Reverse Logistics Models and Algorithms: Optimizing WEEE Recovery Systems

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Abstract. This is a summary of the author's PhD thesis supervised by Jose Luis González-Velarde (Tecnológico de Monterrey, Mexico) and Belarmino Adenso-Díaz (Universidad de Oviedo, Spain) and defended on October 11, 2010 at the Tecnológico de Monterrey. The thesis is written in English and is available from the author upon request. This research focuses on Reverse Logistics. Its main objective is to develop mathematical programming models and algorithms to optimize emerging Waste of Electric and Electronic Equipment (WEEE) collection systems. The thesis begins with an overview of the WEEE collection process and identifies key strategic decision areas which impact the performance of a collection system. It specifically identifies three closely interrelated problems within the logistics–manufacturing interface: network design, vehicle routing and cellular manufacturing (disassembly). Even though there is plenty of published literature on each of these individual problems, this research bridges a gap in existing literature on vehicle routing and cellular disassembly systems. The research aims to provide efficient solution approaches to optimize WEEE collection systems, therefore it uses real-world data and case studies (when possible) to test the proposed solution procedures. Computational results using real data show that the proposed methods outperform real existing approaches to reverse logistics.

Keywords. Reverse logistics, vehicle routing, cellular manufacturing, integer programming, metaheuristics.

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Modelos y algoritmos para logística inversa: optimización de sistemas de recolección de RAEE

Resumen. Este artículo presenta un resumen de la tesis doctoral del autor, la cual fue supervisada por José Luis González-Velarde (Tecnológico de Monterrey, México) y Belarmino Adenso-Díaz (Universidad de Oviedo, España) y defendida el 11 de Octubre de 2010 en el Tecnológico de Monterrey. La tesis está escrita en inglés y disponible sobre petición directa al autor. Esta investigación se enfoca en el estudio de la logística inversa. Su principal objetivo consiste en desarrollar modelos de programación matemática y algoritmos para optimizar los emergentes sistemas de recolección de Residuos de Aparatos Eléctricos y Electrónicos (RAEE). La tesis comienza con una descripción general del proceso de recolección de RAEE, e identifica las principales áreas de decisión que impactan el rendimiento de los sistemas de recolección. De forma específica se identifican tres problemas altamente interrelacionados dentro de la interfaz logística–producción–manufactura: diseño de redes, ruteo de vehículos y manufactura (desensamble) celular. Aun cuando existe una plenitud de literatura publicada sobre cada uno de estos temas, esta investigación llena un vacío en la literatura de ruteo de vehículos y manufactura celular. La investigación tiene por meta proporcionar enfoques de solución eficientes para optimizar los sistemas de recolección de RAEE, por ello utiliza datos reales y casos de estudio para probar los procedimientos de solución propuestos. Los resultados computacionales muestran que los métodos sobresalen respecto a los enfoques actuales en logística inversa.

Palabras clave. Logística inversa, ruteo de vehículos, manufactura celular, programación entera, metaheurísticas.

1 Introduction

The aim of this research is to develop mathematical programming models and metaheuristic algorithms to optimize emerging WEEE collection systems. The research begins by identifying the key strategic decision areas which impact the operation of WEEE collection systems. This was carried out through a series of meetings with managers of logistics service providers (3PL) and a representative of the ECOLEC Foundation (http://www.ecolec.es), one of the largest Collective Management Systems in Spain. Three key strategic decision areas were identified: 1) design of collection networks, 2) optimization of collection routes, and 3) optimization of disassembly systems. For each of these areas, we described the related optimization problem and proposed a solution algorithm. To ensure that the solution algorithms are able to solve real-size instances, the ECOLEC Foundation provided classified information to test the performance of the proposed models and algorithms. The computational results on the models and algorithms were analyzed by statistical methods to demonstrate the efficiency of the proposed approaches to solve these problems.

The remainder of this paper briefly describes the contributions on each problem.

2 Network Design Issues

Network design issues in WEEE collection have been widely studied over the last years (Aras *et al*. [1], Grunow and Gobbi [2]). This part of the research provides a methodological approach to (re)design WEEE collection networks. As a basis for our study, a three-phase hierarchical approach is proposed, which combines three operational research techniques, namely, integer programming, heuristic algorithms and simulation, as follows: in the first phase a facility location problem is formulated and solved by means of a mixed integer linear problem; in the second phase a new integer programming formulation for the corresponding heterogeneous fleet vehicle routing problem is presented, and a savings-based heuristic algorithm is developed to efficiently solve the related collection routing problems; in the third phase a simulation study is performed on the collection routes in order to assess the overall performance of the recovery system (see Mar-Ortiz *et al.* [3]).

