CO-ORDINATION OF A SUPPLY CHAIN WITH REVERSE LOGISTICS – VEHICLE ROUTING PROBLEM AND CO_2 EMISSION

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Co-ordination of a Supply Chain with Reverse Logistics – Vehicle Routing Problem and CO_2 Emission

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CERTIFICATE OF ORIGINALITY

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Abstract

In a supply chain model, coordination of the vendor and buyers plays an important role to minimize the system cost. However, in many coordinated systems, environmental issues such as reverse logistics and greenhouse gas emission are not considered because of the complexity of the problem. Reverse logistics includes waste management, parts recovery or product recovery through recycling. Most research in reverse logistics focuses only on a small area of reverse logistics systems, such as network design, production planning and environmental issues. Air pollution resulting from transportation is an important negative environmental impact of supply chains. Hence, taking environmental concerns such as reverse logistics and CO_2 emission into vendor-buyer coordination is of vital importance and optimized planning of the routing and delivery schedule is critical.

This thesis proposes and develops mathematical models and solution methods for a coordinating system involving reverse logistics and CO_2 emissions.

1. A coordination model for a single-vendor multi-buyer supply chain with reverse logistics is proposed. The coordination in the model is achieved by synchronizing the delivery and used products pick-up cycles of the buyers with the production cycle of the vendor. Buyers are allowed to choose their own ordering cycles but these cycles must be integer factors of the vendor's production cycle. The performance of the synchronized cycles model in terms of minimizing the total system cost is compared with that of the independent policy model where buyers and vendor are optimizing their own cost independently.

2. The second area of investigation of this research is to incorporate the vehicle routing problem into the model developed in 1 so as to better represent the real-life situation. Transportation cost for delivery and used product pick-up is added to the total system cost. The transportation cost includes the cost of dispatching trucks and the cost per unit distance travelled by the trucks. Due to the complexity of the problem, one-step and two-step hybrid heuristics involving GA and ALNS are developed to obtain near optimal solution for the coordinated supply chain with the vehicle routing problem. Performance of these heuristics are compared.

3. In addition to reverse logistics and vehicle routing problem, CO_2 emission is also incorporated in the coordinated supply chain. The first objective is to minimize the total system cost which includes the inventory cost, routing cost, and the cost of CO_2 emission. Secondly, instead of minimizing the total system cost, the objective function is changed to minimize the CO_2 emission. The performance in terms of CO_2 emission is compared with previous models presented in this thesis.

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Basic parameters

d_i : demand rate of buyer *i* per unit time

A_i : ordering cost of buyer *i* per order

h_i : inventory holding cost per item per unit time of buyer *i*

r_i : recycling rate of buyer *i*

B_i : used product pick-up cost of buyer *i* per order

h_i' : used product inventory holding cost per item per unit time of buyer *i*

D : average demand for vendor per unit time

R : average recycle pick-up rate for vendor per unit time

P : production rate of vendor per unit time

β : recycling rate of vendor per unit time

S_v : set-up cost of vendor per production run

S_v' : set-up cost of vendor per recycling production run

h : holding cost of the vendor per item per unit time

C_i : fixed shipment cost of buyer *i* per order

G_i : fixed recycling cost of buyer *i* per recycling pick-up order

L : delivery lead-time

T : basic time unit

R_j : used products collected at time jT

M_j : inventory level of un-recycled used products at time jT

I_j : inventory level of recycled used products at time jT

D_t : total demand for the vendor at time tT

c_d : transportation cost per unit distance travelled

c_r : cost of dispatching a vehicle

ϕ_i : fixed CO_2 emission per unit item per unit distance for truck i

γ_i : variable CO_2 emission per unit item per unit distance for truck i

$\eta_{i,j,k,t}$: quantity transported by truck i at time tT from location j to k

ε : unit cost per kg of CO_2 emitted

Basic variables and cost functions

T_i : ordering cycle of buyer i in the independent policy model

Q_i : ordering quantity of buyer i in the independent policy model

F_i : used product pick-up cycle of buyer i in the independent policy model

U_i : used product pick-up quantity of buyer i in the independent policy model

$K_i(T_i, F_i)$: total cost per unit time for buyer *i* in the independent policy model

T_v : production cycle of the vendor of the independent policy model

Q_v : total production of a production run of the vendor

$K_v(T_v)$: total cost per unit time of the vendor

$K(T_v, T_1, T_2, ..., T_n, F_1, F_2, ..., F_n)$: total system cost of the independent policy model

NT : production cycle of the vendor in the synchronized cycles model

$k_i T$: ordering cycle of buyer *i* in the synchronized cycles model

$g_i T$: used product pick-up cycle of buyer *i* in the synchronized cycles model

ST : production run start time

$\pi_i T$: the first time buyer *i* orders new products

$\tau_i T$: the first time buyer *i* orders used products pick-up

Ψ : surplus stock above the demand D_1 at time T

$\left\{X\right\}$: an ordered-vector which depicts the sequence of the route of trucks

λ_t : number of vehicles used at time tT

f_{TC} : total system cost of the synchronized cycles model in 4.2

$f_{CO_2,t}$: total CO_2 emissions at time tT

f_{CO_2} : total cost of CO_2 emission per unit time

$f_{Green,TC}$: total system cost per unit time including CO_2 cost

Chapter 1

Introduction

1.1 Introduction

In a supply chain model, coordination of the vendor and buyers plays an important role to minimize the inventory cost. Classical model such as Economic Order Quantity (EOQ) and Economic Production Quantity (EPQ) models allow buyers and vendor to act independently in minimizing their own cost but the cost of the entire supply chain is not optimal. Therefore, coordination between vendor and buyers is essential for the optimization of the whole system. Effective supply chain coordination can significantly reduce the total system cost of the supply chain. Many integrated models involving vendor-buyer coordination have been established since the 1970s (Lal and Staelin (1984) and Dada and Srikanth (1987)). Chan and Kingsman (2007) proposed a synchronized single-vendor multi-buyer production and delivery model which allows buyers to choose their own lot sizes and order cycles while coordinating them with the vendor's production cycle.

However, in many coordinated system, the objective has been to minimizing the total system cost. Little attention is paid to considering environmental performance such as reverse logistics and greenhouse gas emissions in the co-ordination models.

In the mid-1990s, increasing awareness of environmental health issue among the general public led supply chain practitioners and researchers to pursue research related to environmental issues, known as green supply chain management (GSCM). Companies have adopted green principles during the production process, such as using environmentally friendly resources, minimizing the use of petroleum, and using recycling materials for packaging (Beamon (1999); Hervani and Helms (2005)). Sbihi and Eglese (2010) discussed the use of combinatorial optimization in GSCM, in the areas of reverse logistics, waste management and vehicle routing and scheduling. However, the authors did not directly incorporate green performance measures into the mathematical models. Sbihi and Eglese (2010) also pointed out that there has been limited literature that links the vehicle routing problem with green supply chain models.

Reverse logistics (RL) has received considerable attention due to the potential of value recovery from the used products. Research on RL has been growing since the 1960s (Zikmund and Stanton (1971); Gilson (1973); Schary (1977); Fuller (1978)). The focus on RL is on waste management, material recovery (recycling), parts recovery or product recovery (through remanufacturing). Most research focuses only on a small area of RL systems, such as network design, production planning or environmental issue. In this research, reverse logistics is incorporated in the coordinated supply chain system in a way that used products are picked up and recycled to meet the overall demand.

For mathematical models, the objective has mainly been minimizing the total system cost, while including environmental costs, such as the cost of greenhouse gas emissions. Greenhouse gases include CO_2, CH_4 and N_2O. Most of the literatures focus only on the CO_2 emissions because it is the most abundant greenhouse gas. For example, Tiwari and Chang (2015) considered a green vehicle routing problem that used the distance based approach to calculate CO_2 emission where truck load was considered as a factor of CO_2

emission. However, as in many articles about CO_2 emission, the inventory model is not coordinated and reverse logistics is not considered in the routing problem. To consider environmental performance in this research, vehicle routing problem is also incorporated in the coordinated model to consider the total cost and the CO_2 emission of the whole supply chain. Besides minimizing the total system cost, minimizing CO_2 emissions is also considered as the objective function so as to investigate more about the green performance of the supply chain.

1.2 Motivation and Research Objectives

In this research, a coordination model for a single-vendor multi-buyer supply chain with reverse logistics is developed. This model is an extension of the synchronized cycles model of Chan and Kingsman (2007) by including reverse logistics such as picking up used products from buyers for recycling production. The objective of this model is to determine the delivery and pick-up cycles of buyers and production cycle of the vendor when minimizing the total system cost of the supply chain. The performance of the synchronized cycles model and the independent policy model are compared. The objective is to investigate whether the synchronized cycles model can work better than the independent optimization model under situation that reverse logistics is also considered.

The above model only considers shipment cost as a fixed cost per order. This can hardly represent the actual transportation cost which depends on the schedule routings. For a more realistic transportation cost, vehicle routing cost which depends on the distance travelled and the number of trucks dispatched is added to the synchronized cycles model. Hybrid one-step and two-step methods combining GA and ALNS are developed to find the optimal solution of the modified model. The objective is to find a route that optimizes the total system cost which now includes also the routing cost.

Furthermore, environmental performance is incorporated by considering the CO_2 emission in the vehicle routing problem of the coordinated supply chain model with reverse logistics. Instead of minimizing the routing cost, the objective is changed to determining the optimal solution of vehicle routing for deliveries and used products pick-ups that minimizes the CO_2 emission. The performances of the three models with different objectives are compared.

1.3 Outline of the Thesis

This thesis is divided into six chapters.

Chapter 1 introduces the background of supply chain coordination, reverse logistics and green supply chain management. The research objectives and outline of this thesis are also presented.

Chapter 2 presents a literature review on supply chain models with respect to the areas of inventory management, reverse logistics and green performance.

A co-ordination model for a single-vendor multi-buyer supply chain with reverse logistics is presented in Chapter 3. In this model, buyers can select their own delivery cycles and used product pick-up cycles but these cycles must be integer factor of the vendor's production cycle. Numerical experiments are carried out to test the performance of this model when compared with the independent policy model.

In Chapter 4, the model developed in Chapter 3 is extended to include the vehicle routing problem for delivery and used product pick-up. One-step and two-step hybrid heuristics are developed to obtain “near optimal” solutions for three numerical examples. The objective function is to minimize the total system cost which includes the routing cost.

In Chapter 5, the model is further extended to incorporate CO_2 emission. First, CO_2 emission is evaluated for the model developed in Chapter 4. Then the cost of CO_2 emission is added to the objective function when finding the optimal solution of minimizing the total system cost. Moreover, the objective function is changed to minimizing the CO_2 emission instead of minimizing the routing cost which includes the cost of CO_2 emission. Performance of the three models are compared for the three numerical examples.

Chapter 6 summarizes and concludes the whole thesis and suggests some possible future research directions arising from this thesis.

Chapter 2

Literature Review

2.1 Supply Chain Co-ordination

Coordination among various parties in a supply chain is essential for the successful operation of the supply chain. Effective supply chain coordination can significantly reduce the total expected cost of the entire supply chain. Various integrated inventory coordination models are established dating back to the 1970s (Sarmah et al. (2006) and Khouja and Goyal (2008)). Some earlier research on single-vendor multi-buyer coordination models include Lal and Staelin (1984), Dada and Srikanth (1987) and Joglekar and Tharthare (1990).

Lu (1995) considered a supply chain problem in which the objective is to minimize the vendor's total annual cost subject to the constraint that the maximum cost for each buyer does not exceed some upper limit. In this model, the vendor only needed to know the buyer's annual demand and past ordering behavior.

Woo et al. (2001) considered an integrated inventory model where a single vendor delivers finished items to multiple buyers using a common ordering cycle. Their work is an extension of the model of Banerjee and Banerjee (1994) in which the vendor makes replenishment decisions for all buyers to optimize the joint total cost.

Banerjee et al. (2003) proposed using simulation to investigate the effect of lateral shipment in a two level supply chain, involving one supplier and multiple retailers.

Sarmah et al. (2006) reviewed literature dealing with supply chain coordination and suggested that future research should include stochastic demand and lead-time so that the supply chain models are more realistic. A dynamic division of surplus amongst the channel members was also suggested to be further investigated.

Zhou (2007) studied quantity discount pricing policies in a channel of one manufacturer and one retailer. Four quantity discount pricing policies were proposed and numerical examples were presented to compare their efficiencies.

Sarmah et al. (2008) incorporated the credit option concept into the common cycle model developed by Banerjee and Burton (1994). The increase in cost to the buyers due to coordinated ordering policy is compensated through a uniform credit policy in one of the proposed models. In another policy, all the buyers in one region agree to order at a common time in order to save the transportation cost which is borne by the buyers.

Chang et al. (2008) carried out an intensive review on inventory models with trade credit policy and suggested that future research should develop a win-win coordination for the vendor-buyer system.

Chu and Leon (2009) considered a coordination mechanism between the vendor and the buyers in a private cost information environment where the objective function and cost parameters of each facility are regarded as private information that no other facilities in the system has access to.

Sinha and Sarmah (2010) developed an algorithm for the single-vendor multi-buyer discount pricing model where the vendor offers multiple pricing schedules to the buyers and each buyer selects a schedule that maximize the corresponding individual profit. The reaction of each buyer was considered and it was ensured that each buyer selecting local optima can also lead to global optima with maximum channel profits.

Chan and Kingsman (2007) developed the synchronized cycle model in a one-vendor multi-buyer supply chain so as to significantly reduce the system costs, in contrast to the situation where each partner operates independently.

As an extension, Chan et al. (2010) and Chan and Lee (2012) developed an incentive mechanism that incorporates the delayed payment method and quantity discount scheme, respectively, in a vendor-buyer coordinated supply chain, without acquiring any cost information from the buyers.

Furthermore, Chan et al. (2013) demonstrated how to effectively incorporate environmental issues into vendor-buyer coordination by developing a single-vendor multi-buyer coordination model that includes both costs and environmental performance measures in its objective function.

More recently, Lee et at. (2016) developed an integrated single-vendor multi-buyer inventory-transportation synchronized supply chain model where the decision of truck assignment and routing are also considered.

However, most of the literature on vendor-buyer coordination concentrates only on an objective of minimizing the total system costs. There is little attention paid to considering environmental issues in the co-ordination models. With increasing environmental awareness in the general public, many organizations are beginning to acknowledge that strategies and practices that incorporate environmental sustainability considerations are becoming essential to acquire and maintain a competitive advantage. Hence, taking environmental impacts such as reverse logistics and greenhouse gas emission into vendor-buyer coordination is of vital importance.

2.2 Green Supply Chain

In the mid-1990s, increasing awareness of environmental health issues among the general public led supply chain practitioners and researchers to pursue research related to environmental issues, known as green supply chain management (GSCM).

Beamon (1999) carried out an intensive study on GSCM to investigate and identify essential environmental factors for a green supply chain system. In addition, the author also specified some performance measures to evaluate the effectiveness of the green components.

Hervani et al. (2005) also carried out similar, but more updated and intensive research on identifying performance metrics and measures for GSCM. In their paper, companies adopt green principles during the production process, such as using environmentally friendly resources, and minimize the use of petroleum.

Srivastava (2007) provided an extensive literature review which summarizes various mathematical models and techniques used in modelling GSCM. For mathematical models, the objective has mainly been minimizing the total cost which includes environmental costs. Srivastava (2007) also highlighted the importance of green supply chain design and supply chain operations.

Seuring (2013) provided a review (for the past 15 years) on sustainable supply chain management which applies mathematical modeling techniques. It was noted that in the economic dimension, “total” cost-based or decision related cost and revenue approaches dominate and this does not capture the proactivity of companies striving to implement green supply chain.

2.2.1 Reverse Logistics

Reverse logistics (RL) has received considerable attention due to the potential of value recovery from the used products. Research on RL has been growing since the 1960s (Zikmund and Stanton (1971); Gilson (1973); Schary (1977); Fuller (1978)). Besides, legislations and directives, consumer awareness and social responsibilities towards environment are also the drivers of RL (Melnyk et al. (1999); Ferrer and Ayres (2000); Ravi and Shankar (2005); Cooper, (1994); Yang (1995); Boks et al. (1998); Castell et al. (2004)). The focus on RL is on waste management, material recovery (recycling), parts recovery or product recovery (through remanufacturing). However, efforts to synthesize the research in an integrated broad-based body of knowledge are limited. Most research focuses only on a small area of RL systems, such as network design, production planning or environmental issues.

Fleischmann et al. (1997) studied RL from the perspectives of distribution planning, inventory control and production planning. It was suggested that the new reverse material flows and the traditional forward flows cannot be treated independently but have to be considered simultaneously to achieve adequate planning.

Carter and Ellram (1998) focused on the transportation and packaging, purchasing and environmental aspects in their review of RL literature. They found that the factors influencing reverse logistics activities differ from those of traditional logistics.

Dowlatshahi (2000) identified two broad categories of factors essential for effective implementation of RL: strategic factors and operational factors. The strategic factors include strategic costs, overall quality, customer service, environmental concerns and legislative concerns. The operational factors include cost-benefit analysis, transportation, warehousing, supply chain management, remanufacturing and recycling, and packaging.

Guide (2000) identified and discussed seven complicated characteristics that require significant changes in production planning and control activities for remanufacturing firms. It was noted that remanufacturing represents a much larger industrial segment than previously thought.

De Koster et al. (2001) identified both aggravating factors and facilitating actions for return handling in RL. The authors conjecture that for retailers that supply a sufficient number of stores, it is more efficient to collect the returned material to the distribution centre with the same truck that delivers the products.

Min et al. (2006) developed a mathematical model for the RL network design problem involving product returns and proposed a genetic algorithm (GA) for finding the minimum cost of the network. The proposed model and solution procedure consider explicitly trade-offs between freight rate discounts and inventory cost savings due to consolidation and transshipment.

Linton et al. (2007) studied the interactions between sustainability and supply chains by considering environmental issues regarding product design, product life extension and product recovery at end-of-life.

Maity et al. (2008) developed a product-recycling model in fuzzy environment where demand is selling price dependent, selling price is serviceable stock dependent, and holding costs are fuzzy variables. An optimal control approach is proposed in this paper to optimize the production, recycling and disposal strategy so that the expected value of total profit is maximized.

Chung et al. (2008) analyzed an inventory system with traditional forward-oriented material flow as well as a reverse material flow supply chain where the used products are returned, remanufactured and shipped to the retailer for resale.

Rubio et al. (2008) reviewed the literature on RL published between 1995 and 2005 by focusing on management of the recovery, distribution of end-of-life products, production planning and inventory management, and supply chain management issues.

Pokharel and Mutha (2009) used content analysis method to show a holistic perspective of RL system in their review of RL literature until 2008.

Sbihi and Eglese (2010) discussed the use of combinatorial optimization in GSCM, in the areas of reverse logistics, waste management and vehicle routing and scheduling. However, the authors did not directly incorporate green performance measures into the mathematical models.

