The Hong Kong Polytechnic University

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Coordinated Inventory-Transportation Supply Chain Models

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A thesis submitted in partial fulfillment

of the requirements of the

Degree of Master of Philosophy

Dec 2011

CERTIFICATE OF ORIGINALITY

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Abstract

Supply chain, which is a flow of materials, information and funds between different parties, is one of the important issues in today's business and industrial sectors. In a supply chain, a vendor is required to produce items to satisfy the needs of buyers. If vendor and buyers operate independently to minimize their own costs, it may not be optimal to the system as a whole. Most of the literature has found that a supply chain can achieve better system cost performance through coordination of vendor and buyers, hence effective coordination plays an important role in the successful operation of supply chains. Chan and Kingsman (2005, 2007) proposed a synchronized cycles model for the coordination of a single-vendor multi-buyer supply chain in which vendor and buyers synchronize the production and ordering cycles so as to minimize the total system cost. The synchronized cycles model performs better than independent optimization as well as common order cycle model developed by Banerjee and Burton (1994) in terms of total system cost. Furthermore, the synchronized cycles model addresses some of the shortcomings of previous coordination models. For example, the model considers vendor as a manufacturer producing an item to supply multiple heterogeneous buyers and tackles the discrete vendor inventory depletion into the model. This issue was rarely addressed in the literature (see Sarmah et. al.(2006)).

In the synchronized cycles model, the process of finding the optimal solution involves the determination of production cycle NT of vendor, ordering cycle k_iT

and ordering time t_i of buyers where k_i are integer factors of N. Due to the complexity of the model, it is very difficult to find the optimal solution analytically. Chan and Kingsman (2007) proposed a heuristic algorithm to find a "near-optimal" solution. The algorithm has been found to be competitive when compared with genetic algorithm. However, it is believed that there are still rooms for improvement in the algorithm in terms of the "optimal" solution and computational time.

Transportation is also a key component in a supply chain. Most of the literature of single-vendor multi-buyer coordination usually assumed that transportation cost is a constant (i.e $/order) for simplicity. Truck capacity and truck transportation cost were not considered. Different transportation modes such as less-than-truckload (LTL) and full-truckload (FTL) have been studied, but are limited to single-vendor single-buyer supply chain. It is rarely mentioned that transportation mode with truck capacity and truck cost are applied to a coordinated single-vendor multi-buyer supply chain.

Finally, environmental problem is a key issue nowadays as people become more concerned about environmental performance. However, existing supply chain models which put stress on financial performance did not pay much attention to the environment. For instance, more frequent deliveries can reduce average inventory level in a supply chain but cause more air pollution during transportation. Also, holding too many stocks consume more materials and resources. Hence, raw materials wastage and energy wastage should be taken into consideration in supply chain models. It is worth addressing and incorporating these environmental measures into a coordinated supply chain system.

Publications Arising From the Thesis

1. YEUNG, H.K., CHAN, C.K. and LEE Y.C.E., Synchronized cycles model with less-than-truckload and full-truckload transportation, Conference Proceedings in Second International Workshop on Successful Strategies in Supply Chain Management (IWSSSCM), 8-9th January 2009, 391-400.

2. YEUNG, H.K., CHAN, C.K. and LEE Y.C.E., Hybrid transportation in a coordinated single-vendor multi-buyers supply chain, Conference Proceedings of the 8th International Conference on Supply Chain Management and Systems (SCMIS), 6-8th October 2010, 387-392.

Acknowledgements

I would like to thank my chief supervisor Dr. Chi Kin Chan and co-supervisor Dr. Joseph Heung Wing Lee. Thanks for their continuous support (both academically and personally) and mentorship in these five years of study. Dr. Chan and Dr. Lee provide me valuable and brilliant ideas on my research and they also give me many opportunities to explore various field of applied mathematics which I have never encountered before in my undergraduate studies. They are always willing to discuss with me by giving valuable insight of my research. Thanks Dr. Eugene Lee for his dedication in sharing his wealth of knowledge and advice with me. Thanks to Prof. André Langevin with his knowledge in transportation (Chapter 4).

Many thanks to the Board of Examiners, Prof. Xiaojun Chen as the chairman, Prof. Sui Hoi Hou and Dr. Wai Ki Ching as the external examiners, for their constructive comments and suggestions which definitely lead to a significant improvement in this thesis.

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Basic parameters

d_i:	Demand rate of buyer i.
A_i:	Ordering cost per order of buyer i.
h_i:	Inventory holding cost per unit per time unit of buyer i.
Q_i:	Order size of buyer i in independent optimization.
T_i:	Ordering cycle of buyer i.
D:	Total demand rate of all buyers.
P:	Production rate of vendor.
C_i:	Transportation cost to deliver items to buyer i.
S_v:	Setup cost of vendor.
h:	Inventory holding cost per unit per time unit of vendor.
T_v:	Production cycle of vendor in independent optimization.

Independent optimization

B_i^{IND}:	Total cost of buyer i of independent optimization.
VC^{IND}:	Total cost of vendor of independent optimization.
TC^{IND}:	Total system cost of independent optimization.

Synchronized cycles model

T:	Basic cycle time.
NT:	Production cycle of vendor, where N is an integer.
$k_i T$:	Ordering cycle of buyer i, where k_i is an integer..
$\delta_{i,j}$:	0-1 variable that represents that buyer i places order at time jT.

ψ_j: Surplus stock at time jT.

ψ: Surplus stock over the planning horizon.

FT: Production period of vendor, where F is an integer. .

D_j: Total demand of all buyers at time jT.

B_i^{SYN}: Buyer i's cost of synchronized cycles model.

VC^{SYN}: Vendor's cost of synchronized cycles model.

TC^{SYN}: Total system cost of synchronized cycles model.

Inventory approach

$D_{1,j}$: Accumulated demand of all buyers from time T to time jT.

$D_j^{'}$: Assigned demand at time jT,

S_j: Inventory available at time jT.

t_i: The first ordering time of buyer i.

D^a: A set of assigned demand over the planning horizon.

P_j: Production level at time jT.

Genetic algorithm

f_i: The fitness value of string i.

$\widehat{f}_i$: The transformed fitness value of string i.

p_c: Crossover rate.

p_m: Mutation rate.

$r / r' / r''$: Random generated number.

Transportation

s: The freight cost per item.

Q^T : Truck size.

C^T : Truck cost.

j_i : Number of full truck employed for buyer i.

$C_i\left(Q_i\right)$: Transportation cost which is a function of order size.

$F(Q_i)$: Freight cost which is a function of order size.

$C_{\min}^0$: Minimum freight charge in diminishing freight rate transportation.

s_i : Freight rate of the tier i in two-tier-freight-rate transportation.

C_b : Base cost in LTL/Hybrid transportation.

$C_{\min}$: Minimum freight charge in LTL/Hybrid/two-tier-freight-rate transportation.

Environmental performance

T : Basic cycle time.

x_{ij} : The real measured value on costs and environmental measurement of buyer i (of vendor, $i = 0$) on the j^{th} measure.

$U_{ij}\left(.\right)$: The utility function of the i^{th} party on the j^{th} measure.

Δ_{ij} : The maximum value (worst situation) of the j^{th} measure of party i.

$N^{\max}T$: The maximum planning horizon under synchronized cycles model.

$N'T$: Production cycle of vendor in green utility optimization, where N' is an integer.

$k_i^{'}T$: Ordering cycle of buyer i in green utility optimization, where $k_i^{'}$ is an integer.

c_{ij} : The coefficient of utility function of the i^{th} party on the j^{th} measure.

I^{SYN} : The average inventory level of the vendor in the synchronized cycles model.

I^{IND} : The average inventory level of the vendor in independent optimization.

α_j : The weight of the j^{th} measure.

U_j : The utility value of sum of all party on the j^{th} measure.

Chapter 1

Introduction and Outline

1.1Introduction

Supply chain, which is a flow of materials, information and funds between different parties, is one of the important issues in today's business and industrial sectors. In a supply chain, a vendor is required to produce items to satisfy the needs of buyers. If the vendor and buyers operate independently to minimize their own costs (e.g. according to the classical EBQ and EOQ models), i.e. independent optimization, it may not be optimal to the system as a whole. Most of the literature has found that a supply chain can achieve better system cost performance through coordination of the vendor and buyers, hence effective coordination plays an important role in the successful operation of supply chain. Chan and Kingsman (2005, 2007) proposed a synchronized cycles model for the coordination of a single-vendor multi-buyer supply chain in which vendor and buyers synchronize the production and ordering cycles so as to minimize the total system cost. The synchronized cycles model performs better than independent optimization as well as common order cycle model in terms of total system cost. Furthermore, the synchronized cycles model addresses some of the shortcomings of previous coordination models. For example, the model considers the vendor as a manufacturer producing an item to supply multiple heterogeneous buyers and tackles the discrete vendor inventory depletion into the model. This issue was rarely addressed in the literature (see Samah et. al.(2006)).

In the synchronized cycles model, the process of finding the optimal solution involves the determination of production cycle NT of vendor, ordering cycle k_iT and ordering time t_i of buyers. Note that k_i are integer factors of N. Due to the complexity of the model, it is very difficult, if not impossible, to find the optimal solution analytically. Chan and Kingsman (2007) proposed a heuristic algorithm to find a "near-optimal" solution. The algorithm has been found to be competitive when compared with genetic algorithm. However, it is believed that there are still rooms for improvement in the algorithm in terms of the "optimal" solution and computation time.

Transportation is also a key component in a supply chain. Most of the literature of single-vendor multi-buyer coordination usually assumed that transportation cost is a constant (i.e. $/order) for simplicity. Truck capacity and truck transportation cost were not considered. Different transportation modes such as less-than-truckload (LTL) and full-truckload (FTL) have been studied, but are limited to single-vendor single-buyer supply chain. It is rarely mentioned that transportation mode with truck capacity and truck cost are applied to a coordinated single-vendor multi-buyer supply chain.

Finally, environmental problem is a key issue nowadays as people become more concerned about environmental performance. However, existing supply chain models which put stress on financial performance did not pay much attention to the environment. For instance, more frequent deliveries can reduce average inventory level in a supply chain but cause more air pollution during transportation. Also, holding too many stocks consume more materials and resources such as electricity, coal and water, etc. Hence, raw materials wastage and energy wastage should be taken into consideration in supply chain models. It is worth addressing and incorporating these environmental measures into a coordinated supply chain system.

1.2 Objectives of the Thesis

Chan and Kingsman (2005, 2007) developed a synchronized cycles model and showed that the coordination between vendor and buyers works well in a single-vendor multi-buyers supply chain, when compared to independent optimization and common cycles model such as that developed by Banerjee and Burton (1994). The authors also developed a heuristic algorithm to minimize the total system cost of the model and the heuristic was compared with genetic algorithm. The first objective of this research is to explore further improvement of the heuristic. A modified approach will be introduced which can further improve the performance. Total cost and computation time by different approaches will also be compared.

There are increasing concerns about transportation in supply chain coordination. Previous researchers usually assumed the transportation cost to be constant in a single-vendor multi-buyers supply chain system, regardless of the order size of the buyers. This assumption obviously simplifies the impact of transportation on the total cost of the system. Furthermore, the cost of trucks and capacity of trucks are also important to devising optimal strategies for the supply chain system. Some existing models assumed that the transportation cost follows freight charge schedule which includes truck size and truck cost, but these models only consider a single-vendor single-buyer supply chain. Hence, the second objective of this research is to incorporate different transportation modes into a single-vendor multi-buyer supply chain by relaxing the assumption of constant transportation costs. In considering different modes of transportation, the truck size and truck cost will be taken into account. In this research, coordinated single-vendor multi-buyer supply chain models with hybrid transportation modes are proposed and compared with independent optimization in terms of cost performance.

Green supply chain has become a hot topic recently since the awareness of environment is raised. Most of the research on coordination between vendor and buyers only put stress on minimizing the total system cost. There is little work addressing environmental issues as an objective of vendor-buyer coordination. This research is concerned with developing a sustainable supply chain on both economic and environmental sustainability. As costs and the environmental performance measures have different units of measurements, it is necessary to transform the different measurements to a common one so that all measures can be integrated into the objective function. In economics, utility is a measure of relative satisfaction of different choices. This satisfaction is quantified by means of utility functions. In this research, the utility measures are adopted in evaluating both costs and environmental performance.

1.3 Outline of the Thesis

Chapter 1 introduces the background of a single-vendor multi-buyer coordinated supply chain in which various components such as environment awareness and transportation are worth addressing. Objectives of the thesis and outline of the thesis are also presented. Chapter 2 presents the literature review on coordination models, transportation problems including less-than truckload (LTL) and full-truckload (FTL) transportation modes and also environmental issues of supply chains. Chapter 3 discusses the performance of different improvement sub-algorithms in solving the synchronized cycles coordination model. Chapter 4 introduces five different transportation modes, namely, diminishing rate, less-than truckload, full-truckload, hybrid mode and two-tier mode for the synchronized cycles model and independent optimization. The performances of the five transportation modes are discussed. Chapter 5 incorporates green measures into the synchronized cycles model in which cost and environmental performance are represented by utility functions. The objective is to maximize the utility of the supply chain. Chapter 6 summarizes and concludes the whole thesis and suggests further possible research directions arising from the results of this thesis.

Chapter 2

Literature Review

2.1 Coordination in Supply Chain Models

2.1.1 Coordinated Single-vendor Single-buyer Supply Chain Models

Since 1970s, many researchers including Goyal (1976), Monahan (1984), Banerjee (1986), Rosenblatt and Lee (1985), Joglekar (1988) have had the views that coordination between vendor and buyer is more efficient than independent optimization. Goyal (1976) suggested a joint economic lot size (JELS) model which allows coordination between buyer and vendor in order to minimize the total cost of both parties. Monahan (1984) suggested a quantity discount offered by vendor to encourage the buyer to increase their order size. This discount is financed by the cost saved due to reduced delivery cost. Banerjee (1986) extended the work of Monahan (1984) by incorporating vendor's inventory holding cost in the model. The author also formulated a joint economic lot size (JELS) model by considering buyer and vendor system with finite production rate for vendor and developed upper and lower bounds for the quantity discount offered to the buyers. Rosenblatt and Lee (1985) determined the optimal order quantity of the vendor as an integer multiple K of the buyer's order quantity in quantity discount model. The authors relaxed the assumption on lot-for-lot policy. Joglekar (1988) further extended Monahan's (1984) model to determine an optimal production lot-size policy which is superior to the policy of optimal price discounts when the setup cost of vendor is significantly larger than that in buyer. The author also suggested that vendor could use both optimal price discount and production lot strategy at the same time. Also, Dolan (1987) provided a survey on quantity discount literature. Goyal (1987) proposed a simpler method to determine the value of ordering cycle k of buyer and production cycle K of vendor by maximizing supplier's yearly profit. The author also suggested another model by considering the compensating offered by vendor to the buyers. Joglekar and Tharthare (1990) refined the joint economic lot size model by relaxing the lot-for-lot assumption, and separating the traditional setup cost into two independent costs such as manufacturing setup cost per production run and order processing cost. Weng and Wong (1993) formulated an all unit quantity discount model which allows vendor to decide a series of optimal quantity policies based on the incentive to buyer. Sarmah et.al. (2007) proposed coordination between a manufacturer and a buyer through credit option such that the parties can divides the surplus equitably after satisfying their own profit targets.

2.1.2 Coordinated Single-vendor Multi-buyer Supply Chain Model

Maxwell (1964) combined the production cycle of vendor with ordering cycles of buyers by common production cycle approach. Chakrabarty and Martin (1988, 1989) considered that the buyers and vendor have a common order cycle such that the finished goods are directly delivered to buyers. They assumed infinite replenishment rate of production and a decreasing demand function in their model. Drezner and Wesolowsky (1989) also extended Monahan's (1984) model and discussed the optimal price break quantities for a given discount scheme to all buyers. Banerjee and Burton (1994) suggested a common replenishment cycle model for a single-vendor multi-buyer supply chain and showed this approach is superior to independent optimization. In the model, all the buyers in the system have the same ordering cycle and the production cycle is an integer multiple of the ordering cycles of buyers.

Different policies were proposed to optimize the coordinated single-vendor multi-buyers supply chain models. Lu (1995) developed a coordinated model to minimize the vendor's cost subject to the maximum cost of buyers willing to pay, and then further extended this model to multi-buyer case. The author allowed shipments to take place during production. Later, Hill (1997) generalized a policy to find factor for increasing the shipment sizes. This paper illustrated that neither increasing shipment size policy nor equal shipment size policies are always optimal. Viswanathan (1998) compared the identical delivery quantity (IDQ) strategy proposed by Lu (1995) and delivery what it produced (DWP) strategy suggested by Goyal (1995). The author found that neither strategy dominates the other for all problem parameters. Under the condition of high buyer inventory holding cost, the author illustrated that IDQ strategy is better than DWP strategy. Viswanathan and Piplani (2001) proposed common replenishment epoch (CRE) with price discount in single-vendor multi-buyer model. Wang (2004) showed that power-of-two time coordination may not be able to provide a stable equilibrium coordination strategy when the buyers act independently and opportunistically. The author further stated that the improvement by integer-ratio over power-of-two time coordination is limited to 2% of optimality.

Lai and Staelin (1984) started with a single-vendor multi-homogenous buyer model. The authors then extended the model to heterogeneous groups of buyers.

Goyal and Nebebe (2000) proposed that the production lot size of the vendor to be an integer multiple of buyer's order size. The authors further proposed a policy that the size of successive shipments from manufacturer to customer within a production cycle increases by a factor equals to the ratio of production rate to demand rate. Goyal (1988) extend Bannerjee' (1986) model by removing the assumption of lot-for-lot production and suggested the economic production quantity could be an integer multiple of buyer's purchasing quantity so as to reduce the cost. However, a safety lot should be produced before the first delivery of goods. Joglekar and Tharthare (1990) refined the joint economic lot size model by relaxing the lot-for-lot assumption, and separating the traditional setup cost into two independent costs-manufacturing setup cost per production run and order processing cost per cost. Banerjee and Burton (1994) suggested a common cycle coordination system for a single-vendor multi-buyer supply chain system facing constant deterministic demands. Under the common cycle policy, buyers replenish with the same pre-determined ordering cycle. Mishra (2004) modified the common replenishment epochs strategy of selective discount offered by vendor. Selective discount is the maximum of the minimum discount required by a subset of all the buyers. The buyer with a new ordering interval near to the original ordering interval will receive fewer discounts. Chan and Kingsman (2007) improved the shortcoming of the model proposed by Banerjee and Burton (1994) and formulated a synchronized cycles model that allows each buyer to choose its ordering cycle. This cycle should be a factor of vendor's production cycle. The lengths of the ordering cycles are integer factors of the length of vendor's production cycle. The authors showed that the synchronized cycles model outperforms both the common cycle policy and independent optimization. Recently, Jaber and Goyal (2008) considered the coordination of players in supply chain to generate savings in a multiple-supplier single-vendor and multiple-buyer supply chain system. When buyers and suppliers are compensated offered by vendor after joining coordination, the total cost of buyers and supplier will remain the same as before coordination. The total cost saved is larger than the compensation offered to buyers and supplier. Chan et.al. (2010) proposed a co-ordination mechanism that incorporates a delayed payment method which can guarantee that a buyer's total relevant cost of coordination will not be increased when compared with independent optimization.

