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Abstract

The disassembly process is getting more and more important for tackling the burden of waste electrical and electronic equipment. Its complexity and frequently manual operation makes this process relatively expensive compared to its potential profit. Thus, the decisions taken for collection and disassembly of End–of–Life products need to be coordinated. In this work, an optimisation model is developed for incorporating these problems. Our experimental study shows that the coordination allows improving the global performance of the supply chain including lower total cost corresponding to the component demand satisfaction.

Keywords: Routing, Production, Collection, Disassembly, Reverse Supply Chain, Waste Electrical and Electronics Equipment.

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1. Introduction

The annual amount of waste within EU territory is around 4 million tons including waste electrical and electronic equipment (WEEE) of which is prohibited by EU Council Regulation 2002/96/EC on WEEE. This directive stipulates that WEEE is "*one of target areas to be regulated, in view of prevention of the application of the principles of prevention, recovery and disposal waste*". High amount of WEEE is mainly caused by the linear economic pattern adopting "take-make-dispose" paradigm where the waste is disposed and disregarded for being further processed. To deal with this issue, the circular economy offers another approach. Due to the reverse part of its cycle as depicted by Figure 1, the waste can be taken back and processed as the alternative supply source of production process. Among the waste flows considered, WEEE is viewed as the most hazardous but profitable one since it contains valuable materials and/or parts.
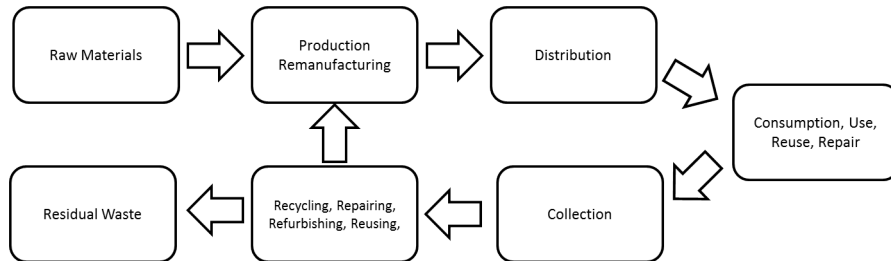

Figure 1: The circular economy

Being a part of reverse flow in closed–loop supply chain (CLSC), the disassembly process is the essential step enabling the circular economy. It is a set of activities aiming to extract the subassemblies, raw materials and/or other forms from End–of–Life (EOL) products [1]. The implementation of this process helps to enhance the sustainability of supply chain (SC) since it also practically promotes better employment and decreases the number of WEEE. Whilst augmenting the image of companies involved, it allows creating a market of EOL
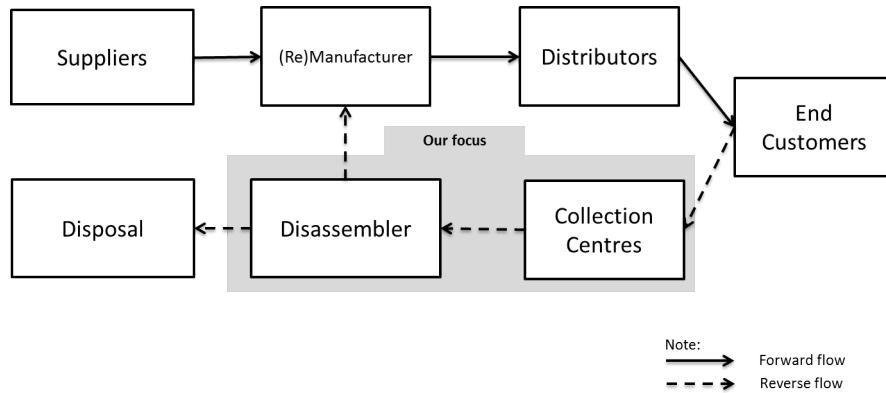
Figure 2: Closed–loop supply chain

products. In compliance, the forward SC that is common form used on linear economy must be redesigned into CLSC by incorporating the reverse flow corresponding to WEEE.

However, the disassembly process remains expensive due to its complexity as time consuming endeavour and labour intensive [2]. Furthermore, collecting EOL products is considered as an indispensable process preceding the disassembly one. It is widely known that this transportation activity contributes to the increase on the total cost of SC. Compared to the assembly process that has been studied in decades, the supply side of disassembly process is less structured and more unstable so that it needs to be managed for avoiding inefficiency leading to high cost. Considering this process as a part of CLSC as shown in Figure 2, dealing with the supply side of EOL products as a collection process may be expected. Thereby, incorporating the collection and the disassembly processes of EOL products in reverse SC context is proposed in this article.

Dealing with several processes, the integrated logistical planning has drawn intention of both practitioners and researchers for proposing better forward SC. Particularly, it has been encouraged since the practice of the vendor–managed inventory and distribution (VMI/D).

In reverse context, the disassembly process is located in the reverse side pre-

3

ceded by the collection process. Motivated by [3] on dealing with the production-distribution problem (PDP), our work proposes an optimisation model coordinating the decisions on reverse side. PDP incorporates production and routing aspects in order to jointly optimise production, inventory and routing decisions [4]. In our case, the decision of collection and disassembly process is considered as the key point to diminish the total cost. To show it, the case with coordination and the case without coordination are compared in the experimental study which, henceforth, called as case I and case II, respectively.

Our work may be intended in the case where the reverse flow handled by a third–party reverse logistics provider (3PRL) due to the nature of disassembly process. Such circumstance is expected when (i) 3PRL performs better in term of speed, accuracy, cost and revenue on dealing with return process and (ii) few products returns and no dedicated personnel or procedures working on [5]. Moreover, it may lead to gain more economic efficiency for processes considered [6].

