*S*: This tree, selected from a given supply chain network, represents the minimum total unit cost. Please note that *S* includes both segments of the supply chain network: the product manufacturing supply chain and the used-product reverse supply chain. The unit costs on some arcs of the given supply chain can include fixed and/or variable recycling penalties, as well as inventory holding costs.
- **A**vailable **C**apacity of *S* based on DUE_{rp}—AC_S: This available capacity is computed from the minimum available capacity at each node of *S*, based on DUE_{rp}, (the due date time bucket for final product *p* for demand *r*).

The five steps of RPAA are listed below:

(P1) Convert a given closed-loop $G(V, L)$ to an open-loop supply chain network.

(P2) Sort demands using the RPAA sorting mechanism explained later in this section.

(P3) If there are no unplanned demands, stop and output the final plan. Otherwise, retrieve the next demand for final product *p* of demand *r* based on the sequences determined in (P2) with DUE_{rp} and DEM_{rp} (the demand quantity for final product *p* of demand *r*.), and initialize the planning results.

(P4) Find the minimum cost production tree, *S*, and the available capacity of *S*, AC_S, using the Recycling Penalty and Variable Cost Balancing Algorithm (RVBA) explained later in this section.

(P5) If $DEM_{rp} \geq AC_S$, allocate the AC_S of all the nodes on tree *S* to this demand, where $DEM_{rp} = DEM_{rp} - AC_S$. Then, re-set DUE_{rp} to the original due date time bucket, initialize the planning results as *0*, and go to (P4). Otherwise, allocate the DEM_{rp} of all the nodes on tree *S* to this demand, and go to (P3).

In the first step (P1), RPAA adds a virtual node, A1, between the buyer node and the collector nodes so that the closed-loop network structure can be transformed into an open-loop network (Figure 3). The cost of finding *S* is equal to the sum of the production and transportation costs. The supply chain network for each final product is then separated (Figures 4 and 5). RPAA sorts demands based on a rule-based mechanism (P2). RPAA then checks the stopping condition and retrieves the next unplanned demand (P3). RPAA looks for the minimum cost production tree, *S*, and computes the maximum available capacity, AC_S, using RVBA (P4). In (P5), RPAA verifies that there is enough capacity to fill the demand. If there is, the demand quantity (DEM_{rp}) of *S* is allocated to the demand. If not, the total capacity of *S* (AC_S) is assigned to the demand, with another tree assigned to cover the residual demand quantity. If *S* does not have sufficient capacity to fill the demand completely, RPAA adjusts the supply chain network and looks for the next best production tree (P4).

4. COMPUTATIONAL ANALYSIS

A prototype based on RPAA was constructed on a Pentium IV 3.5 GHz server and 2 GB RAM. This prototype was programmed with Microsoft C#.net on a Microsoft SQL Server 2000 and run in the Microsoft Windows Server 2000 environment. Both ILOG CPLEX and MOMPA were used here as the basis of comparison for cases with less than 40 demands. ILOG CPLEX was used to provide a lower benchmark, and MOMPA to provide an upper benchmark for the delay penalty and the recycling penalty. As mentioned before, MOMPA can not handle the fixed recycling costs and thus simply ignores this cost. The overall recycling penalty for the MOMPA planning results will be much greater than the results with RPAA and thus can be used as the upper bound.

To demonstrate the time efficiency and effectiveness of RPAA, *R* demands were planned. The first ten of the *R* demands (quantities of 600 and 800 units) are presented in Table 1. The same 10 demands were repeated *n* times (n = 20, 30, 40, 50, and 60), with 3 time buckets added to the due dates of all the demands at each iteration. Since MIP models with 40 or more demands cannot be solved with ILOG CPLEX, unlimited capacities were assumed for all nodes and solved by RPAA to obtain the minimum cost for the lower bounds, which was denoted as ILOG Lower-Bound.

The gap between the results obtained by ILOG Lower-Bound and the results produced by RPAA and MOMPA reflects the maximal difference between the optimal solution and the respective RPAA or MOMPA solutions. (These results are presented in Figure 3.) The solution times of RPAA increased linearly as the number of demands increased. The gaps between the lower bounds of the total costs and the results with RPAA increased linearly as the number of demands incremented and were much smaller than the gaps between lower bounds and the results with MOMPA.