2.2 Transportation in Supply Chains

Baumol and Vinod (1970) are the pioneers of introducing the integration of transportation and inventory cost into inventory-theoretical models. The optimal choice of transportation modes depends on freight rates, speed, and variance in speed. Lippman (1971) explored full-truckload (FTL) transportation in inventory model. In full-truckload (FTL) transportation, there is a fixed cost per load up to a given truck capacity. Whybark (1971) proposed to change freight cost using all-unit quantity discount schedule. Langley (1980) was one of the first researchers to include the freight rate into lot sizing decision using actual freight rate or function to estimate freight rates. Aucamp (1982) gave a solution to a standard economic order quantity (EOQ) problem in which freight costs are at least partially determined by the integer number of full-truckload. Some researchers such as Carter and Ferrin (1996), Gaither (1982), Wehrman (1984) and Tyworth (1991) developed lot sizing model by incorporating actual freight schedules in the determination of the optimal purchase order. Sethi (1984) was the first researcher to consider disposals in all-unit quantity discount structure and hinted at an allowance for the unutilized transport capacity. Lee (1986) considered an EOQ model offering quantity discount to freight cost. Tersine et al. (1989) formulated an economic inventory-transportation model with freight rate discounts. Hwang et al. (1990) included all unit quantity discounts on EOQ model for both purchase price and freight cost. Benjamin (1990) considered choice of transportation mode in a production-distribution network with multiple supply and demand points and a single product class in which both linear and concave transportation costs were considered. Swenseth and Buffa (1990, 1991) used freight rate function to estimate freight rate as part of ordering size decision. Tersine and Barman (1991, 1994) proposed inventory models combining freight rate discount and all-unit/incremental discount. Ballou (1991) approximated the transportation costs as linear function of distance and studied the error. Russell and Karjewski (1991) solved the less-than-truckload (LTL) transportation with several indifference points by analytical procedure. Less-than-truckload (LTL) transportation do not need to pay for the whole truck, but based on "rate per unit weight/mile" such that only a portion of the own freight is charged. Usually, LTL transportation is represented by a freight cost which is defined as a function of the actual shipment weight. It was discovered that over-declared shipments are economical when the shipment volume is less than the rate breakpoint, but larger than a cost indifference point between two adjacent marginal rates. Adelwahab and Sargious (1992) studied the LTL and FTL transportations with freight rate structure to determine optimal shipment size in freight transportation. Van Eijs et al. (1994) presented a heuristic procedure for linear transportation costs with multiple indifference points for a buyer of multiple items with a coordinated period review system. Carter et al. (1995) considered the effect of different less-than-truckload cost functions such that the overall logistics costs can be lowered by minimal increases in order or shipment size. Carter and Ferrin (1996) developed lot sizing model to explicitly consider actual freight schedules in the determination of the optimal purchase order quantity. Swenseth et al. (1996) determined that a simple linear freight rate function as a proportional function which outperformed other complex functions in terms of its ability to emulate actual freight rate. Burwell et al. (1997) developed a model to determine the lot size and price of reseller, and assumed there were freight and all-unit quantity discount breakpoints in the pricing schedule offered by the supplier. Hoque and Goyal (2000) assumed capacitated transport equipment. They developed an optimal solution procedure for the single-vendor single-buyer production-inventory system with unequal and equal-sized shipments from the vendor to the buyer with under the capacity constraint of transport equipment. Swenseth and Godfrey (2002) incorporated different freight rate functions by parametric adjusted inverse function to approximate the actual transportation cost into inventory replenishment decisions to minimize the total annual logistics cost. Existing models for the problem have treated freight breakpoints in the same way as price breakpoint in a quantity discount schedule. Abad and Aggarwal (2005) formulated a single stage model for determining the optimal lot size and the selling price for the reseller. They considered a reselling situation where the final demand is sensitive to the selling price and the reseller is responsible for paying the freight charge. They chose the policy between less-than-truckload and full-truckload by setting the size of order/shipment. Chu (2005) developed a heuristic algorithm in the selection of LTL and FTL by minimizing the total cost for vehicle routing problem. Hoque (2008) developed the integrated inventory model with equal batch or unequal batch full-truckload transportation. Rieksts and Ventura (2008) considered truckload with fixed costs, a package delivery carrier with a constant cost per unit or using a combination of both modes simultaneously for single stage model over both finite and infinite planning horizon. They proposed the combination of LTL and FTL transportation modes. Also, Özkaya et al. (2010) combined the quantitative methods with qualitative knowledge to produce a better LTL market rate estimates which can be used in benchmarking studies allowing carriers and shippers to identify cost saving opportunities.

2.3 Supply Chain and Environmental Problems

Starting in the mid-90s, the general public began to be aware of environmental health issue, many of the environmental organization had been formed and new environmental legislations were adopted in some countries. The International Organization for Standardization (ISO) has also adopted the ISO14000 series for environmental management. Beamon (1999) carried out an intensive (qualitative) study on green supply chain management (GSCM). The author investigated and identified essential environment factors for a green supply chain system. In addition, the author also specified some performance measures to evaluate the effectiveness of the green components. Dias et al. (2004) used the Life Cycle Assessment (LCA) technique to evaluate the printing and writing paper industry in Portugal. Hervani and Helms (2005) also carried out similar, but more updated and intensive, research on identifying performance metrics and measures for GSCM. Recently, there had been numerous researches carried out, with various techniques and different industries, in identifying and evaluating green performances measures. Yung et al. (2009) applied the LCA technique for eco-redesign of an electronic product. A life cycle assessment LCA , also called life cycle analysis, is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling). H'Mida and Lakhal (2007) applied gap analysis to evaluate the green effort of a supply chain and illustrated a case study of a refrigerator manufacturing company. Vachon and Klassen (2006) and Vachon (2007) examined the impact of environmental related interactions in a supply chain in the Canadian and United States packing printing industries. Ford and Scanlon (2007) adopted the supply chain network to the United States health care systems. Chien and Shih (2007) performed an empirical study on the green supply chain network in the electronic industry in Taiwan. They studied the impacts of environmental regulations on carried out the GSCM practices and in turn, the effects on environmental and financial performances. Zhu and Sarkis (2004) and Zhu et al. (2008) used factor analysis to identify and evaluation the green measures in the Chinese manufacturing industry. Marsillac (2008) explored the relationship between green supply chain and reverse logistics and suggested the possible integration of the two components. The author also listed out some real-life applications of such integration.

Srivastava (2007) provided an intensive literature reviews summarizing various mathematical models and techniques used in modeling GSCM. From the literature cited in the paper, most of the papers are empirical studies which include surveys, case studies, and scenario simulations. For the papers that include mathematical models, the objective is mainly minimizing the total cost function. Most of the models only optimize the operational strategies by adding some green components (i.e. recycle policy, remanufacturing policy, etc) to the “standard” supply chain models. As mentioned in the paper, more studies should be focused on “intra- and inter-firm diffusion of best practices, green technology transfer and environmental performance measurement”. There is little work on building GSCM models that directly measure environmental performance. The most relevant one is the paper by Kainuma and Tawara (2006). The authors adopted multiple attribute utility theory to the lean and green supply chain. However, the authors mainly focused on information sharing among echelons of the supply chain and the model did not directly involved green components.

2.4 Conclusions

Most of the literature discovered that the system cost of a supply chain can be reduced, when compared with independent optimization, through coordination. Chan and Kingsman (2005, 2007) proposed a synchronized cycle model, which is one of the most comprehensive coordinated supply chain model, includes major characteristics of coordination models in the literature. Also, the model has further considered the manufacturing of vendor and buyer’s ordering time given ordering cycles. The process of finding an optimal solution in synchronized cycles model involved some heuristics. The authors proposed heuristics namely incremental approach and genetic algorithm, to further reduce the total system cost. Incremental approach is a search procedure to find a better solution by alternating the ordering time of each buyer each time, until the solution is not better off. These may take many iterations or stop searching before the true optimal solution is obtained. Genetic algorithm is commonly used in many researches, but it takes a lot of time to find the near optimal solution. In views of these shortcomings, this research will focus on the study of improvement algorithm of synchronized cycles model in Chapter 3 to develop algorithmic improvements that can improve the results in terms of both cost and computational time.

Moreover, in single-vendor multi-buyer supply chain model, a lot of literature (Monahan's (1984), Lai and Staelin (1984), Drezner and Wesolowsky (1989) Banerjee and Burton (1994), Chan and Kingsman (2007), Jaber and Goyal (2008)) simplifies the assumption of transportation cost by a constant cost. Most of the research in coordinated supply chain models did not consider truck capacity and truck cost. A few researchers (Abad and Aggarwal (2005), Swenseth and Godfrey (2002) and Rieksts and Ventura (2008)) did consider truck sizes and truck costs but they limited their models to consider a single-vendor single-buyer supply chain. Transportation modes involving truck cost and capacity is worth to address. This thesis will focus on effect on total cost and transportation by employing different transportation modes in a single-vendor multi-buyer coordinated supply chain. By incorporating different transportation mode in a coordinated single-vendor multi-buyer supply chain model, total cost and transportation cost of synchronized cycles model are then compared with independent optimization in Chapter 4.

Most of the literature in coordinated supply chain model put stress on financial performance. They did not consider environmental performance, namely energy wastage, raw material wastage and air pollution. Also, their objectives are usually on cost minimization. In order to incorporate environmental performance into the objectives, it is necessary to transform the different measurements (cost and environmental measures) into a common measurement. The mechanism of optimizing different measurements will be addressed in Chapter 5.

Chapter 3

Algorithmic Improvement of Synchronized Cycles Model

3.1 Introduction

3.1.1 Independent Optimization

In a single-vendor multi-buyer supply chain, it is assumed that each of the n buyers faces a deterministic demand rate d_i per unit time with an ordering cost A_i each time of order and an inventory holding cost h_i per unit per time. The ordering cost is the cost of order processing and inventory holding cost is the cost of carrying a unit of product per unit time. The total cost of a buyer is composed of holding cost and ordering cost. If independent optimization (independent policy model) is used, buyers and vendor work independently such that buyer i orders quantity Q_i with an ordering cycle of T_i which is based on the cost and demands of buyer i.

The total cost per unit time for i^{th} buyer is expressed as

$$B_i^{IND} = \frac{A_i}{T_i} + \frac{1}{2} h_i d_i T_i . \tag{3.1}$$

where the first term is the ordering cost per unit time and the second term is the average inventory holding cost per unit time.

Under the traditional economic order quantity (EOQ) model assumption, the economic order interval T_i for buyer i to place order is given by

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

and the economic order quantity (EOQ) is given by

$$Q_i^* = d_i T_i^* = \sqrt{\frac{2A_i d_i}{h_i}} . \tag{3.3}$$

By equations (3.1) - (3.3), the minimum total cost of buyer i is given by

$$B_i^{IND} = \sqrt{2A_i h_i d_i} . \tag{3.4}$$

Vendor is faced with orders from each of the n buyers based on the deterministic demand rates of $d_1, d_2, \ldots, d_n$ per unit time. Therefore, vendor needs to satisfy a demand of all buyers at an average rate of D per unit time, where

$$D = d_1 + d_2 + ... + d_n . \tag{3.5}$$

Vendor produces items at a rate of P per unit time with the assumption that the production rate is larger than the demand rate of buyers ($P > D$) and there is infinite planning horizon. It is assumed that vendor incurs a setup cost S_v for each production run, incurs an inventory holding cost h per item per unit time and incurs a transportation cost C_i to deliver items to buyer i. The setup cost of vendor S_v is the cost per unit time for billing, order processing, paper works, and machine setup. Inventory holding cost includes the inventory carrying cost, shortage cost, taxes on inventory, and insurance cost. Transportation cost of buyers, usually paid by vendor, represents the cost of delivery per unit time. For simplicity, the transportation cost of buyer i is denoted by a constant C_i. Besides, as vendor needs to carry a sufficient stock of items to satisfy all the demand on time, otherwise, buyers will have to suffer stock outs and /or late deliveries. Let T_v be the production cycle of vendor. Under the assumption that no stock out and no lead time for each delivery occur, the largest possible aggregate ordering size (safety stock) is $\sum_{i=1}^{n} Q_i^* = Q_1^* + Q_2^* + ... + Q_n^*$ unit of stock when all the buyers replenish at the same time.

Then, total cost of the vendor per unit time is given by

$$VC^{IND} = \frac{S_v}{T_v} + \frac{1}{2} hDT_v \left(1 - \frac{D}{P}\right) + \sum_{i=1}^{n} \frac{C_i}{T_i^*} + h\sum_{i=1}^{n} Q_i^* \ . \tag{3.6}$$

where the first term is the average setup cost per unit time; the second term is the average inventory holding cost per unit time; the third term is the average transportation cost per unit time; the last term is the holding cost of safety stock per unit time.

The economic production interval T_v^* of vendor is given by

$$T_v^* = \sqrt{\frac{2S_v}{hD\left(1 - \frac{D}{P}\right)}} \ . \tag{3.7}$$

By equations (3.1) - (3.7), the optimal total system cost is

$$TC^{IND} = \sqrt{2S_v Dh\left(1 - \frac{D}{P}\right)} + h\sum_{i=1}^{n} Q_i^* + \sum_{i=1}^{n} C_i \sqrt{\frac{h_i d_i}{2A_i}} + \sum_{i=1}^{n} \sqrt{2A_i h_i d_i} \ . \tag{3.8}$$

3.1.2 Synchronized Cycles Model (Coordinated Model)

Coordination between vendor and buyer on the timing of delivery can help to avoid stock out. Banerjee and Burton (1994) proposed that buyer should take a common ordering cycle of T periods apart. In order to meet these scheduled demands the vendor will have to adopt a production cycle that is some integer multiple of T, say NT for $N \geq 1$.

However, it is costly to force all buyers to use the same common cycle time of T. It is more economical to have a short ordering cycle for the low-demand buyer and long ordering cycle for the high-demand buyer. The synchronized cycles model developed by Chan and Kingsman (2005, 2007) resolved the shortcoming in the common cycle model. In the synchronized cycles model, given a basic cycle time T, say one day, week, or month etc., vendor will produce goods at a certain production cycle NT. For the buyers, buyer i is allowed to choose its ordering interval, k_i, as an integer factor of the vendor's production cycle time. For simplicity, it is assumed that delivery to the buyers is instantaneous, or more exactly that buyer's orders are received and deducted from the vendor's inventory at regular intervals T apart.

Under synchronized cycles model, which buyer i orders at an interval of k_iT, the total cost B_i^{SYN} of buyer i is given by

$$B_i^{SYN} = \frac{A_i}{k_i T} + \frac{1}{2} h_i d_i k_i T \,. \tag{3.9}$$

Let $\delta_{i,j} = 1$ represents that buyer i places order at time jT.

Chan and Kingsman (2005, 2007) showed that the average stock held by the vendor is

$$T\left\{\frac{1}{N}\sum_{i=1}^{n}k_i d_i \sum_{j=1}^{N}\left(j-1\right)\delta_{i,j}+\frac{\psi D}{PT}-\frac{D}{P}\sum_{i=1}^{n}\delta_{i,1}k_i d_i-\frac{ND^2}{2P}\right\} \tag{3.10}$$

where $\delta_{i,j}=\begin{cases}1 & \text{if buyer } i \text{ places order at time } jT\\ 0 & \text{otherwise}\end{cases}$

It is assumed that buyer i places order every k_i period. Hence,

$$\delta_{i,j}=\delta_{i,j+k_i}\,. \tag{3.11}$$

Also, buyer i places order once every k_i period, therefore

$$\sum_{j=1}^{k_i}\delta_{i,k_i+j}=1\,. \tag{3.12}$$

Define $\psi \geq 0$ as surplus stock above demand D_1 at time T such that

$$(1+S)PT=\psi+D_1 \tag{3.13}$$

and
$$\psi \geq \sum_{i=1}^{n}d_i k_i T\left(\sum_{t=2}^{j}\delta_{i,t}\right)-(j-1)PT \tag{3.14}$$

for $2 \leq j \leq b$ where $b=\lfloor F \rfloor$ and FT is the production period of vendor. The details of the surplus stock $\psi \geq 0$ are shown in Figure 3.1.

Since the demand at period jT is equal to the sum of all buyers demand at time jT, the demand at period jT can be written as

$$D_j=\sum_{i=1}^{n}\delta_{i,j}d_i k_i T\,. \tag{3.15}$$

By (3.10), the vendor‘s holding cost per unit time is

$$hT\left\{\frac{1}{N}\sum_{i=1}^{n}k_i d_i \sum_{j=1}^{N}\left(j-1\right)\delta_{i,j}+\frac{\psi D}{PT}-\frac{D}{P}\sum_{i=1}^{n}\delta_{i,1}k_i d_i-\frac{ND^2}{2P}\right\}. \tag{3.16}$$

The total vendor cost per unit time is given by

$$VC^{SYN} = \frac{S_v}{NT} + hT\left\{\frac{1}{N}\sum_{i=1}^{n} k_i d_i\left(\sum_{j=1}^{N}(j-1)\delta_{i,j}\right) + \frac{\psi D}{PT} + \frac{D}{P}\sum_{i=1}^{n}\delta_{i,1}k_i d_i - \frac{ND^2}{2P}\right\} + \sum_{i=1}^{n}\frac{C_i}{k_i T}. \quad (3.17)$$

Therefore, the total system cost per unit time of synchronized cycles model, can be expressed as:

$$TC^{SYN} = hT\left\{\frac{1}{N}\sum_{i=1}^{n} k_i d_i\left(\sum_{j=1}^{N}(j-1)\delta_{i,j}\right) + \frac{\psi D}{PT} + \frac{D}{P}\sum_{i=1}^{n}\delta_{i,1}k_i d_i - \frac{ND^2}{2P}\right\}$$

$$+\frac{1}{2}\sum_{i=1}^{n} h_i k_i d_i T + \left\{\frac{S_v}{N} + \sum_{i=1}^{n}\frac{C_i + A_i}{k_i}\right\}\frac{1}{T}. \quad (3.18)$$

Subject to the constraints by equation (3.11), (3.13) and (3.14)

and $\quad \psi \geq 0$ (3.19)

and $\quad k_i$ is an integer factor of N for $k_i, N \in \mathbb{N}$. (3.20)

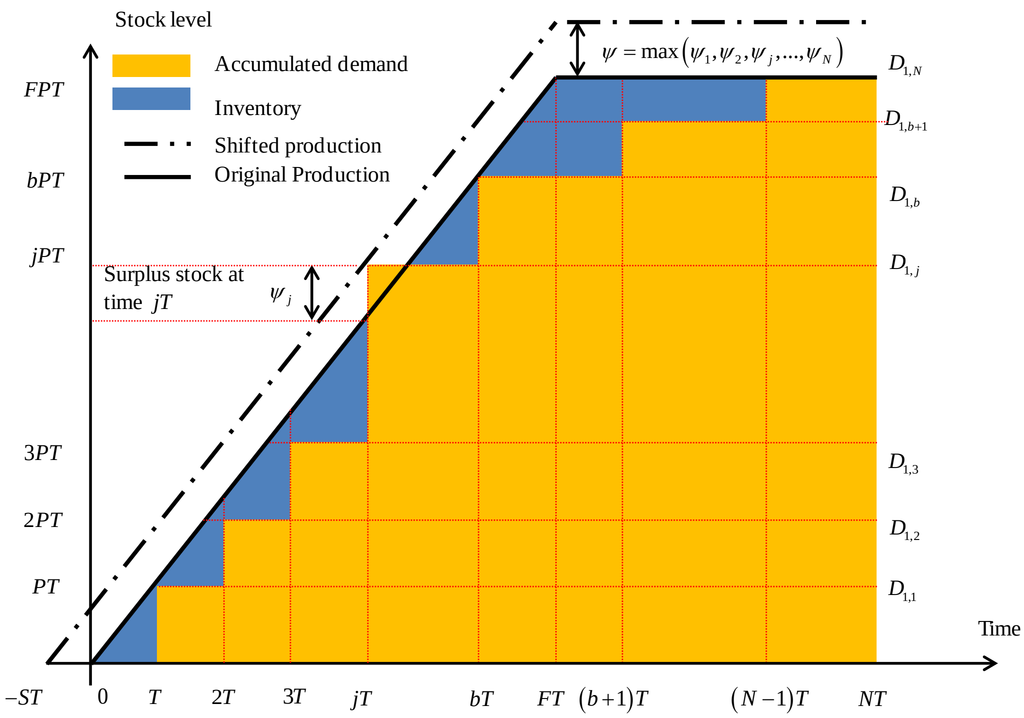


Figure 3.1: Diagram of surplus stock due to the shifted production.