The remaining parts of this article are organized as follows. The state-of-the-art is provided in Section 2. The optimisation problems are formalised in section 3. Section 4 depicts the instance generation for the experimental study. The obtained results are analysed in Section 5. Section 6 gives the concluding remarks.

2. Literature review

After some industrial practices of VMI/D e.g. Kellogg Company in [7] and Frito-Lay's North America in [8], the integrated logistical planning is favourable for proposing an SC with better performance. Particularly, the coordinated management of production and distribution process lead to the reduction of the total cost. It may take various configuration such as (i) integrated lot-sizing with direct shipment, (ii) inventory routing problem and (iii) production–distribution problem (PDP). The first problem minimizes the total cost of set-up, production, inventory and direct shipment while disregarding the routing aspect. The
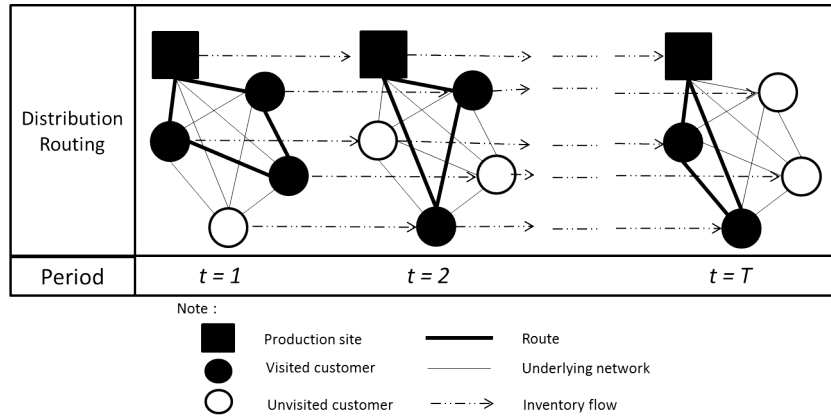
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Figure 3: Network representations of Production-Distribution Problem [9]

second problem exposes the decisions on routing aspect but ignores on production detail. Whereas, PDP focuses on both production and distribution aspects by incorporating the production decision and routing part in operational level decision as depicted in Figure 3. We encourage the lecturer to see extensive review on PDP in [4] and [9].

As aforementioned, the circular economy requires a CLSC by embedding the disassembly and its corresponding processes to form the reverse flow. Compared to forward flow, its differences include geographical location, inventory and financial aspects. It deals with many dispersed collection centres as supply sources to collect EOL products and transport them to producer or recovery facilities such as disassembly facility or disposal area. Its lack of proven and effective inventory management leads to inconsistency. Additionally, unclear financial implication results on higher inefficiency [1].

However, as far as our knowledge, there is only few works considering integrated decisions which may lead to optimise the cost particularly on tactical/operational level ones. [10] and [11] investigated the integration across strategic-tactical decisions in disassembly context. A mixed–integer non–linear problem was provided integrating the decisions of closed–loop network design and disassembly line balancing. Although the disassembly process has been
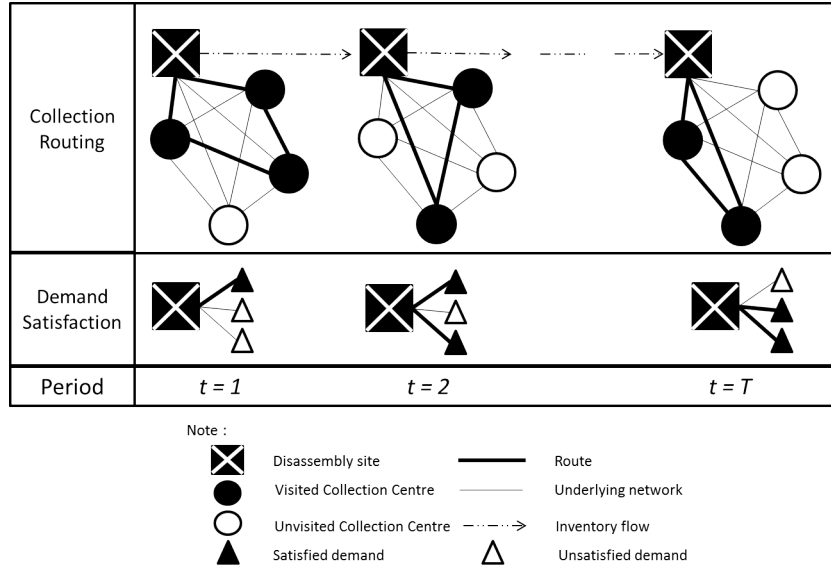
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Figure 4: Representations of our problem

extensively investigated in the literature, the majority of researches considered

90   only single decision e.g. lot-sizing [12], line balancing [13, 14], sequencing prob-

lem [15], inventory control [16], RFID application [17]. Thus, this work provides

an integrated logistical planning in the next section focusing on the collection

routing problem and the disassembly lot–sizing problem. Following our work

[18], this current work is the consecutive attempt of implementing such an in-

95   tegration into reverse context by considering collection routing and disassembly

aspects.

3. Problem definition

This section provides case I as depicted in Figure 4 and case II as sepa-

rated problems of collection routing and disassembly lot-sizing focusing on EOL

100   product.

Suppose that a single disassembly site is responsible for gathering a single

type of EOL products available at dispersed collection centres. A vehicles with

6

fixed capacity is available for gathering the products under full truck load policy.