5. CONCLUSION

This study proposes a heuristic algorithm called the Recycling Penalty Avoidance Algorithm (RPAA) to solve a master planning problem for a supply chain network with multiple final products and a recycling process. Mixed Integer Programming (MIP) is usually used to solve these types of problems, but for a scenario including recycling, the MIP model is unsolvable due to the complexity of the variables and constraints. To improve the efficiency and effectiveness of the planning procedure, this study proposed RPAA to solve such multi-objective planning problems for supply chains with a recycling process.

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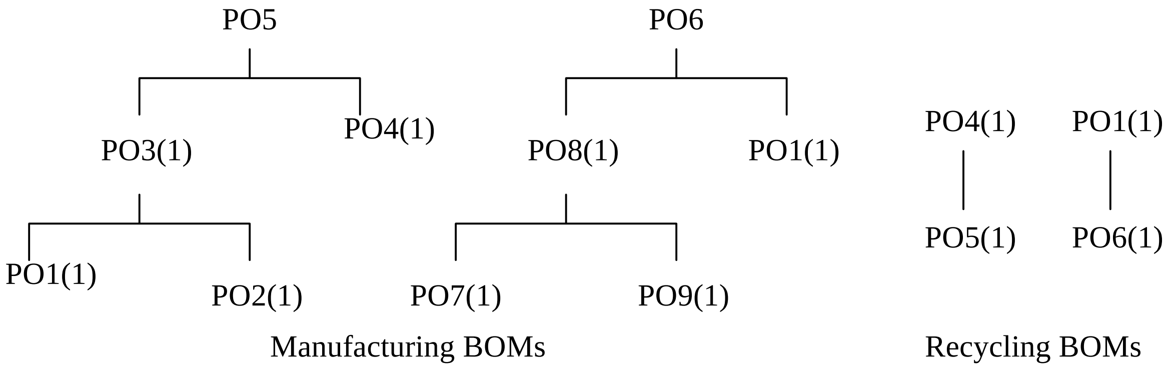