Let $D_{1,j}$ be defined as the accumulated demand $\sum_{i=1}^{j} D_i$ from time T to time jT. Hence, $D_{1,N}$ will be the total demand of all n buyers. Let FT be the production period of vendor and NT be the length of production cycle. When production stops at time FT, the total production FPT is equal to the total demand $D_{1,N} = NDT$ and the production line becomes horizontal after time FT as shown in Figure 3.1.

Let ψ_j be the surplus stock at time jT for $1 \le j \le N$. The production starts at time 0. If the total demand D_1 at time T is less than the production PT at time T, i.e., $PT \ge D_{1,1} = D_1$, the production may start at other time $-ST$ so no surplus stock at time T is required, i.e., $\psi_1 = 0$, and equation (3.13) is satisfied. However, if the production PT at time T is less than the total demand D_1 at time T, i.e. , $PT < D_{1,1} = D_1$, the production may start earlier at time $-ST$ to avoid stock out that equation (3.13) is satisfied and $\psi_1 = 0$. Let S_j be the inventory of vendor at time jT. The inventory of vendor S_j at time jT is calculated by the difference between the accumulated production $(j-1)PT$ and the accumulated demand $D_{2,j}$ from time $2T$ to time jT where $D_{2,j} = D_{1,j} - D_{1,1}$, i.e., $S_j = (j-1)PT - \sum_{i=1}^{n} d_i k_i T \left(\sum_{t=2}^{j} \delta_{i,t} \right)$. If the accumulated demand is larger than the accumulated production from time $2T$ to time jT, stock out occurs at time jT since $S_j < 0$. Then, by producing the items at time $-ST$, a surplus stock ψ_j at time jT is produced and calculated by $\psi_j = \max\left(0, \sum_{i=1}^{n} d_i k_i T\left(\sum_{t=2}^{j} \delta_{i,t}\right) - (j-1)PT\right) = \max(0, -S_j)$ since $\psi_j \geq 0$. Since surplus stock may occur at any time jT over the planning horizon, the surplus stock ψ is calculated by $\psi = \max\left(\psi_1, \psi_2, ..., \psi_N\right)$ so equation (3.14) is satisfied. Also, the change of the starting point of production at time $-ST$ shifts the production line upward by ψ as shown in Figure 3.1.

3.2 Improvement Algorithms

Chan and Kingsman (2005, 2007) proposed the synchronized cycles model in a coordinated single-vendor multi-buyer supply chain. To find the optimal ordering cycles k_i^* of buyers and optimal production cycle N^* of vendor, they first assumed that all buyers place their first orders at time T, i.e. $\delta_{i,1} = 1 \quad \forall i$. By equation (3.18), the total system cost can be written as:

$$TC^{SYN} = \frac{Sv}{NT} + \frac{1}{2}hD\left(1 - \frac{D}{P}\right)NT + \sum_{i=1}^{n}\left[d_i h k_i T\left(\frac{D}{P} - \frac{1}{2}\right) + \frac{1}{2}d_i h_i k_i T\right] + \sum_{i=1}^{n}\frac{A_i + C_i}{k_i T}. \tag{3.21}$$

See Chan and Kingsman (2007) for the detailed derivation of (3.21). However, they also considered that the total system cost can be further reduced when the buyers placed their first orders at some other time $tT, t \in \mathbb{N}$. The algorithm to improve the total cost by considering the first order time is called the improvement algorithm.

Vendor determines the ordering time within the ordering cycle $k_i T$. Since vendor has k_i selections for the first ordering time of buyer i, there are $k_1 k_2 ... k_n$ selections for n buyers. Owing to the huge combinations of first ordering times of all buyers, it is difficult to find the optimal solution analytically. Some heuristics are needed to find the near optimal solution.

In order to further reduce the total system cost, Chan and Kingsman (2005, 2007) proposed an incremental approach to find a near-optimal solution. Also, it is considered that there might still be rooms for further improvement on solution, so this research will focus on developing another improvement algorithm to replace the incremental approach so as to further improve the solution and computational time.

3.3 Incremental Approach

After the ordering cycle k_iT of buyer and production cycle NT of vendor have been determined by equation (3.21) with $\delta_{i,1} = 1$, the solution can be improved by considering the first ordering time of buyers at some other time. The search procedure in Chan and Kingsman (2007) is basically called an incremental approach. The procedure starts by incrementing one buyer at a time, t to $t+1$ in $\delta_{i,t} = 1$ every time, n different increments for n distinct buyers and hence n new solutions are obtained. Then, the best solution is selected from a set of new solutions by comparing it with that before increment. If the new solutions cannot be improved, the process will stop and treat the best solution before the increment as the optimal solution. Otherwise, the incremental procedure is continued until the time t in $\delta_{i,t} = 1$ for all the buyers equals to their k_i's. That is, $\delta_{i,k_i} = 1$ for all i.

For example, let t_i be the first ordering time of buyer i and (t_1,t_2,t_3,t_4,t_5) be a vector that contain the first ordering time of the buyers in a 5-buyer example as shown in Table 3.1. DP ratio is defined as $\frac{D}{P}$. When DP ratio is 0.1 of 5-buyer case in Example 1, the procedure starts with step 1 that all five buyers place orders at time T, that is, $(1,1,1,1,1)$ in the 2nd column in Table 3.1. The total cost for $(1,1,1,1,1)$ is 23.188. Then, in step 1.1, only buyer 1 places the first order at time $2T$ but other buyers place orders at time T, that is, $(2,1,1,1,1)$. The total cost for $(2,1,1,1,1)$ is reduced to 23.048. Then, in step 1.2, only buyer 2 places the first order at time $2T$ but other buyers place orders at time T, that is, $(1,2,1,1,1)$. The total cost for $(1,2,1,1,1)$ is 22.973. Similarly, only buyer 3 places an order at time $2T$ but other buyers place orders at time T i.e. $(1,1,2,1,1)$ in step 1.3 with total costs of 23.013. Only buyer 4 places an order at time $2T$ but other buyers place orders at time T i.e. $(1,1,1,2,1)$ in step 1.4 with total costs of 23.101. Only buyer 5 places an order at time $2T$ but other buyers remain unchanged i.e. $(1,1,1,1,2)$ in step 1.5 with total costs of 22.998. Then, from steps 1.1 to 1.5, it is found that first ordering time of $(1,2,1,1,1)$ by step 1.2 gives the best solution which produces the least total cost at this stage and other steps are decided to be rejected.

In step 2, it starts from $(1,2,1,1,1)$ with total cost of 22.973. Then, in step 2.1, both buyers 1 and 2 place their first orders at time $2T$ but other buyers place orders at time T, that is, $(2,2,1,1,1)$. The total cost for $(2,2,1,1,1)$ is 23.013.

Then, in step 2.2, only buyer 2 places the first order at time $3T$ but other buyers place orders at time T, that is, $(1,3,1,1,1)$. The total cost for $(1,3,1,1,1)$ is 23.001. Similarly, both buyers 2 and 3 place orders at time $2T$ but other buyers place orders at time T i.e. $(1,2,2,1,1)$ in step 2.3 with total costs of 23.023. Both buyers 2 and 4 place orders at time $2T$ but other buyers place orders at time T i.e. $(1,2,1,2,1)$ in step 2.4 with total costs of 22.998. Both buyers 2 and 5 place orders at time $2T$ but other buyers place orders at time T i.e. $(1,2,1,1,2)$ in step 2.5 with total cost of 23.073. After steps 2.1 to 2.5, it is found that no improvement can be obtained. Stop iteration. The optimal solution is $(1,2,1,1,1)$ with total cost of 22.973.

Steps	First ordering time	Total cost	Decision
1	(1,1,1,1,1)	23.188	start
1.1	(2,1,1,1,1)	23.048	reject
1.2	(1,2,1,1,1)	22.973	best
1.3	(1,1,2,1,1)	23.013	reject
1.4	(1,1,1,2,1)	23.101	reject
1.5	(1,1,1,1,2)	22.998	reject
2	(1,2,1,1,1)	22.973	start
2.1	(2,2,1,1,1)	23.013	reject
2.2	(1,3,1,1,1)	23.001	reject
2.3	(1,2,2,1,1)	23.023	reject
2.4	(1,2,1,2,1)	22.998	reject
2.5	(1,2,1,1,2)	23.073	reject

Table 3.1:First ordering time by incremental approach in Example 1 when DP ratio is 0.1 in 5-buyer example.

Incremental approach provides a simple improvement method to find the solution for the value of t in $\delta_{i,t} = 1$ given that the value of k_i and N have been determined. However, there are rooms to improve the solution since the iteration may stop at a local optimal solution. Also, it takes a lot of iterations (computational time) to get the near optimal solution when the optimal first ordering time t_i of buyer i is large.

3.4 Inventory Approach

Inventory approach is a heuristic method based on the schedule of first ordering time of all buyers by considering the inventory level of vendor. Let $t_i T$ be the first ordering time of buyer i. The value of t_i is not larger than ordering cycle $k_i T$ of buyer i i.e. $1 \le t_i \le k_i \; \forall \; i$. Also, as mentioned, the value of t_i in $\delta_{i,t_i} = 1$ affects the value of average inventory holding cost of vendor. Hence, total system cost can be reduced by shifting the first ordering time $t_i T$ of buyer i.

3.4.1 Inventory Approach Algorithm

Let $D_j^{'}$ be the assigned demand at time jT, and S_j be the inventory level available at time jT. Let D^a be a set of assigned demand $\left(D_1^{'}, D_2^{'}, ..., D_j^{'}, ..., D_N^{'}\right)$. Let ψ_j be the surplus stock at time jT and t_i be the first ordering time of buyer i.

The algorithm of inventory approach is stated below:

Step A1: Start with time T, $j = 1$.

Step A2: Initialize $D_j^{'} = 0$, $t_i = 0$, and $S_j = P_j = PT$.

Step A3: Consider unassigned buyers with smallest k_i.

Step A4: If $k_i = j$, go to step A5, or else go to Step A7.

Step A5: Assign $\delta_{i,j} = 1$ for buyers with $k_i = j$ and $t_i = j$.

Update D^a and $D_j^{'}$ by $D_{j+lk_i}^{'} = D_{j+lk_i}^{'} + \sum_{i=1}^{n} \delta_{i,j} d_i k_i T$ for

$l = 0,1,2,..., \frac{N}{k_i} - 1$.

Update $S_j = S_j - \sum_{i=1}^{n} \delta_{i,j} d_i k_i T$.

If buyers are assigned completely, exit.

Step A6: If $S_j \geq 0$, go to step A7 , or else go to Step A9.

Step A7: If $S_j \geq \min\{d_i k_i T\}$ for unassigned buyers, go to Step A8.

Else $j = j+1$, $S_j = S_{j-1} + P_j - D_j^{'}$. Go to Step A3.

Step A8: Select buyer i such that $S_j = S_j - d_i k_i T$ is the least.

Assign $\delta_{i,j} = 1$ for the selected buyer i and $t_i = j$.

Update D^a and $D_j^{'}$ by $D_{j+lk_i}^{'} = D_{j+lk_i}^{'} + \sum_{i=1}^{n} \delta_{i,j} d_i k_i T$ for

$l = 0,1,2,..., \frac{N}{k_i} - 1$.

Update $S_j = S_j - \sum_{i=1}^{n} \delta_{i,j} d_i k_i T$.

If buyers are assigned completely, exit, or else go to Step A6.

Step A9: Update surplus stock $\psi_j = -S_j$.

$j = j+1$, $S_j = S_{j-1} + P_j - D_j$.

If $S_j \geq 0$, go to Step A3, or else repeat Step A9.

Remarks:

By equation (3.14), the surplus stock at time jT is given by

$$\psi_j = \max\left\{ \sum_{i=1}^{n} d_i k_i T \left(\sum_{t=2}^{j} \delta_{i,t} \right) - (j-1)PT, 0 \right\} \tag{3.22}$$

for $2 \le j \le b$ where $b = \lfloor F \rfloor$ and FT is the production period of vendor.

After considering the overall planning horizon NT, the surplus stock can be written as $\psi = \max(\psi_1, \psi_2, ..., \psi_N)$. At time T ($j=1$), the surplus stock is zero since $S_1 = PT - \sum_{k_i=1} d_i T \ge 0$ for $\frac{D}{P} \le 1$. Besides, the production at time jT is denoted by $P_j = \max\{0, \min(P, (F-(j-1))P)\}$. The inventory approach algorithm are also shown in Figure 3.2

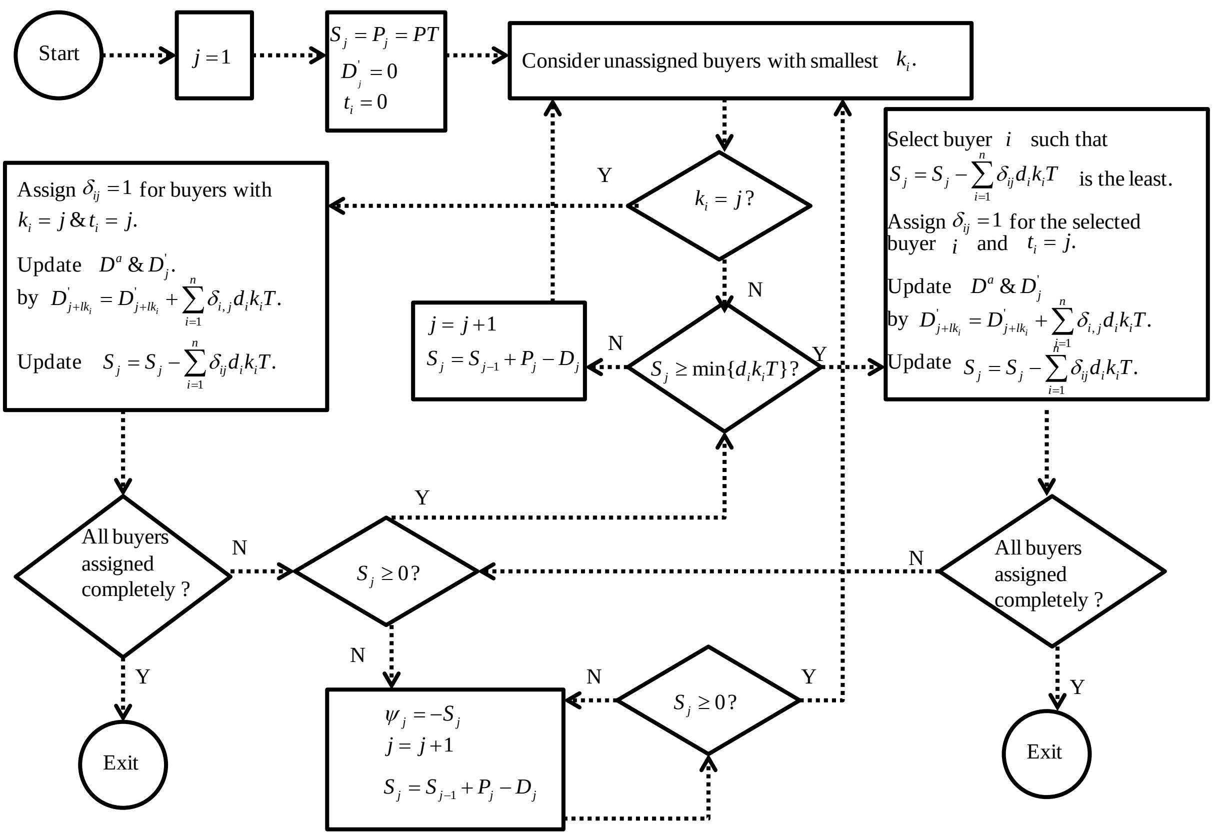


Figure 3.2: Flowchart of inventory approach algorithm.

3.4.2 Illustrative Examples

3.4.2.1 Example 1

The demand rate, ordering sizes, and ordering cycles in a 5-buyer example when DP ratio is 0.1 are shown in Table 3.2. The production cycle of vendor NT is 45 and the ordering cycles k_i of buyers are 45 by equation (3.21), with basic cycle time $T = 1$. Since $\sum_{i=1}^{n} d_i$ =58, the production rate of the vendor P is 580. Since total demand is equal to the total production, $NDT = PFT$, the production period of vendor $F = 4.5$.

Buyer i	Demand rate d_i	Ordering cycle k_i	Ordering size $d_i k_i T$	First ordering time t_i
1	8	45	360	3
2	15	45	675	2
3	10	45	450	1
4	5	45	225	3
5	20	45	900	5

Table 3.2:Demand rate, ordering size, ordering cycle and first ordering time of buyers in a 5-buyer example when DP ratio is 0.1.

The first ordering time of buyers by inventory approach are shown in Table 3.2. The procedures of inventory approach in Example 1 when DP ratio is 0.1 are shown below:

Step 1: Start with time T, $j = 1$. [Step A1]

Step 2: Initialize $D_1^{'} = D_2^{'} = D_3^{'} = ... = D_{45}^{'} = 0$, $t_1 = t_2 = t_3 = t_4 = t_5 = 0$,

Initialize $S_1 = 580$. [Step A2]

Step 3: Consider unassigned buyers with smallest $k_i = 45$. [Step A3]

Since $k_i = 45 \neq j$. [Step A4]

Step 4: Since $S_1 \geq \min\{360, 675, 450, 225, 900\}$. [Step A7]

Select buyer 3 as $S_1 = 580 - 450 = 130$ is the least. [Step A8]

Assign $\delta_{3,1} = 1$ and $t_3 = 1$.

Update $D_1^{'} = 0 + 450 = 450$.