It is assumed that the nomenclature is known and identical. Each product has several components, $a, a \in A$ where each component has one quantity, n_a. Once the products collected, it will be disassembled into a disassembly line in order to release the components requested for satisfying the demands. The disassembly line has a fixed capacity $DisCap$ corresponding to its cycle time. The unmet demand of components results a penalty cost for each unit, $CP_a, a \in A$. The problem includes multi–periods since it concerns with inventory having capacity $InvCap$. There is no salvage value or disposal cost for any leftover components. The parameters and the decision variables used are provided as follows:

Parameters. :

A	set of component: $a = \{1, 2, \cdots, A\}$;
N	set of nodes: $i, j = \{1, 2, \cdots, N\}$;
N_c	set of collection centres: $i, j = \{2, \cdots, N\}$;
T	planning horizon: $t = \{1, 2, \cdots, T\}$;
n_a	amount of component a in product $a \in A$;
S_{it}	amount of products available at collection centre i at period t, $i \in N_c$, $t \in T$;
q_{at}	demand of component a at period t, $a \in A$, $t \in T$;
Q	vehicle capacity;
$InvCap$	inventory capacity;
$DisCap$	disassembly line capacity imposed from its cycle time;
CF	fixed vehicle dispatch cost;
c_{ij}	mileage cost from node i to j, $i \in N$, $j \in N$;
CD	unit disassembly cost;
CH	unit holding cost;
CP_a	unit penalty cost of component $a, a \in A$.

Decision variables. :

7

$$
x_{ijt} \quad \begin{cases} 1 & \text{if } j \text{ is visited after } i \text{ directly at period } t,\ i \in N,\ j \in N,\ t \in T\ ; \\ 0 & \text{otherwise.} \end{cases}
$$

y_{it} vehicle load after visiting i at period t, $i \in N$, $t \in T$;

I_t product inventory at period t, $t \in T$;

P_t number of products disassembled at period t, $t \in T$;

SO_{at} unmet demand of component a at period t, $a \in A$, $t \in T$.

3.1. Formulation of case I (with coordination)

The following formulation provides the integration of collection routing and disassembly lot–sizing problem. It deals with the decisions on routing, inventory and disassembly.

Integer Linear Programming (ILP) model.

$$
\textbf{Min} \sum_{t \in T} \left\{ \sum_{j \in N_c} CF \cdot x_{1jt} + \sum_{i \in N} \sum_{j \in N} c_{ij} \cdot x_{ijt} + CH \cdot I_t + CD \cdot P_t + \sum_{a \in A} CP_a \cdot SO_{at} \right\} \tag{1}
$$

Subject to:

$$
\sum_{j \in N, i \neq j} x_{ijt} \leq 1 \qquad\qquad \forall i \in N_c, \forall t \in T; \tag{2}
$$

$$
\sum_{i \in N, i \neq v} x_{ivt} = \sum_{j \in N, j \neq v} x_{vjt} \qquad\qquad \forall v \in N, \forall t \in T; \tag{3}
$$

$$
y_{it} + (Q - S_{it}) \cdot x_{1it} \leq Q \qquad\qquad \forall i \in N_c, \forall t \in T; \tag{4}
$$

$$y_{it} - y_{jt} + Q \cdot x_{ijt} + (Q - S_{jt} - S_{it}) \cdot x_{jit} \leq Q - S_{jt} \quad i \neq j, \forall i, j \in N_c, \forall t \in T;$$

$$(5)$$

$$I_t = I_{t-1} + \sum_{i \in N} \sum_{j \in N, i \neq j} S_{it} \cdot x_{ijt} - P_t \qquad \forall t \in T; \qquad (6)$$

$$n_a \cdot P_t + SO_{at} \geq q_{at} \qquad \forall a \in A, \forall t \in T; \qquad (7)$$

$$\sum_{j \in N, i \neq j} S_{it} \cdot x_{ijt} \leq y_{it} \leq \sum_{j \in N, i \neq j} Q \cdot x_{ijt} \qquad \forall i \in N, \forall t \in T; \qquad (8)$$

$$I_t \leq InvCap \qquad \forall t \in T; \qquad (9)$$

$$P_t \leq DisCap \qquad \forall t \in T; \qquad (10)$$

$$x_{ijt} \in \{0, 1\} \qquad \forall i, j \in N, \forall t \in T; \qquad (11)$$

$$SO_{at}, I_t, P_t \geq 0 \text{ and integer} \qquad \forall a \in A, \forall t \in T; \qquad (12)$$

The objective function (1) minimizes the total cost summing the costs of collection routing, holding, disassembly and penalty. The collection routing consists of the dispatch and mileage cost. The holding cost concerns about the number of products stored at inventory. The disassembly cost is responsible of the number of products disassembled. The penalty cost corresponds to the unmet component demands.

Constraints (2) state that each collection centre is visited at most once during a period. The flow balance of each node is assured by constraints (3). The subtour elimination constraints (4) and (5) are based on lifting method proposed by [19]. Constraints (6) are the inventory balance of disassembly site for all periods. Constraints (7) impose the demand fulfilment. Constraints (8–10) limit the decisions of vehicle load, inventory and disassembly, respectively. Constraints (11) and (12) define the nature of decision variables.

3.2. Formulation of case II (without coordination)

This subsection assumes that the decisions on collection and disassembly are optimised independently. The problem is deployed into two subproblem: (1) disassembly lot–sizing and (2) collection routing. As depicted in Figure 5, the

9

early problem concerns with the decisions on the amount of products intended for satisfying the component demands for all periods. Based on this decision, the collection routing attempts to fulfil by gathering the products available at collection centres. The penalty cost is applied when the demands of component are unmet. Variable $Collection_t$ is introduced denoting the amount of products intended for all periods.