The computational results show good performance of the heuristic algorithm: it reaches an average deviation lower than 1.2% over optimal solutions in very short computing times. The experimental analysis shows that by means of an iterative repetition of the route construction procedure, the algorithm is able to perform a change on the in-use vehicle to improve previous tours. To test the performance of the methodological approach, the CMS provided information about its recovery network in the Spanish region of Galicia, where in 2008 more than 3,239 tons of WEEE was collected. The results show good performance of the proposed procedure and an improved configuration of the recovery network compared to the one currently in use.

3 Vehicle Routing in WEEE Reverse Logistics

This part of the research focuses on studying a vehicle routing problem for reverse logistics. It specifically addresses the problem of designing routes for the collection of WEEE with a fixed and heterogeneous fleet of capacitated vehicles. Each vehicle can at most perform a predefined number of trips without the given maximum operation time being exceeded. The amount of end-of-life items to be collected (hereafter referred to as demand) of each customer can be greater than the capacity of the largest vehicle in the fleet. As a result, the demand of a single customer may be split to be carried out by more than one route. Thus, each customer can be visited more than once on the same day. Collection orders to customers are triggered by a call from them. With each order there is an associated demand to be met and a range of dates within which the collection should take place. This collection scheme has been reported in technical papers for collection of white goods, and is characteristic of several reverse logistics systems.

Formally speaking, mathematical formulation of the problem requires a definition of a directed graph $G = (V, E)$ where $V = \{v_0, v_1, \ldots, v_n\}$ is a set of vertices and $E = \{(v_i, v_j): i \neq j\}$ is a set of arcs connecting the vertices. Vertex v_0 denotes the depot where a heterogeneous fleet of $K = \{1, \ldots, k\}$ vehicles with capacity Q_k are stationed, while the remaining n vertices of V represent the customers to be visited. For every arc $e \in E$, the distance d_e is known. For each vehicle k we know the maximum load capacity, the set of customers which vehicle k can visit (because of street access restrictions), and the variable travelling cost of vehicle k. For collection, the independent customers make use of a call system with a timely collection guarantee. Each collection order predefines the quantity of items w_i to be collected from customer i and the range of dates within which the collection should take place. The time interval to carry out the collection from a single customer is specified by its date window $[s_i, f_i]$, where s_i and f_i are respectively the first and last day of a period within which the collection must take place, such that $s_i \leq f_i$. For all customers the service time μ_i is assumed to be constant, since each customer is usually served in a full truck load, being visited when it has at hand a sufficient number of items to be collected. For the sake of real practice, when the number of items to be collected from any customer i is less than a constant factor ε, those items are not collected and are labeled as backorders to be considered in a following request.

Given the complexity of the problem, a Greedy Randomized Adaptive Searching Procedure (GRASP) algorithm was designed to solve it. The motivation for using GRASP in this particular application is based on the fact that there is a natural form to define a priority function to select the customer to be inserted in the initial solution: by linking the customer demand and the available time for its collection (see Mar-Ortiz *et al.* [4]).

Experimental results on a set of 540 generated random instances show the convenience of the algorithm to solve problems in which the date window and the collection capacity are tightly constrained. These kinds of problems are commonly found in real situations. As a result, a good behavior in real problems is expected. The results of the ANOVA test showed that factors like the date windows and the capacity tightness regarding demand are statistically significant for the algorithm performance. On the other hand, it cannot be demonstrated that a factor like dispersion of customers affects the quality of the solutions obtained, which is a sign of the robustness of the algorithm to deal with this kind of problems. Finally, the comparison of the proposed approach with current practice reveals that the transportation costs are reduced an average of 15.96% from the current levels.

4 Disassembly Cell Formation Problems

The cell formation problem has been one of the most studied problems in the manufacturing literature, and it is the first technical problem faced in the design of a cellular manufacturing system. To address this problem, several diverse solution procedures have been developed and published over the last years (Papaioannou and Wilson [5]). Given the practical differences between manufacturing systems and disassembly systems, typical cell formation problem formulations are not suitable for disassembly systems.