Update $S_1 = 580 - 450 = 130$.

Step 5: Since $S_1 = 130 \geq 0$ [Step A6]

and $S_1 = 130 \leq \min\{360, 675, 225, 900\}$. [Step A7]

$j = 1 + 1 = 2$, $S_2 = 130 + 580 - 0 = 710$.

Step 6: Consider buyers 1, 2, 4, and 5 with smallest $k_i = 45$. [Step A3]

Since $k_i = 45 \neq j$. [Step A4]

Since $S_2 = 710 \geq \min\{360, 675, 225, 900\}$. [Step A7]

Select buyer 2 as $S_2 = 710 - 675 = 35$ is the least. [Step A8]

Assign $\delta_{2,2} = 1$ and $t_2 = 1$.

Update $D_2^{'} = 0 + 450 = 450$.

Update $S_1 = 710 - 675 = 35$.

Step 7: Since $S_2 = 35 \geq 0$. [Step A6]

$S_2 = 35 < \min\{360, 225, 900\}$. [Step A7]

$j = 2 + 1 = 3$, $S_2 = 35 + 580 - 0 = 615$.

Step 8: Consider buyers 1, 4, and 5 with smallest $k_i = 45$. [Step A3]

Since $k_i = 45 \neq j$. [Step A4]

Since $S_2 = 615 \geq \min\{360, 225, 900\}$. [Step A7]

Select buyer 1 with the least $S_3 = 615 - 360 = 255$. [Step A8]

Assign $\delta_{1,3} = 1$ and $t_1 = 1$.

Update $D_3^{'} = 0 + 360 = 360$.

Update $S_3 = 615 - 360 = 255$.

Step 9: Since $S_3 = 255 \geq 0$. [Step A6]

Since $S_3 = 255 \geq \min\{225, 900\}$. [Step A7]

Select buyer 4 as $S_3 = 255 - 225 = 30$ is the least. [Step A8]

Assign $\delta_{4,3} = 1$ and $t_4 = 1$.

Update $D_3^{'} = 360 + 225 = 585$.

Update $S_3 = 255 - 225 = 30$.

Step 10: Since $S_3 = 30 \geq 0$. [Step A6]

$S_3 = 30 < \min\{900\}$. [Step A7]

$j = 3 + 1 = 4$, $S_4 = 30 + 580 - 0 = 610$.

Step 11: Consider buyer 5 with smallest $k_i = 45$. [Step A3]

Since $k_i = 45 \neq j$. [Step A4]

Since $S_4 = 610 < \min\{900\}$. [Step A7]

$j = 4 + 1 = 5$,

Since $P_5 = \max\{0, \min(P, (4.5 - (5-1)P))\} = 0.5P$,

$S_5 = 610 + 580 \times 0.5 - 0 = 900$

Step 12: Consider buyer 5 with smallest $k_i = 45$. [Step A3]

Since $k_i = 45 \neq j$. [Step A4]

Since $S_5 = 900 \geq \min\{900\}$. [Step A7]

Select buyer 5 as $S_5 = 900 - 900 = 0$ is the least. [Step A8]

Assign $\delta_{5,5} = 1$ and $t_5 = 1$.

Update $D_5^{'} = 0 + 900 = 900$.

Update $S_5 = 900 - 900 = 0$.

All buyers are assigned completely, exit.

Since the inventory S_j at time jT is non-negative, no surplus stock ψ_j at time jT is required when $j \leq 5$. Besides, as the ordering cycles of buyers are equal and no surplus stock is required in the above example, a more complicated example is considered that buyers have different ordering cycles and surplus stock exists.

3.4.2.2 Example 2

Suppose the production cycle of vendor NT is 6, DP ratio is 0.9 and the basic cycle time T is 1. Suppose also the demand rate d_i and ordering cycle k_i of buyer i are given, the ordering size $d_i k_i T$ can be determined as shown in Table 3.3. The first ordering time t_i of buyer i, which is the result of inventory approach, is also shown in the last column in Table 3.3.

Since total demand rate per unit time, $D = \sum_{i=1}^{8} d_i = 36$, the production rate per unit time P is equal to $\frac{D}{0.9} = 40$. Since the total demand is equal to the total production in a planning horizon, $NDT = PFT$, the production period of vendor, F is equal to $\frac{NDT}{PT} = 5.4$.

Buyer i	Demand rate d_i	Ordering cycle k_i	Ordering size $d_i k_i T$	First ordering time t_i
1	2	1	2	1
2	3	1	3	1
3	8	3	24	2
4	4	2	8	1
5	5	2	10	1
6	3	3	9	1
7	7	6	42	4
8	4	2	8	1

Table 3.3:Demand rate, ordering size, ordering cycle and first ordering time of buyers in Example 2 when DP ratio is 0.9.

The procedures of inventory approach in Example 2 are shown below:

Step 1: Start with time T, $j = 1$. [Step A1]

Step 2: Initialize $S_1 = 40$, $D_1^{'} = D_2^{'} = D_3^{'} = D_4^{'} = D_5^{'} = D_6^{'} = 0$,

$t_1 = t_2 = t_3 = t_4 = t_5 = t_6 = t_7 = t_8 = 0$. [Step A2]

Step 3: Consider buyers 1 and 2 with smallest $k_i = 1$. [Step A3]

Since $k_i = j$ [Step A4]

Step 4: Select buyers 1 and 2 with $d_1 k_1 T = 2$ and $d_2 k_2 T = 3$, respectively. [Step A5]

Assign $\delta_{1,1} = \delta_{2,1} = 1$ and $t_1 = t_2 = 1$.

Update $D_1^{'} = D_2^{'} = D_3^{'} = D_4^{'} = D_5^{'} = D_6^{'} = 0+5=5$ and

$D^a = (5,5,5,5,5,5)$

Update $S_1 = 40-5=35$.

Step 5: Since $S_1 \geq 0$. [Step A6]

Since $S_1 = 35 \geq \min\{24,8,10,9,42,8\}$. [Step A7]

Step 6: Consider buyer 4, 5, and 8 with smallest $k_i = 2$. [Step A3]

Since $k_i = 2 \neq j$ [Step A4]

Since $S_1 = 35 \geq \min\{8,10,8\}$. [Step A7]

Select buyer 5 with $d_5 k_5 T = 10$, [Step A8]

as $S_2 = 35-10 = 25$ is the least.

Assign $\delta_{5,1} = 1$ and $t_5 = 1$.

Update $D_1^{'} = D_3^{'} = D_5^{'} = 5+10=15$ and $D^a = (15,5,15,5,15,5)$.

Update $S_1 = 35-10=25$.

Step 7: Since $S_1 = 25 \geq 0$ [Step A6]

Since $S_1 = 25 \geq \min\{8,8\}$. [Step A7]

Select buyer 4 with $d_4 k_4 T = 8$, [Step A8]

as $S_1 = 25-8=17$ is the least.

Assign $\delta_{4,1} = 1$ and $t_4 = 1$.

Update $D_1^{'} = D_3^{'} = D_5^{'} = 15+8=23$ and $D^a = (23,5,23,5,23,5)$.

Update $S_1 = 25-8=17$.

Step 8: Since $S_1 = 17 \geq 0$. [Step A6]

Since $S_1 = 17 \geq \min\{8\}$. [Step A7]

Select buyer 8 with $d_8 k_8 T = 8$, [Step A8]

as $S_1 = 17 - 8 = 9$ is the least.

Assign $\delta_{8,1} = 1$ and $t_8 = 1$.

Update $D_1^{'} = D_3^{'} = D_5^{'} = 23 + 8 = 31$ and $D^a = (31, 5, 31, 5, 31, 5)$.

Update $S_1 = 17 - 8 = 9$.

Step 9: Since $S_1 = 9 \geq 0$ [Step A6]

Since $S_1 = 9 \geq \min\{24, 9, 42\}$. [Step A7]

Select buyer 6 with $d_6 k_6 T = 9$, [Step A8]

as $S_1 = 9 - 9 = 0$ is the least.

Assign $\delta_{6,1} = 1$ and $t_6 = 1$.

Update $D_1^{'} = D_3^{'} = D_5^{'} = 31 + 9 = 40$ and $D^a = (40, 5, 31, 14, 31, 5)$.

Update $S_1 = 9 - 9 = 0$.

Step 10: Since $S_1 = 0 \geq 0$. [Step A6]

Since $S_1 = 0 < \min\{24, 42\}$ [Step A7]

$j = 1 + 1 = 2$, $S_2 = 0 + 40 - 5 = 35$.

Consider buyer 3 with smallest $k_i = 3$. [Step A3]

Since $k_i = 3 \neq j$ [Step A4]

Since $S_2 = 35 \geq \min\{24, 42\}$. [Step A7]

Select buyer 3 with $d_3 k_3 T = 24$, [Step A8]

as $S_2 = 37 - 24 = 13$ is the least.

Assign $\delta_{3,2} = 1$ and $t_3 = 2$.

Update $D_2^{'} = D_5^{'} = 5 + 24 = 29$ and $D^a = (40, 29, 31, 14, 55, 5)$.

Update $S_2 = 35 - 24 = 11$.

Step 9: Since $S_2 = 11 \geq 0$ [Step A6]

Since $S_2 = 11 < \min\{42\}$. [Step A7]

$j = 2 + 1 = 3$, $S_3 = 11 + 40 - 40 = 11$.

Step 10: Consider buyer 7 with smallest $k_i = 6$. [Step A3]

Since $k_i = 6 \neq j$ [Step A4]

Since $S_3 = 11 < \min\{42\}$. [Step A7]

$j = 3 + 1 = 4$, $S_4 = 11 + 40 - 5 = 46$.

Step 11: Consider buyer 7 with smallest $k_i = 6$. [Step A3]

Since $k_i = 6 \neq j$ [Step A4]

Since $S_4 = 46 \geq \min\{42\}$. [Step A7]

Select buyer 7 with $d_7 k_7 T = 42$, [Step A8]

as $S_4 = 46 - 42 = 4$ is the least.

Assign $\delta_{7,4} = 1$ and $t_7 = 4$.

Update $D_4^{'} = 5 + 42 = 47$ and $D^a = (40, 29, 31, 56, 55, 5)$.

Update $S_4 = 42 - 42 = 0$.

Since all buyers assigned completely, exit.

Since the inventory S_j at time jT are non-negative for $j \leq 4$, surplus stock

ψ_j is zero before time $4T$. Since the production period F is 5.4, there is a possibility that a surplus stock is required at time $5T$. In order to calculate the surplus stock, equation (3.22) is applied.

	Orders placed by buyer i at time jT, $\delta_{i,j}d_ik_iT$					
Buyer i	$j=1$	$j=2$	$j=3$	$j=4$	$j=5$	$j=6$
1	2	2	2	2	2	2
2	3	3	3	3	3	3
3		24			24	
4	8		8		8	
5	10		10		10	
6	9			9		
7				42		
8	8		8		8	
$D_j^{'}$	40	29	31	56	55	5
P_j	40	40	40	40	40	16
$\sum_{i=1}^{n} d_ik_iT\left(\sum_{t=2}^{j}\delta_{i,t}\right)$		29	60	116	171	176
$(j-1)PT$		40	80	120	160	176
ψ_j	0	0	0	0	11	0

Table 3.4:Orders placed by buyer i at time jT in Example 2 and surplus stock ψ_j.

As shown in Table 3.4, the order placed by buyer i at time jT is given by $\delta_{i,j}d_ik_iT$. If $\delta_{i,j}$ is 0, no order is placed so the cell is blank for buyer i at time jT. If $\delta_{i,j}$ is 1, orders are placed by buyer i at time jT with order size d_ik_iT. The row of $D_j^{'}$, which is computed by $\sum_{i=1}^{n}\delta_{i,j}d_ik_iT$, shows the assigned demand at time jT. The row of P_j shows the production at time jT where $P_j = \max\{0, \min(P, (F-(j-1))P)\}$. The surplus stock ψ_j at time

jT is computed by the difference between accumulated demand $\sum_{i=1}^{n} d_i k_i T \left(\sum_{t=2}^{j} \delta_{i,t} \right)$ and accumulated production $(j-1)PT$ from time $2T$ to time jT as shown in the last third row and the last second row, respectively, in Table 3.4. Hence, the surplus stock ψ_j at time jT is calculated by equation (3.22) as shown in the last row of Table 3.4. Hence, the surplus stock ψ of the system is calculated by $\max\{\psi_1, \psi_2, \psi_3, \psi_4, \psi_5\} = \max\{0, 0, 0, 0, 11, 0\} = 11$.

3.5 Genetic Algorithm

A genetic algorithm is a heuristic search process that resembles natural selection in which any genetic algorithm has the features of reproduction, crossover and mutation. There are many variations and refinements. Generally, a small population is randomly selected initially, and then the offspring are produced by means of crossover among the members of the population and by means of mutation of members of the population. The better offsprings can remain in the population because of “survival of the fittest”. This idea was first invented by Holland (1975). Genetic algorithm (GA) is one of the popular meta-heuristics to find the near optimal solution. GA comprises a set of population (string) of which every gene (called chromosome) in the string is a feasible solution to the problem. GA has been used to solve the problem in single-vendor multi-buyer supply chain (see Chan and Kingsman 2007). However, as the data sets have been changed in which cost parameters are changed, genetic algorithms are conducted again with some modifications in this research. The modifications include changing the size of initial population, crossover rate, mutation rate, and the number of iterations. The new initial population size, crossover rate, mutation rate, and the number of iterations are 200, 0.6, 0.1, and 500, respectively. With this new set of parameters, some preliminary experiments showed that the computational time of the GA is reduced. Using the terminology of genetics, a population is a set of feasible solutions of the problem. A member of the population is a genotype, a chromosome, a string or a permutation which corresponds to the ordering pattern (including production cycle, ordering cycles, and ordering time) of buyers and vendors in supply chain. When a genotype is decoded, an ordering pattern is formed, and it is called a phenotype. Its fitness value can be calculated by total cost.

3.5.1 Gene Representation

The non-negative values are coded to represent the entries (genes) of a string. The first entry of the string denotes the value of N which is the production cycle of vendor. Then, the total cost represents the fitness value for the string. The lower value of the total cost, the higher the rank in the population. Next, the values of k_i are coded to represent the ordering cycles of each buyer i. Lastly, the values of $t_i \left(1 \le t_i \le k_i\right)$ denotes the first ordering time of buyer i such that $\delta_{i,t_i} = 1$. The string can be represented in Figure 3.3.

N	Total Cost	k_1	k_2	…	k_n	t_1	…	t_n

Figure 3.3: A string in genetic algorithm.

3.5.2 Population

There is no clear indication on how large a population should be. If the population is too large, there may be difficulty in storing the data, but if the population is too small, there may not be enough strings for good crossovers. In this research, the initial population size is set to be 20. When new offsprings are produced, they are combined with initial population and then ranked according to their fitness values. The top 20 members will be kept and for the reproduction of next generation. In general, in order to avoid obtaining local optima, mutation can improve the population which is homogenous.

3.5.3 Stopping Criterion

A stopping criterion is that there is a limit on the number of iterations (generations) to stop the process when the solution is settled down. If this value is too large, it wastes a lot of time. However, if it is too small, the process will stop before convergence. The stopping criterion is 100 which is the maximum number of iterations in this research since the solution will be settled down before 100 iterations. The solutions of different number of iterations in the 5-buyer example, 30-buyer example, and 50-buyer example are shown in Figure 3.4, Figure 3.5, and Figure 3.6, respectively.

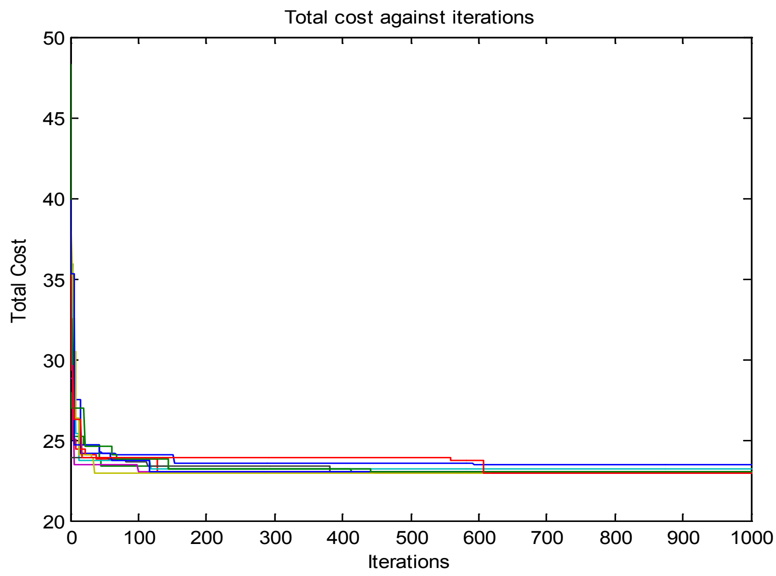


Figure 3.4: Total cost for a 5-buyer example when DP ratio 0.1.

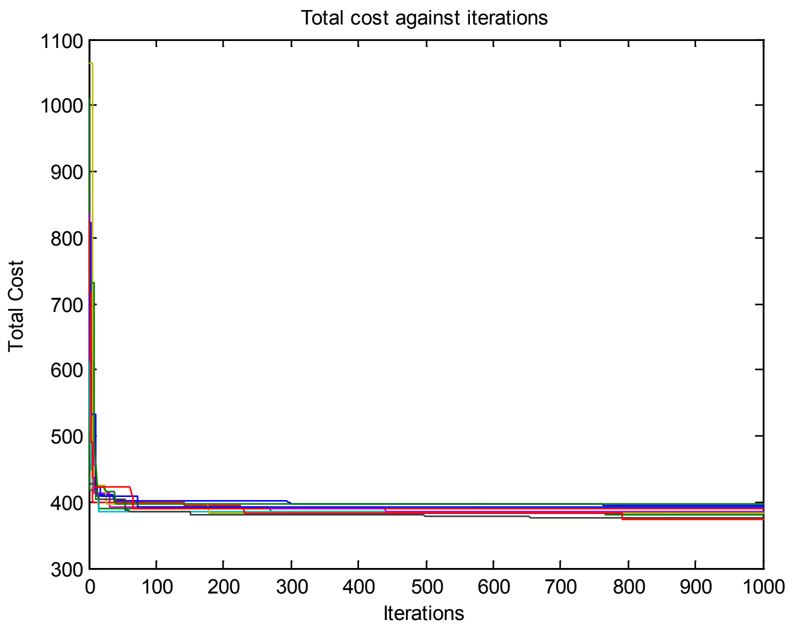


Figure 3.5: Total cost for a 30-buyer example when DP ratio 0.1.