Figure 5: Relation of disassembly lot-sizing and collection routing

ILP of disassembly lot-sizing.

$$Min \sum_{t \in T} \{CD \cdot P_t + CH \cdot I_t + \sum_{a \in A} CP_a \cdot SO_{at}\}; \tag{13}$$

Subject to:

$$I_t = I_{t-1} + Collection_t - P_t, \forall t \in T; \tag{14}$$

Constraints (7), (9), (10) and (12)

$$Collection_t \geq 0 \text{ and integer}, \forall t \in T; \tag{15}$$

The objective function (13) minimizes the total cost of disassembly, inventory and penalty. Constraints (14) balance the number of products in inventory for all periods. Constraints (15) are the nature of variable $Collection_t$.

Using the value of $Collection_t$ obtained from the previous problem, the collection routing is dedicated to yield the route of vehicles as follows:

ILP model of collection routing.

$$Min \sum_{t \in T} \{\sum_{i \in N} \sum_{j \in N} C_{ij} \cdot x_{ijt} + \sum_{j \in N_c} CF \cdot x_{1jt} + \sum_{a \in A} CP_a \cdot SO_{at}\}; \tag{16}$$

Subject to:

$$Collection_t \geq \sum_{j \in N} \sum_{i \in N, i \neq j} S_{it} \cdot x_{ijt}, \forall t \in T; \tag{17}$$

10

$$n_a \cdot \sum_{i \in N, i \neq j} S_{it} \cdot x_{ijt} + SO_{at} \geq q_{at}, \forall a \in A, \forall t \in T; \qquad (18)$$

Constraints (2)–(5), (8) and (11)

The objective function (16) minimizes the dispatch and mileage cost corresponding to the vehicles used as well as the penalty cost emerged by the unmet component demands. Constraints (17) assure that the number of products collected is lower than $Collection_t$ for preventing the excess mileage cost. Constraints (18) impose the satisfaction of component demands.

4. Instances

Due to lack of benchmark instances available for our problem, the test instances were generated in following way. The data sets diagram is given in Figure 6. The first data set varies the location of collection centres, A, N, T, q_{at} and $DisCap$. The second data set focuses on S_{it}, Q and I_0. The third data set is used to evaluate the impact of the different costs between disassembly process and collection routing involving CD, CH, CF_a, CF and c_{ij}.

In the first data set, the collection centres' location is generated into either at random or by cluster as presented by Figure A.1. In the random category, the location is generated uniformly with $U(0:100)$ corresponding to ordinates and axis. In the cluster category, their location is uniformly generated as shown in Table 1. Correspondingly, N decreases from 25 into its subsets by 10 and 5 (see Figure A.2 and A.3). A is set to 10 and 5. T is fixed to 25, 10 and 5. q_{at} is generated with $U(40\%; 60\%) \cdot S_{it}$ and $U(90\%; 110\%) \cdot S_{it}$. $DisCap$ is relative to $\frac{\sum_{a \in A} \sum_{t \in T} q_{at}}{T}$ by $85\%, 118\%$ and infinite as representing under constrained, constrained, and infinite disassembly capacity, respectively. The other values are shown in Table 2.

In the second data set, S_{it} is generated as $U(9:11)$ and $U(40:60)$. Q is generated with 2,3 and 4 times $\frac{\sum_{i \in N_c} \sum_{t \in T} S_{it}}{T}$.
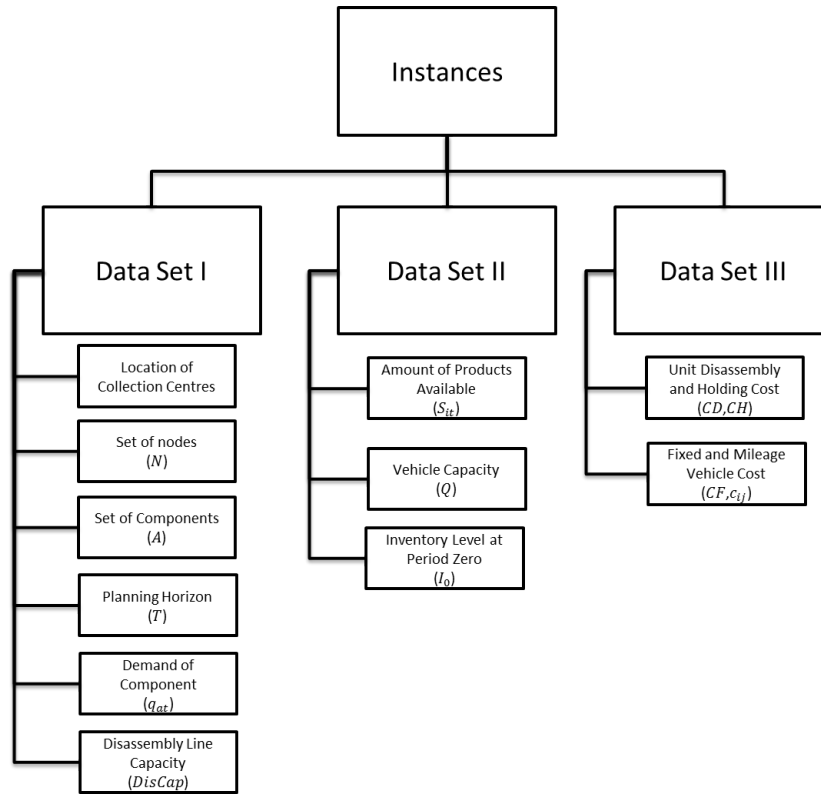
11

Figure 6: Data sets diagram

In the third data set, the value of CF is 5, 10 and 25. CD is 50%, 100% and 200% times CF. CH is fixed to $10\% \cdot CD$. The remaining parameters are shown in Table 4.