Hsueh (2011) investigated inventory control policies in a manufacturing/remanufacturing system during the product life cycle, where both demand rate and return rate of products are random variables following the normal distribution.

Sheriff et al. (2012) focused on various issues affecting the performance of RL network in terms of strategic perspective in their review of RL network design. One of the suggested future research area is the management of production collection processes since many companies are hesitating to implement RL concept due to the complications involved in the collection process of returned products.

Jonrinaldi and Zhang (2013) proposed a model and solution method for coordinating integrated production and inventory cycles in a whole manufacturing supply chain involving RL for multiple items with finite horizon periods.

Govindan and Popiuc (2013) focused on the analysis of the supply chain performance measures under coordination by revenue sharing contract on the three-echelon reverse supply chain.

Because of the complexity of the problem, vehicle routing and CO_2 emissions are rarely considered in the coordinated model with reverse logistics.

2.2.2 Air Pollution - CO_2 Emission

Air pollution resulting from transportation is an important negative environmental impact of supply chains. Hence, taking environmental impacts into vendor-buyer coordination is of vital importance and optimized planning of the routing and delivery schedule is critical. Further, note that there are synergies between environmentally "friendly" and economically efficient transportation systems, since reducing the number of trucks required and total distance traveled gives rise to environmental benefits from the reduced fuel consumption and air pollution (e.g. CO_2 emissions).

Jaegler and Burlat (2012) studied CO_2 emissions along supply chains, from freight energy use to inventories storage, using simulation models. They have found that the types of products affected the CO_2 emissions considerably.

Chaabane et al. (2012) considered sustainable supply chains under an emission trading scheme. Their model shows that various environmental legislations must be strengthened and harmonized at a global level in order to drive a long-term environmental strategy.

Yang et al. (2013) studied the impact of internal green practices, external green collaboration on green performance, and firm competiveness in the container shipping industry in Taiwan.

Fahimnia et al. (2013), via a case study, examined a supply chain model on the possible trade-offs between transportation costs, the costs of carbon emission and fuel consumption.

Tiwari and Chang (2015) considered a green vehicle routing problem that used the distance based approach to calculate CO_2 emission where truck load was considered as a factor of CO_2 emission.

Soysal et al. (2015) presented a multi-period inventory routing problem model that included truck load dependent distribution costs for the evaluation of CO_2 emission and fuel consumption. However, like in many literatures, reverse logistics is not incorporated in the routing problem.

There is limited research on environmental performance, and air pollution, in supply chain coordination models. To attain economic and environmental goals requires that the vendor and the buyers compromise on delivery schedules to benefit all parties involved. Such collaborative decision can only be achieved via vendor-buyer coordination.

Chapter 3

A Co-ordination Model for a Single-vendor Multi-buyer Supply Chain with Reverse Logistics

3.1 Introduction

Reverse logistics has received considerable attention due to the potential of value recovery from the used products. The focus on reverse logistics is on waste management, material recovery (recycling), parts recovery or product recovery (through remanufacturing). However, efforts to synthesize the research in an integrated broad-based body of knowledge are limited. Most research focuses only on a small area of reverse logistics systems, such as network design, production planning or environmental issues. In this chapter, a co-ordination model for a single-vendor multi-buyer supply chain with reverse logistics is developed. This model is an extension of the synchronized cycles model of Chan and Kingsman (2007) by including reverse logistics. Similar to Chan and Kingsman (2007), synchronization of the supply chain is achieved by allowing the buyers to select their own delivery cycles and used product pick-up cycles, although these cycles must be integer multiples of the basic time period and integer factors of the vendor's production cycle. The independent optimization model is introduced first. The synchronized cycles model is then solved by the genetic algorithm. Three numerical examples are used to compare the performance of the independent optimization model to that of the synchronized cycles model. Sensitivity analysis is also carried out to determine the effect on the savings of the total cost when different cost parameters vary.

3.2 Independent Optimization Model for Buyers and Vendor with Reverse Logistics

During each production cycle of the vendor, it is assumed that buyer *i* (*i*=1,…,*n*) faces a deterministic demand at rate d_i per unit time, incurs an ordering cost A_i per order and incurs an inventory holding cost h_i per unit item per unit time. It is also assumed that buyer *i* faces a deterministic recycling rate of r_i, incurs a used product pick-up cost B_i per pick-up order and incurs a used product inventory holding cost h_i' per unit item per unit time. If the buyers and the vendor operate independently, then buyer *i* will order a quantity Q_i every T_i units of time and place an order for used product pick-up with quantity U_i every F_i units of time, where T_i and F_i are determined on the basis of minimizing the costs of the buyer *i* only. The total cost per unit time for buyer *i* can thus be expressed as

$$K_i(T_i, F_i) = \frac{A_i}{T_i} + \frac{h_i d_i T_i}{2} + \frac{h_i' r_i F_i d_i}{2} + \frac{B_i}{F_i} \tag{3.1}$$

where $Q_i = d_i T_i$ and $U_i = r_i F_i d_i$.

The total cost per unit time is minimized when

$$T_i = \sqrt{\frac{2A_i}{h_i d_i}} \tag{3.2}$$

and $F_i = \sqrt{\dfrac{2B_i}{h_i' r_i d_i}}$. (3.3)

The vendor faces orders from the *n* buyers with demand rates $d_1, d_2, ..., d_n$ per unit time, respectively. Thus the vendor has to satisfy a demand that occurs at an average rate of *D* per unit time, where $D = d_1 + d_2 + ... + d_n$. The vendor faces recycle pick-up orders from the *n* buyers with recycling rates of $r_1 d_1, r_2 d_2, ..., r_n d_n$ per unit time, respectively. Thus the vendor has to satisfy a recycle pick-up quantity that occurs at an average rate of *R* per unit time, where $R = r_1 d_1 + r_2 d_2 + ... + r_n d_n$.

The vendor produces new items at a rate of *P* per unit time and recycle used products at a rate of $\min\{R, \beta\}$ per unit time, where β is the upper limit of the recycling rate. Assume that the vendor incurs a set-up cost S_v for each production run and a set-up cost S_v' for each recycling production run and incurs a holding cost for the new or recycled items at *h* per unit item per unit time. The vendor also incurs a holding cost for the un-recycled used products (which arrive at an average rate of R items per unit time, waiting for being recycled) at h' per unit item per unit time. If the vendor is operating independently, he should start a production run every T_v units of time and produces a total lot size of Q_v, where $Q_v = DT_v$, and T_v is determined on the basis of minimizing the cost of the vendor only. The total cost per unit time for the vendor is

$$K_v(T_v) = \frac{S_v + S_v'}{T_v} + \frac{T_v}{2}\left\{hD\left[1 - \frac{D}{P + \min(\beta, R)}\right] + h'\left[\max(0, R - \beta)\right]\right\} + \sum_{i=1}^{n}\frac{C_i}{T_i} + \sum_{i=1}^{n}\frac{G_i}{F_i} \tag{3.4}$$

where C_i is the fixed shipment cost incurred for each delivery to buyer *i* and G_i is the fixed recycling cost incurred for each pick-up from buyer *i*.

The total cost per unit time for the vendor is minimized when

$$T_v = \sqrt{\frac{2(S_v + S_v')}{hD\left[1 - \frac{D}{P + \min\left(\beta, R\right)}\right] + h'\left[\max\left(0, R - \beta\right)\right]}}. \tag{3.5}$$

The above model for the vendor assumes that the buyers' demand occurs continuously at the average rate *D*. However, demands made on the vendor actually occur as aggregated orders $Q_1, Q_{2,} ..., Q_n$. Therefore, the above model for the vendor cannot guarantee that there are no any stock outs at all, i.e. failures to meet the buyers' demands on time. The maximum demand occurs when all buyers require a delivery order at the same time. So to ensure that all demands are satisfied on time, the vendor should not have less than $Q_1 + Q_2 + ... + Q_n$ in stock at the time that the vendor starts a new production run. This applies to the case of instantaneous delivery. This quantity $Q_1 + Q_2 + ... + Q_n$ becomes the re-order level. Thus an extra term

$$h\sum_{i=1}^{n} Q_i \tag{3.6}$$

needs to be added to equation (3.4) to give the true costs per unit time for the vendor if the vendor is to have zero stock outs.

If the vendor does not provide products instantaneously, where part of the lead-time allows for partial production after orders are received, the situation is more complicated. If L is part of the delivery lead-time used for production, then approximately

$(P+\min\{R,\beta\}-D)L$ can be produced to meet the maximum delivery at any time. Thus we have

$$\text{Re-order level} = \sum_{i=1}^{n} Q_i - (P+\min\{R,\beta\}-D)L\,. \tag{3.7}$$

However, if all the lead-time is required for the transportation of items between the vendor and the buyers then $L=0$. This introduction of a re-order level is to determine when to start each new production run. The re-order level does not affect the optimal production quantity of the vendor. It just increases the costs for the vendor and hence the total cost of the supply chain. Using the optimal order cycles and pick-up cycles for the buyers, the optimal production cycle for the vendor, together with the optimal order quantities for the buyers and the optimal production quantity for the vendor, the total system cost ensuring that no stock outs occur becomes

$$\begin{aligned}
&K(T_v,T_1,T_2,\ldots,T_n,F_1,F_2,\ldots,F_n)\\
&=\sqrt{2(S_v+S_v{}')\left\{hD\left[1-\frac{D}{P+\min\left(R,\beta\right)}\right]+h'\left[\max\left(0,R-\beta\right)\right]\right\}}\\
&+\sum_{i=1}^{n}\left(C_i\sqrt{\frac{h_i d_i}{2A_i}}+G_i\sqrt{\frac{h_i{}' r_i d_i}{2B_i}}+\sqrt{2h_i d_i A_i}+\sqrt{2h_i{}' r_i d_i B_i}\right)\\
&+h\left\{\sum_{i=1}^{n} Q_i-\left[P+\min\left(R,\beta\right)-D\right]L\right\}
\end{aligned} \tag{3.8}$$

3.3 Synchronized Cycles Model with Reverse Logistics

In the independent optimization model, the vendor needs to carry a large stock in order to satisfy all demands, or the buyers will have to suffer stock outs and late deliveries. Coordinating the timing of deliveries and pick-up of used products from the buyers with the production period of the vendor may significantly reduce the amount of stock-outs in the supply chain. Let T be the basic time unit and let the production cycle of the vendor be NT, where N is an integer. Under the coordinated policy, both the delivery cycle and pick-up cycle of each buyer are restricted to be an integer factor of the production period of the vendor. In other words, the delivery cycle and pick-up cycle of buyer must be $k_i T$ and $g_i T$ respectively, where k_i and g_i are integer factor of N.

Consider the inventory levels of the un-recycled used products and the recycled used products. Used products are collected at time jT for $j=0$ to N from the buyers. Let R_j be the number of items collected at time jT. These used products are first stored by the vendor and then recycled at a constant rate of β per unit time. The holding cost of the un-recycled used products and the recycled used products are h' per unit item per unit time and h per unit item per unit time, respectively.

Let M_j be the inventory level of the un-recycled used products at time jT. Recycling production of the used products continues as long as the inventory level of the un-recycled used products is not zero.

At $j=0$, $M_0 = 0$ (3.9)

At $j=1$, $$M_1 = R_1 + \begin{cases} M_0 - \beta T & if \quad M_0 > \beta T \\ 0 & if \quad 0 \le M_0 \le \beta T \end{cases} \tag{3.10}$$

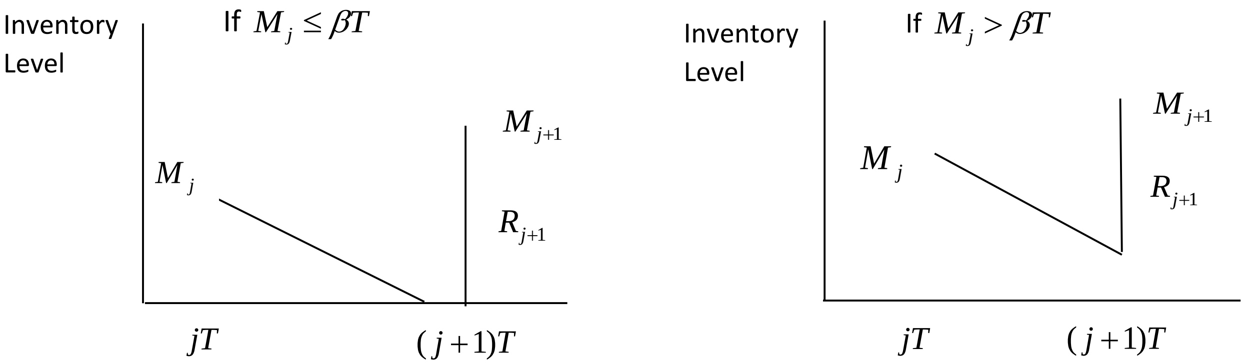

Fig.3.1. Inventory Level of the Un-Recycled Used Products

$$M_{j+1} = R_{j+1} + \begin{cases} M_j - \beta T & if \quad M_j > \beta T \\ 0 & if \quad 0 \le M_j \le \beta T \end{cases}, \text{ for } 1 \le j \le N-1. \tag{3.11}$$

The area under the un-recycled used product inventory curve from *jT* to *(j+1)T* for $1 \le j \le N-1$ is

$$\lambda_j = \begin{cases} \frac{T}{2}(2M_j - \beta T) & if \quad M_j > \beta T \\ \frac{M_j^{\,2}}{2\beta} & if \quad 0 \le M_j \le \beta T \end{cases} \tag{3.12}$$

Therefore, the total area under the un-recycled used product inventory curve is.

$$\chi' = \sum_{j=1}^{N-1} \lambda_j \ . \tag{3.13}$$

Let I_j be the inventory level of the recycled used products at time *jT*.

At $j=0$, $I_0 = 0$. (3.14)

Then, $I_{j+1} = I_j + \begin{cases} M_j & if \quad 0 \le M_j \le \beta T \\ \beta T & if \quad M_j > \beta T \end{cases}$ for $0 \le j \le N-1$. (3.15)

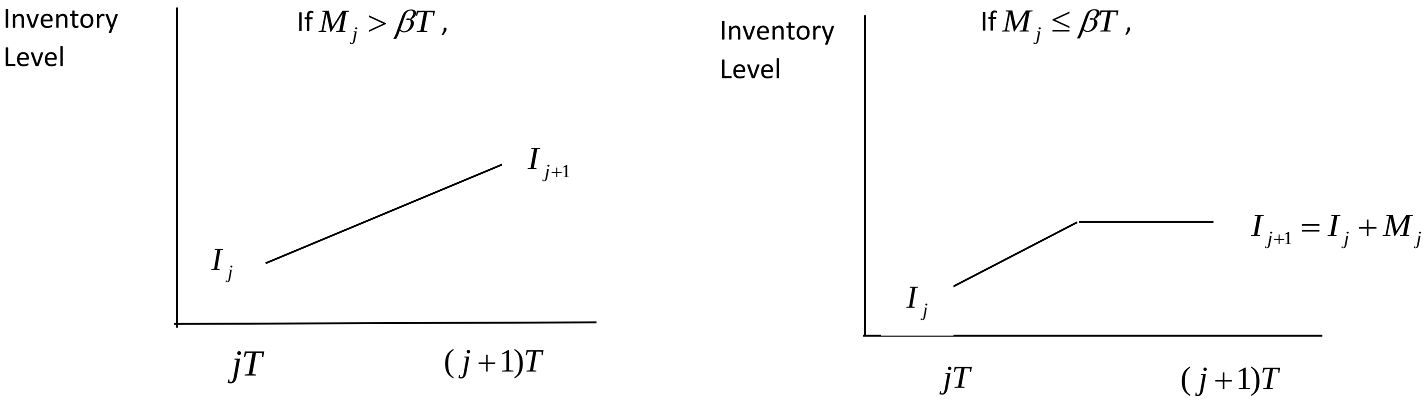

Fig.3.2. Inventory Level of the Recycled Used Products

The area under the recycled used product inventory curve from *jT* to *(j+1)T* for $0 \le j \le N-1$ is

$$\mu_j = \begin{cases} T(I_j + M_j) - \dfrac{M_j^{\,2}}{2\beta} & if \quad 0 \le M_j \le \beta T \\ \dfrac{T}{2}(2I_j + \beta T) & if \quad M_j > \beta T \end{cases} \tag{3.16}$$

Therefore, the total area under the recycled used product inventory curve is

$$\chi'' = \sum_{j=0}^{N-1} \mu_j \, . \tag{3.17}$$

For the production run of new items, it is assumed that the vendor cycle starts at time 0, immediately after having satisfied the last demand in the previous cycle. Let a production run start at time –*ST*, a time *ST* before the start of the vendor cycle, where *S* may be positive or negative. Production continues, building up stock at a constant rate *P*, and satisfying demand D_1T at time *T*, D_2T at time *2T*, etc. Production stops at time *FT*, where

F is not necessarily an integer. The holding cost of the production inventory is h per unit item per unit time. Let *b* be the nearest integer below *F*. For the sake of calculating the area under the inventory curve, we let $D_{i,j}\,(j>i)$ be the cumulative demand from time *iT* to time *jT*. From Chan and Kingsman (2007), the area χ under the inventory curve is given by

$$\begin{aligned}\chi = {} & \frac{1}{2}P(S+1)^2T^2 + \sum_{j=1}^{b-1}\left\{(S+j)PT^2 - D_{1,j}T + \frac{1}{2}PT^2\right\} + (F+S)PT^2 \\ & -D_{1,b}T - \frac{1}{2}(F-b)^2PT^2 + \sum_{j=b+1}^{N-1}\left\{(F+S)PT^2 - D_{1,j}T\right\}\end{aligned} \qquad (3.18)$$

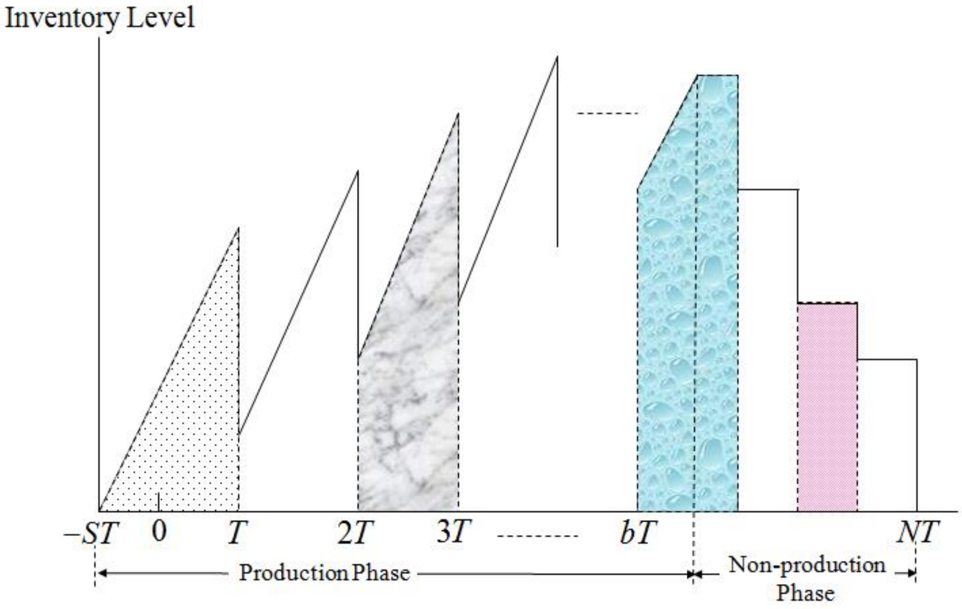

Fig.3.3. Chan and Kingsman (2007)