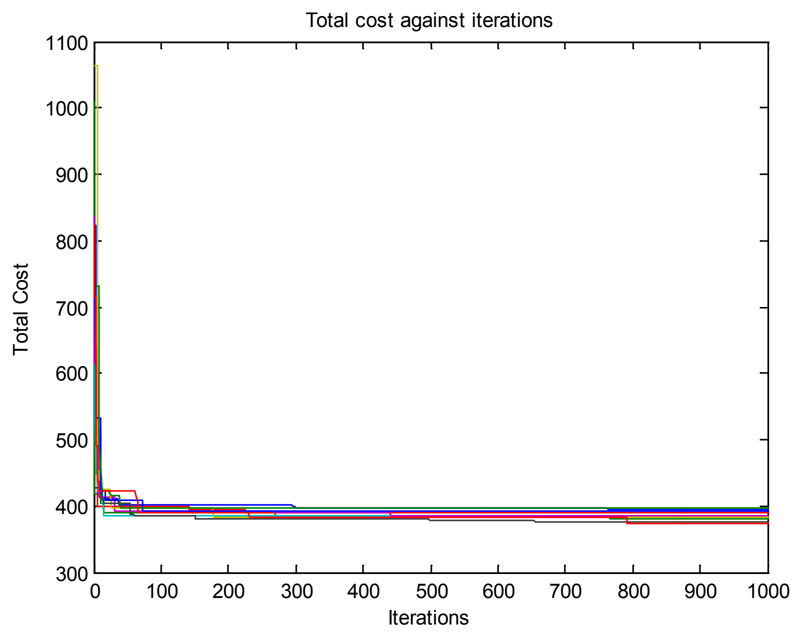


Figure 3.6: Total cost for a 50-buyer example when DP ratio 0.1.

3.5.4 Sample Size (Number of runs)

Since genetic algorithm is a random process, different solutions are obtained from the replication of strings. More trials should be run in order to get the best solution of the samples. If the sample size is too large, a lot of time will be taken; otherwise, the solution will not be best enough. Hence, a suitable sample size is important. In this research, the sample size is 10 obtained from 5-buyer example, 30-buyer example, and 50-buyer example as shown in Figure 3.4, Figure 3.5, and Figure 3.6, respectively.

3.5.5 Biased Roulette Wheel

The selection of a string is based on the fitness values of the strings in the population. Biased roulette wheel is used to choose two parents randomly from the population with replacement. The fitness value f_i of a string represents the total system cost for a particular production cycle, ordering cycles and first ordering time of buyers and the total cost is calculated by equation (3.18). The transformed fitness value $\widehat{f_i}$ of a member is obtained by one minus the fitness values of a member divided by the sum of the fitness values of the population, $\widehat{f}_i = 1 - \frac{f_i}{\sum_{i=1}^{n} f_i}$. The higher the transformed fitness value $\widehat{f_i}$, the higher the probability of being selected. Then, the interval [0,1] is partitioned into subintervals, with each interval having length equal to the relative fitness of a string in the population. Two random numbers from [0,1] are then chosen and two intervals are determined from two random numbers, and then two strings are selected corresponding to those two subintervals.

3.5.6 Crossover

The crossover operation corresponds to the concept of mating. It is hoped that the crossover (mating) of good parents may produce a good offspring. Thus, the crossover operation is a simple and powerful way of exchanging information and creating new solutions. When the production cycles (N) of two parents are equal, their values of ordering cycle (k_i) and first ordering time (t_i) of buyers can be exchanged. In this problem, a random number r between 0 and 1 is generated. If the random number of a string is smaller than or equal to the pre-determined crossover rate p_c, crossover will be applied to the chosen strings. During crossover, crossover operator will randomly select two genes of the parents. The two selected genes of the strings are swapped between two parents. If the random number r of a string is larger than the pre-determined crossover rate p_c, no crossover will be carried out.

For example, two strings are randomly selected from the population as shown in Figure 3.7. Two random numbers are selected, e.g. 2 and 4. If the production cycles (N^1, N^2) of vendor of two strings (parents) are the same, the genes $\left(k_2^1, k_3^1, k_4^1\right)$ and $\left(k_2^2, k_3^2, k_4^2\right)$ are swapped between string 1 and string 2. Total cost (TC^1 and TC^2) in the two strings are shown in Figure 3.7. After crossover, Total cost ($\underline{TC}^1$ and $\underline{TC}^2$) of the strings are computed again shown as Figure 3.8.

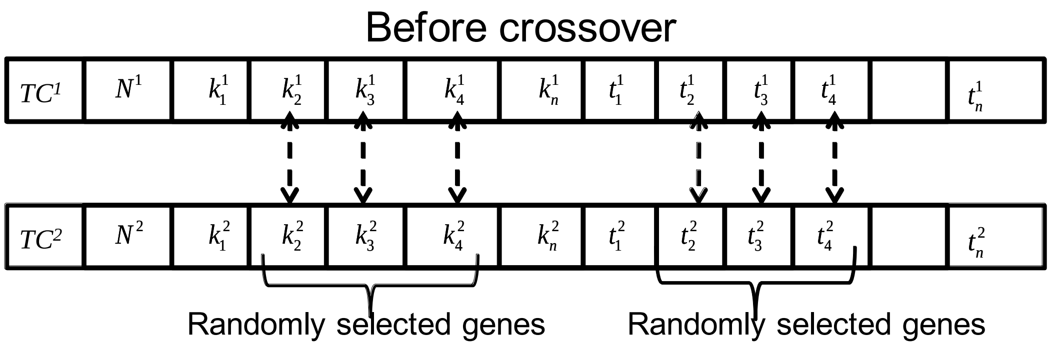


Figure 3.7: Two randomly selected strings before crossover.

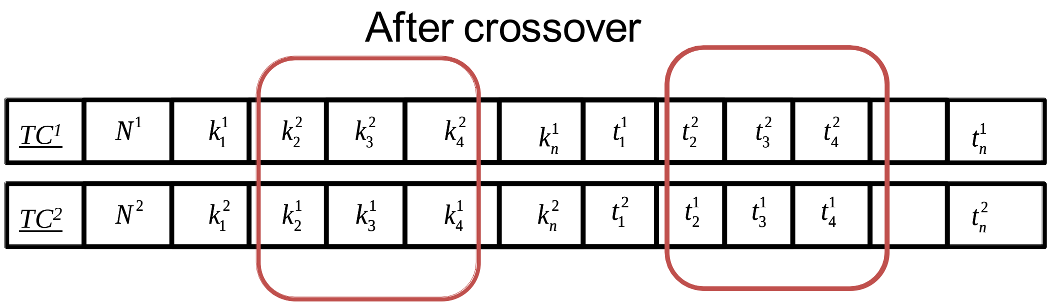


Figure 3.8: Two randomly selected strings after crossover.

3.5.7 Mutation

When the production cycles (N) are different, crossover of two strings would cause mismatch between the production cycles N of vendor and the ordering cycles k_i of buyers in the genes of offsprings. To cope with this problem, a mutation plays an important role to produce offsprings when the production cycles (N) between the parents are different. Mutation can operate on a single string. Mutation occurs when the production cycles (N) of parents are different or equal. In a mutation, a random numbers r is assigned to the strings. If the random number of a string is smaller than or equal to the pre-determined mutation rate p_m, then mutation will be applied to the chosen strings. During the mutation, the mutation operator randomly selects two genes in a string so that one gene for k_i and another gene for t_i are mutated, and then two random numbers, r_1 from a list of factors of N and r_2 from Uniform $\left[1, k_i\right]$, are assigned in the selected positions of a gene to produce a new offspring.

For example, a string is randomly selected from the population as shown in Figure 3.9. A random number between 0 and 1 is generated to each gene of the string. The random numbers of gene 2, 3, and 4 are below the pre-determined mutation rate p_m. Then, the new genes (k_2^1, k_3^1, and k_4^1) associated with (t_2^1, t_3^1, and t_4^1) are randomly regenerated from a list of factors of N^1. Suppose that k_2^1 is mutated to k_3^1, k_3^1 remain unchanged, and k_4^1 is mutated to k_2^1 after random generation as shown in Figure 3.10. Suppose that t_2^1 is mutated to t_3^1, t_3^1 is mutated to t_2^1, and t_4^1 remain unchanged after mutation by random generation of t_i^1 as shown in Figure 3.10. Total cost $\underline{TC}^1$ of the new string is also computed again as shown in Figure 3.10.

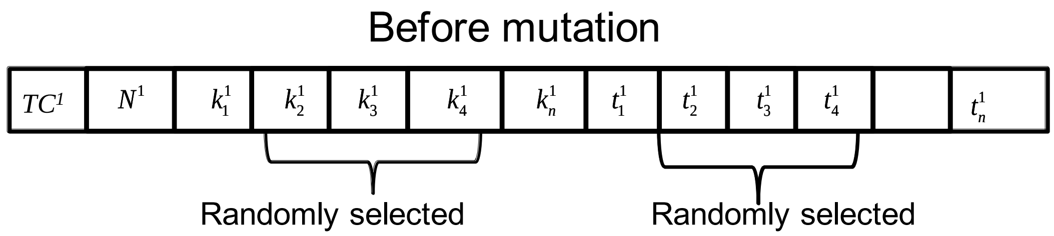


Figure 3.9: A string before mutation.

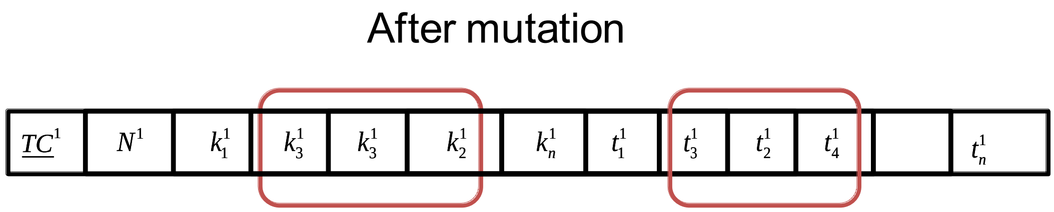


Figure 3.10: A string after mutation.

3.5.8 Procedures

The process of genetic algorithm is described as follows:

Step 1: Firstly, an initial population of size 20 is created by a random process. The fitness values of the strings in the initial population are also calculated.

Step 2: 1 pair of parents is chosen by using a biased roulette wheel from population.

Step 3: Two offsprings of the chosen parents are produced from the parents by crossover and by mutation. If the production cycles (N) of a pair of parents are equal, then reproduce by crossover and mutation. A random number r between 0 and 1 is generated. If $r \leq p_c$, produce an offspring by a crossover process. If $r > p_c$, no crossover will be started and then another random number r' is generated. If $r' \leq p_m$ mutation will be conducted; otherwise, no mutation will be started. If production cycles (N) of a pair of parents are not equal, since it is possible that no common factor k'_i can be exchanged by crossover, thus reproduce the offspring only by the mutation process. A random number r'' between 0 and 1 is generated. If $r'' \leq p_m$, produce an offspring by a mutation process. If $r > p_m$, no mutation will be started. Note that the mutation rate p_m and crossover rate p_c are pre-determined.

Step 4: Repeat Step 2 and Step 3, 20 times until 20 pairs of offspring have been produced.

Step 5: Keep the top 20 strings from the combined group of population and offsprings. These 20 strings become the population for next reproduction.

Step 6: Repeat Step 2 to Step 5 until the stopping criterion has been reached. Choose the best (fittest) solution in the population as the "optimal" solution of the problem.

Step 7: Repeat Step 1 to Step 6, 10 times (samples), select the best solution of the 10 as the final solution.

3.6 Results

3.6.1 Comparison between Inventory Approach and Synchronized Cycles Model without Improvement Algorithm

The effects of shifting the ordering cycle are illustrated by inventory approach with three different examples of 5, 30, and 50 buyers. The data are provided in Tables A1 to A3 of Appendix A. As mentioned in section 3.3, inventory approach can further reduce the total system cost by shifting the ordering time of buyers, compared to the solution without improvement algorithm. Let k_i be the ordering cycle of buyers under synchronized cycles model and t_i be the first ordering time of buyer i.

		Without improvement algorithm	Inventory approach
Buyer i	k_i	t_i	t_i
1	45	1	3
2	45	1	2
3	45	1	1
4	45	1	3
5	45	1	5
Total cost		23.19	22.71

Table 3.5: The results of the shifted ordering time of buyers in Example 1.

When the DP ratio is 0.1 in Example 1 for the 5 buyers, the total system cost for all $\delta_{i,1} = 1$ is 23.19 as shown in Table 3.5. Without improvement algorithm, all buyers start to order at time *T*, that is, $\delta_{i,1} = 1$. After shifting the first ordering times for the 5 buyers by inventory approach, the total system cost is found to be 22.71, reduced by 0.48 (2.11%) . The results of the shifted ordering time of buyers in Example 1 are shown in Table 3.5. By inventory approach, buyer 3 places orders at time *T*; Buyer 2 places orders at time 2*T*; Buyers 1 and 4 place an order at time *T* and 4*T* and buyer 5 places orders at time 5*T*.

		Without improvement algorithm	Inventory approach			Without improvement algorithm	Inventory approach
Buyer i	k_i	t_i	t_i	Buyer i	k_i	t_i	$\boldsymbol{t_i}$
1	24	1	2	16	24	1	2
2	12	1	1	17	24	1	2
3	12	1	1	18	24	1	2
4	24	1	2	19	12	1	1
5	8	1	1	20	24	1	2
6	6	1	1	21	12	1	1
7	24	1	2	22	12	1	1
8	24	1	2	23	24	1	1
9	12	1	1	24	24	1	1
10	24	1	2	25	12	1	1
11	24	1	1	26	24	1	2
12	24	1	2	27	12	1	1
13	24	1	2	28	24	1	1
14	8	1	1	29	12	1	1
15	24	1	2	30	12	1	1
Total cost		374.15	370.40				

Table 3.6: The results of the shifted ordering time of buyers in Example 2.

As shown in Table 3.6, when the DP ratio is 0.1 in Example 2 for the 30 buyers, the total system cost for all $\delta_{i,1} = 1$ is 374.15. After shifting the first ordering times for the 30 buyers by inventory approach, the total system cost is found to be 370.40, reduced by 3.75 (1.0%) . The results of the shifted ordering time of buyers in Example 2 are shown in Table 3.6. Buyers 1, 4, 7, 8, 10, 12, 13, 15, 16, 17, 18, 20, and 26 place first orders at time 2*T*, the rest of the buyers still place an order at time *T*.

		Without improvement algorithm	Inventory approach			Without improvement algorithm	Inventory approach
Buyer i	k_i	t_i	t_i	Buyer i	k_i	t_i	t_i
1	7	1	1	26	14	1	1
2	14	1	2	27	14	1	2
3	7	1	1	28	14	1	1
4	14	1	2	29	7	1	1
5	14	1	1	30	14	1	1
6	14	1	1	31	14	1	2
7	14	1	1	32	14	1	2
8	14	1	1	33	14	1	2
9	7	1	1	34	7	1	1
10	7	1	1	35	14	1	1
11	14	1	1	36	14	1	1
12	14	1	1	37	14	1	1
13	14	1	1	38	14	1	1
14	7	1	1	39	7	1	1
15	7	1	1	40	7	1	1
16	14	1	1	41	14	1	2
17	14	1	2	42	7	1	1
18	14	1	2	43	14	1	1
19	14	1	1	44	14	1	1
20	14	1	1	45	14	1	1
21	7	1	1	46	14	1	1
22	7	1	1	47	7	1	1
23	14	1	2	48	7	1	1
24	7	1	1	49	14	1	1
25	14	1	1	50	7	1	1
Total cost		714.84	714.22				

Table 3.7: The results of the shifted ordering time of buyers in Example 3.

As shown in Table 3.7, when the DP ratio is 0.1 in Example 3 for the 50 buyers, the total system cost for all $\delta_{i,1} = 1$ is 714.84. After shifting the first ordering times for the 50 buyers by inventory approach, the total system cost is found to be 714.22, reduced by 0.62 (0.09%). The results of the shifted ordering time of buyers in Example 3 are shown in Table 3.7. Buyers 2, 4, 17, 18, 23, 27, 31, 32, 33, and 41 place first orders at time 2T, but the rest of the buyers place an order at time T.

From the above examples, the savings of total system cost range from 0.09% to 2% by shifting the ordering times of buyers. In Examples 1 and 2, which give zero surplus stock, shifting the ordering times of the buyers can help to reduce the inventory holding cost and hence the total system cost. In Example 3, surplus stock exists and the total system cost is reduced by inventory approach.

	Total system cost					
	Inventory approach			Without improvement algorithm		
DP ratio	Example 1	Example 2	Example 3	Example 1	Example 2	Example 3
0.1	22.71	370.40	714.22	23.19	374.15	714.84
0.2	22.96	365.03	705.30	23.83	378.10	722.37
0.3	22.71	357.32	694.76	24.25	378.80	723.68
0.4	22.37	350.09	678.37	24.43	378.09	720.04
0.5	22.19	342.29	664.22	24.61	375.62	713.27
0.6	22.35	333.47	639.45	24.60	369.10	701.31
0.7	21.71	321.34	612.77	24.31	361.76	681.41
0.8	21.03	302.77	582.06	24.02	349.08	657.76
0.9	20.05	289.00	549.06	23.16	329.53	617.57

Table 3.8: Results of total cost between inventory approach and without improvement algorithm with various DP ratios for Examples 1, 2 and 3.

Table 3.8 depicts the total costs of various DP ratios for the three examples between inventory approach and without improvement algorithm. The detailed results of ordering cycle k_i and the first ordering times t_i of buyer i with various DP ratios are shown in Tables B1 to B3 of Appendix B.

3.6.2 Comparison between Incremental Approach, Inventory Approach and Genetic Algorithm.

Most importantly, operational effectiveness is worked out by considering different approaches such as incremental approach, inventory approach and genetic algorithm. Usually, total system cost is employed to measure the effectiveness of the system. Now, initial population size is assumed to be 20, the stopping criteria is 100 iterations, and sample size of 10 in genetic algorithm. Also, the total system costs are computed by genetic algorithm with mutation rate, p_m, and crossover rate, p_c, are 0.1 and 0.9, respectively. Total Costs (TC) and production cycle of vendor, N, by different approaches are recorded with DP ratios ranging from 0.1 to 0.9 where the DP ratio is calculated by $\frac{D}{P}$.

The results of comparison of total system cost among without improvement algorithm, incremental approach, inventory approach and genetic algorithm for various DP ratios in Example 1 are shown in Table 3.9 and the percentage of cost saved compared with the total cost without improvement algorithm is also shown in Table 3.9. The cost saved by inventory approach ranging from 2.1% to 13.4% is higher than that of incremental approach from 0.9% to 10.1% with DP ratios from 0.1 to 0.9, compared with the total cost without improvement algorithm. On the other hand, the total cost by inventory approach is close to that by genetic algorithm. After all, all approaches give lower costs than independent optimization. The computational time of incremental approach and inventory approach are nearly the same with time 0.53 seconds and 0.55 seconds, respectively, but genetic algorithm requires a computational time of 5 minutes

16.46seconds.