The model was implemented in java JDK 7 using ILOG CPLEX 12.6 on a PC with processor Intel®Core™i7 CPU 2.9 GHz and 4 Go RAM under Windows 7 Professional. The first data set containing 488 instances was executed within 10 minutes since it corresponds to six parameters. The second and third data sets containing 18 and 9 instances, respectively, were executed within 100 minutes in which they correspond to three parameters each.

Table 1: Location of Collection Centres

Collection Centres	Distribution Parameters	
	Ordinate	Axis
2nd-7th	$U(0:25)$	$U(0:25)$
8th-14th	$U(75:100)$	$U(30:50)$
15th-19th	$U(75:100)$	$U(75:100)$
20th-25th	$U(0:25)$	$U(75:100)$

Table 2: Parameter of Data Set 1

Parameters	Value
$S_{it}, \forall i \in N_c, \forall t \in T$	$U(9:11)$
Q	$2 \cdot \frac{\sum_{i \in N_c} S_{it}}{T}$
I_0	0
$InvCap$	∞
CD	10
CH	1
$CP_a, \forall a \in A$	4
CF	10
$c_{ij}, \forall i, j \in N$	1

13

Table 3: Parameter of Data Set 2

Parameters	Value
A	5
N	10
T	10
$q_{at}, \forall a \in A, \forall t \in T$	$U(90\% : 110\%) \cdot \frac{\sum_{i \in N_c} \sum_{t \in T} S_{it}}{N \cdot T}$
I_0	$2 \cdot \frac{\sum_{a \in A} \sum_{t \in T} q_{at}}{A \cdot T}$
$DisCap$	∞
CD	10
CH	1
$CP_a, \forall a \in A$	4
CF	10
$c_{ij}, \forall i, j \in N$	1
Collection Centres Location	Random

Table 4: Parameter of Data Set 3

Parameters	Value
A	5
N	10
T	10
$S_{it}, \forall i \in N_c, \forall t \in T$	$U(9 : 11)$
q_{at}	$U(40\% : 60\%) \cdot \frac{\sum_{i \in N_c} \sum_{t \in T} S_{it}}{N \cdot T}$
$InvCap$	∞
$DisCap$	∞
I_0	0
SO_{at}	4
c_{ij}	1
Collection Centres Location	Random

5. Results and Discussion

This part discusses our findings obtained from our proposition (case I) compared to independently solved problems (case II) as depicted by the following figures. The analysis on managerial factor of each interpretation is also available. TC, TDC, TCC and TPC correspond to the average difference of total cost, of total disassembly cost, of total collection cost and of total penalty cost, respectively, between case I and II. For clarity, the following equation computes TC value with corresponding parameter:

$$TC = \frac{average\ total\ cost_{caseII} - average\ total\ cost_{caseI}}{average\ total\ cost_{caseII}}$$

The other average cost differences (TDC, TCC and TPC) are calculated by same manner based on cost associated.

Data Set I. According to figure 7, the value of TC is always non zero indicating that lower cost is always obtained for case I. In other words, our proposition indeed permits the reverse SC having better performance. Whilst the values of TDC are nearly zero showing that the number of products disassembled is almost similar.

While TCC alternates from axis line, TPC is near 1. It indicates that the elevation of collection cost affects the decrease on unmet demand. Henceforth, the satisfaction of customers will be elevated along with the reduction on penalty cost.

Concerning to collection process, we note that for higher values of number of nodes N, number of periods T and number of components A TCC is increased as depicted by figure 7(b), 7(c) and 7(d), respectively. It is natural since their elevation requests a higher number of products to be collected for avoiding higher penalty cost. Correspondingly, the value of component demand q_{at} alternates TCC proportionally. In other words, the increase of demand naturally requires a higher number of products to be collected incurring higher collection cost.

Disassembly capacity $DisCap$ has no significant influence except in the under-constrained disassembly capacity instances. It can be concluded that

15

$DisCap$ is not a sensitive parameter for influencing the result as long as its number is higher than q_{at}. Consequently, setting up disassembly line balanc-