This thesis provides a formal definition of the Disassembly Cell Formation Problem (DCFP) as follows: let M and P be, respectively, a set of machine/tools (such as screwdrivers, shears for cutting material, mechanical multi-devices for grinding, separation and treatment of gases…) and a set of products (such as washing machines, dryers, refrigerators…) which need to be dismantled with the aim of obtaining parts or materials of economic value and/or remove toxic elements to promote their proper disposal. Let Q be a set of disassembly operations (such as removal of a printed circuit board and a power supply, or removal of mercury switches and batteries), and let $Q_p \subseteq Q$ be a set of disassembly operations required to dismantle a product p. To this end, a product p and an operation q are not independent, and each pair $\{p, q\}$ represents a disassembly task. Let $N = \Sigma_{p \in P}$ card(Q_p) be the total number of disassembly tasks, which have to be grouped into a subset of cells *C*. The amount of returned products (hereafter referred as demand) is known with certainty. However, it should be noted that reverse logistics systems are mainly characterized by variability in both quantity (demand) and quality (physical conditions) of returned products. For each product, the sequence in which the disassembly operations need to be performed is known. Two cost elements are considered: machine/tools acquisition (i.e., amortization) costs and material handling costs. Assuming that cell sizes are not large and that inter-cell distances are small, intercellular transportation costs are considered as surrogate of material handling costs. To keep cell sizes bounded, a maximum number of operations per cell is imposed. Thus the objective of the DCFP consists in grouping disassembly tasks and assigning them to their corresponding cells with their resources so that: 1) total costs are minimized, 2) all recovered items are disassembled and 3) the following restrictions are met: a) the total number of disassembly tasks assigned to a given cell must be within the corresponding lower and upper bounds, b) the operating time assigned to a machine must not exceed its capacity and c) any task should be assigned to a single cell.

This part of the research begins with a case study in a disassembly plant of the ECOLEC Foundation using a Tabu Search algorithm. The optimal solution was also found by CPLEX and compared to the one obtained by the heuristic procedure. The Tabu Search algorithm generated a solution with 2.93% deviation from optimality. With the aim to extend the results to the DCFP with demand variability, a Variable Neighborhood Search (VNS) algorithm was designed, which incorporates a new neighborhood based on the λ-insertion move, which reallocates λ disassembly tasks at a time. The motivation for using VNS in this particular application is based on the fact that although being a simple metaheuristic which combines a systematic change of neighborhoods with a local search, it has shown to be highly efficient and easy to implement. Furthermore, in the literature several neighborhood structures have been proposed for the cell formation problem, which have been used under different metaheuristic schemes such as tabu search or simulated annealing, among others. A modification of some of such structures can be easily applied to define the shaking and local search functions in a proper manner with the aim of reaching high quality solutions. Moreover, the use of a VNS algorithm should be considered as a side step from the typical population approaches like genetic algorithms, and a step beyond from the typical use of similarity coefficient algorithms. A general description of the VNS algorithm is depicted as follows:

Obtain an INITIAL SOLUTION x_0.
Apply the **Local Search** procedure within all neighborhoods to obtain an improved INITIAL SOLUTION (x^*). Let x^* be the incumbent solution.
Make k = 1.
while $k \leq k_{\max}$ **do**
    Apply the **Shake** procedure to x^* (the incumbent solution) within the k^{th} shake neighborhood. Let x' be the resulting solution.
    Make l = 1.
    while $l \leq l_{\max}$ **do**
        Apply the **Local Search** procedure to x' (the incumbent solution) within the l^{th} local search neighborhood. Let x'' be the resulting solution.
        if (*better inner solution*)
            Update inner loop solution.
            Let l = 1;
        else go to the next local search neighborhood ($l = l + 1$).
    end while
    if (*current solution is better than incumbent solution*)
        Update incumbent (outer loop) solution.
        Let k = 1
    else go to the next shake neighborhood ($k = k + 1$)
end while

Experimental results on a set of 60 instances show the convenience of the algorithm on obtaining near optimal solutions for the reconfigurable problem in a short computing time. In average, the algorithm reaches solutions 2% above best-known solutions in an average computing time of 222.37 seconds.

5 Conclusions and Future Research

The thesis aims to describe, model and solve three problems faced by a collective management system when (re)designing a WEEE collection network. The research contributions not only bridge a gap in existing literature on vehicle routing and cellular disassembly systems, but also outline some directions for future research. The routing problem describes a new variant of a vehicle routing problem with split loads and date windows, which could be widely applied in other collection schemes. As a future work, it would be desirable to derive lower bounds to further evaluate the obtainable results. Modifications of existing exact solution procedures for the split delivery vehicle routing problem could yield such bounds. The study on disassembly cells shows the need to develop models and algorithms to face demand variability in disassembly systems. Given that the VNS algorithm shows to be quite efficient for the reconfigurable DCFP, future research should be addressed towards the robust problem. We would like to see if by incorporating memory into the shaking procedure or by using a tabu search with varying tabu list sizes could yield better bounds. Studying alternative robust schemes (minimax regret models or simulation-optimization frameworks) for the DCFP with uncertain data is an open opportunity.

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