	Independent optimization	Inventory approach			Incremental approach			Genetic algorithm			Without improvement algorithm	
DP ratio	TC	N	TC	%	N	TC	%	N	TC	%	N	TC
0.1	36.58	45	22.71	-2.1%	45	22.97	-0.9%	48	22.82	-1.6%	45	23.19
0.2	35.92	44	22.96	-3.6%	44	23.36	-2.0%	42	23.08	-3.2%	44	23.83
0.3	35.23	56	22.71	-6.3%	56	23.14	-4.6%	46	23.13	-4.6%	56	24.25
0.4	34.48	56	22.37	-8.4%	56	23.92	-2.1%	62	22.78	-6.7%	56	24.43
0.5	33.67	56	22.19	-9.8%	56	23.12	-6.0%	56	22.87	-7.1%	56	24.61
0.6	32.77	78	22.35	-9.1%	78	24.07	-2.1%	56	22.62	-8.0%	78	24.60
0.7	31.75	78	21.71	-10.7%	78	22.34	-8.1%	90	22.19	-8.7%	78	24.31
0.8	30.54	78	21.03	-12.5%	78	22.36	-6.9%	104	21.48	-10.6%	78	24.02
0.9	28.96	144	20.05	-13.4%	144	20.81	-10.1%	144	20.42	-11.8%	144	23.16
Time		0.55 seconds			0.53 seconds			5 mins 16.46 sec				

Table 3.9: Comparison of total system cost among without improvement algorithm, incremental approach, inventory approach and genetic algorithm for various DP ratios in Example 1.

	Independent optimization	Inventory approach			Incremental approach			Genetic algorithm			Without improvement algorithm	
DP ratio	TC	N	TC	%	N	TC	%	N	TC	%	N	TC
0.1	567.0	24	370.4	-1.0%	24	368.0	-1.6%	26	374.7	0.1%	24	374.1
0.2	554.6	24	365.0	-3.5%	24	369.6	-2.2%	24	372.3	-1.5%	24	378.1
0.3	541.4	28	357.3	-5.7%	28	362.5	-4.3%	28	369.0	-2.6%	28	378.8
0.4	527.2	30	350.1	-7.4%	30	369.4	-2.3%	30	365.4	-3.4%	30	378.1
0.5	511.7	30	342.3	-8.9%	30	358.1	-4.7%	28	357.0	-4.9%	30	375.6
0.6	494.7	36	333.5	-9.7%	36	348.8	-5.5%	36	345.2	-6.5%	36	369.1
0.7	475.3	36	321.3	-11.2%	36	352.5	-2.6%	36	331.3	-8.4%	36	361.8
0.8	452.3	48	302.8	-13.3%	48	339.7	-2.7%	48	314.1	-10.0%	48	349.1
0.9	422.3	72	289.0	-12.3%	72	320.3	-2.8%	84	290.3	-11.9%	72	329.5
Time		0.98 seconds			1.6 seconds			15 mins 28.09 sec				

Table 3.10: Comparison of total system cost among without improvement algorithm, incremental approach, inventory approach and genetic algorithm for various DP ratios in Example 2.

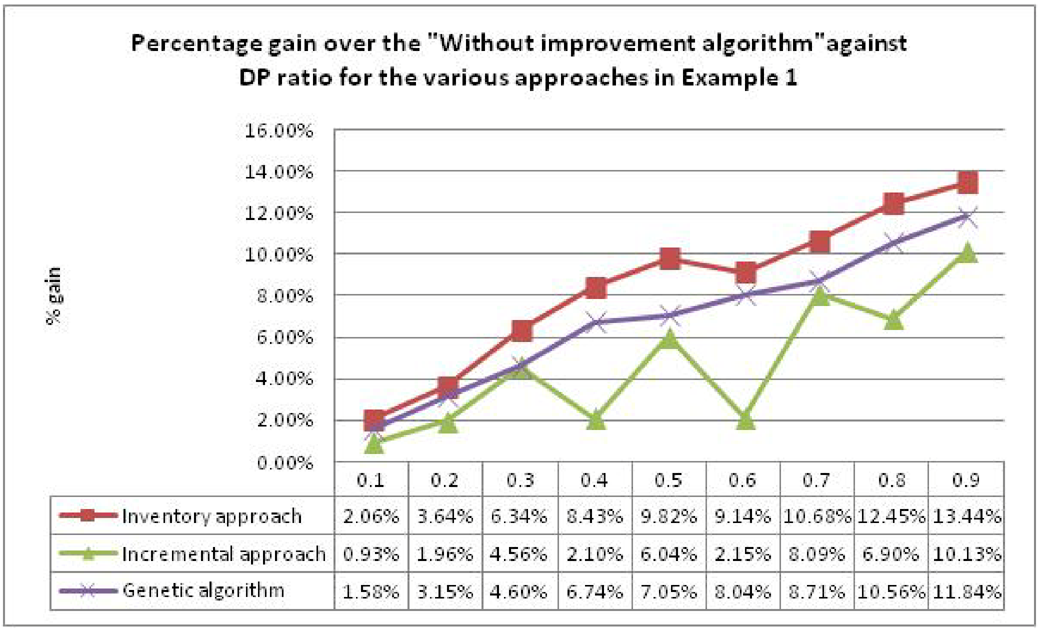
The results of comparison of total system cost among without improvement algorithm, incremental approach, inventory approach and genetic algorithm for various DP ratios in Example 2 are shown in Table 3.10 and the percentage of cost saved compared with the total cost without improvement algorithm is also shown in Table 3.10. The cost saved by inventory approach ranging from 3.5% to 12.3% is higher than that of incremental approach from 2.2% to 5.5% with DP ratios ranging from 0.2 to 0.9, except when DP ratio is 0.1. On the other hand, the total cost by inventory approach is lower than that by genetic algorithm. After all, all approaches give lower costs than independent optimization. The computational time of incremental approach and inventory approach are close with time 1.6 second and 0.98 second, respectively, but genetic algorithm requires a computational time of 15 minutes 28.09 seconds.

	Independent optimization	Inventory approach			Incremental approach			Genetic algorithm			Without improvement algorithm	
DP ratio	TC	N	TC	%	N	TC	%	N	TC	%	N	TC
0.1	1025.5	14	714.2	-0.1%	14	707.6	-1.0%	14	714.1	-0.1%	14	714.8
0.2	1000.7	16	705.3	-2.4%	16	703.1	-2.7%	16	720.2	-0.3%	16	722.4
0.3	974.3	16	694.8	-4.0%	16	700.5	-3.2%	16	707.4	-2.3%	16	723.7
0.4	945.9	18	678.4	-5.8%	18	693.2	-3.7%	20	702.6	-2.4%	18	720.0
0.5	915.1	18	664.2	-6.9%	18	687.4	-3.6%	20	685.6	-3.9%	18	713.3
0.6	880.9	24	639.5	-8.8%	24	667.4	-4.8%	24	660.2	-5.9%	24	701.3
0.7	842.2	24	612.8	-10.1%	24	683.6	0.3%	24	632.0	-7.2%	24	681.4
0.8	796.2	30	582.1	-11.5%	30	627.5	-4.6%	30	595.1	-9.5%	30	657.8
0.9	736.3	48	549.1	-11.1%	48	563.2	-8.8%	48	549.2	-11.1%	48	617.6
Time		1.14 seconds			3.7 seconds			25 min 12.04 sec				

Table 3.11: Comparison of total system cost among without improvement algorithm, incremental approach, inventory approach and genetic algorithm for various DP ratios in Example 3.

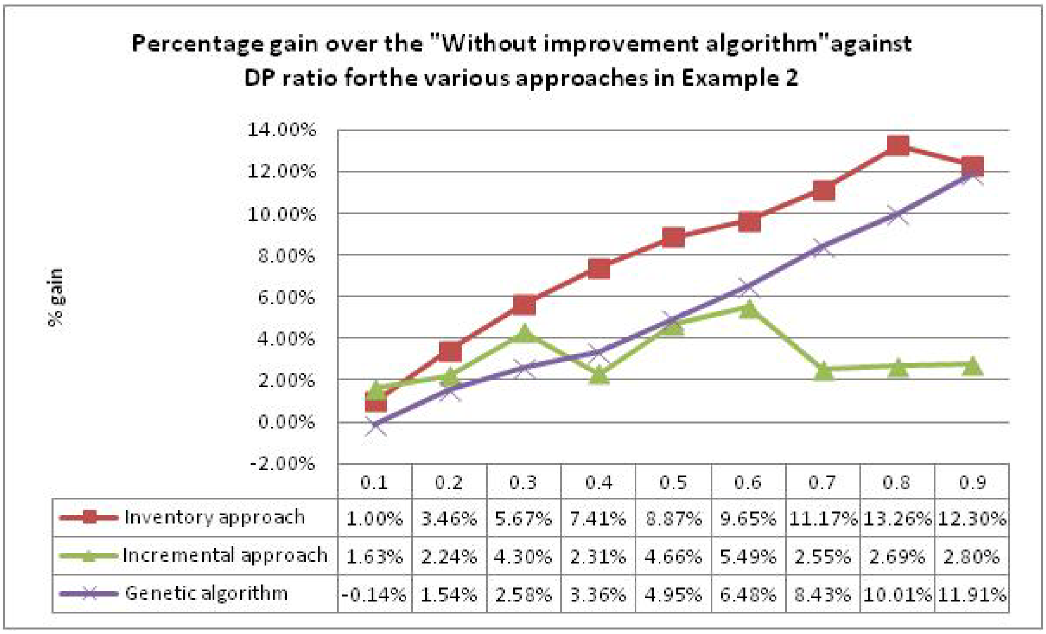
The results of comparison of total system cost among without improvement algorithm, incremental approach, inventory approach and genetic algorithm for various DP ratios in Example 3 are shown in Table 3.11 and the percentage of cost saved compared with the total cost without improvement algorithm is also shown in Table 3.11. The cost saved by inventory approach ranging from 4.0% to 11.1% is higher than that of incremental approach from 0.3% to 8.8% with DP ratio from 0.3 to 0.9, except when DP ratio is 0.1 and 0.2. On the other hand, the total costs of inventory approach and genetic algorithm are close. It is concluded that all approaches give lower costs than independent optimization. The computational time of incremental approach and inventory approach are 3.7 second and 1.14 second, respectively, but genetic algorithm requires a computational time of 25 minutes 12.04 seconds. The Intel (R) core (TM) Quad CPU Q9550 with speed of 2.83GHz is used to run the results.

The percentage gains over “Without improvement algorithm” against DP ratio for the various approaches in Example 1, Example 2, and Example 3 are shown in Figure 3.11, Figure 3.12, and Figure 3.13, respectively.



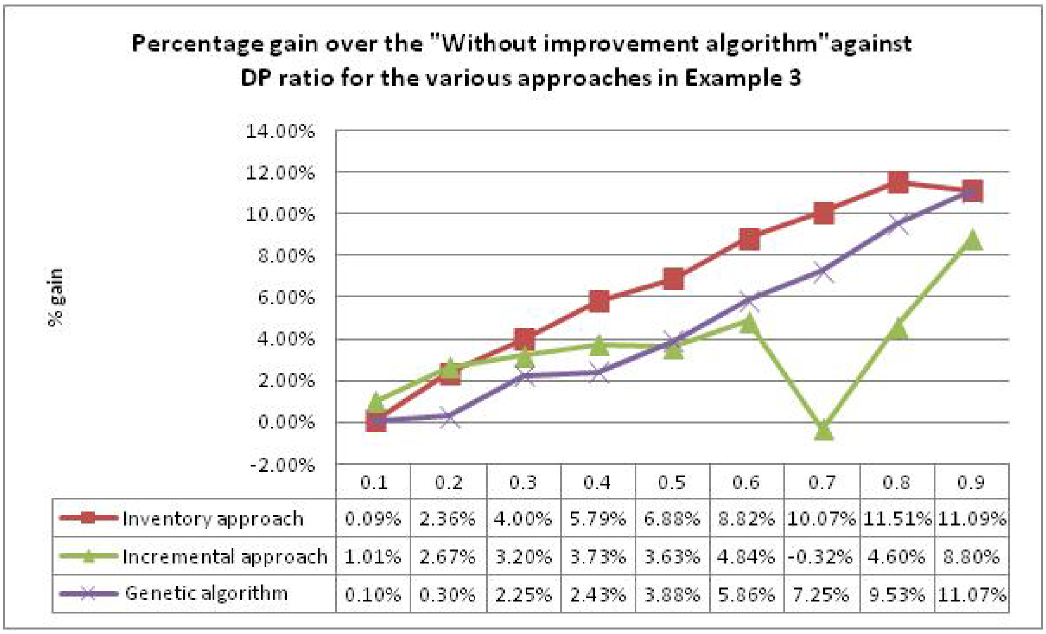
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Inventory approach	2.06%	3.64%	6.34%	8.43%	9.82%	9.14%	10.68%	12.45%	13.44%
Incremental approach	0.93%	1.96%	4.56%	2.10%	6.04%	2.15%	8.09%	6.90%	10.13%
Genetic algorithm	1.58%	3.15%	4.60%	6.74%	7.05%	8.04%	8.71%	10.56%	11.84%

Figure 3.11: The percentage gain over “Without improvement algorithm” against DP ratio for the various approaches in Example 1.



	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Inventory approach	1.00%	3.46%	5.67%	7.41%	8.87%	9.65%	11.17%	13.26%	12.30%
Incremental approach	1.63%	2.24%	4.30%	2.31%	4.66%	5.49%	2.55%	2.69%	2.80%
Genetic algorithm	-0.14%	1.54%	2.58%	3.36%	4.95%	6.48%	8.43%	10.01%	11.91%

Figure 3.12: The percentage gain over “Without improvement algorithm” against DP ratio for the various approaches in Example 2.



	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Inventory approach	0.09%	2.36%	4.00%	5.79%	6.88%	8.82%	10.07%	11.51%	11.09%
Incremental approach	1.01%	2.67%	3.20%	3.73%	3.63%	4.84%	-0.32%	4.60%	8.80%
Genetic algorithm	0.10%	0.30%	2.25%	2.43%	3.88%	5.86%	7.25%	9.53%	11.07%

Figure 3.13: The percentage gain over "Without improvement algorithm" against DP ratio for the various approaches in Example 3.

3. 7 Discussions

After comparing the result among incremental approach, inventory approach, and genetic algorithm, inventory approach could also give a near optimal solution by comparing the order size of buyers and inventory level of vendor. In addition, compared with incremental approach, inventory approach works well for medium/high DP ratios. When the number of buyers is large, inventory approach works much better than genetic algorithm in terms of computational time.

Incremental approach gives an easy way to find the near-optimal solution, but it will stop searching when no further improvement is observed in the next step and a local optimal solution may be achieved. Also, inventory approach can use limited information such as demand rate of buyers, ordering cycles of buyers and production rate of vendor but incremental approach and genetic algorithm require all the information such as setup cost and holding cost of buyers and vendor to calculate the total cost every iteration.

Inventory approach can be extended to third party logistics since the third party may not have complete information about costs from the vendor and buyers. Moreover, it can also be extended to delivery items with different sizes.

Chapter 4

Inventory Transportation Models

4.1 Introduction

Transportation cost is one of the important elements in a supply chain, however previous researchers of supply chain coordination model usually assumed that transportation cost is a fixed cost per order. This means that, for simplicity reason, the transportation cost did not take account of order size. In the real world, there are mainly two modes of transportation cost, namely, less-than-truckload (LTL) and full-truckload (FTL) transportations. Many researchers, for example, Russell and Karjewski (1991), Swenseth and Godfrey (2002) and Abad and Aggarwal (2005), studied the combination of these two modes of transportation, but the authors only considered the single-vendor single-buyer case. In this session, by relaxing the assumption of fixed transportation cost per order, some transportation modes are considered and incorporated into the independent optimization and synchronized cycles model in a single-vendor multi-buyer supply chain system.

Most of the literature assumed that the vendor pays all the transportation costs and employs only one transportation mode. One of the reasons is that the transportation mode is restricted by some business contracts between vendor and logistics companies. Vendor has no choice but take available transportation mode. How many transportation modes available in the market is one of the key factors on the business contract. Under the circumstances that different transportation modes are available in the market, the vendor can select one of them such that the total cost is minimized.

In this research, the vendor can select a third-party logistics which can use any transportation mode to deliver the items to all buyers, based on the availability of transportations. Different transportation modes have different parameters. The objective is to compare the coordinated model with independent optimization when different possible modes of transportation are employed by third party logistics. Some common transportation modes in the literature and some modified transportation modes will be discussed in this thesis. The first transportation mode is diminishing freight rate, which is commonly used by other researchers. The larger the order size, the lower the per-unit freight rate. Secondly, less-than-truckload (LTL) is considered in which the freight rate is directly proportional to the lot size with a minimum fixed freight rate. Thirdly, full-truckload (FTL) is considered in which an order size within a particular range will employ a corresponding number of full trucks. Then, hybrid transportation is introduced in which vendor can select any one of the FTL or LTL mode of transportation whichever the transportation cost lower. Finally, two-tier freight-rate transportation is introduced in which there are two freight rates in a truck. The per-unit freight rate is initially high for an additional truck. If the order size increases but still within a truck capacity, a lower per-unit freight rate is charged.

4.2 Assumptions

Throughout this chapter, the following assumptions on transportation are made:

1. Each truck is identical with size Q^T and cost C^T.

2. No overload is allowed for each truck.
3. Unlimited number of trucks can be employed.

4.3 Transportation Cost

In most of the literature of single-vendor multi-buyer supply chain model, it is usually assumed that the transportation cost $C_i(Q_i)$ of buyer i is a fixed cost per order no matter how many items are delivered. In the real world, transportation cost should consider the order sizes and transportation distances. Hence, $C_i(Q_i)$ should comprise a delivery cost C_i, which is based on the distance and a freight cost $F(Q_i)$ which depends on the order size. Hence, the transportation cost is expressed as

$$C_i(Q_i) = F(Q_i) + C_i \,. \tag{4.1}$$

Five different transportation modes are discussed in the following sections.

4.3.1 Diminishing Freight Rate Transportation

The diminishing freight rate transportation mode is commonly used for simplicity reason in which the total shipment cost depends on the order size. Also, marginal freight rate decreases after the order size reaches some breakpoints. Moreover, the diminishing freight rate transportation does not consider truck size Q^T.

Let Q_i be the order size of buyer i. In general, the freight cost function $F(Q_i)$ with m marginal freight rates and minimum freight cost $C^0_{\min}$ is shown in Figure 4.1. The m different marginal freight rates are represented by the slopes s_1 , s_2 ,..., s_{m-1} and s_m of the lines L_1, L_2, L_{m-1} and L_m where $s_1 > s_2 > \ldots > s_{m-1} > s_m$.