215 ing with a slightly higher time cycle will lead to more efficient TCC since the collection process permits optimizing more products gathered.
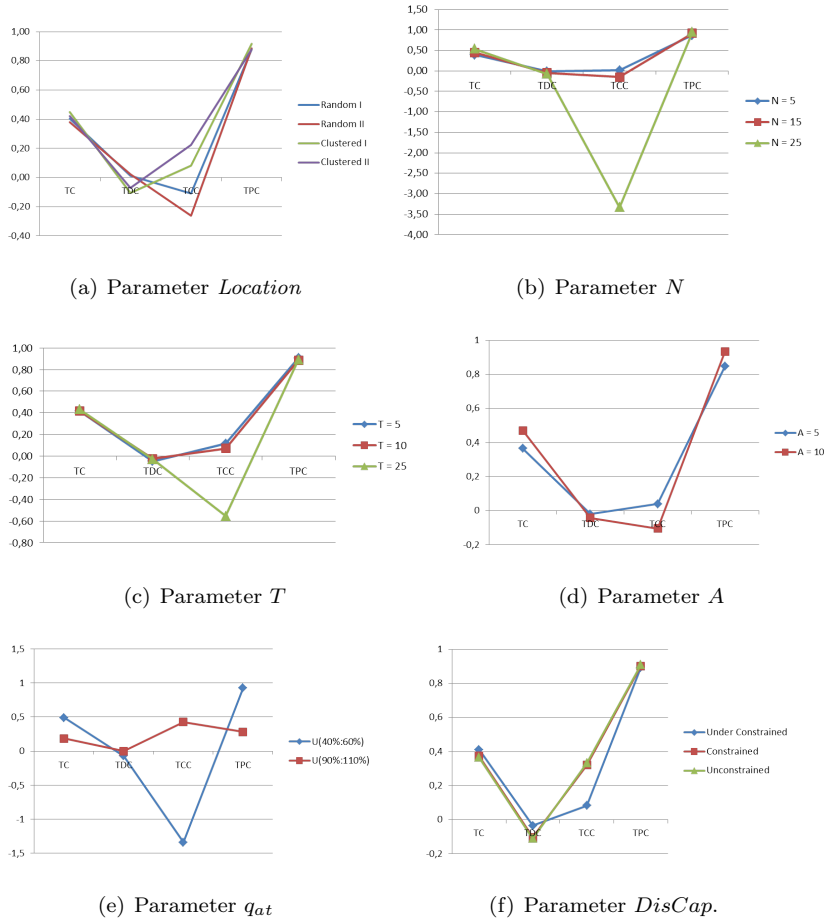

(a) Parameter *Location*

(b) Parameter N

(c) Parameter T

(d) Parameter A

(e) Parameter q_{at}

(f) Parameter $DisCap$.

Figure 7: The results of Data Set I

Regarding the computational time as shown in Figure 8, it is directly proportional to either N or T and inversely proportional to A and q_{at}. $DisCap$ has a particular effect since *constrained* instances require more computational

220 time due to the trade off between penalty cost and collection cost.

16

(a) Parameter *Location*

(b) Parameter N

(c) Parameter T

(d) Parameter A

(e) Parameter q_{at}

(f) Parameter $DisCap$.
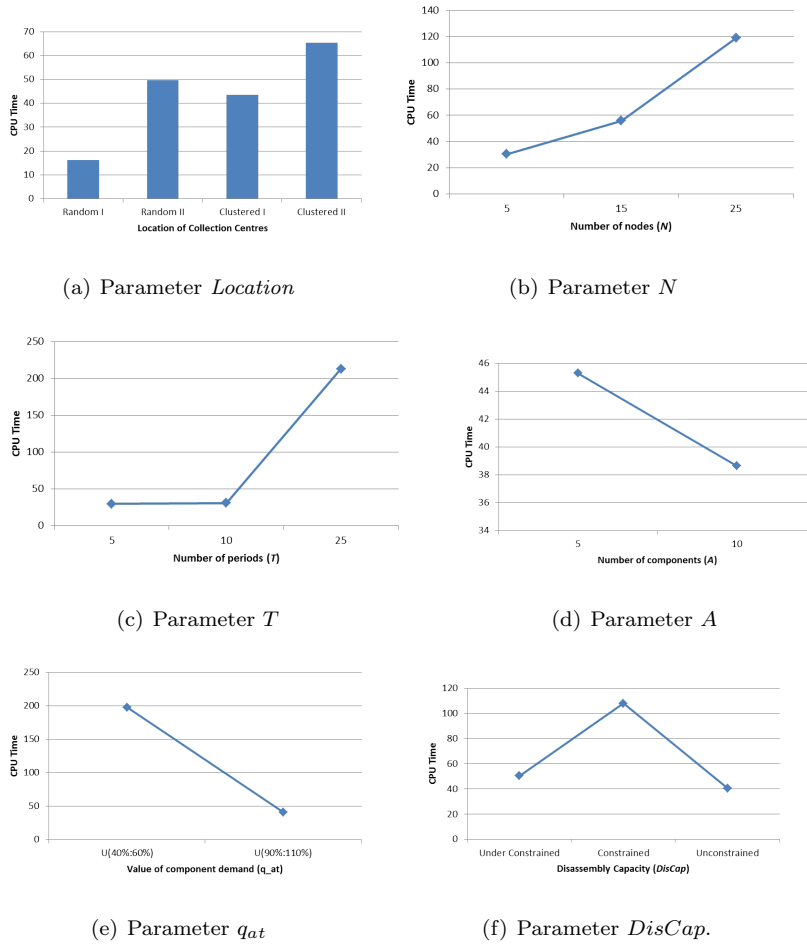
Figure 8:   The computational time of Data Set I (in second)

Data Set II. Corresponding to figure 9(a) and 9(b), parameter supply S_{it} affects the costs slightly rather than vehicle capacity Q. Meanwhile parameter inventory level at period zero I_0 shows that providing higher inventory leads to the decrease of TPC since the demand will be more satisfied. Consequently, it raises the efficiency on TC. Thus, the inventory of components required at period zero will reduce the total cost.