Simplifying the above equation, we get

$$\chi = \frac{1}{2}P(S+1)^2T^2 + S(b-1)PT^2 + \frac{b}{2}(b-1)PT^2 + \frac{(b-1)}{2}PT^2 - \frac{1}{2}(F-b)^2PT^2$$
$$-\sum_{j=1}^{b-1} D_{1,j}T + \sum_{j=b+1}^{N-1}\left\{(F+S)PT^2 - D_{1,j}T\right\}. \tag{3.19}$$

Since $(F-b)^2 = \left\{(F+S)-(S+b)\right\}^2 = (F+S)^2 + (S+b)^2 - 2(F+S)(S+b)$, the first part of χ can be written as

$$\frac{1}{2}PT^2\left\{(S+1)^2 + 2S(b-1) + b(b-1) + b - 1 - (b+S)^2 - (F+S)^2 + 2(b+S)(F+S)\right\}$$
$$= \frac{1}{2}PT^2\left\{S^2 + 2S + 1 + 2bS - 2S + b^2 - b + b - 1 - b^2 - 2bS - S^2 - (F+S)^2 + 2(b+S)(F+S)\right\}$$

$$= \frac{1}{2}PT^2\left\{-(F+S)^2 + 2(b+S)(F+S)\right\} \tag{3.20}$$

Thus,

$$\chi = -\frac{1}{2}PT^2(F+S)^2 + (b+S)PT^2(F+S) + (N-b)(F+S)PT^2 - \sum_{j=1}^{b-1} D_{1,j}T - \sum_{j=b}^{N-1} D_{1,j}T$$
$$= -\frac{1}{2}PT^2(F+S)^2 + (N+S)PT^2(F+S) - \sum_{j=1}^{N-1} D_{1,j}T \tag{3.21}$$

Since the vendor must produce sufficient stock over the *N*-period cycle to meet the demands $D_1, D_2, ..., D_N$, total production of new and recycled used products must equal to total demand over a cycle. That is,

$$(F+S)PT + I_N = \sum_{j=1}^{N} D_j = D_{1,N} = NDT\ . \tag{3.22}$$

Simplifying χ by substituting $D_{1,N} - I_N$ for $(F+S)PT$, we get

$$\chi = -\frac{(D_{1,N} - I_N)^2}{2P} + (N+S)(D_{1,N} - I_N)T - \sum_{j=1}^{N-1} D_{1,j}T \tag{3.23}$$

Furthermore,

$$D_{1,j} = D_{1,N} - D_{j+1,N} \tag{3.24}$$

so that

$$-\sum_{j=1}^{N-1} D_{1,j} = -(N-1)D_{1,N} + \sum_{j=1}^{N-1} D_{j+1,N} = -(N-1)D_{1,N} + \sum_{j=1}^{N-1}\sum_{i=j+1}^{N} D_i = -(N-1)D_{1,N} + \sum_{j=1}^{N}(j-1)D_j.$$

Hence, the total area under the production inventory curve is

$$\chi = -\frac{(D_{1,N} - I_N)^2}{2P} + (N+S)(D_{1,N} - I_N)T - (N-1)D_{1,N}T + \sum_{j=1}^{N}(j-1)D_jT$$

$$= -\frac{(D_{1,N} - I_N)^2}{2P} - (N+S)I_NT + (S+1)D_{1,N}T + \sum_{j=1}^{N}(j-1)D_jT \tag{3.25}$$

The final stage is to allocate individual buyer’s orders to each vendor demand period. Assume buyer *i* orders every k_i periods and recycles every g_i periods.

Define

$$\delta_{i,t} = \begin{cases} 1 & \text{if buyer } i \text{ orders in period } tT, \\ 0 & \text{otherwise.} \end{cases} \tag{3.26}$$

and

$$\omega_{i,t} = \begin{cases} 1 & \text{if buyer } i \text{ recycles in period } tT, \\ 0 & \text{otherwise.} \end{cases} \tag{3.27}$$

Since the buyer orders every $k_i\,T$ units of time and recycles every $g_i\,T$ units of time, we have

$$\delta_{i,t+k_i} = \delta_{i,t} \tag{3.28}$$

and

$$\omega_{i,t+g_i} = \omega_{i,t} \tag{3.29}$$

Since the buyer orders only once in each successive k_i periods and recycles only once in each successive g_i period, we have

$$\sum_{j=0}^{k_i-1} \delta_{i,t+j} = 1 \tag{3.30}$$

and

$$\sum_{j=0}^{g_i-1} \omega_{i,t+j} = 1 \tag{3.31}$$

Let $\pi_i T$ and $\tau_i T$ be the first time that buyer *i* order new products and used product pick-up, respectively, in the production cycle of the vendor. (That is, $\delta_{i,\pi_i} = 1$, $\omega_{i,\tau_i} = 1$ and $1 \le \pi_i \le k_i$, $1 \le \tau_i \le g_i$)

Over the *NT* vendor production cycle, the buyer orders $\frac{NT}{k_i T} = \frac{N}{k_i}$ times and recycles $\frac{NT}{g_i T} = \frac{N}{g_i}$ times.

Thus,

$$\sum_{t=1}^{N} \delta_{i,t} = \frac{N}{k_i} \tag{3.32}$$

and

$$\sum_{t=1}^{N} \omega_{i,t} = \frac{N}{g_i}. \tag{3.33}$$

From (3.26), (3.28), (3.30), and (3.32), the total demand for the vendor at time *tT* is

$$D_t = \sum_{i=1}^{n} \delta_{i,t} k_i d_i T\,. \tag{3.34}$$

From (3.27), (3.29), (3.31), and (3.33), the recycle pick-up products for the vendor at time *tT* is

$$R_t = \sum_{i=1}^{n} \omega_{i,t} g_i r_i d_i T\,. \tag{3.35}$$

Hence,

$$D_{1,N} = \sum_{i=1}^{N} D_i = \sum_{t=1}^{N} \sum_{i=1}^{n} \delta_{i,t} k_i d_i T = \sum_{i=1}^{n} \left\{ \left(\sum_{t=1}^{N} \delta_{i,t} \right) k_i d_i T \right\} = \sum_{i=1}^{n} \frac{N}{k_i} k_i d_i T = NT \sum_{i=1}^{n} d_i = NDT \tag{3.36}$$

and

$$R_{1,N} = \sum_{i=1}^{N} R_i = \sum_{t=1}^{N}\sum_{i=1}^{n} \omega_{i,t} g_i r_i d_i T = \sum_{i=1}^{n} \left\{ \left(\sum_{t=1}^{N} \omega_{i,t} \right) g_i r_i d_i T \right\}$$
$$= \sum_{i=1}^{n} \frac{N}{g_i} g_i r_i d_i T = NT \sum_{i=1}^{n} r_i d_i = NRT \tag{3.37}$$

where *D* and *R* are, respectively, the total demand rate and the total recycle rate of the supply chain.

Also, $D_t = \sum_{i=1}^{n} \delta_{i,t} k_i d_i T$, $D_{1,N} = NDT$, and

$$\sum_{t=1}^{N} (t-1) D_t = \sum_{t=1}^{N} (t-1) \left(\sum_{i=1}^{n} \delta_{i,t} k_i d_i T \right) = \sum_{i=1}^{n} k_i d_i T \left\{ \sum_{t=1}^{N} (t-1) \delta_{i,t} \right\}. \tag{3.38}$$

Since no shortages are allowed for the vendor, the production of the new products over the time from –*ST* to *T* and the recycled used products over the time from *0* to *T* must be sufficient to meet the first demand in the full cycle, D_1 at time *T*. Let us define Ψ as the surplus stock above the demand D_1 at time *T*, then

$$(1+S)PT = \Psi + D_1, \tag{3.39}$$

i.e. $$(1+S)T = \frac{\Psi + D_1}{P}. \tag{3.40}$$

Substituting the above into χ yields the following expression

$$\chi = -\frac{(NDT - I_N)^2}{2P} - (N+S) I_N T + \frac{\Psi + D_1}{P} NDT + \sum_{j=1}^{N} (j-1) D_j T \tag{3.41}$$

$$= -\frac{(NDT - I_N)^2}{2P} - (N+S)I_N T + \left(\frac{\Psi + \sum_{i=1}^{n} \delta_{i,1} k_i d_i T}{P} \right) NDT + \sum_{i=1}^{n} k_i d_i \left\{ \sum_{t=1}^{N} (t-1)\delta_{i,t} \right\} T^2$$

(3.42)

Since the vendor's production cycle is *NT*, the average production inventory plus the recycled inventory held by the vendor is

$$\frac{\chi + \chi''}{NT} \tag{3.43}$$

and the average un-recycled used product inventory held by the vendor is

$$\frac{\chi'}{NT}\,. \tag{3.44}$$

To summarize, the vendor's total holding cost per unit time is given by

$$\frac{h(\chi + \chi'') + h'\chi'}{NT}\,. \tag{3.45}$$

In addition to the vendor's holding cost, the other relevant costs per unit time of the vendor in this coordinated system model are as follows:

Vendor's setup cost = $\frac{S_v + S_v'}{NT}$ (3.46)

Vendor's order processing and shipment cost = $\sum_{i=1}^{n} \frac{C_i}{k_i T}$ (3.47)

Vendor's recycle order processing and pick-up cost = $\sum_{i=1}^{n} \frac{G_i}{g_i T}$ (3.48)

The relevant costs per unit time of the buyers are as follows:

Buyers' ordering cost = $\sum_{i=1}^{n} \frac{A_i}{k_i T}$ (3.49)

Buyers' recycle ordering cost = $\sum_{i=1}^{n} \frac{B_i}{g_i T}$ (3.50)

Buyers' holding cost = $\frac{1}{2}\sum_{i=1}^{n} (h_i d_i k_i T + h_i' r_i d_i g_i T)$ (3.51)

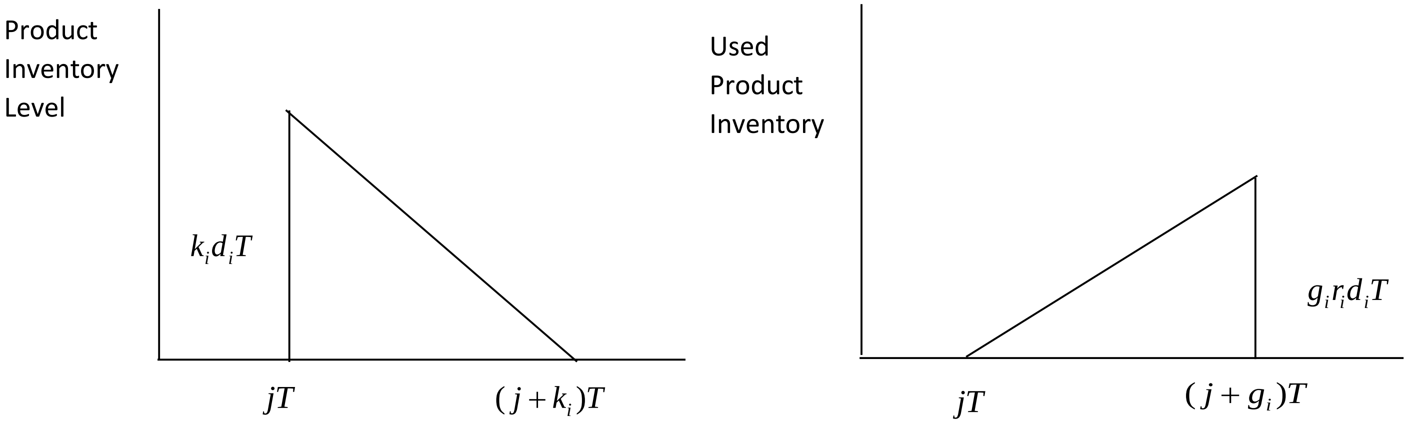

Fig.3.4. Product Inventory Level and Used Product Inventory Level for buyer

From (3.45) – (3.51), the total cost of the coordinated one-vendor multiple-buyer supply chain per unit time is

$$f_{TC} = \frac{1}{2}\sum_{i=1}^{n} (h_i d_i k_i T + h_i' r_i d_i g_i T) + \left\{ \frac{h(\chi + \chi'') + h'\chi'}{N} + \frac{S_v + S_v'}{N} + \sum_{i=1}^{n} \left(\frac{C_i + A_i}{k_i} + \frac{G_i + B_i}{g_i} \right) \right\} \frac{1}{T}$$

(3.52)

Since no stock outs or late deliveries are permitted, we need

$$(S+1)PT \geq D_{1,1} = D_1, \tag{3.53}$$

$$(S+j)PT + I_j \geq D_{1,j} \text{ for all } j = 1,2,...,b \tag{3.54}$$

From equation (3.39), the constraints (3.53) and (3.54) become

$$(1+S)PT = \Psi + D_1 \geq D_1, \tag{3.55}$$

$$(j+S)PT + I_j = \Psi + D_1 + I_j + (j-1)PT \geq D_{1,j}, \; j = 2,...,b, \tag{3.56}$$

That is,

$$\Psi \geq 0, \tag{3.57}$$

$$\Psi + I_j + (j-1)PT \geq T\left(\sum_{i=1}^{n} k_i d_i \sum_{t=2}^{j} \delta_{i,t}\right), \; 2 \leq j \leq b \tag{3.58}$$

The objective is to find the nonnegative values for $N, k_i, \pi_i, g_i, \tau_i$ and Ψ that minimize the cost function f_{TC} in (3.52) subject to the constraints (3.57) and (3.58) being satisfied.

3.4 Application of the Genetic Algorithm to solve the Synchronized Cycles Model

Genetic Algorithm (GA) is a heuristic search process that resembles natural selection and survival. All genetic algorithms have the features of reproduction, crossover and mutation. The algorithm starts by randomly generating a population made of feasible solutions of a certain problem. A member of the population is known as a chromosome and it consists of the decision variables of the objective function. For each chromosome, the fitness value, which is the value of the objective function, is calculated. Offsprings are produced by crossovers among members or mutations of members of the population. The fitness values of new members are calculated and compared with the population. Chromosomes with the worst fitness value are removed. This process continues until the stopping criterion is met. The chromosome with the best fitness value is then the final solution of the problem. Parameters like population size, crossover rate, mutation rate, and stopping criteria are decided before running the genetic algorithm.

In this synchronized cycles model, the decision variables are the production cycle of vendor *NT*, the delivery cycle and used product pick-up cycle of buyer *i*, k_iT and g_iT, respectively, and the first time that buyer *i* order new products and used product pick-up, π_iT and τ_iT respectively, in the production cycle of the vendor.

In order to determine what parameters to be used in the GA, many trial runs have been conducted and it was found that the following parameters such as the population size, crossover rate and mutation rate would yield good results.

Population size = 100

Crossover rate = 0.8

Mutation rate = 0.01

Stopping criteria: When the fitness value does not improve for more than 0.0001 for over 300 steps in Example 1 of 5 buyers, 600 steps in Example 2 of 30 buyers and 1000 steps in Example 3 of 50 buyers.

Note that in the GA, we also fixed $T = 1$ and maximum of $N = 365$.

Example 1 is taken from Banerjee and Burton (1994), which consists of 5 buyers with randomly generated recycling rates and costs. Data for 30 and 50 buyers are randomly generated in Example 2 and 3, respectively. The data are shown in Appendix I. *D/P* is the ratio of the system demand per period to the vendor's production rate per period. As different values of *D/P* may have different effects on different models, we include a full range of different values of *D/P* from 0.1, 0.2, …, up to 0.9 for comparison purpose.

In the GA, an initial population of size 100 is generated randomly encoded with the solutions of $N, k_i, \pi_i, g_i, \tau_i$ in each chromosome as integers. Hence the value of Ψ and the fitness value f_{TC} for each chromosome are determined.

A pair of parent chromosomes is selected from the population. If the vendor's production cycle for the two parent chromosomes are the same, a random number r_1 between 0 to 1 is generated. If r_1 is less than the crossover rate, two new offsprings are produced after crossover. Otherwise another random number r_2 is generated. If r_2 is less than the mutation rate, two new offsprings are produced by mutation. However, if the vendor's production cycle for the two parent chromosomes are not the same, crossover cannot be done as there may be uncommon factors in the parent chromosomes. Another random number r_3 is then generated and if it is less than the mutation rate, two new offsprings are produced by mutation. When 100 new offsprings are produced, they are combined with the original population. Ranking all 200 chromosomes by the fitness value, the top 100 chromosomes are selected as the updated population. Then another pair of parent chromosomes is selected from this updated population and the above procedures are repeated until the stopping criterion is met. The chromosome with the lowest fitness value is the final solution to our problem.

In the next section, the results of the independent policy model are compared with those of the synchronized cycles model solved by the GA.

3.5 Comparison of Results

The performance of the synchronized cycles model with recycling production solved by the GA is compared with that of the independent policy model, where the buyers and vendor are optimizing their costs independently. The results of Example 1, presented in Table 3.1, show that the synchronized cycle model with recycling production outperforms the independent optimization model over the whole range of *D/P* from 0.1 to 0.9. The improvement of the synchronized cycle model over the independent policy model ranges from 28% to 44%. The average percentage decrease in the total relevant costs is 35%.

Table 3.1
Results for Example 1

α=D/P	Synchronized cycle model with recycling production		Independent Policy	Percentage Change
	N	Total relevant cost	Total relevant cost	
0.1	196	32.29	52.67	-38.68
0.2	70	29.22	51.92	-43.73
0.3	99	30.87	51.21	-39.73
0.4	80	30.94	50.53	-38.76
0.5	67	33.90	49.87	-32.04
0.6	96	31.50	49.24	-36.02
0.7	112	32.26	48.62	-33.65
0.8	69	34.23	48.02	-28.72
0.9	124	34.22	47.43	-27.84

The results of Example 2, presented in Table 3.2, show that the synchronized cycles model with recycling production also outperforms the independent policy model over the whole range of *D/P* from 0.1 to 0.9. The improvement of the synchronized cycles model over the independent policy model ranges from 25% to 41% with an average of 33%.