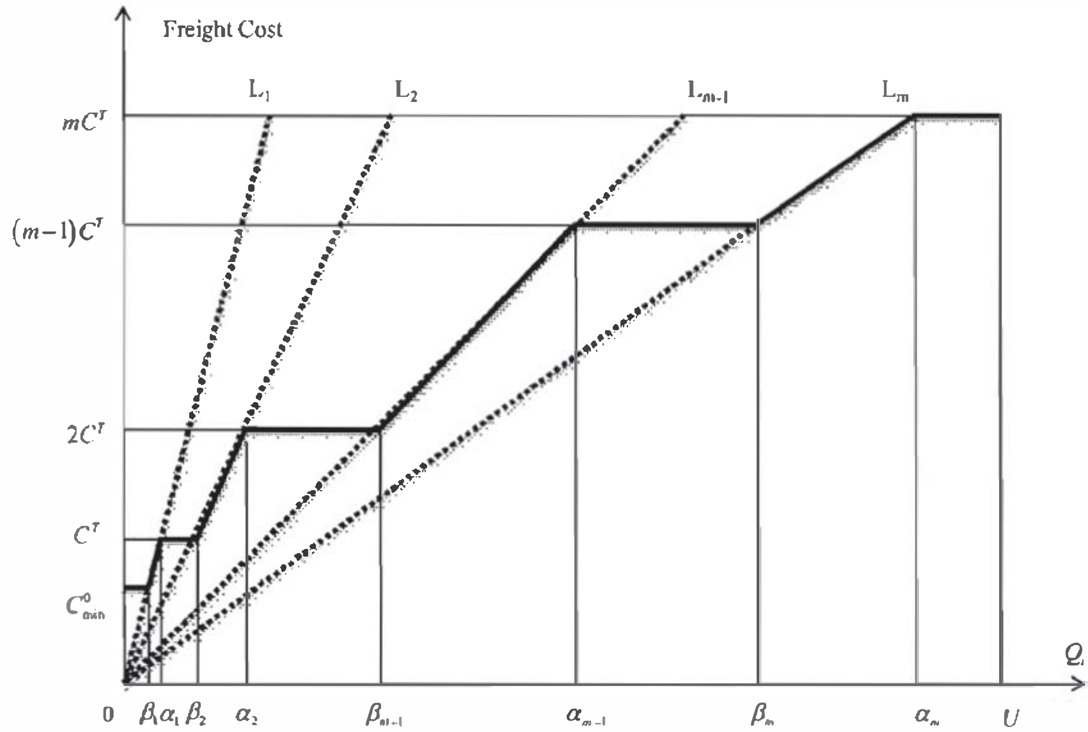


Figure 4.1: Freight cost of diminishing freight rate of buyer i .

When the order size Q_i is less than or equal to β_1, minimum freight charge $C^0_{\min}$ is imposed (see Figure 4.1). When order size Q_i is between β_1 and α_1, the freight cost $F(Q_i)$ will be charged along the line L_1 with marginal freight rate of s_1. When order size Q_i is between α_1 and β_2 (see Figure 4.1), the freight cost $F(Q_i)$ is C^T. When order size Q_i is between β_2 and α_2, the freight cost $F(Q_i)$ will be charged along the line L_2 with marginal freight rate of s_2. When order size Q_i is between α_2 and β_3, the freight cost $F(Q)$ is $2C^T$. When the order size Q_i is capped at U, the corresponding freight cost $F(Q_i)$ is mC^T. In general, when order size Q_i is between β_i

and α_l, the freight cost $F(Q_i)$ will be charged along the line L_i with marginal freight rate of s_l. When order size Q_i is between α_l and β_{l+1}, the freight cost $F(Q_i)$ is lC^T. With the breakpoints α_l and β_l such that $0 \le \beta_l \le \alpha_1 \le \beta_{l+1} \le U$ for each $l = 1, 2, ..., m-1$, it is shown that $s_m \alpha_m = mC^T$, $s_l \alpha_l = s_{l+1} \beta_{l+1}$, and $C_{\min}^0 = s_1 \beta_1$ where $l = 1, 2, ..., m-1$

Therefore the freight cost with diminishing freight rate is expressed as

$$F(Q_i) = \begin{cases} C_{\min}^0 & \text{for } 0 < Q_i \le \beta_1 \\ s_1 Q_i & \text{for } \beta_1 < Q_i \le \alpha_1 \\ s_l \alpha_1 & \text{for } \alpha_l < Q_i \le \beta_{l+1}, l = 1, 2, 3, ..., m-1 \\ s_{l+1} Q_i & \text{for } \beta_{l+1} < Q_i \le \alpha_{l+1}, l = 1, 2, 3, ..., m-1 \\ mC^T & \text{for } \alpha_{\mathrm{m}} < Q_i \le U \end{cases}. \tag{4.2}$$

Since the transportation cost $C_i(Q_i)$ consists of freight cost function $F(Q_i)$ and delivery cost C_i, by equations (4.1) and (4.2), the transportation cost with diminishing freight rate is written as

$$C_i(Q_i) = \begin{cases} C_{\min}^0 + \mathrm{C_i} & \text{for } 0 < Q_i \le \beta_1 \\ s_1 Q_i + \mathrm{C_i} & \text{for } \beta_1 < Q_i \le \alpha_1 \\ s_l \alpha_1 + \mathrm{C_i} & \text{for } \alpha_l < Q_i \le \beta_{l+1}, l = 1, 2, 3, ..., m-1 \\ s_{l+1} Q_i + \mathrm{C_i} & \text{for } \beta_{l+1} < Q_i \le \alpha_{l+1}, l = 1, 2, 3, ..., m-1 \\ mC^T + \mathrm{C_i} & \text{for } \alpha_{\mathrm{m}} < Q_i \le U \end{cases}. \tag{4.3}$$

4.3.2 Less –than Truckload (LTL) Transportation

Less-than-truckload (LTL) transportation is also commonly used in third-party logistics in which all the goods enjoy the same freight rate s per item with a base cost C_b per delivery. The vendor pays transportation fee to third-party logistics so that the transportation cost depends on how many items to be delivered and the distance of delivery. The transportation cost $C_i\left(Q_i\right)$ consists of freight cost function $F(Q_i)$ and delivery cost C_i. The freight cost function $F(Q_i)$ of LTL is illustrated in Figure 4.2.

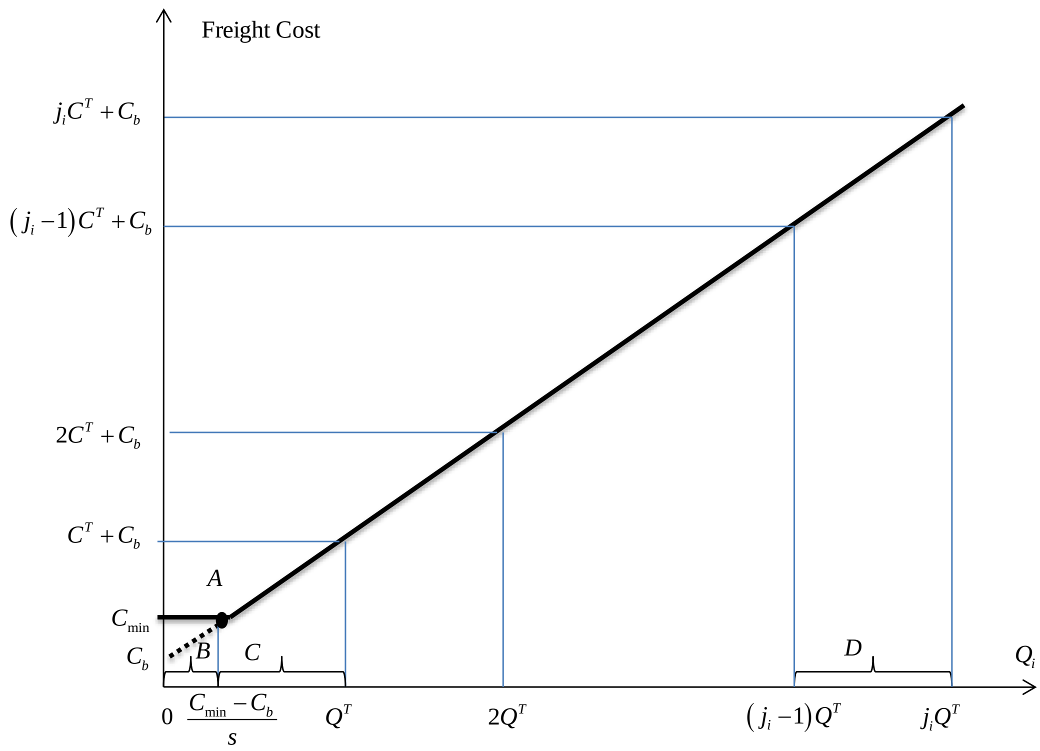


Figure 4.2: Freight cost of less-than-truckload (LTL) transportation against order size Q_i of buyer i.

Let Q^T, s, and C^T be the truck capacity (size), the freight cost per item, and the cost of a hiring a truck, respectively. It is assumed that there are unlimited number of trucks available and that the third party logistics needs a base cost C_b to compensate the overheads of delivery, the freight charge $C_b + sQ_i$ of LTL (shown by a dotted line in Figure 4.2) is less than the minimum charge $C_{\min}$ when the order size Q_i of buyer i is less than $\frac{C_{\min}-C_b}{s}$ (shown in region *B)*. Therefore, the freight cost is $C_{\min}$ if the order size Q_i is not large enough. Hence, the LTL freight cost $F(Q_i)$ is expressed as $\max\left\{C_{\min}, C_b+sQ_i\right\}$ shown by a solid line in region *B*. The freight cost of LTL is expressed as $F\left(Q_i\right)=\max\left\{C_{\min}, C_b+sQ_i\right\}$. At point *A*, when the order size Q_i of buyer i is $\frac{C_{\min}-C_b}{s}$, the freight cost is $C_{\min}$. When the order size Q_i of buyer i is larger than $\frac{C_{\min}-C_b}{s}$ as shown in region *C*, the LTL freight cost can cover the overhead cost of third party logistics, i.e. $C_{\min}$, so the freight cost of LTL is $F(Q_i)=C_b+sQ_i$. When the order size Q_i of buyer i is Q^T, the freight cost of LTL is C_b+sQ^T. In general, when the order size Q_i of buyer i is between $\left(j_i\text{ -}1\right)Q^T$ and j_iQ^T for $j_i>1$ (region *D*) where j_i denotes the number of full trucks employed, the freight cost of LTL is expressed as $F(Q_i)=C_b+sQ_i$ for $\left(j_i-1\right)Q^T<Q_i\le j_iQ^T$ and $j_i>1$. Hence, the freight cost $F_i(Q_i)$ is expressed as:

$$F_i\left(Q_i\right)=\begin{cases}\max\left\{C_{\min}, C_b+sQ_i\right\} & \text{for } 0<Q_i\le Q^T\\ C_b+sQ_i & \text{for } \left(j_i-1\right)Q^T<Q_i\le j_iQ^T \text{ and } j_i>1\end{cases}. \tag{4.4}$$

Since, the transportation cost $C_i\left(Q_i\right)$ comprises a delivery cost C_i and a freight cost $F(Q_i)$ by equation (4.1). Hence, the LTL transportation cost can be expressed as

$$C_i(Q_i) = \begin{cases} \max\{C_{\min}, C_b + sQ_i\} + C_i & \text{for } 0 < Q_i \le Q^T \\ C_b + sQ_i + C_i & \text{for } (j_i - 1)Q^T < Q_i \le j_i Q^T \text{ and } j_i > 1 \end{cases} . \tag{4.5}$$

4.3.3 Full-truckload (FTL) Transportation

In addition to less-than-truckload transportation, full-truckload (FTL) transportation mode is another commonly adopted transportation mode. Each truck charges a cost of C^T if the order size Q_i is within the capacity Q^T of a truck. One full-truck is employed even though only a small amount of goods is delivered. The transportation cost depends on how many trucks employed per delivery as well as the distance of delivery.

Full-truckload freight cost (horizontal solid line) is shown in Figure 4.3. In general, when the ordering size Q_i lies in the region $(j_i - 1)Q^T < Q_i \le j_i Q^T$ for $j_i \ge 1$, the third-party logistics employs j_i full trucks with freight cost $j_i C^T$. The FTL freight cost function $F(Q_i) = j_i C^T$ is shown in Figure 4.3. Since the transportation cost $C_i(Q_i)$ comprises a delivery cost C_i and a freight cost $F(Q_i)$ by equation (4.1), the full-truckload transportation cost is expressed as

$$C_i(Q_i) = j_i C^T + C_i \quad \text{for } (j_i - 1)Q^T < Q_i \le j_i Q^T \text{ and } j_i \ge 1 . \tag{4.6}$$

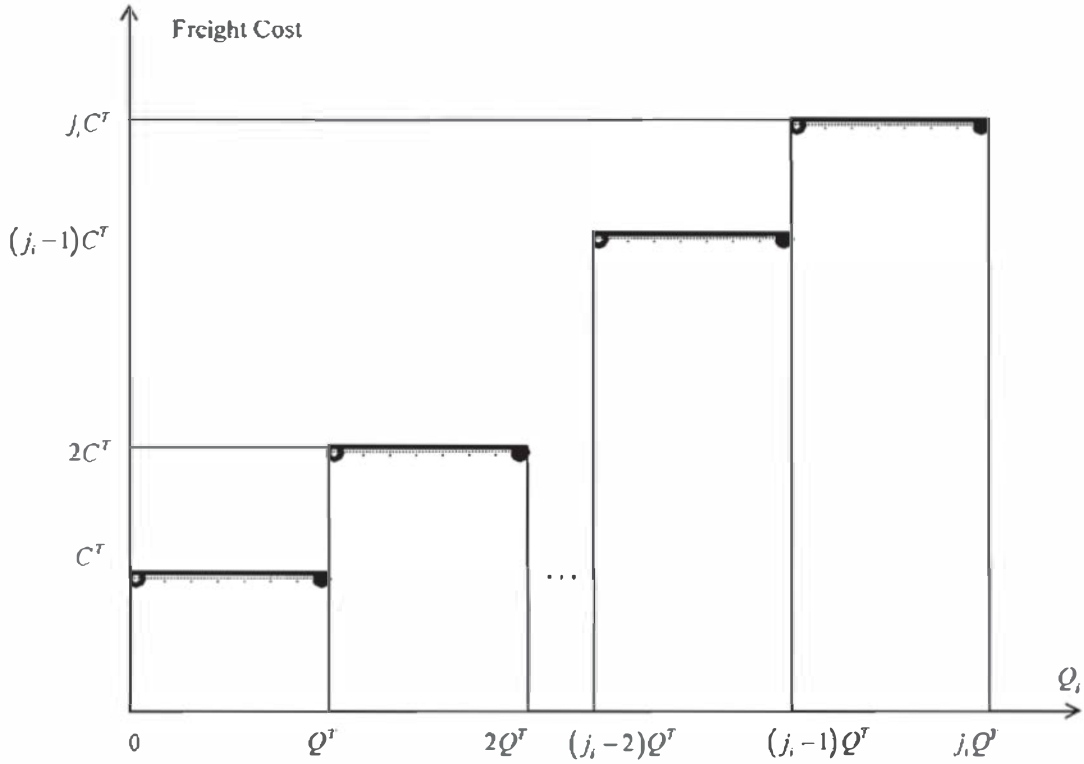


Figure 4.3: Freight cost of full-truckload (FTL) mode against ordering size Q_i of buyer i.

4.3.4 Hybrid Transportation

The vendor may either outsource delivery to third-party logistics by paying a per item fee or hire trucks (includes employing own trucks) for the delivery. Outsourcing delivery can be modeled by less-than-truckload transportation which involves "per-unit" fee s and a base cost C_b. Hiring trucks can be modeled by full-truckload transportation which involves the cost of employing a full truck. It has been discussed in section 4.3.2 that the vendor employs less-than-truckload transportation with the freight cost $F(Q_i) = \max\{C_{\min}, C_b + sQ_i\}$ when the vendor outsources delivery to a third-party logistics. It has also been discussed in section 4.3.3 that the vendor employs full-truckload transportation with the freight cost $F_i(Q_i) = j_iC^T$ when the vendor hires trucks or uses their own trucks.

The vendor may employ a hybrid transportation which allows the vendor to select between less-than-truckload (LTL) and full-truckload (FTL) transportation to deliver items so as to minimize the transportation cost. LTL transportation represents outsourcing delivery and FTL represents hiring trucks. Figure 4.4 illustrates the freight cost of hybrid transportation.

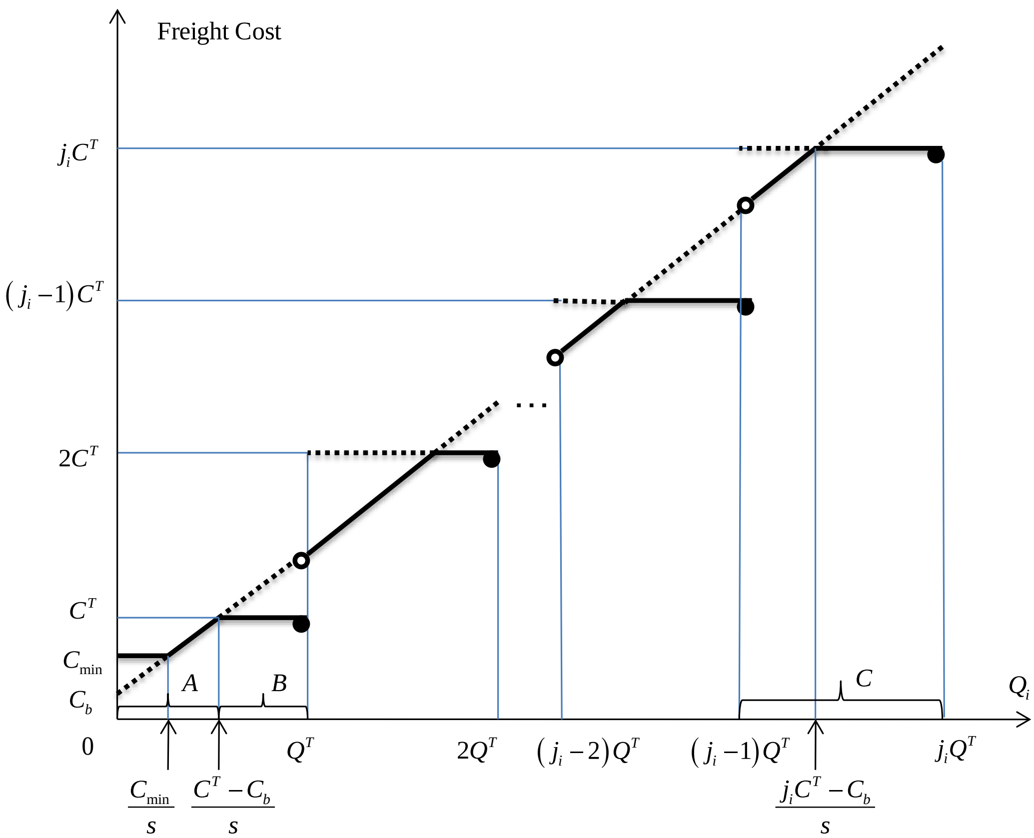


Figure 4.4: Freight cost of hybrid transportation against the order size Q_i of buyer i.