17

(a) Parameter S_{it}

(b) Parameter Q

(c) Parameter I_0
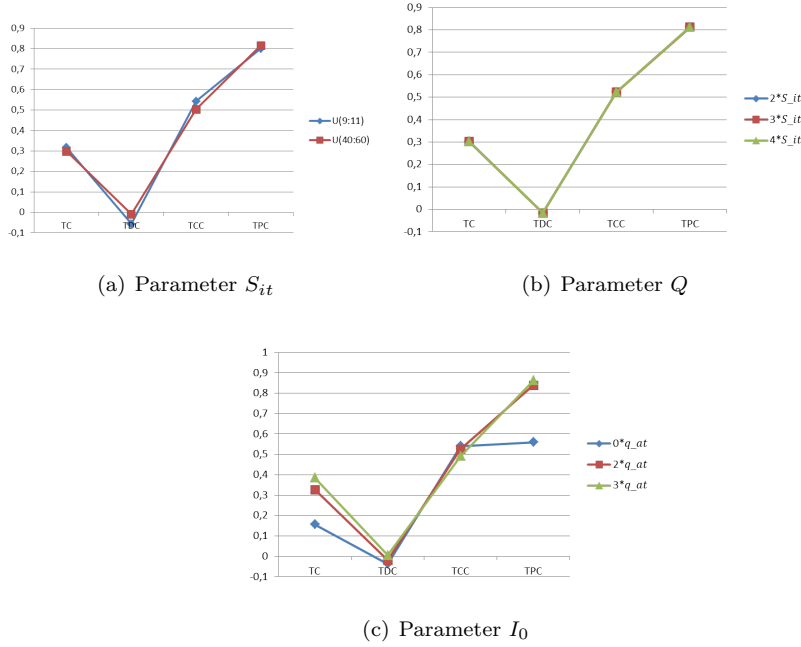
Figure 9: The results of Data Set II

According to figure 10, the associated computational time is directly proportional to S_{it} and I_0. Since S_{it} is high, it naturally results to less collection centres visited. As a consequence, it reduces the computational time.

Data Set III. Observing figure 11(a), the value of unit disassembly cost CD is directly proportional to all costs except TPC. When $CD = 50\% * CF$ as fixed vehicle dispatch cost, TPC is zero showing that no difference between case I and II. Whilst, TDC is lower indicating that the disassembly process deals with more products.

Looking on figure 11(b), particular behaviour is revealed when $CF = 25$ since both the values of TDC and TCC are zero. In this case, CF is six times of unit penalty cost CP_a. It marks clearly that paying penalty cost will avoid more expensive collection cost. In application, CF covers costs e.g. cost of maintenance, assurance, driver salary. Thus, the ratio between fixed vehicle has
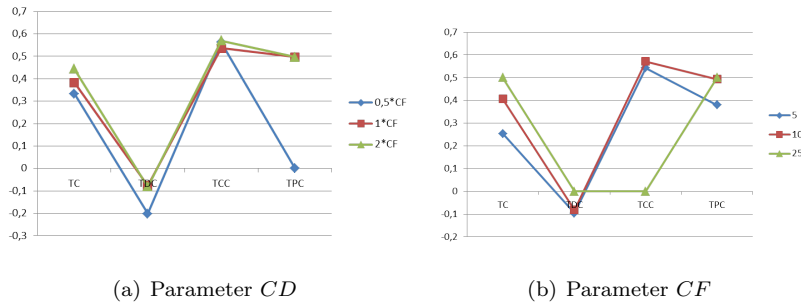
18

to be considered compared to the unit penalty cost.
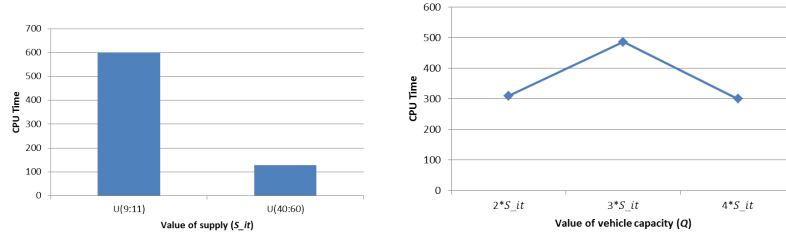
(a) Parameter S_{it}

(b) Parameter Q
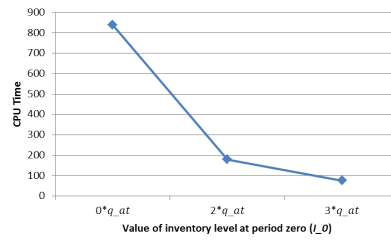
(c) Parameter I_0

Figure 10:   The computational time of Data Set II

(a) Parameter CD

(b) Parameter CF

Figure 11:   The results of Data Set III

We need to point out that our problem is $\mathcal{NP}$–hard. One of its special cases is vehicle routing problem (VRP) when the disassembly capacity is infinite and the values of unit production and penalty costs are very small or unconsidered.

Figure 12 shows that the CPU time declines along with the increase of CD and CF. Since CD reflects an expensive unit disassembly cost, the collection process gathers less products. To this point, it reduces the permutation of routing vehicle yielding lower computational time. Whilst expensive fixed vehicle cost is reflected by CF. It yields less vehicles used resulting less computational time.

(a) Parameter CD (b) Parameter CF
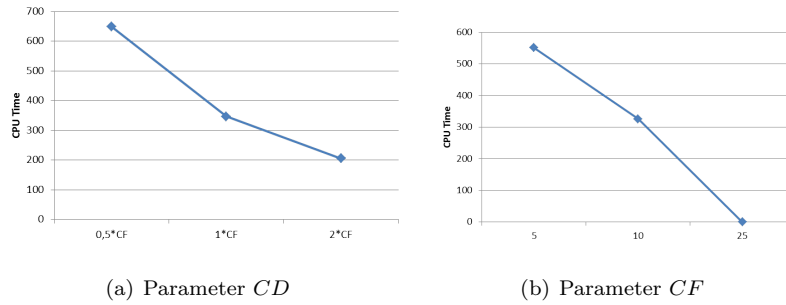
Figure 12: The computational time of Data Set III

6. Conclusion and Future Works

This work supports the development of circular economy by proposing better management on WEEE as the most hazardous and valuable waste. The implementation is done by incorporating the decisions in operational level in reverse SC. Based on our numerical experiments, we prove that integrating the decisions on disassembly and collection processes allows proposing reverse SC by optimising total cost associated.