Table 3.2
Results for Example 2

α=D/P	Synchronized cycle model with recycling production		Independent Policy	Percentage Change
	N	Total relevant cost	Total relevant cost	
0.1	28	345.34	587.16	-41.18
0.2	30	354.22	577.47	-38.66
0.3	30	353.61	568.32	-37.78
0.4	24	357.47	559.62	-36.12
0.5	28	361.77	551.31	-34.38
0.6	45	369.76	543.34	-31.95
0.7	48	378.79	535.67	-29.29
0.8	18	394.08	528.25	-25.40
0.9	48	388.81	522.58	-25.60

The results of Example 3, presented in Table 3.3, also show that the synchronized cycles model with recycling production outperforms the independent policy model over the whole range of *D/P*. The improvement of the synchronized cycle model over the independent policy model ranges from 24% to 39% with an average of 31%.

Table 3.3
Results for Example 3

α=D/P	Synchronized cycle model with recycling production		Independent Policy	Percentage Change
	N	Total relevant cost	Total relevant cost	
0.1	30	994.18	1638.71	-39.33
0.2	48	1041.08	1604.44	-35.11
0.3	48	1050.00	1571.86	-33.20
0.4	36	1030.49	1540.75	-33.12
0.5	48	1056.01	1510.89	-30.11
0.6	36	1038.58	1482.12	-29.93
0.7	45	1064.19	1454.27	-26.82
0.8	30	1080.39	1427.19	-24.30
0.9	36	1058.82	1400.96	-24.42

From the results shown in Tables 3.1-3.3, it can be seen that the synchronized cycle model with recycling production outperforms the independent policy model over the whole range of *D/P* for all Examples 1-3.

The division of the system costs between the vendor and the buyers of the two models are also investigated. This is shown in Tables 3.4-3.6. On average, the buyers' costs have an increase of 56%, 33% and 25% while the vendor's costs have a decrease of 67%, 65%, and 58% for Examples 1-3, respectively, when compared with the independent policy model. In all the examples, the buyers' costs for the independent policy model are about one-third of the vendor's costs. The large saving for the vendor is more than outweighing the increase in cost for the buyers so that there is an increase in saving of more than 30% on average for the entire supply chain, when compared with the independent policy model.

Table 3.4

The costs for the buyers and for the vendor -- Example 1

α=D/P	Synchronized cycle model with recycling production solved by GA			Independent Policy Model			Percentage change		
	Buyers' cost	Vendor's cost	Total relevant cost	Buyers' cost	Vendor's cost	Total relevant cost	Buyers' cost	Vendor's cost	Total relevant cost
0.1	21.55	10.74	32.29	12.77	39.90	52.67	68.82	-73.08	-38.68
0.2	20.97	8.25	29.22	12.77	39.16	51.92	64.24	-78.92	-43.73
0.3	19.65	11.22	30.87	12.77	38.45	51.21	53.92	-70.82	-39.73
0.4	21.91	9.03	30.94	12.77	37.77	50.53	71.67	-76.09	-38.76
0.5	25.97	7.93	33.90	12.77	37.11	49.87	103.41	-78.63	-32.04
0.6	16.53	14.98	31.50	12.77	36.47	49.24	29.46	-58.93	-36.02
0.7	17.01	15.25	32.26	12.77	35.86	48.62	33.23	-57.46	-33.65
0.8	16.19	18.04	34.23	12.77	35.25	48.02	26.80	-48.82	-28.72
0.9	19.67	14.55	34.22	12.77	34.66	47.43	54.08	-58.01	-27.84

Table 3.5

The costs for the buyers and for the vendor -- Example 2

α=D/P	Synchronized cycle model with recycling production solved by GA			Independent Policy			Percentage change		
	Buyers' cost	Vendor's cost	Total relevant cost	Buyers' cost	Vendor's cost	Total relevant cost	Buyers' cost	Vendor's cost	Total relevant cost
0.1	256.50	88.85	345.34	178.93	408.22	587.16	43.35	-78.24	-41.18
0.2	245.45	108.78	354.22	178.93	398.54	577.47	37.17	-72.71	-38.66
0.3	257.19	96.42	353.61	178.93	389.38	568.32	43.73	-75.24	-37.78
0.4	230.88	126.58	357.47	178.93	380.68	559.62	29.03	-66.75	-36.12
0.5	236.78	124.98	361.77	178.93	372.37	551.31	32.33	-66.44	-34.38
0.6	235.23	134.53	369.76	178.93	364.41	543.34	31.46	-63.08	-31.95
0.7	232.57	146.21	378.79	178.93	356.74	535.67	29.98	-59.01	-29.29
0.8	214.09	179.99	394.08	178.93	349.31	528.25	19.65	-48.47	-25.40
0.9	230.69	158.12	388.81	178.93	343.64	522.58	28.92	-53.99	-25.60

Table 3.6

The costs for the buyers and for the vendor -- Example 3

α=D/P	Synchronized cycle model with recycling production solved by GA			Independent Policy			Percentage change		
	Buyers' cost	Vendor's cost	Total relevant cost	Buyers' cost	Vendor's cost	Total relevant cost	Buyers' cost	Vendor's cost	Total relevant cost
0.1	654.67	339.51	994.18	501.40	1137.31	1638.71	30.57	-70.15	-39.33
0.2	661.87	379.20	1041.08	501.40	1103.03	1604.44	32.00	-65.62	-35.11
0.3	672.72	377.28	1050.00	501.40	1070.46	1571.86	34.17	-64.75	-33.20
0.4	623.47	407.03	1030.49	501.40	1039.34	1540.75	24.34	-60.84	-33.12
0.5	623.35	432.66	1056.01	501.40	1009.49	1510.89	24.32	-57.14	-30.11
0.6	595.03	443.56	1038.58	501.40	980.72	1482.12	18.67	-54.77	-29.93
0.7	600.15	464.04	1064.19	501.40	952.87	1454.27	19.69	-51.30	-26.82
0.8	605.40	474.99	1080.39	501.40	925.79	1427.19	20.74	-48.69	-24.30
0.9	584.04	474.78	1058.82	501.40	899.56	1400.96	16.48	-47.22	-24.42

3.6 Sensitivity Analysis

In this section, sensitivity analysis is performed to investigate the effect of the variation of different cost parameters on the “optimal” solution. Example 2 with 30 buyers is used and the effect of the following groups of parameters are examined:

1. The fixed shipment cost incurred for each delivery to buyer *i* (C_i) and the fixed recycling cost incurred for each used product pick-up from buyer *i* (G_i)
2. The ordering cost per order for buyer *i* (A_i) and the used product ordering cost for buyer *i* (B_i)
3. The inventory holding cost for buyer *i* (h_i) and the used product holding cost for buyer *i* (h_i')

4. The vendor's set-up cost per production run (S_v) and the vendor's set-up cost for each recycling production run (S_v').

For each group of parameters, percentage changes of -75%, -50%, -25%, +25%, +50%, +75%, and +100% are applied to the original value. The total cost of the synchronized cycles model and the independent policy model are then evaluated and compared in each scenario. The plots of the percentage saved in the total cost vs. the percentage changed in different cost parameters are shown in Figures 3.5 to 3.8. In all the scenarios, the synchronized cycles model outperforms the independent policy model. From Table 3.7 and Figure 3.5, it is found that the saving increases as the vendor's fixed cost (i.e. C_i and G_i) increases. However, the saving decreases when the buyers' fixed cost increases or when the buyers' holding cost increases as shown in Table 3.8, Figure 3.6, Table 3.9 and Figure 3.7. The change in the setup costs does not have significant effect on the saving in the total cost as shown in Table 3.10 and Figure 3.8.

Table 3.7 Percentage saved in total cost when changing vendor fixed cost

percentage change in vendor's fixed cost	Total cost in the synchronized cycles model	Total cost in the Independent policy model	percentage saved in total cost
-75	306.82	441.85	30.56
-50	331.65	478.33	30.67
-25	348.44	514.82	32.32
0	367.91	551.31	33.27
25	379.16	587.80	35.49
50	392.88	624.28	37.07
75	406.14	660.77	38.54
100	422.91	697.26	39.35

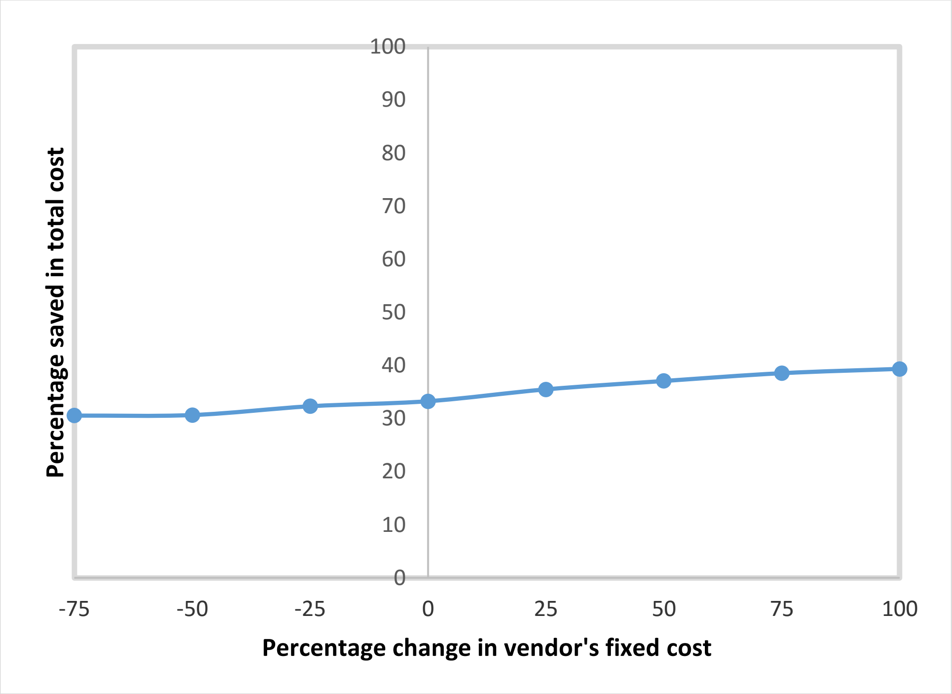

Fig. 3.5. Percentage saved in total cost VS percentage changed in vendor’s fixed cost

Table 3.8 Percentage saved in total cost when changing buyers' fixed cost

percentage change in buyers' fixed cost	Total cost in the synchronized cycles model	Total cost in the Independent policy model	percentage saved in total cost
-75	319.38	577.87	44.73
-50	335.21	541.83	38.13
-25	350.47	541.90	35.32
0	367.91	551.31	33.27
25	373.81	564.08	33.73
50	386.54	578.19	33.15
75	403.82	592.78	31.88
100	414.74	607.47	31.73

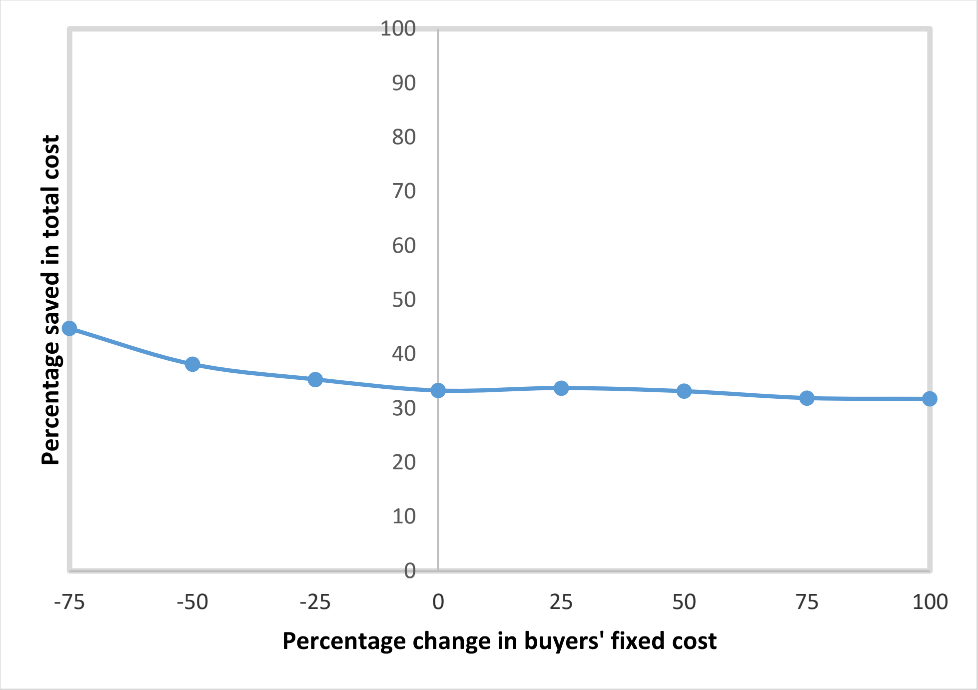

Fig. 3.6. Percentage saved in total cost VS percentage change in buyers' fixed cost

Table 3.9 Percentage saved in total cost when changing buyers' holding cost

percentage change in buyers' holding cost	Total cost in the synchronized cycles model	Total cost in the Independent policy model	percentage saved in total cost
-75	167.10	448.71	62.76
-50	248.17	480.94	48.40
-25	313.89	517.04	39.29
0	367.91	551.31	33.27
25	400.94	583.34	31.27
50	440.17	613.34	28.23
75	475.18	641.60	25.94
100	499.70	668.35	25.23

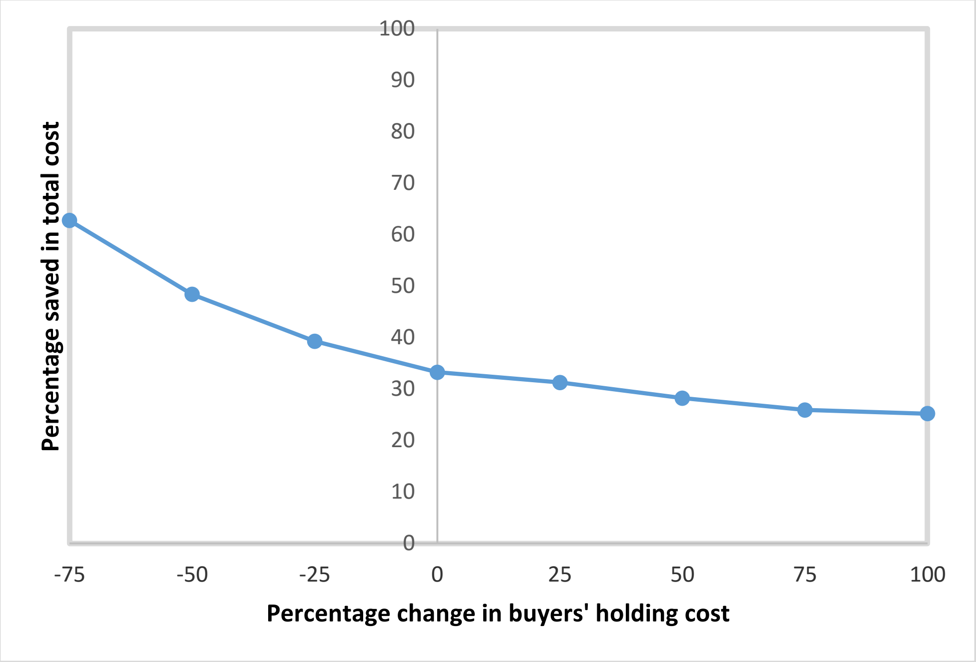

Fig. 3.7. Percentage saved in total cost VS percentage change in buyers’ holding cost

Table 3.10 Percentage saved in total cost when changing setup costs

percentage change in setup costs	Total cost in the synchronized cycles model	Total cost in the Independent policy model	percentage saved in total cost
-75	316.15	468.02	32.45
-50	335.76	502.52	33.18
-25	349.75	528.99	33.88
0	367.91	551.31	33.27
25	380.84	570.97	33.30
50	391.25	588.75	33.55
75	403.46	605.09	33.32
100	414.93	620.31	33.11

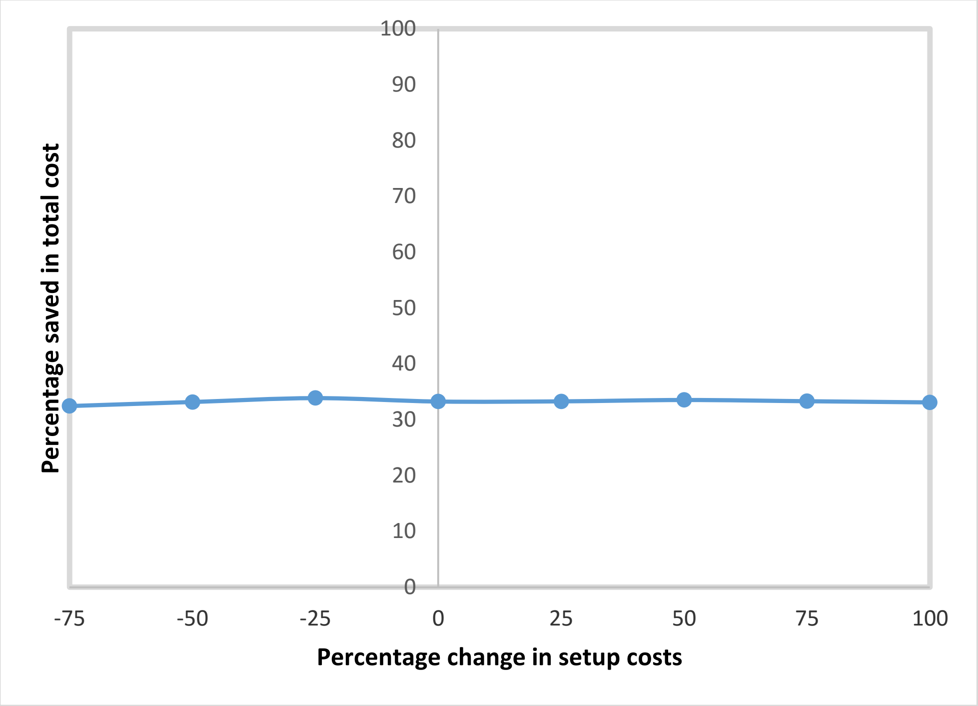

Fig. 3.8. Percentage saved in total cost VS percentage change in setup costs

3.7 Conclusion

In this chapter, an extension of the synchronized cycles model by Chan and Kingsman (2007) has been developed. This extended model with reverse logistics includes the pick-up and recycling production of used products. The synchronized cycles model with reverse logistics is solved by the genetic algorithm and the performance is then compared with the independent policy model. It is found that for the whole range of *D/P* ratios, the synchronized cycles model outperforms the independent policy model for all the three examples. When examining the cost of buyers and the vendor separately, it is found that even though the buyers' total costs have been increased, the saving in the vendor's total cost is so significant that it outweighs the increase in the buyers' total costs such that there is an average of over 30% saving in the total system cost. Sensitivity analysis is carried out to investigate the effect of the variation of different cost parameters on the "optimal" solution. It is found that the synchronized cycles model outperforms the independent policy model in all scenarios. The percentage saved in the total cost of the synchronized cycles model over the independent policy model increases as the vendor's fixed cost increases. However, the percentage saved decreases as the buyers' cost increases or when the buyers' holding cost increases. The setup costs do not seem to have any significant effect on the percentage saved.