Figure 1: An Example of a Product Structure

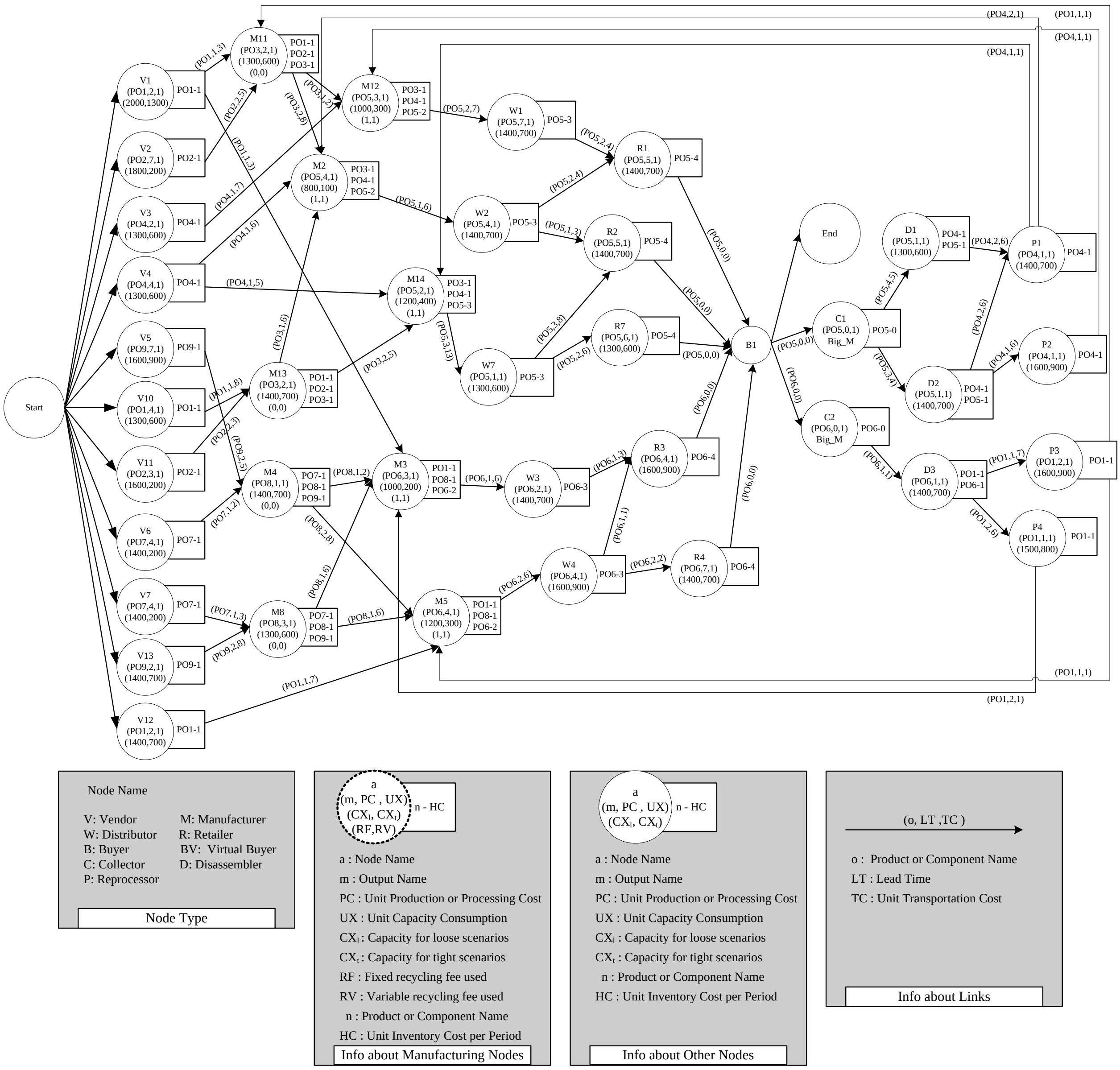
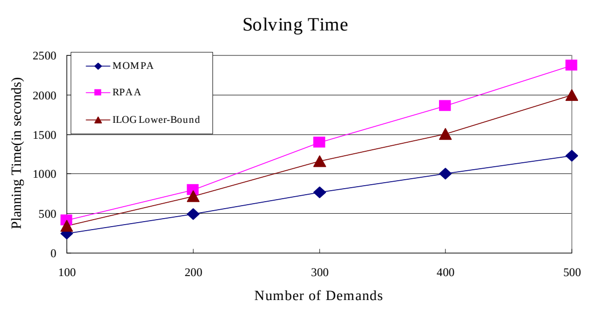
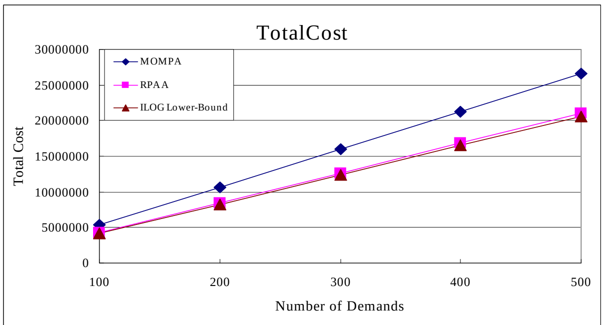


Figure 2: An Example of a Supply Chain Network



Number of Demands	100	200	300	400	500
MOMPA	246	497	763	1,004	1,228
RPAA	416	795	1,397	1,861	2,376
ILOG Lower-Bound	348	721	1,161	1,502	1,996



Number of Demands	100	200	300	400	500
MOMPA	5,320,400	10,642,400	15,964,400	21,286,400	26,608,400
RPAA	4,243,184	8,443,424	12,643,664	16,843,904	21,044,144
ILOG Lower-Bound	4,151,880	8,263,080	12,374,280	16,485,480	20,596,680

Figure 3: Results for RPAA, MOMPA, and ILOG Lower-Bound

Table 1: The Ten Demands for the Scenarios Tested

Demand ID	Qty	Due Date	Delay Cost	Final Product	Demand ID	Qty	Due Date	Delay Cost	Final Product
1	800	8	3	PO5	6	800	8	3	PO6
2	800	8	2	PO5	7	800	8	2	PO6
3	600	13	3	PO5	8	600	13	3	PO6
4	600	13	2	PO5	9	600	13	2	PO6
5	800	17	3	PO5	10	800	17	3	PO6