All parameters associated have been investigated by changing corresponding values. Accordingly, some parameters have significant impact on average total cost TC and CPU computational time. They are set of nodes N, planning horizon T, set of component A, demand of component q_{at}, unit disassembly cost CD, inventory level at period zero I_0 and unit fixed vehicle cost CF. The disassembly capacity $DisCap$ and fixed vehicle cost CF alter on computational time in some instances.

20

Bridging on general view, this work allows sustaining reverse SC of WEEE

in two ways. In one hand, it assures the satisfaction of component demand of EOL products for customers. In other hand, the recycler / remanufacturer will be allowed to gain more profit by optimising efficiency yielding on lower total cost. As the result, better circular economy will be preserved while fulfilling economics needs and protecting environment.

For future works, it is necessary to consider the uncertainty at the supply side since it is practically common for EOL products. The hypothesis of encouraging the customers to bring back their EOL products has to be considered. On the other side, the different type of recyclers have to be studied.

7. Acknowledgement

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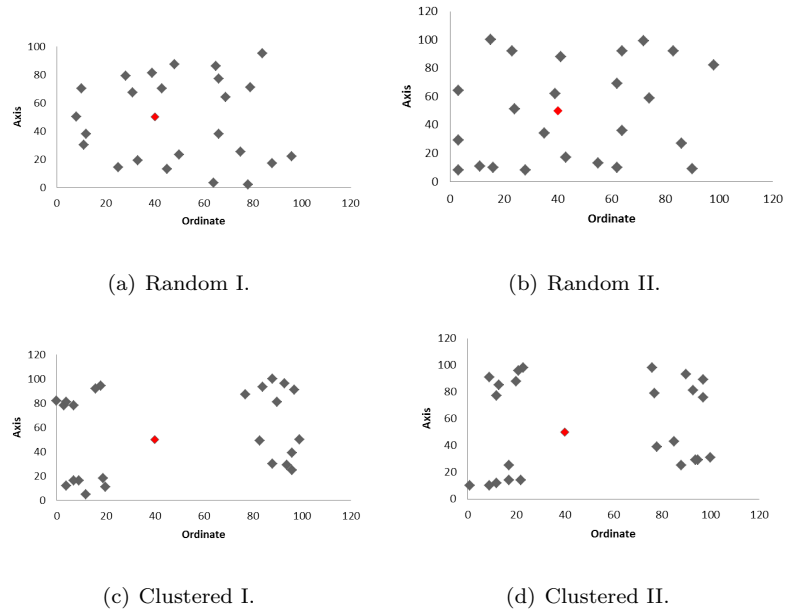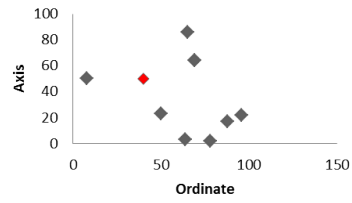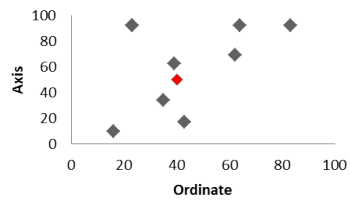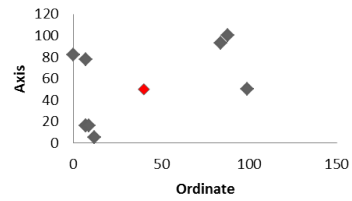# Appendices

A. Location of Collection Centres

(a) Random I.

(b) Random II.

(c) Clustered I.

(d) Clustered II.

Figure A.1:   The position of disassembly site (in red) and Collection Centres (in grey) in large instances.
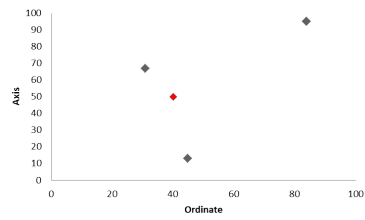
(a) Random I.
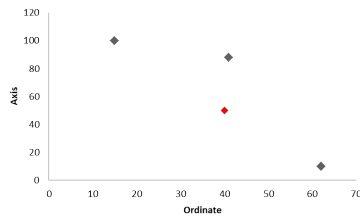
(b) Random II.
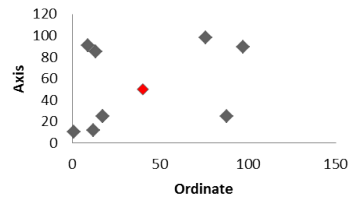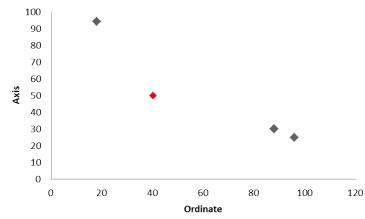
(c) Clustered I.

(d) Clustered II.

Figure A.2:   The position of disassembly site (in red) and Collection Centres (in grey) in medium instances.
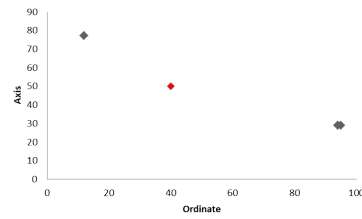

(a) Random I.

(b) Random II.

(c) Clustered I.

(d) Clustered II.

Figure A.3:   The position of disassembly site (in red) and Collection Centres (in grey) in medium instances.