Chapter 4

Vehicle Routing of the Synchronized Cycles Model with Reverse Logistics

4.1 Introduction

In this chapter, the synchronized cycles model with reverse logistics in Chapter 3 is extended to include vehicle routing for delivery and used product pick-up. Recall that in Chapter 3, C_i is the fixed shipment cost incurred for each delivery to buyer *i* and G_i is the fixed recycling cost incurred for each pick-up from buyer *i*. Assuming that these two costs only include the ordering processing, loading and unloading cost, a vehicle routing cost which depends on the distance traveled and number of vehicles used is added to formulate the transportation cost in the synchronized cycles model. Similar to the model in Chapter 3, synchronization of the supply chain is achieved by allowing the buyers to select their own delivery cycles and used product pick-up cycles which must be integer factors of the vendor's production cycle. In order to find the optimal routing to minimize the transportation costs in this model, a series of NP hard vehicle routing problems is solved by the meta-heuristics 'adaptive large neighborhood search (ALNS)'. Performances of the one-step and two-step methods are compared for Example 1 with 5 buyers. Then the two-step methods are used to solve Examples 2 and 3 with 30 and 50 buyers, respectively. Sensitivity analysis is also performed to investigate the effect in the change of different transportation cost parameters.

4.2 Synchronized Cycles Model with Vehicle Routing

In this section, the synchronized cycles model is extended to include vehicle routing of its deliveries of orders. It is assumed that the order of a single buyer can be split into different trucks and each truck can deliver orders to different buyers. The location of each party is expressed as coordinates in the Cartesian plane, so that the actual distance traveled can be expressed as a distance function, $dist\{X_t\}$, where $\{X_t\}$ is an ordered-vector which depicts the sequence of the route for truck *i* at time *tT*, based on the fact that all the trucks first depart from the vendor's location, and returns to the vendor after delivery and/or used product pick-up at time *tT*.

Recall from equation (3.47) and (3.48) in Chapter 3 that the vendor's order processing and shipment cost per unit time is $\sum_{i=1}^{n} \frac{C_i}{k_i T}$ and the vendor's recycle order processing and pick-up cost per unit time is $\sum_{i=1}^{n} \frac{G_i}{g_i T}$. Assuming that these two costs include the order processing and loading and unloading costs only, the vendor's vehicle routing transportation cost per unit time is defined as follows:

$$= \frac{1}{NT}\left[c_d \sum_{t=1}^{N} \sum_{i} \sum_{\substack{(j,k)\in \text{the sequence} \\ \text{of the routes for truck } i \\ \text{depicted by the vector } \{X_t\}}} dist\{segment(j,k)\} + c_r \sum_{t=1}^{N} \lambda_t \right] \qquad (4.1)$$

where c_d is the transportation cost per unit distance travelled, λ_t is the number of vehicles used at time tT and c_r is the cost of dispatching a vehicle.

Thus, the total cost of the coordinated single-vendor multiple-buyer supply chain per unit time is now

$$
\begin{aligned}
f_{TC} &= \frac{1}{2}\sum_{i=1}^{n}(h_i d_i k_i T + h_i' r_i d_i g_i T) \\
&+ \sum_{i=1}^{n}\left(\frac{A_i + C_i}{k_i T} + \frac{G_i + B_i}{g_i T}\right) + \left[h(\chi + \chi'') + h'\chi' + S_v + S_v'\right]\frac{1}{NT} \\
&+ \left\{ c_d \sum_{t=1}^{N}\sum_{i}\sum_{\substack{(j,k)\in \text{the sequence} \\ \text{of the routes for truck } i \\ \text{depicted by the vector } \{X_t\}}} dist\left\{segment(j,k)\right\} + c_r \sum_{t=1}^{N}\lambda_t \right\}\frac{1}{NT}
\end{aligned}
\tag{4.2}
$$

4.3 Solution Strategies

In order to solve the vehicle routing problem of the synchronized cycles model, a relative newly developed heuristics, namely, the adaptive large neighborhood search (ALNS) (Ropke and Pisinger, 2006) is used to determine the route-sequence of the truck-visits. In the one-step method, the synchronized cycles model is solved by the GA with the embedded vehicle routing problem solved by the ALNS simultaneously. Since it is found that solving the synchronized cycles model and the vehicle routing problem simultaneously takes over an hour even for the smallest example, a two-step method is produced. The synchronized cycles model without the vehicle routing part is first solved by the GA and then the vehicle routing problem is solved by the ALNS for the optimal solution of the GA.

4.3.1 The ALNS Implementation

To determine the route sequence for the synchronized cycles model with any given feasible solution $N, k_i, \pi_i, g_i, \tau_i$:

Step 1: With a feasible solution $N, k_i, \pi_i, g_i, \tau_i$ of the synchronized cycles model, the route sequences are first randomly assigned for each ordering time *tT*. ($t = 1, ..., N$)

Step 2: Perform ALNS on the route sequences as described in sections 4.3.1.1 and 4.3.1.2.

Step 3: The stopping criterion is when there is no improvement in the best fitness value in 500 consecutive iterations.

4.3.1.1 Neighborhood Definition

For the route sequence, seven neighborhood operators are designed for Step 2 in the ALNS implementation, namely,

1. For each truck, randomly swap the sequence of any 2 delivery/pick-up orders.
2. For each truck, randomly swap the sequence of any 3 delivery/pick-up orders.
3. For each truck, reverse the sequence of all the orders.
4. For each truck, randomly select part of the route and reverse the sequence of orders.
5. Randomly pick one buyer and reassign its order to another truck.
6. Swap the end of routes of two randomly selected trucks.
7. Reverse the sequence of orders for two randomly selected trucks and swap the end of routes of the two trucks. (Combining neighborhood 3 and 6)

Neighborhoods 1, 2, 3 and 4 are to diversify the search locally. Neighborhoods 5, 6 and 7 are to diversify the search to avoid being trapped in a local optimal.

4.3.1.2 Neighborhood Probability Adjustment

Initially the probabilities of choosing any one of the neighborhoods are equally likely, each equals to $\frac{1}{7}$. The score of each neighborhood is set to be zero at the beginning. In each iteration, one neighborhood is randomly selected and the score of the neighborhood will increase by 1 if there is any improvement in the fitness value. After a certain number of iterations (a segment), depending on the number of buyers in the example, the probability of each neighborhood is updated according to their performance. The probability of the worst performing neighborhood is halved while the probability of the best performing neighborhood is increased by the decreased probability from the worst performing neighborhood. Then the updated probabilities are used for the operation in the next segment.

4.4 Comparison of One-step and Two step methods for Example 1

A comparison of the two solution strategies, i.e. one-step and two-step methods, is conducted for Example 1 with 5 buyers of Chapter 3. The coordinates for the vendor and buyers in the Cartesian plane are randomly generated for the vehicle routing problem. The data are shown in Appendix I. The synchronized cycles model with vehicle routing is first solved by the one-step hybrid method (one-step GALNS) where the vehicle routing problem solved by the ALNS is embedded in the synchronized cycles model solved by the GA.

The parameters for the GA are set as follows:

D/P ratio=0.5

Population size = 20

Crossover rate=0.8

Mutation rate=0.01

$c_d = 1.0$, $c_r = 100$

Stopping criterion: When there is no improvement on the best fitness value in 200 consecutive iterations.

The synchronized cycles model with vehicle routing is also solved by another one-step hybrid method (one-step LNSLNS) where both of the synchronized cycles model and the vehicle routing problem are solved by the ALNS.

In order to make direct comparison with the GA, the parameters for the ALNS are set as follows:

D/P ratio=0.5

Population size = 20

The performance of the two one-step hybrid methods of Example 1 is shown in Table 4.1:

Table 4.1
Comparison of the one-step GALNS and one-step LNSLNS methods

	one-step GALNS	one-step LNSLNS	Percentage change
N	126	132	
Total cost	66.84	66.57	-0.40
Buyers' cost	38.81	38.70	-0.29
Vendor's cost	20.44	20.97	2.55
Routing cost	7.58	6.91	-8.90

The result in Table 4.1 shows that the performance of the one-step GALNS method and the one-step LNSLNS method are very similar. The cost of the whole supply chain differs by just 0.4%. There is a more significant difference in the routing cost where the one-step LNSLNS method outperforms the one-step GALNS method by 8.9%. It is noted that the computational time required for the one-step GALNS method for Example 1 with 5 buyers is 12 hours and that for the one-step LNSLNS method is 5.5 hours. Therefore, the two-step GALNS and LNSLNS methods which are more time-efficient are introduced.

In the two-step methods, the synchronized cycles problem is first solved by either the GA or the ALNS. Then the vehicle routing problem is solved by the ALNS for the optimal solution found in the first step. Thirty repeated runs for each two-step method are done and the best optimal solutions are compared. As shown in Table 4.2, the two-step GALNS method is worse than the one-step GALNS method by 5.25% while the two-step LNSLNS method is worse than the one-step LNSLNS method by 7.31%. When comparing the costs, it is found that there is a decrease in the buyers’ cost but an increase in both the vendor’s cost and the routing cost. The increase of the routing cost in both of the two-step methods are quite significant at 58% and 105% and contributes most to the increase in the total cost. Running with the “Intel(R) Core™ i7-4790” CPU and programming in the Matlab R2016a platform, the average CPU time of the two-step GALNS and LNSLNS methods are 10.04 and 6.80 seconds, which are significantly shorter than the one-step methods. The decrease in the total inventory cost (buyers’ cost plus vendor’s cost) of the two-step methods suggests that optimizing just the inventory cost in step 1 can yield a better solution than optimizing all the costs together in the one-step methods. However, the increase in the routing cost in the two-step methods suggests that using the optimal solution from step 1, the optimal solution for the routing part generated from step 2 is not as “optimal” as the result obtained from the one-step methods.

Table 4.2

Comparison of one-step and two-step methods for Example 1 with 5 buyers

	one-step GALNS	two-step GALNS	Percentage change	one-step LNSLNS	two-step LNSLNS	Percentage change
N	126	60		132	84	
Total cost	66.84	70.34	5.25	66.57	71.44	7.31
Buyers' cost	38.81	34.98	-9.89	38.70	35.31	-8.76
Vendor's cost	20.44	23.37	14.28	20.97	21.98	4.82
Routing cost	7.58	12.00	58.34	6.91	14.15	104.86

Even though the one-step methods outperform the two-step methods by a few percent, the computational time would make them infeasible for Examples 2 and 3 with 30 and 50 buyers, respectively. Therefore, in the next section, only the two-step methods are used to solve the synchronized cycles model with vehicle routing for these two examples.

4.5 Comparison of Two-step methods for Examples 2 and 3

In this section, the two-step GALNS and LNSLNS methods are used to solve Examples 2 and 3 with 30 and 50 buyers, respectively, for the synchronized cycles model with vehicle routing. The parameters used for the GA and the ALNS are the same as in section 4.3 and 4.4.

From Table 4.3, it is found that the performance of the two-step GALNS and the two-step LNSLNS methods for Example 2 with 30 buyers are quite similar, with a difference in the total cost of about 1%. However, the average CPU time for the two-step LNSLNS method is longer than that of the two-step GALNS method by 76%. It is noted that the routing cost contributes to just about 7% of the total system cost in Example 2.

Table 4.3

Comparison of two-step methods for Example 2 with 30 buyers

	two-step GALNS	two-step LNSLNS	Percentage change
N	28	40	
Total cost	391.83	394.96	0.80
Buyers' cost	235.95	229.27	-2.91
Vendor's cost	128.25	137.50	7.21
Routing cost	27.63	28.19	2.04
Average computational time (in seconds)	112.74	198.39	75.97

From Table 4.4, it is found that the two methods also yield similar results for Example 3 with 50 buyers. However, the average CPU time for the two-step GALNS method is shorter than that of the two-step LNSLNS method by about 69%. It is noted that the routing cost contributes to only about 3% of the total system cost in Example 3.

Table 4.4
Comparison of two-step methods for Example 3 with 50 buyers

	two-step GALNS	two-step LNSLNS	Percentage change
N	36	45	
Total cost	1080.20	1084.16	0.37
Buyers' cost	580.93	597.22	2.80
Vendor's cost	467.42	454.50	-2.76
Routing cost	31.85	32.44	1.86
Average computational time (in seconds)	681.42	1186.25	74.09

It is observed that there is a decrease in the proportion of routing cost out of the total system cost as the number of buyers increases. This decrease might be due to the fact that while there are more buyers in Examples 2 and 3, the vendor's production cycles have become much shorter compared to Example 1. The inventory cost for the buyers and vendor per unit time has increased significantly because of the increase of buyers and the shorter vendor's production cycle and contributes most to the increase in the total cost. However, the increase in the transportation cost which depends on the number of trucks used and the distance traveled per unit time is not as significant because the routing schedule is actually more efficient when there are more buyers and hence more deliveries and used product pick-up orders in a shorter period of time. As a result, the routing schedule coordination is more effective and therefore, the increase in the number of trucks used and the distance traveled is not as great as the increase in the inventory cost.

4.6 Sensitivity Analysis

In this section, sensitivity analysis is performed to investigate the effect of the variations of different transportation cost parameters. The two-step GALNS method is used to solve Example 2 with 30 buyers and the effect of c_d - the transportation cost per unit distance, and c_r - the cost of dispatching a vehicle are examined.

For each parameter, percentage changes of -25%, -50%, -75%, +25%, +50%, +75%, +100%, +125%, +150%, +175%, and +200% are applied to the original value. The total system cost, transportation cost and inventory cost of the synchronized cycles model with vehicle routing are then evaluated and compared in each scenario. The results of changing the parameter c_d are shown in Table 4.5 below:

Table 4.5 Change in different costs when changing c_d

Percentage change in c_d	Total cost	Transportation cost	Inventory cost
-75	377.75	8.37	369.38
-50	394.95	16.40	378.56
-25	392.12	22.41	369.72
0	397.55	27.92	369.62
25	403.16	34.54	368.61
50	422.81	45.93	376.88
75	418.68	46.71	371.98
100	425.04	53.87	371.17
125	438.69	72.32	366.36
150	440.79	68.12	372.68
175	453.00	77.11	375.89
200	471.42	80.21	391.21

The plots of the total cost, the transportation cost and the inventory cost vs. the percentage change in the transportation cost per unit distance are shown in Figures 4.1-4.3. From Figure 4.1, it is found that in general the total system cost increases as the transportation cost per unit distance increases. From Figure 4.2, it is found that the transportation cost increases significantly as the transportation cost per unit distance increases, as expected. However, from Figure 4.3, the inventory cost does not show a significant trend of change when the transportation cost per unit distance increases.

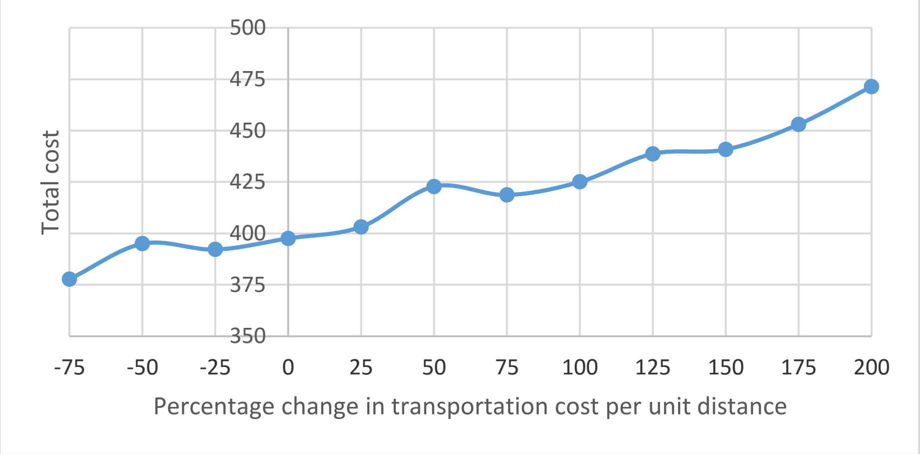

Fig. 4.1. Change in total cost VS percentage change in c_d

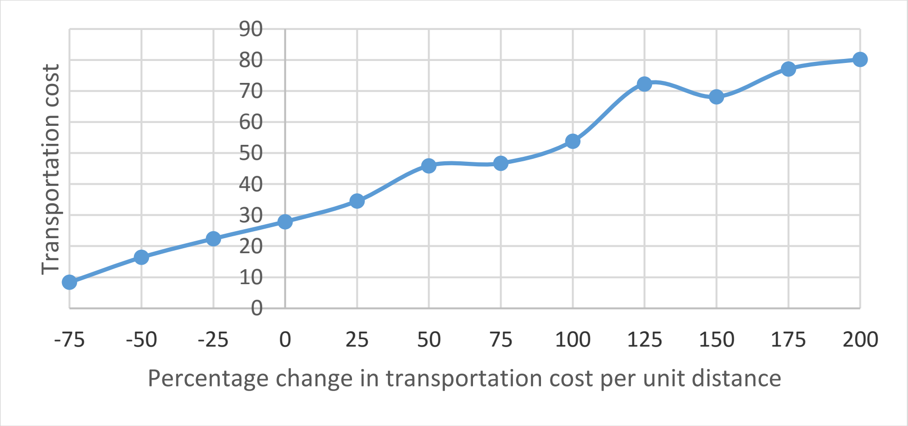

Fig. 4.2. Change in transportation cost VS percentage change in c_d

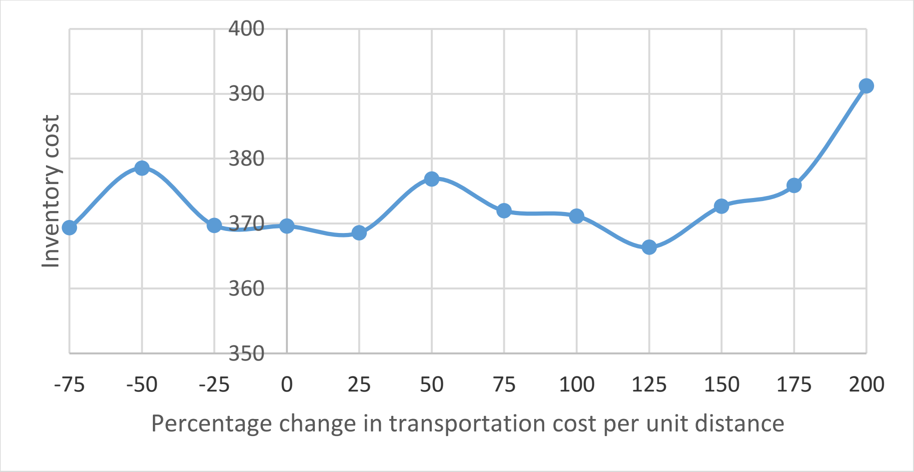

Fig. 4.3. Change in inventory cost VS percentage change in c_d

The results of changing the parameter c_r are shown in Table 4.6 below:

Table 4.6 Change in different costs when changing c_r

Percentage change in c_r	Total cost	Transportation cost	Inventory cost
-75	400.09	31.54	368.54
-50	405.00	29.21	375.79
-25	403.26	28.34	374.93
0	397.55	27.92	369.62
25	401.63	32.81	368.82
50	398.97	26.80	372.17
75	399.28	30.65	368.62
100	400.45	29.71	370.74
125	403.86	34.20	369.66
150	396.03	27.33	368.70
175	403.43	26.59	376.85
200	396.27	27.87	368.40

The plots of the total cost, the transportation cost, and the inventory cost vs. the percentage change in the transportation cost of dispatching a vehicle are shown in Figures

4.4-4.6. From the three figures, it can be seen that the change in the transportation cost of dispatching a vehicle does not have any significant effect on all the three costs, i.e. the total system cost, the transportation cost and the inventory cost are all robust to the transportation cost per truck c_r.

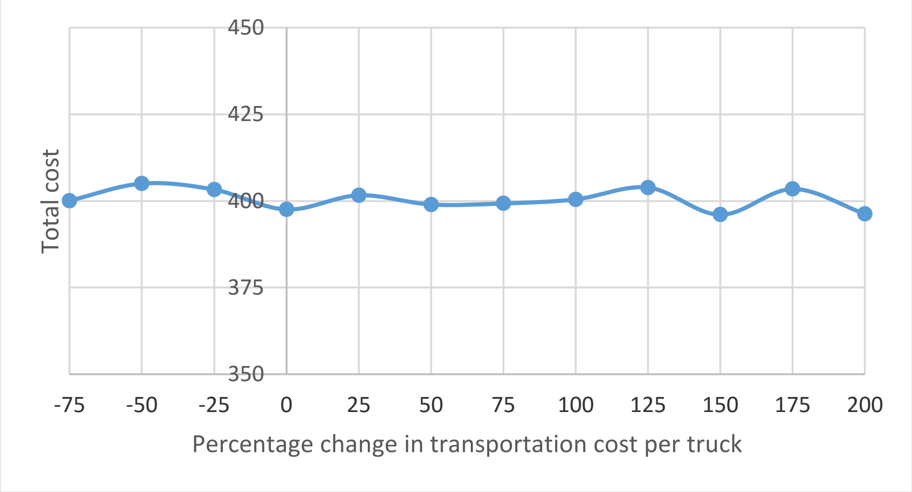

Fig. 4.4. Change in total cost VS percentage change in c_r

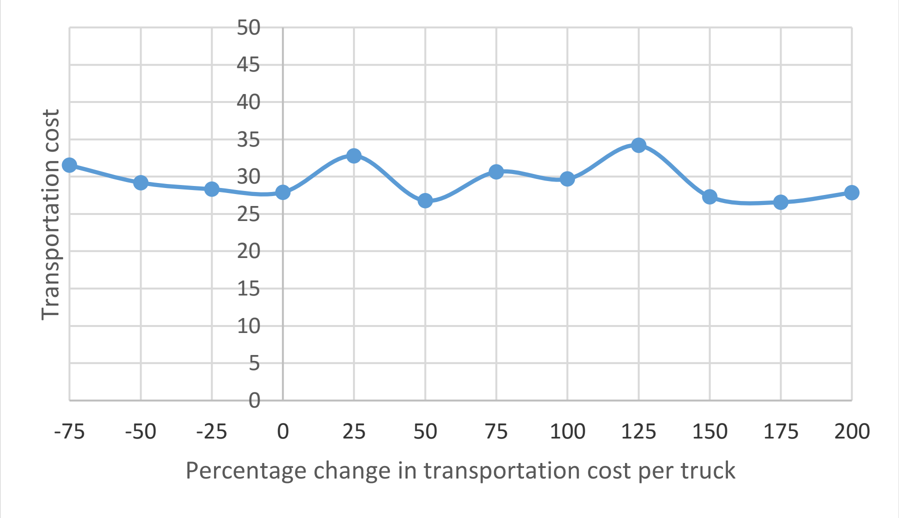

Fig. 4.5. Change in transportation cost VS percentage change in c_r

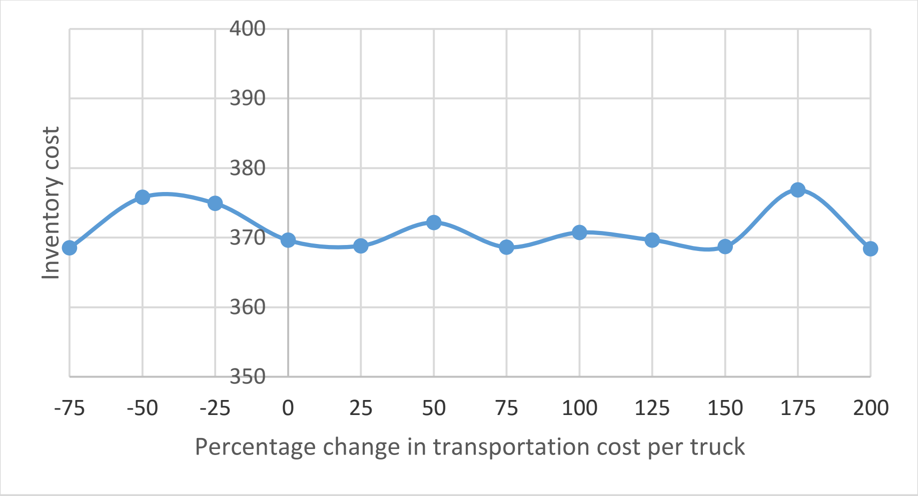

Fig. 4.6. Change in inventory cost VS percentage change in c_r

4.7 Conclusion

In this chapter, the synchronized cycles model with reverse logistics is extended to include vehicle routing. The vehicle routing problem is solved by the meta-heuristics ‘adaptive large neighborhood search (ALNS)’. The synchronized cycles model is solved by both the genetic algorithm (GA) and the ALNS. For Example 1 with 5 buyers, two hybrid one-step methods, namely GALNS and LNSLNS, are used. It is found that the two hybrid one-step methods yield similar results but the computational times are both very long. Therefore, the two-step GALNS and LNSLNS methods are introduced. While the two-step methods are outperformed by the one-step methods by a few percent in Example 1, the CPU time for the two-step methods are much shorter so they are used to solve Examples 2 and 3 of 30 and 50 buyers, respectively. It is found that both of the two two-step methods yield similar results in Examples 2 and 3. However, it is observed that when the number of buyers increases from 5 in Example 1 to 30 and 50 in Examples 2 and 3, the proportion of routing cost in the total system cost decreases. This might be due to the shorter vendor's production cycle. As the vendor's production cycle is shortened and the number of buyers is increased, the inventory cost per unit time for the whole supply chain would increase significantly but the routing cost per unit time which depends on the number of trucks used and the distance traveled would not increase as much because the routing schedule is more efficient for problems of larger sizes. For sensitivity analysis, since the CPU time for using the two-step GALNS method is shorter than that for using the two-step LNSLNS method by over 10%, the two-step GALNS method is used. To investigate the effect on the transportation cost parameters c_d and c_r on the total system cost, the transportation cost and the inventory cost, the two parameters are subject to the following percentage changes: -75%, -50%, -25%, +25%, +50%, +75%, +100%, +125%, +150%, +175%, +200%. It is found that when the transportation cost per unit distance c_d increases, the total system cost and the transportation cost of the whole supply chain also increase. However, the transportation cost per unit distance does not have any significant effect on the inventory cost. When varying the transportation cost c_r for dispatching a vehicle, it is found that the total system cost, the transportation cost and the inventory cost are all not significantly affected.

Chapter 5

Incorporating CO_2 Emission in the Synchronized Cycles Model

5.1 Introduction

In the mid-1990s, increasing awareness of environmental health issues among the general public led supply chain practitioners and researchers to pursue research related to environmental issues, known as green supply chain management (GSCM). For GSCM publications with mathematical models, most of the objectives have been minimizing the total system cost, instead of optimizing environmental performance such as CO_2 emission. To simultaneously achieve economic and environmental goals, coordination in the supply chain is essential when considering environmental performance. In this chapter, the synchronized cycles model with reverse logistics is extended to incorporate carbon dioxide emission resulted from vehicle deliveries. First, CO_2 emission is calculated for the model of Chapter 4 (Model 1) which only minimizes inventory and transportation costs. Then the cost due to carbon dioxide emission is incorporated into the transportation cost of Model 1 to form a modified transportation cost. Thus, the determination of the optimal modified transportation costs in this green supply chain model generates a series of modified routing problems. The two-steps GALNS and LNSLNS methods proposed in Chapter 4 are used to find the optimal solution for this modified model (Model 2). Lastly, the objective for the vehicle routing problem is then changed to minimizing CO_2 emission instead of minimizing the total routing cost in step 2 of the two-step methods. The optimal solution for this new model (Model 3) is compared with those of Model 1 and Model 2. All the assumptions about the carbon dioxide emissions function are adopted from the Network for Transport and Environment (NTM 2013).

5.2 Synchronized Cycles Model with CO_2 Emission

In the vehicle routing problem of Chapter 4, it is assumed that the order of a single buyer can be split into different trucks and each truck can deliver orders to different buyers. The location of each party is expressed as coordinates in the Cartesian plane, so that the actual distance traveled can be expressed as a distance function, $dist\{X\}$, where $\{X\}$ is an ordered-vector which depicts the sequence of the route. Denote the fixed CO_2 emissions for truck i as ϕ_i, the variable CO_2 emissions (per unit item on the truck per unit distance traveled) for truck i as γ_i, the capacity of truck i as θ_i, and the quantity transported by truck i at time tT from location j to k as $\eta_{i,j,k,t}$.

With the above assumption, the total CO_2 emissions at time tT is

$$f_{CO_2,t} = \sum_i \phi_i \sum_{\substack{(j,k)\in\text{the sequence}\\ \text{of the routes for truck } i\\ \text{depicted by the vector } \{X_t\}}} dist\{segment(j,k)\} + \sum_i \gamma_i \sum_{\substack{(j,k)\in\text{the sequence}\\ \text{of the routes for truck } i\\ \text{depicted by the vector } \{X_t\}}} \eta_{i,j,k,t} \times dist\{segment(j,k)\} \tag{5.1}$$

where $\{X_t\}$ is defined in section 4.2. The first term is the fixed CO_2 emission associated with truck i and the second term is the CO_2 emission based upon the quantity held. Both terms are based on the distance traveled by truck i between two locations, j and k, where location k is the immediate next stop from location j.

The total cost of CO_2 emission per unit time is

$$f_{CO_2} = \frac{\varepsilon}{NT}\sum_{t=1}^{N} f_{CO_{2,t}} \tag{5.2}$$

where ε denotes the unit cost per kg of CO_2 emitted.

5.3 CO_2 Emission Calculation

To calculate how much CO_2 is emitted for the synchronized cycles model, the following assumptions are made about the truck used and the product:

Size of vehicle used: 10-foot truck (from U-Haul)

Capacity of a truck = 2810 lbs. (max.)

Weight of an empty truck = 5790 lbs.

Weight per product unit = 1 kg

1 unit distance = 10 km

CO_2 emission coefficient = 0.1693 kg per Ton per Mile =105 g per Ton per km (https://en.wikipedia.org/wiki/Environmental_impact_of_transport)

(http://timeforchange.org/co2-emissions-shipping-goods)

Unit cost per kg of CO_2 emitted = ε =$93/Ton=$0.093 per kg of CO_2 emitted (Tol (2005))

With the above, CO_2 emission is calculated for the synchronized cycles model with vehicle routing in Chapter 4 (Model 1). The two-step GALNS and LNSLNS methods are used for evaluating the CO_2 emission in Examples 1, 2 and 3 with 5, 30 and 50 buyers, respectively, using the coefficients in section 5.3. For each method, 30 repeated runs are conducted and the best solutions are shown in Table 5.1. In Example 1, it is found that while the two methods yield similar optimal solutions for the total system cost, the CO_2 emission of the two-step GALNS method is smaller than that of the two-step LNSLNS method by 13%. However, the average CPU time of the two-step GALNS method is longer than that of the two-step LNSLNS method by 53%. In Example 2, while the two methods yield similar optimal solutions for the total system cost, the CO_2 emission of the two-step LNSLNS method is smaller than that of the two-step GALNS method by 5.6%. In Example 3, while the difference in the total system cost is less than 1%, the CO_2 emission of the two-step LNSLNS method is smaller than that of the two-step GALNS method by 14%. The average CPU time for the two-step GALNS method is much shorter than that of the two-step LNSLNS method in Examples 2 and 3.

Table 5.1

Comparison of the two-step methods in Model 1 for Examples 1, 2, and 3

	Example 1			Example 2			Example 3		
	two-step GALNS	two-step LNSLNS	Percentage Changed	two-step GALNS	two-step LNSLNS	Percentage Changed	two-step GALNS	two-step LNSLNS	Percentage Changed
N	60	84		28	40		36	45	
Total system cost	70.34	71.44	1.55	391.83	394.96	0.80	1080.20	1084.16	0.37
Buyers' cost	34.98	35.31	0.96	235.95	229.27	-2.91	580.93	597.22	2.80
Vendor's cost	23.37	21.98	-6.31	128.25	137.50	7.21	467.42	454.50	-2.84
Routing cost	12.00	14.15	17.86	27.63	28.19	2.04	31.85	32.44	1.86
CO_2 emission (gram per unit time)	34053.58	39169.61	13.06	37962.17	35855.64	-5.55	41685.32	35921.54	-13.83
Average CPU time (seconds)	10.40	6.80	-52.91	112.74	198.39	75.97	681.42	1186.25	74.09

5.4 Performance of the Synchronized Cycles Model with CO_2 Cost (Model 2)

If the CO_2 emission cost is incorporated into the cost function of Model 1, the total cost of the supply chain per unit time is given by

$$
\begin{aligned}
f_{green,TC} &= f_{TC} + f_{CO_2} = \frac{1}{2}\sum_{i=1}^{n}(h_i d_i k_i T + h_i' r_i d_i g_i T) \\
&+ \left\{ \frac{h(\chi+\chi'')+h'\chi'}{N} + \frac{S_v+S_v'}{N} + \sum_{i=1}^{n}\left(\frac{A_i+C_i}{k_i}+\frac{G_i+B_i}{g_i}\right)\right\}\frac{1}{T} \\
&+ \left\{ c_d \sum_{t=1}^{N}\sum_{i} \sum_{\substack{(j,k)\in\text{the sequence}\\ \text{of the routes for truck } i\\ \text{depicted by the vector } \{X_t\}}} dist\{segment(j,k)\} + c_r \sum_{t=1}^{N}\lambda_t \right\} \frac{1}{NT} \\
&+ \frac{\varepsilon}{NT}\sum_{t=1}^{N}\left[\sum_{i}\phi_i \sum_{\substack{(j,k)\in\text{the sequence}\\ \text{of the routes for truck } i\\ \text{depicted by the vector } \{X_t\}}} dist\{segment(j,k)\} + \sum_{i}\gamma_i \sum_{\substack{(j,k)\in\text{the sequence}\\ \text{of the routes for truck } i\\ \text{depicted by the vector } \{X_t\}}} \eta_{i,j,k,t} \times dist\{segment(j,k)\} \right]
\end{aligned}
\tag{5.3}
$$

Thus, the objective is to find the nonnegative values for N, k_i , g_i , $\delta_{i,t}$, $\omega_{i,t}$ and Ψ that minimize the cost function $f_{green,TC}$ subject to the constraints (3.58) and (3.59). As mentioned, the above model is denoted as Model 2.

The optimal solutions of the modified model (Model 2) for Examples 1, 2, and 3 are obtained by the two-step GALNS and LNSLNS methods. For each method, 30 repeated runs are conducted and the results are shown in Table 5.2. In Example 1 of 5 buyers, it is found that the optimal solution of the two methods differs by less than 1%. However, the

CO_2 emission of the two-step LNSLNS method is smaller than that of the two-step GALNS method by 7.5% and the average CPU time is also shorter by 68%. In Example 2 of 30 buyers, it is found that the optimal solution obtained and the CO_2 emission calculated are very similar for the two methods. However, the average CPU time for the two-step GALNS method is shorter than that of the two-step LNSLNS method by 24.5%. In Example 3 of 50 buyers, the results are again similar for the two methods. The average CPU time of the two-step GALNS method is shorter than that of the two-step LNSLNS method by about 41%. It is noted that there is a significant difference in the CO_2 emission as the CO_2 emission of the two-step GALNS method is lower than that of the two-step LNSLNS method by 25%.

Table 5.2

Comparison of the two-step methods in Model 2 for Example 1, 2, and 3

	Example 1			Example 2			Example 3		
	two-step GALNS	two-step LNSLNS	Percentage Changed	two-step GALNS	two-step LNSLNS	Percentage Changed	two-step GALNS	two-step LNSLNS	Percentage Changed
N	96	72		36	32		40	42	
Total system cost	73.47	73.07	-0.55	395.73	393.92	-0.46	1084.39	1089.15	0.44
Buyers' cost	35.93	35.53	-1.12	225.95	228.48	1.12	604.97	593.87	-1.87
Vendor's cost	21.42	22.27	3.97	140.45	136.47	-2.92	443.11	458.42	3.46
Routing cost	16.12	15.27	-5.59	29.34	28.98	-1.24	36.31	36.86	1.51
CO_2 Cost	3.36	3.12	-7.47	2.67	2.62	-1.97	3.27	4.10	25.44
CO_2 emission (gram per unit time)	36077.68	33569.39	-7.47	28747.74	28191.07	-1.97	35139.12	44076.87	25.44
Average CPU time (seconds)	14.29	4.51	-68.42	138.78	183.80	-24.50	826.27	1400.69	-41.01

5.5 Synchronized Cycles Model with CO_2 Emission as the Objective (Model 3)

Most vendor-buyer coordination research concentrates only on an objective of minimizing the total system cost such as in Model 1 and Model 2. In this section, to put more emphasis on environmental performance, the objective function is changed to minimizing the CO_2 emission in the vehicle routing problem (Model 3) instead of the routing cost in the step 2 of the two-step methods. The total system cost function for Model 3 is the same as that of Model 1. For each two-step method, 30 repeated runs are conducted and a comparison of the performance of Model 3 with the performances of the previous two models for Examples 1, 2, and 3 are shown in Tables 5.3, 5.4, and 5.5, respectively. Note that the cost of CO_2 emission is not included in Model 2 for direct comparison.

Table 5.3 Comparison of Model 1, Model 2, and Model 3 for Example 1

	Model 1		Model 2		Model 3	
	two-step GALNS	two-step LNSLNS	two-step GALNS	two-step LNSLNS	two-step GALNS	two-step LNSLNS
N	60	84	96	72	105	80
Total system cost (without cost of CO_2)	70.34	71.44	70.12	69.95	69.57	70.55
Buyers' cost	34.98	35.31	35.93	35.53	36.39	36.40
Vendor's cost	23.37	21.98	21.42	22.27	21.32	21.42
Routing cost	12.00	14.15	12.77	12.15	11.86	12.73
CO_2 emission (gram per unit time)	34053.58	39169.61	36077.68	33569.39	918.48	925.28
Average CPU time (seconds)	10.40	6.80	14.29	4.51	19.33	8.18

From Table 5.3, it is found that the total system costs excluding the cost of CO_2 emission are all similar in Example 1 for Models 1, 2 and 3. It is also noted that the average CPU time for the two-step LNSLNS method for all the models are shorter than that of the two-step GALNS method. The most significant difference observed is that the CO_2 emission of Model 3 for both methods is just about 2 to 3% of those of Model 1 and Model 2. The large amount of decrease in CO_2 emission is due to the change in the objective function that minimizes the CO_2 emission instead of the routing cost in the step 2 of the two-step methods.

Table 5.4 Comparison of Model 1, Model 2, and Model 3 for Example 2

	Model 1		Model 2		Model 3	
	two-step GALNS	two-step LNSLNS	two-step GALNS	two-step LNSLNS	two-step GALNS	two-step LNSLNS
N	28	40	36	32	30	36
Total system cost (without cost of CO_2)	391.83	394.96	393.06	391.30	396.93	396.68
Buyers' cost	235.95	229.27	225.95	228.48	224.28	223.62
Vendor's cost	128.25	137.50	140.45	136.47	141.47	140.72
Routing cost	27.63	28.19	26.66	26.35	31.17	32.34
CO_2 emission (gram per unit time)	37962.17	35855.64	28747.74	28191.07	8552.87	8011.25
Average CPU time (seconds)	112.74	198.39	138.78	183.80	147.96	406.22

From Table 5.4, the total system costs of the three models are quite similar in Example 2. However, it is found that the CO_2 emissions in Model 2 is significantly smaller than that of Model 1. It is also observed that the routing cost in Model 2 is about 6% smaller than that of Model 1. For Model 3, the CO_2 emissions is significantly smaller than those of

Model 1 and Model 2. However, the routing cost in Model 3 is about 20% greater than that of Model 2 and 15% greater than that of Model 1.

Table 5.5 Comparison of Model 1, Model 2, and Model 3 for Example 3

	Model 1		Model 2		Model 3	
	two-step GALNS	two-step LNSLNS	two-step GALNS	two-step LNSLNS	two-step GALNS	two-step LNSLNS
N	36	45	40	42	42	45
Total system cost (without cost of CO_2)	1080.20	1084.16	1081.12	1085.05	1101.22	1102.08
Buyers' cost	580.93	597.22	604.97	593.87	619.37	598.78
Vendor's cost	467.42	454.50	443.11	458.42	436.73	453.09
Routing cost	31.85	32.44	33.04	32.76	45.12	50.21
CO_2 emission (gram per unit time)	41685.32	35921.54	35139.12	44076.87	16953.48	16724.07
Average CPU time (seconds)	681.42	1186.25	826.27	1400.69323	972.37	1479.22

From Table 5.5, it is found that the total system costs in Example 3 are all similar for Models 1, 2 and 3. However, it is observed that the CO_2 emission in Model 3 is significantly smaller than that of Model 1 and Model 2. The large amount of decrease in CO_2 emission is again due to the change of the objective function in the step 2 of the two-step methods. Another observation is that the routing cost in Model 3 is greater than those of Model 1 and Model 2 by about 30-50%. The significant increase in the routing cost of Model 3 in Examples 2 and 3 suggests that changing the objective function to minimizing CO_2 emission, which depends on the load of trucks and distance travelled, the routing cost which depends on the distance travelled and the number of trucks dispatched is no longer optimized. When minimizing CO_2 emission, the routing schedule yields a solution that is lower in the load of trucks and higher in the routing cost.

5.6 Sensitivity Analysis

In this section, sensitivity analysis is performed to investigate the effect of the variations of the transportation cost per unit distance c_d and CO_2 emission unit cost ε. The two-step GALNS method is used to solve Model 2 for Example 2 with 30 buyers and the effect of c_d and ε are examined.

For each parameter, percentage changes of -25%, -50%, -75%, +25%, +50%, +75%, +100%, +125%, +150%, +175%, and +200% are applied to the original value. The total system cost, routing cost, CO_2 emission, and the cost of CO_2 emission are then evaluated and compared in each scenario. The results of changing the parameter ε are shown in Table 5.6 below:

Table 5.6 Change in different costs when changing CO_2 unit cost (ε)

Percentage change in CO_2 unit cost(ε)	total cost	transportation cost	CO_2 emission	CO_2 cost
-75	394.12	26.81	33974.46	0.79
-50	398.54	27.81	27315.74	1.27
-25	395.83	28.60	29548.80	2.06
0	395.73	29.34	28747.74	2.67
25	395.73	30.98	22704.04	2.64
50	398.13	28.76	19500.96	2.72
75	399.66	33.04	29974.23	4.88
100	397.04	32.52	24686.32	4.59
125	399.23	33.36	26652.50	5.58
150	398.80	30.84	16552.56	3.85
175	400.84	32.23	19326.86	4.94
200	400.85	31.48	19500.96	5.44

The plots of the total cost, the transportation cost, the CO_2 emission, and the cost of CO_2 emission vs. the percentage change in the CO_2 emission unit cost ε are shown in Figures 5.1-5.4. From Figure 5.1, it is found that there is no significant change in the total cost when the CO_2 emission unit cost varies. From Figure 5.2, it is found that in general the transportation cost increases as the CO_2 emission unit cost increases. From Figure 5.3, there is a slight decreasing trend for the CO_2 emission when CO_2 emission unit cost increases. The cost of CO_2 emission increases as the CO_2 emission unit cost increases as shown in Figure 5.4, as expected.

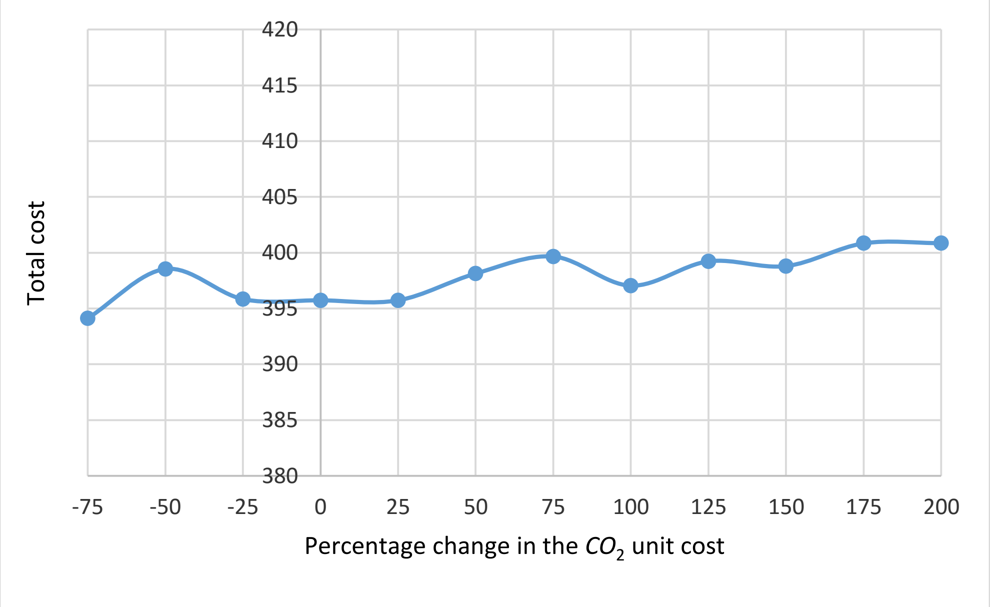

Fig. 5.1. Change in total cost when changing CO_2 unit cost

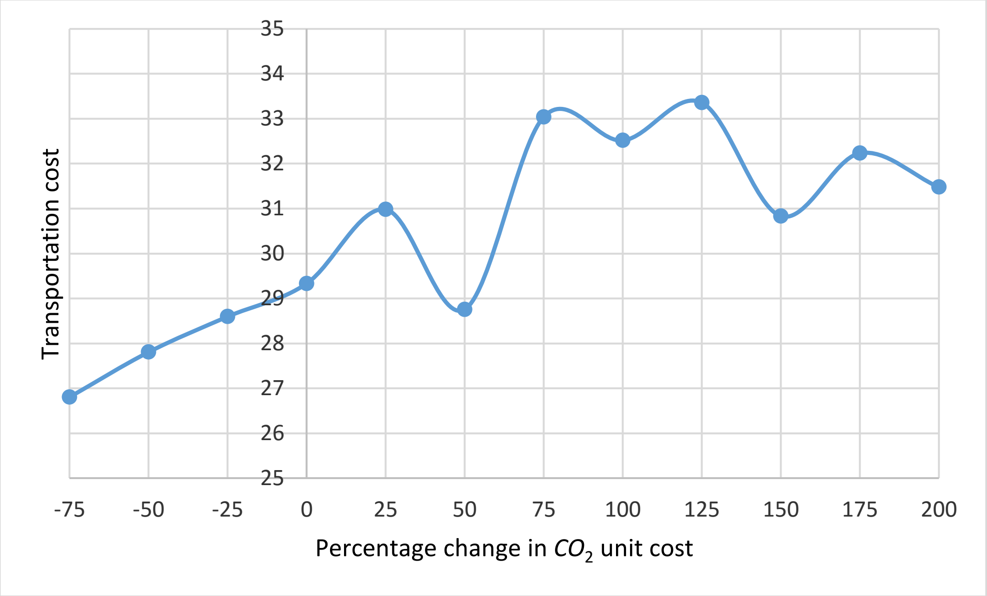

Fig. 5.2. Change in transportation cost when changing CO_2 unit cost

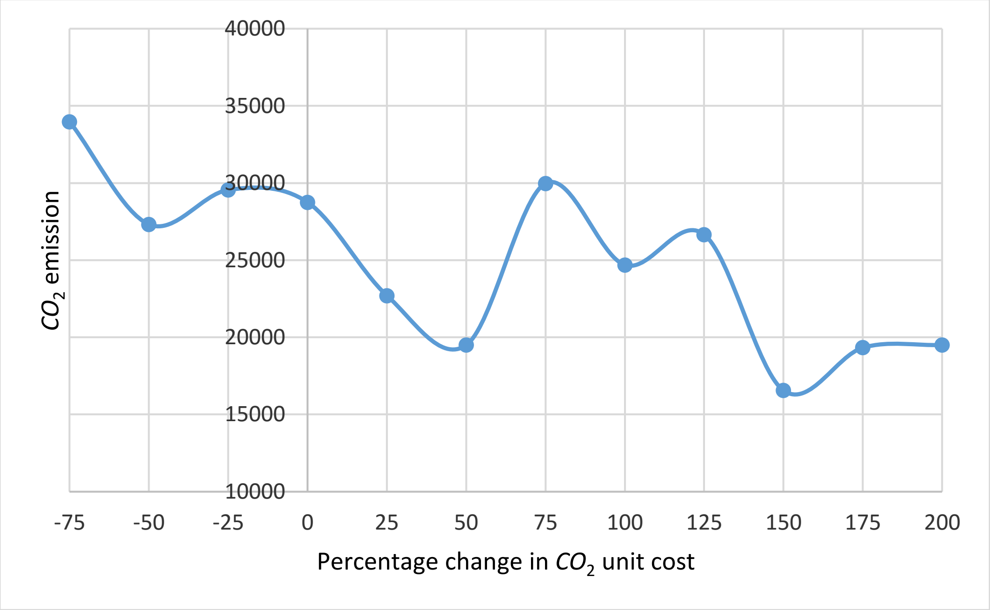

Fig. 5.3. Change in CO_2 emission when changing CO_2 unit cost

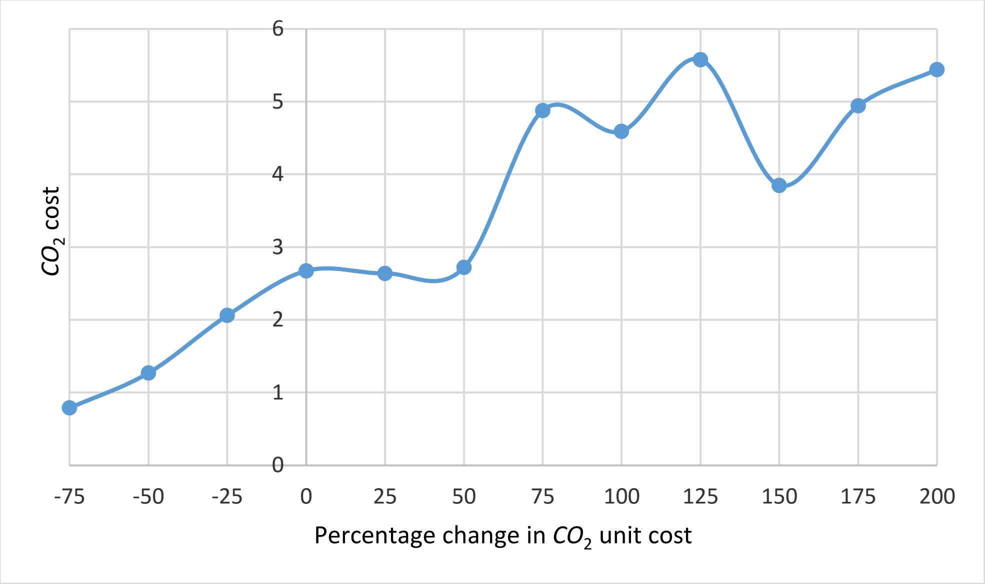

Fig. 5.4. Change in cost of CO_2 emission when changing CO_2 unit cost

The results of changing the parameter c_d are shown in Table 5.7 below:

Table 5.7 Change in different costs when changing c_d

Percentage change in c_d	total cost	transportation cost	CO_2 emission	CO_2 cost
-75	380.09	9.57	34984.27	3.25
-50	379.79	16.92	30621.08	2.85
-25	390.93	23.55	26893.90	2.50
0	395.73	29.34	28747.74	2.67
25	406.76	34.07	24351.68	2.26
50	411.21	42.72	21809.01	2.03
75	417.87	48.96	22027.52	2.05
100	428.66	51.78	24372.87	2.27
125	436.97	63.22	35176.68	3.27
150	438.38	72.89	31834.21	2.96
175	443.75	77.47	42446.59	3.95
200	456.09	85.36	35058.43	3.26

The plots of the total cost, the transportation cost, the CO_2 emission, and the cost of CO_2 emission vs. the percentage change in the transportation cost per unit distance c_d are shown in Figures 5.5-5.8. From Figures 5.5 and 5.6, it is observed that the total cost and also the transportation cost of the system increase as the transportation cost per unit distance increases. From Figures 5.7 and 5.8, it is observed that the CO_2 emission and the cost of CO_2 emission are lowest when c_d has been increased from 25 to 100% of the original value. However, when there is a decrease in c_d or when there is an increase in c_d for more than 100%, it is noted that there are positive increase in the CO_2 emission and the cost of CO_2 emission.

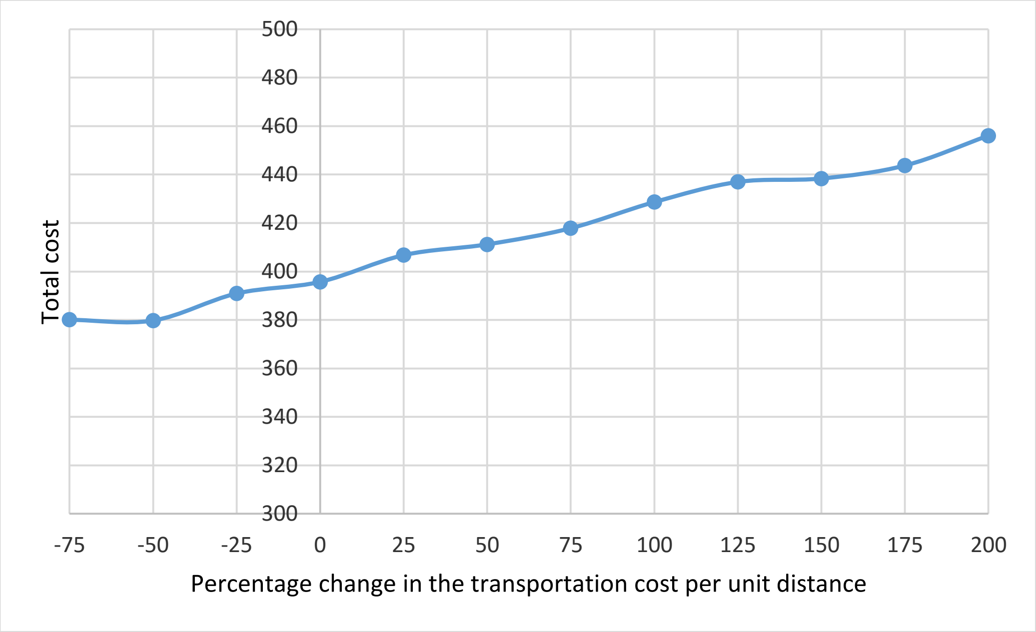

Fig. 5.5. Change in total cost when changing c_d

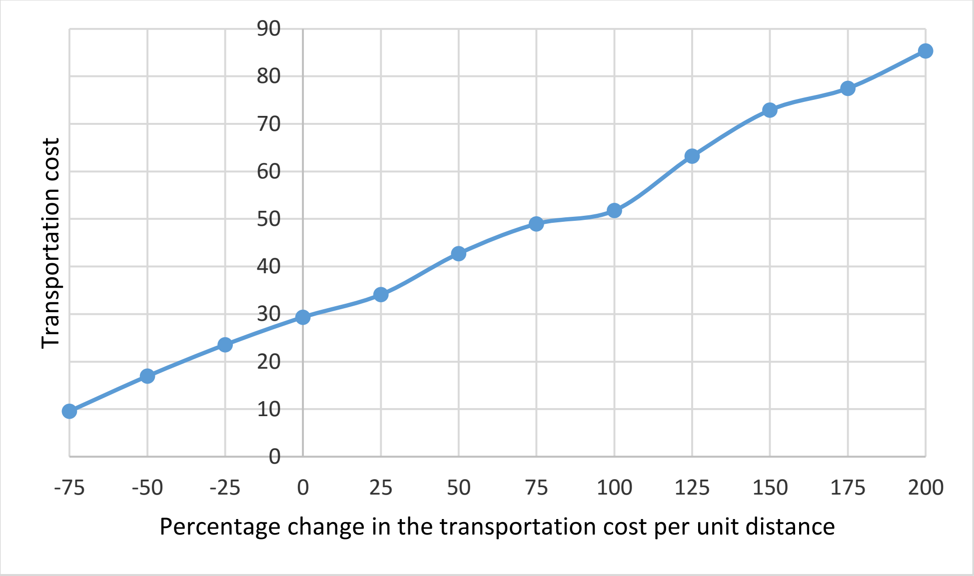

Fig. 5.6. Change in transportation cost when changing c_d

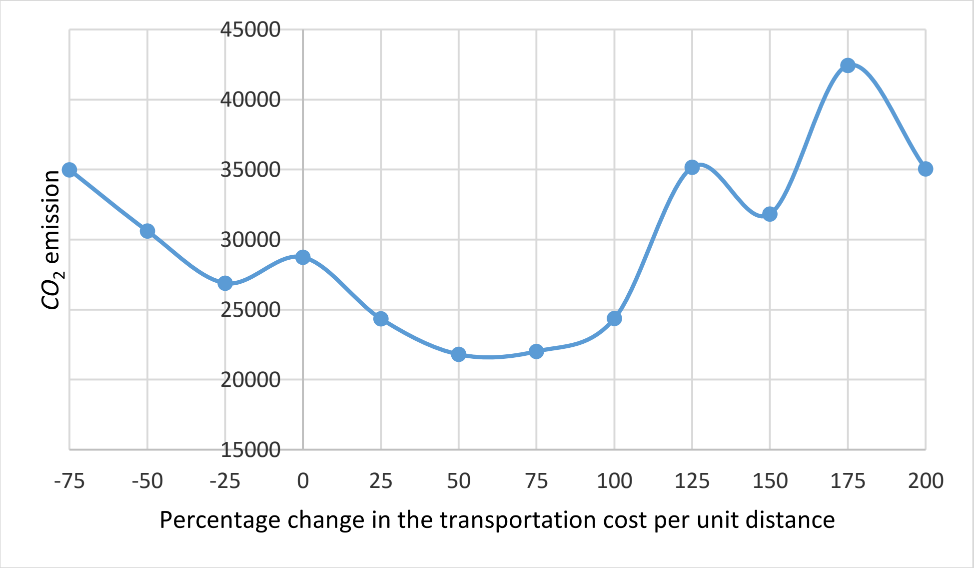

Fig. 5.7. Change in CO_2 emission when changing c_d

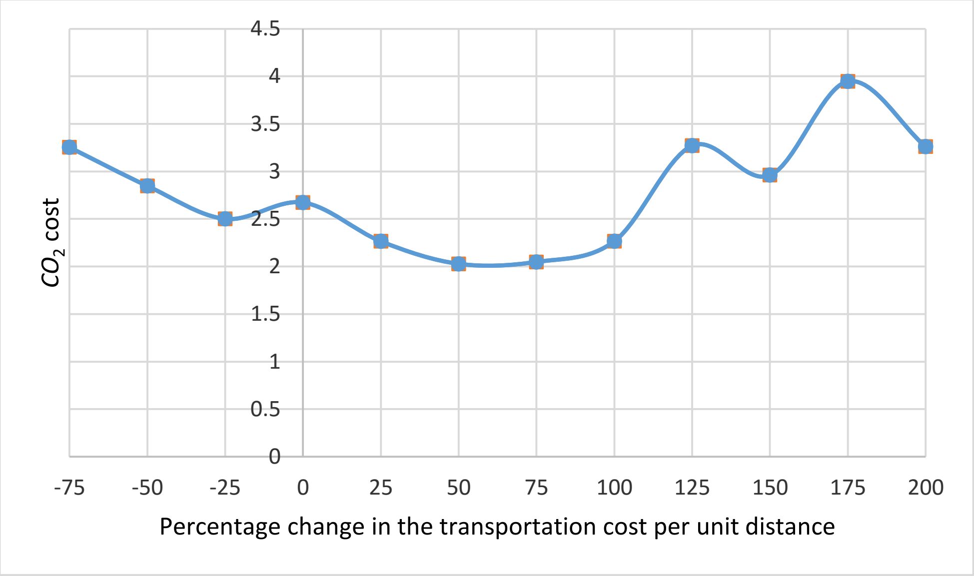

Fig. 5.8. Change in cost of CO_2 emission when changing c_d

5.7 Conclusion

In this chapter, CO_2 emission is incorporated in the model proposed in Chapter 4. The CO_2 emission for the model in Chapter 4 is first calculated. Then the cost of CO_2 emission is added to the total system cost and the two-step GALNS and LNSLNS methods are used to obtain the "near optimal" solution. It is found that the total system cost for the two methods are very similar. However, when the objective is changed to minimizing the CO_2 emission instead of minimizing the total system cost, it is noted that there is a significant decrease in the CO_2 emission when the total system cost excluding the cost of CO_2 emission is still similar to the total system cost in the model in Chapter 4. Also, the routing cost is observed to have a significant increase in larger examples. It might be due to the fact that the calculation of CO_2 emission is based on the load of trucks and the distance travelled while the calculation of routing cost is based on the number of trucks dispatched and the distance travelled. While changing the objective to minimizing the CO_2 emission instead of the routing cost of step 2 of the two-step methods, the routing schedule tries to find a route that minimizes the load of trucks and the cost of routing has become higher as a consequence. Sensitivity Analysis is conducted to determine the effect of varying the CO_2 emission unit cost ε and the transportation cost per unit distance c_d. It is observed that the transportation cost and the cost of CO_2 emission increase and the CO_2 emission decreases when the CO_2 emission unit cost increases. The total cost and the transportation cost also increase when the transportation cost per unit distance increases, as expected.

Chapter 6

Conclusion and Future Research Directions

6.1 Conclusion

In a supply chain model, coordination between vendor and buyers is essential for the optimization of the total inventory cost. Effective coordination can significantly reduce the total system cost. Many integrated models have been established in the past few decades. However, reverse logistics is not considered in many coordinated systems. As reverse logistics has been receiving considerable attention due to the increase in the environmental awareness, much research has been done to incorporate reserve logistics which includes product remanufacturing, waste disposal and parts recovery in a supply chain. In the first part of this research, the synchronized cycles model by Chan and Kingsman (2007) is extended to incorporate reverse logistics, which includes used product pick-up and recycling production. The single-vendor multi-buyer coordination model in Chapter 3 is synchronized in such a way that buyers can choose their own order delivery cycles and used product pick-up cycles but these cycles must be integer factors of the vendor's production cycle. The objective of the problem is to determine the delivery and pick-up cycles of buyers and the production cycle of vendor for minimizing the total system cost of the whole supply chain. The overall demand is satisfied by new production and recycling production of collected used products in the coordinated system. The performance of this model is compared to that of the independent policy model which all buyers and vendor optimize their own cost independently. In all the three numerical examples, it is found that the synchronized cycles model outperforms the independent policy model. Sensitivity analysis is also performed to investigate the effect of varying different cost parameters.

In addition to the reverse logistics, the vehicle routing problem is incorporated in the coordinated supply chain in Chapter 4. Assuming the previously defined ordering and processing cost only covers the loading and uploading costs but not reflecting the more realistic cost of transportation, the routing cost which depends of the distance travelled and the number of trucks dispatched is added to the total system cost. The objective is to determine the optimal routing schedule, delivery and pick-up cycles of buyers and the production cycle of the vendor for minimizing the total system cost of the supply chain. To handle the vehicle routing problem in the coordinated supply chain model, one-step and two-step hybrid heuristics are developed. It is found that the one-step methods outperform the two-step methods by a few percent but the CPU time is unreasonably long for the one-step methods even for an example with only five buyers. This is due to the complexity of the problem. Therefore, the two-step methods are used to solve examples with more buyers. While the two-step methods yield similar solutions for all the examples, it is observed that the proportion of the routing cost out of the total system cost and the vendor's production cycle have both become smaller when the number of buyers is increased. This might be due to the fact that when the number of buyers increases, the inventory cost increases significantly in a shorter production cycle but the routing cost per unit time does not increase as much because the routing schedule coordination is more efficient when there are more buyers in the system. Therefore, the increase in the inventory cost contributes most to the increase in the total system cost. Sensitivity analysis is also conducted to investigate the effect of varying the two transportation parameters.

Furthermore, to simultaneously achieve economic and environmental goals, the coordinated inventory-transportation system with reverse logistics is further extended to incorporate CO_2 emissions in Chapter 5. First, CO_2 emission is evaluated for the model proposed in Chapter 4. Then the cost of CO_2 emissions is added to the total system cost and a near optimal solution is obtained by the two-step methods. The objective is to minimize the updated total system cost of the coordinated supply chain model. To put more emphasis on the environmental performance, the objective function has become minimizing CO_2 emissions instead of minimizing the total system cost in the last model of this thesis. Performance of the modified model is compared with that of the previous models using the three numerical examples. It is found that, as expected, there is a significant drop in CO_2 emissions in all the examples when the objective is changed to minimizing CO_2 emissions. It is also observed that there is a large increase in the routing cost for the two larger examples. It shows that while trying to minimize the CO_2 emissions, the heuristic yields a routing solution with a higher transportation cost. This might be explained by the fact that CO_2 emission depends on the loading of trucks and the distance travelled but the routing cost depends on the number of trucks dispatched and the distance travelled. Sensitivity analysis is also conducted to investigate the effect of varying the CO_2 emission unit cost and the transportation cost per unit distance.

6.2 Future Research Directions

In this research, demands and recycling rates of the buyers are deterministic. Future research directions could focus on stochastic demands and recycling rates of the buyers. Other solution procedures or meta-heuristics such as simulated annealing and traditional non-linear optimization are also possible directions of future research. Incentive schemes to attract members of the supply chain to participate in environmentally friendly coordination may also be investigated.

Appendix I: Data and Results

Appendix IA: Data Sets – Parameters for Supply Chains:

Table 1A-1: Parameters for Example 1 in Chapter 3

vendor	S_v	S_v'	h	h'	D			
	250	200	0.005	0.004	58			
Buyer *i*	d_i	r_i	C_i	G_i	A_i	B_i	h_i	h_i'
1	8	0.7	40	30	20	15	0.008	0.007
2	15	0.6	40	30	15	12	0.009	0.008
3	10	0.5	40	30	6	5	0.010	0.009
4	5	0.7	40	30	10	8	0.010	0.008
5	20	0.4	40	30	18	12	0.007	0.006

Table 1A-2: Parameters for Example 2 in Chapter 3

vendor	S_v	S_v'	h	h'	D			
	1000	800	0.03	0.02	419			
Buyer *i*	d_i	r_i	C_i	G_i	A_i	B_i	h_i	h_i'
1	8	0.22	16	2	21	18	0.085	0.061
2	15	0.57	16	12	14	10	0.079	0.074
3	10	0.28	6	1	7	5	0.064	0.043
4	5	0.19	23	3	15	12	0.042	0.035
5	20	0.85	25	9	6	5	0.077	0.060
6	31	0.92	19	4	2	1	0.045	0.036
7	5	0.91	30	27	10	8	0.041	0.029
8	14	0.24	22	7	15	11	0.055	0.038
9	12	0.37	16	8	7	5	0.044	0.037
10	9	0.75	10	12	6	4	0.081	0.056
11	20	0.69	5	27	9	6	0.092	0.085
12	4	0.73	19	5	12	10	0.062	0.049
13	5	0.62	14	29	7	5	0.051	0.039
14	28	0.91	2	11	12	8	0.060	0.041
15	2	0.45	9	13	11	10	0.072	0.067
16	13	0.54	24	3	9	6	0.035	0.025
17	7	0.98	29	6	10	8	0.033	0.028
18	15	0.43	8	19	18	15	0.067	0.055
19	23	0.90	11	1	17	14	0.087	0.064

20	9	0.19	15	15	17	13	0.056	0.035
21	26	0.17	7	14	18	15	0.043	0.025
22	19	0.26	12	17	8	6	0.049	0.040
23	3	0.59	12	12	10	8	0.050	0.035
24	18	0.91	23	17	16	10	0.062	0.054
25	5	0.57	27	28	6	4	0.041	0.032
26	11	0.81	11	5	3	2	0.081	0.055
27	5	0.45	4	14	2	1	0.053	0.044
28	27	0.40	20	27	7	5	0.032	0.025
29	33	0.64	10	7	8	6	0.055	0.042
30	17	0.25	6	19	17	15	0.082	0.069

Table 1A-3: Parameters for Example 3 in Chapter 3

vendor	S_v	S_v'	h	h'	D			
	5000	3000	0.03	0.02	1162			
Buyer i	d_i	r_i	C_i	G_i	A_i	B_i	h_i	h_i'
1	26	0.85	10	9	8	13	0.054	0.045
2	6	0.62	5	7	19	40	0.062	0.055
3	49	0.59	27	6	7	32	0.044	0.034
4	3	0.75	14	26	26	23	0.069	0.056
5	11	0.22	24	14	22	38	0.044	0.034
6	15	0.35	17	10	24	37	0.077	0.047
7	26	0.38	12	7	21	26	0.048	0.034
8	48	0.21	17	6	20	10	0.034	0.033
9	33	0.74	10	23	1	34	0.083	0.058
10	24	0.89	16	14	4	37	0.088	0.06
11	18	0.82	21	16	11	24	0.09	0.078
12	20	0.46	24	26	27	20	0.038	0.023
13	16	0.51	15	9	22	24	0.073	0.057
14	30	0.47	8	27	17	21	0.088	0.058
15	32	0.56	12	15	2	30	0.08	0.055
16	1	0.39	9	24	10	35	0.085	0.061
17	7	0.27	11	28	5	35	0.079	0.044
18	2	0.64	11	2	1	14	0.064	0.043
19	20	0.17	13	5	5	39	0.042	0.035
20	31	0.85	17	10	18	15	0.077	0.06
21	29	0.15	26	20	11	13	0.045	0.036
22	24	0.52	24	27	19	15	0.041	0.029
23	7	0.21	7	28	12	35	0.055	0.038

24	21	0.78	14	10	22	34	0.044	0.037
25	22	0.86	22	6	15	21	0.081	0.056
26	21	0.76	18	22	17	4	0.092	0.045
27	1	0.87	13	4	26	16	0.062	0.049
28	31	0.97	22	22	14	36	0.051	0.039
29	48	0.16	6	13	5	18	0.06	0.041
30	48	0.67	4	14	22	18	0.072	0.037
31	4	0.46	26	14	28	37	0.035	0.025
32	13	0.94	11	25	8	17	0.033	0.028
33	7	0.91	9	25	11	2	0.067	0.055
34	42	0.39	11	4	6	27	0.087	0.044
35	14	0.81	4	30	10	15	0.056	0.035
36	20	0.85	16	20	39	11	0.043	0.025
37	16	0.49	20	29	22	3	0.049	0.04
38	24	0.16	10	11	14	10	0.05	0.035
39	37	0.78	17	27	26	29	0.062	0.054
40	45	0.9	29	20	20	8	0.041	0.032
41	2	0.18	16	16	4	24	0.081	0.055
42	37	0.46	7	15	16	24	0.053	0.044
43	16	0.97	2	5	29	24	0.032	0.025
44	34	0.5	26	17	23	35	0.055	0.042
45	47	0.1	25	15	20	11	0.082	0.059
46	15	0.85	14	2	17	4	0.046	0.035
47	33	0.69	15	15	10	35	0.052	0.046
48	31	0.7	1	9	18	1	0.039	0.025
49	35	0.2	20	16	27	5	0.064	0.045
50	20	0.69	2	1	5	9	0.085	0.028

Table 1A-4: Parameters for Example 1 in Chapter 4

vendor	S_v	S_v'	h	h'	D			
	250	200	0.005	0.004	58			
Buyer *i*	d_i	r_i	C_i	G_i	A_i	B_i	h_i	h_i'
1	8	0.22	16	2	21	18	0.085	0.061
2	15	0.57	16	12	14	10	0.079	0.074
3	10	0.28	6	1	7	5	0.064	0.043
4	5	0.19	23	3	15	12	0.042	0.035
5	20	0.85	25	9	6	5	0.077	0.060

Table 1A-5: Coordinates of vendor and buyers in Example 1

	x-coordinate	y-coordinate
Vendor	0	0
Buyer 1	7.2	0.08
Buyer 2	8.42	6.29
Buyer 3	3.62	8.52
Buyer 4	8.12	6.49
Buyer 5	6.72	4.17

Table 1A-6: Coordinates of vendor and buyers in Example 2

	x-coordinate	y-coordinate
Vendor	0	0
Buyer 1	2.26	8.24
Buyer 2	9.15	2.83
Buyer 3	3.21	5.68
Buyer 4	9.12	7.64
Buyer 5	7.25	7.68
Buyer 6	8.9	2.17
Buyer 7	2.51	8.05
Buyer 8	9.44	4.9
Buyer 9	1.31	9.59
Buyer 10	3.69	8.11
Buyer 11	7.34	1.53
Buyer 12	9.14	4.54
Buyer 13	5.7	1.89
Buyer 14	6.01	4.96
Buyer 15	9.96	0.13
Buyer 16	9.52	2.13
Buyer 17	6.18	1.47
Buyer 18	7.5	3.7
Buyer 19	0.18	7.24
Buyer 20	7.78	4.58
Buyer 21	0.89	3.26
Buyer 22	9.28	6.03
Buyer 23	9.71	4.84
Buyer 24	9.5	3.18
Buyer 25	2.98	1.37
Buyer 26	2.48	1.16
Buyer 27	8.29	2.58
Buyer 28	6.1	5.64
Buyer 29	4.9	9.62
Buyer 30	6.06	2.99

Table 1-7: Coordinates of vendor and buyers in Example 3

	x-coordinate	y-coordinate
Vendor	0	0
Buyer 1	4.19	7.4
Buyer 2	7.23	4.15
Buyer 3	5.64	3.5
Buyer 4	0.01	8.37
Buyer 5	9.71	8.39
Buyer 6	0.65	7.26
Buyer 7	8.55	7.97
Buyer 8	2.13	9.92
Buyer 9	1.16	9.14
Buyer 10	6.82	2.82
Buyer 11	4.19	7.95
Buyer 12	4.3	0.361
Buyer 13	0.26	8.61
Buyer 14	4.31	4.32
Buyer 15	3.49	8.01
Buyer 16	4.83	3.92
Buyer 17	1.03	3.63
Buyer 18	6.61	3.06
Buyer 19	0.94	1.46
Buyer 20	0	7.3
Buyer 21	9.9	3.5
Buyer 22	5.62	8.84
Buyer 23	8.13	1.96
Buyer 24	7.71	3.5
Buyer 25	2.01	8.29
Buyer 26	8.2	8.13
Buyer 27	6.77	5.41
Buyer 28	8.35	7.58
Buyer 29	0.14	2.02
Buyer 30	6.4	3.74
Buyer 31	3.17	7.29
Buyer 32	0.71	0.64
Buyer 33	0.09	8.1
Buyer 34	2.57	6.22
Buyer 35	2.51	3.05
Buyer 36	1.56	1.08
Buyer 37	2.39	2.96
Buyer 38	4.47	6.19
Buyer 39	3.05	1.32
Buyer 40	5.2	8.61

Buyer 41	2.01	7.69
Buyer 42	9	8.12
Buyer 43	2.44	2.69
Buyer 44	1.29	2.32
Buyer 45	0.13	6.39
Buyer 46	2.59	5.15
Buyer 47	6.57	0.07
Buyer 48	8.59	8.9
Buyer 49	5.35	3.03
Buyer 50	6.15	8.51

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