In Figure 4.4, when the order size Q_i of buyer i is less than the capacity of one truck Q^T as shown in region *A*, less-than-truckload transportation will be adopted with freight cost $F(Q_i) = \max\{C_{\min}, C_b + sQ_i\}$ because the freight cost of less-than truckload is less than the freight cost of one truck C^T. However, when the order size Q_i of buyer i is $\frac{C_{\min}}{s}$, the cost of less-than truckload sQ^T is equal to the cost of one full-truckload C^T. When the order size Q_i of buyer i is larger than $\frac{C^T - C_b}{s}$ but less than the capacity of one truck Q^T shown in region *B* in Figure 4.4, the freight cost of less-than truckload transportation $C_b + sQ^T$ (dotted line) is larger than that of full-truckload transportation C^T (solid line). Hence, full-truckload transportation with freight cost C^T will be adopted. When the order size Q_i of buyer i is $\frac{C^T - C_b}{s}$, both less-than-truckload and full-truckload transportations produce the same freight cost C^T. Generally, when the order size Q_i of buyer i is between $(j_i - 1)Q^T$ and $j_i Q^T$ shown in region *C*, the freight cost of less-than-truckload transportation $C_b + sQ^T$ is less than the freight cost of full-truckload transportation $j_i C^T$ if the order size Q_i of buyer i is less than $\frac{j_i C^T - C_b}{s}$. Thus, less-than-truckload transportation will be adopted with freight cost $C_b + sQ^T$. On the other hand, the freight cost of full-truckload transportation $j_i C^T$ is less than the freight cost of less-than-truckload transportation $C_b + sQ^T$ if the order size Q_i is larger than $\frac{j_i C^T - C_{\min}}{s}$. Thus, full-truckload transportation will be adopted with freight cost $j_i C^T$. When the order size Q_i of buyer i is $\frac{j_i C^T - C_{\min}}{s}$, the freight costs of both less-than-truckload transportation and full-truckload transportation are the same.

In general, when the order size Q_i of buyer i is between $\left(j_i - 1\right)Q^T$ and $j_i Q^T$ as shown in region *C*, the freight cost $F\,(Q_i)$ of hybrid transportation is $\min\left\{j_i C^T, C_b + sQ_i\right\}$ where $j_i > 1$ (j_i denotes the number of trucks employed for buyer i. Hence, the freight cost function $F(Q_i)$ of hybrid transportation is expressed as

$$F\,(Q_i) = \begin{cases} \max\left\{C_{\min}, C_b + sQ_i\right\} & \text{for } 0 < Q_i \le Q^T \\ \min\left\{j_i C^T, C_b + sQ_i\right\} & \text{for } \left(j_i - 1\right)Q^T < Q_i \le j_i Q^T \text{ and } j_i > 1 \end{cases}. \tag{4.7}$$

Since the transportation cost $C_i\left(Q_i\right)$ comprises a delivery cost C_i and a freight cost $F(Q_i)$ (see (4.1)), the hybrid transportation cost is expressed as

$$C_i(Q_i) = \begin{cases} \max\left\{C_{\min}, C_b + sQ_i\right\} + C_i & \text{for } 0 < Q_i \le Q^T \\ \min\left\{j_i C^T, C_b + sQ_i\right\} + C_i & \text{for } \left(j_i - 1\right)Q^T < Q_i \le j_i Q^T \text{and} j_i > 1 \end{cases}. \tag{4.8}$$

4.3.5 Two-tier-freight-rate Transportation

From the point of views of a third-party logistics, employing an additional truck will increase the overhead cost of transportation. Costs arising from employing an additional truck include employees, toll fee, insurance, maintenance, gasoline etc. Therefore, the per-unit freight rate s (charged by a third-party logistics) must be high enough to prevent from running a new truck for a small amount of goods. Also, a third-party logistics can afford a lower per-unit freight rate after an enough certain amount of carried goods have been received. Hence, after considering these two main features of transportation, a two-tier-freight-rate transportation is proposed in this section.

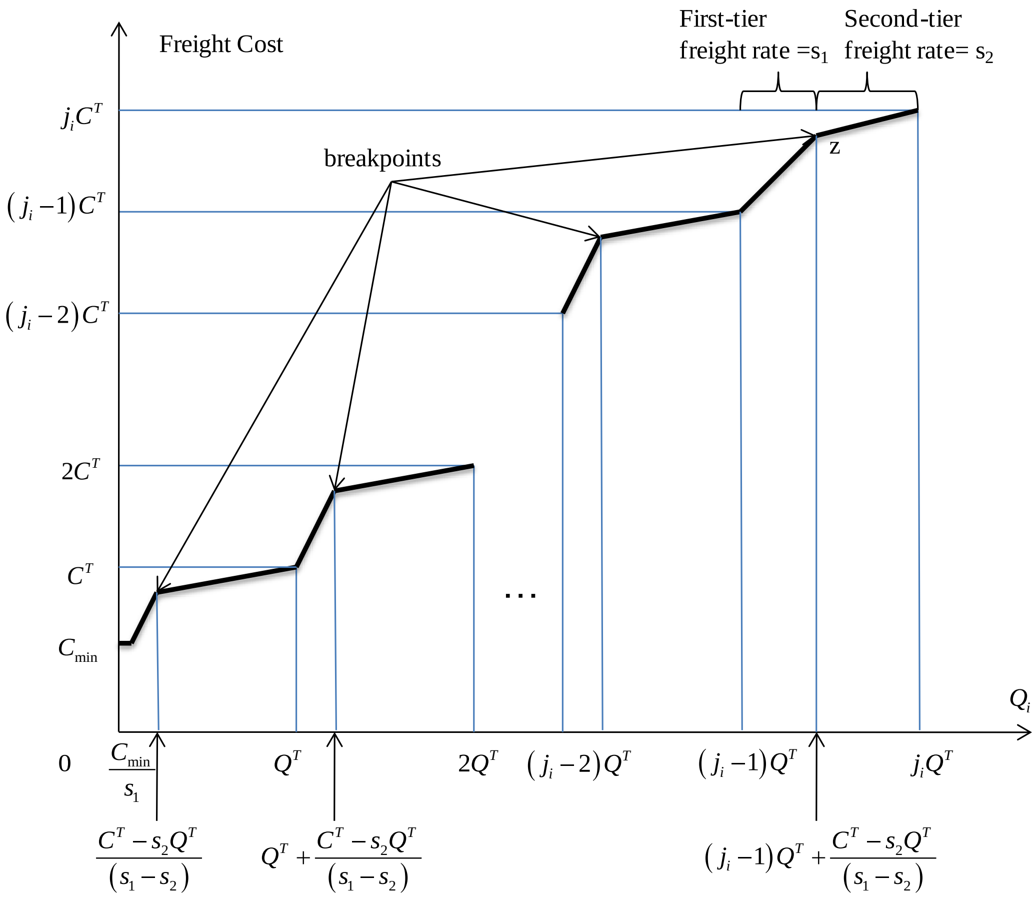


Figure 4.5: Two-tier freight-rate freight cost against order size Q_i of buyer i.

The two-tier-freight-rate transportation freight cost is represented by a solid line in Figure 4.5. When the order size Q_i of buyer i is less than a certain breakpoint z, which is called the first tier of a truck, a per-unit freight rate s_1 is imposed. When the order size Q_i of buyer i is larger than the breakpoint z, which is called the second tier of a truck, another per-unit freight rate s_2 is imposed. Hence, there are two freight rates s_1 and s_2 in a truck. In order to prevent from running a new truck with a small amount of carried goods, the freight rate s_1 in the first tier is larger than the freight rate s_2 in the second tier, $s_1 > s_2$. Let Q_i be the order size of buyer i and j_i be the number of trucks employed. The freight cost by the freight rate of first tier s_1 is $(j_i - 1)C^T + s_1\left(Q_i - (j_i - 1)Q^T\right)$ such that the vendor employs $(j_i - 1)$ full trucks and one less-than truck in the first-tier. On the other hand, the freight cost by the freight rate of second tier s_2 is $j_i C^T - s_2(j_i Q^T - Q_i)$ such that the vendor employs $(j_i - 1)$ full trucks and one less-than truck in the second-tier. At the breakpoint, the freight costs by the two freight rates are the same such that $(j_i - 1)C^T + s_1\left(Q_i - (j_i - 1)Q^T\right) = j_i C^T - s_2\left(j_i Q^T - Q_i\right)$. On solving this equation, when the order size Q_i of buyer i is $(j_i - 1)Q^T + \dfrac{C^T - s_2 Q^T}{s_1 - s_2}$ for $j_i > 1$, the freight costs by the two freight rates are the same which is the breakpoint of the freight rate function.

Similar to section 4.3.2, when the order size is too small, a minimum charge $C_{\min}$ will be imposed to compensate the overheads of third-party logistics. Therefore, the two-tier-freight-rate freight cost is expressed as

$$F\left(Q_i\right) = \begin{cases} max\left\{C_{min}, min\left\{s_1 Q_i, C^T - s_2 Q^T + s_2 Q_i\right\}\right\} & \text{for } 0 < Q_i \le Q^T \\ \left(j_i - 1\right)C^T + s_1\left(Q_i - \left(j_i - 1\right)Q^T\right) & \text{for } \left(j_i - 1\right)Q^T < Q_i \le z,\ j_i > 1 \\ j_i C^T - s_2\left(j_i Q^T - Q_i\right) & \text{for } z < Q_i \le j_i Q^T,\ j_i > 1 \end{cases}$$

where $z = \left(j_i - 1\right)Q^T + \dfrac{C^T - s_2 Q^T}{s_1 - s_2}$.

(4.9)

Since the transportation cost $C_i\left(Q_i\right)$ comprises a delivery cost C_i and a freight cost $F(Q_i)$ (see equation (4.1)). Hence, the two-tier-freight-rate transportation cost is expressed as

$$C_i\left(Q_i\right)=\begin{cases} max\left\{C_{min},min\left\{s_1 Q_i,C^T-s_2 Q^T+s_2 Q_i\right\}\right\}+C_i & \text{for } 0<Q_i\le Q^T \\ \left(j_i-1\right)C^T+s_1\left(Q_i-\left(j_i-1\right)Q^T\right)+C_i & \text{for } \left(j_i-1\right)Q^T<Q_i\le z,\ j_i>1 \\ j_i C^T-s_2\left(j_i Q^T-Q_i\right)+C_i & \text{for } z<Q_i\le j_i Q^T,\ j_i>1 \end{cases}$$

where $z=\left(j_i-1\right)Q^T+\dfrac{C^T-s_2 Q^T}{s_1-s_2}$.

(4.10)

4.4 Models Formulation

In section 4.3, five different transportations have been discussed. The transportation costs of diminishing freight rate, less-than-truckload, full-truckload, hybrid transportation, and two-tier-freight-rate transportation are expressed in equations (4.3), (4.5), (4.6), (4.8) and (4.10), respectively. In reality, the vendor can employ a third-party logistics who adopted one of the available transportation modes. Then, vendor and buyers can optimize their own costs independently or form coordination to optimize the total system cost. In the synchronized cycles model for a single-vendor multi-buyer supply chain, the total system is written as:

$$TC^{SYN}=\frac{S_v}{NT}+\frac{1}{2}hD\left(1-\frac{D}{P}\right)NT+\sum_{i=1}^{n}\left[d_i hk_i T\left(\frac{D}{P}-\frac{1}{2}\right)+\frac{1}{2}d_i h_i k_i T\right]+\sum_{i=1}^{n}\frac{A_i+C_i\left(d_i k_i T\right)}{k_i T}. \tag{4.11}$$

Note that equation (4.11) is extended from equation (3.21) and the transportation cost $C_i\left(d_i k_i T\right)$ depends on what transportation mode is adopted. The objective is to find the optimal solution N and k_i in order to minimize the total system cost TC^{SYN}.

4.5 Algorithm

Since only one of the possible transportation modes is available for all buyers, one of the transportations in equations (4.3), (4.5), (4.6), (4.8) and (4.10) is considered. When all buyers with deterministic demand rate d_i placed the first order at time T (i.e. $\delta_{i,1} = 1$) with order size $Q_i = d_i k_i T$ and ordering cycle $k_i T$ in a single-vendor multi-buyer supply chain system, an optimal solution of equation (4.11) for each N can be obtained by finding the minimum point at $k_i = k_i^*$, where k_i^* is a factor of N with the following algorithm. In the algorithm, the optimal number of trucks $j_i = j_i^*$ is also determined.

Main algorithm for the synchronized cycles model

Main algorithm

Step 1: Set N =1 and T =1

Step 2: Determine the value of k_i and j_i for fixed N and T by sub-algorithm.

Step 3: If $N < N^{\max}$ where $N^{\max}$ is the maximum planning horizon, then set $N = N + 1$ and go back to step 2.

Step 4: Take the value of N^* which gives the lowest total system cost in equation (4.11).

Sub-algorithm to find the value of k_i and j_i for given *N* and *T*

Step 1: Find all the factors of N .

Step 2: Consider each factor as a candidate for order cycle k_i for buyer i, calculate transportation cost $C_i(d_i k_i T)$ for each candidate of k_i such that $(j_i - 1)Q^T < d_i k_i T \leq j_i Q^T$ (each transportation mode has its own transportation cost function, i.e. equations (4.3), (4.5), (4.6), (4.8) or (4.10). Also calculate the cost function

$$f(k_i) = \frac{A_i + C(d_i k_i T)}{k_i T} + \left[h\left(\frac{D}{P} - \frac{1}{2}\right) - \frac{1}{2} h_i \right] d_i k_i T \ .$$

Step 3: Select k_i and its associated j_i which gives the least value of $f(k_i)$.

4.6 Results

4.6.1 Comparison between Independent Optimization and Synchronized Cycles Model with Different Transportation Modes.

Some numerical experiments have been carried out to investigate the performance of the synchronized cycles model and independent optimization. Three examples are used for the purpose of illustration and the data are shown in Tables A1 to A4 of Appendix A. By using the above mentioned algorithm, the results of the examples are found as follows:

The results of three numerical examples are shown in Table 4.1 for a comparison of the performance between Synchronized Cycles (SYN) Model and independent optimization (IND). The data are provided in Tables A1 to A4 of Appendix A. In diminishing freight rate transportation, it is assumed that $m = 4$, $s_1 = 0.7$,

$s_2 = 0.6$, $s_3 = 0.5$, $s_4 = 0.4$, and $U = 2000$. In less-than-truck transportation, full-truckload transportation and hybrid mode transportation, it is assumed that $s = 0.7$, $Q^T = 200$, $C^T = 140$, $C_{\min} = 20$ and $C_{\min}^0 = 50$, and $sQ^T = C^T$. Also, the symbol $j_i = \left\lceil \frac{d_i T_i}{C^T} \right\rceil$ denotes the number of full trucks employed for buyer i.

The average total system cost and average transportation cost of three examples are shown in Table 4.1. The average costs are calculated by DP ratios from 0.1 to 0.9. The individual results of each DP ratio are shown in Tables B4 to B18 of Appendix B. In Example 1, when the vendor delivers the goods to all buyers by diminishing freight rate transportation, the average total system cost of synchronized cycles model is 54.4 which is lower than that of independent optimization 70.8 by 23.16%. The average transportation cost of synchronized cycles model is 31.8 which is lower than that of independent optimization 49.9 by 36.27%. When the vendor delivers the goods to all buyers by less-than truckload (LTL) transportation, the average total system cost of synchronized cycles model is 67.4 which is lower than that of independent optimization 80.1 by 15.85%. The average transportation cost of synchronized cycles model is 48.3 which is lower than that of independent optimization 53.4 by 9.55%. When the vendor delivers the goods to all buyers by full truckload (FTL) transportation, the average total system cost of synchronized cycles model is 67.7 which is lower than that of independent optimization 100.5 by 32.64%. The average transportation cost of synchronized cycles model is 48.5 which is lower than that of independent optimization 79.7 by 39.15%. When the vendor delivers the goods to all buyers by hybrid transportation, the average total system cost of synchronized cycles model is 66.5 which is lower than that of independent optimization 80.1 by 16.98%. The average transportation cost of synchronized cycles model is 47.7 which is lower than that of independent optimization 59.2 by 19.43%. When the vendor delivers the goods to all buyers by two-tier freight-rate transportation, the average total system cost of synchronized cycles model is 65.2 which is lower than that of independent optimization 75.9 by 14.10%. The average transportation cost of synchronized cycles model is 47.1 which is lower than that of independent optimization 55 by 14.36%.

Example		Diminishing freight rate		LTL		FTL		Hybrid		Two-tier freight-rate	
		IND	SYN	IND	SYN	IND	SYN	IND	SYN	IND	SYN
1	Total system cost	70.8	54.4	80.1	67.4	100.5	67.7	80.1	66.5	75.9	65.2
	Transportation cost	49.9	31.8	53.4	48.3	79.7	48.5	59.2	47.7	55.0	47.1
2	Total system cost	843.5	634.0	911.4	703.3	1254.9	733.7	911.0	697.9	863.5	671.3
	Transportation cost	528.1	327.9	600.1	403.7	943.6	422.2	599.7	398.4	552.1	382.0
3	Total system cost	1772.5	1432.5	1953.7	1628.8	2560.9	1684.7	1946.9	1604.7	1835.5	1542.0
	Transportation cost	1027.9	777.8	1209.0	994.5	1816.3	1035.2	1202.2	973.1	1090.9	926.1

Table 4.1:The results of average total system costs and average transportation costs between synchronized cycles (SYN) model and independent optimization (IND) on different transportation modes.

The average cost saved is calculated by the difference between the average total system cost of independent optimization and that of synchronized cycles model. The percentage cost saved is calculated by the average cost saved divided by the total system cost of independent optimization. Then, the results of the average cost saved and percentage cost saved in total system cost and transportation cost under different transportation modes are shown in Table 4.2. In Example 1, when the vendor delivers the goods to all buyers by diminishing freight rate transportation, the average total system cost saved of synchronized cycle model is 16.4 which is reduced by 23.2%, compared with independent optimization. The average total transportation cost saved of synchronized cycle model is 18.1, reduced by 36.3% compared with independent optimization. In general, the synchronized cycles model using full truckload transportation gives the highest percentage of average cost saved in terms of system cost ranging from 32.6% to 41.5% and in terms of transportation cost ranging from 39.1% to 57% as shown in Table 4.2. Also, the diminishing freight rate is the second best transportation mode with percentage of average cost saved in terms of system cost ranging from 19% to 23% and in terms of transportation cost ranging from 24.3% to 37.9% as shown in Table 4.2.

The percentage of average total system cost and percentage of average transportation cost, saved by synchronized cycles model over independent optimization for various transportation modes, are also shown in Figure 4.6 and Figure 4.7, respectively.

Example		Diminishing freight rate		LTL		FTL		Hybrid		Two-tier freight-rate	
		Average cost saved	%	Average cost saved	%	Average cost saved	%	Average cost saved	%	Average cost saved	%
1	Total system cost	16.4	23.2 %	12.7	15.9 %	32.8	32.6 %	13.6	17.0 %	10.7	14.1 %
	Transportation cost	18.1	36.3 %	5.1	9.6 %	31.2	39.1 %	11.5	19.4 %	7.9	14.4 %
2	Total system cost	209.5	24.8 %	208.1	22.8 %	521.2	41.5 %	213.1	23.4 %	192.2	22.3 %
	Transportation cost	200.2	37.9 %	196.4	32.7 %	521.4	55.3 %	201.3	33.6 %	170.1	30.8 %
3	Total system cost	340.0	19.2 %	324.9	16.6 %	876.2	34.2 %	342.2	17.6 %	293.5	16.0 %
	Transportation cost	250.1	24.3 %	214.5	17.7 %	781.1	43.0 %	229.1	19.1 %	164.8	15.1 %

Table 4.2: The results on the average cost saved and the percentage cost saved in the total system cost and the transportation cost of synchronized cycles (SYN) model against independent optimization (IND) on different transportation modes for three examples.

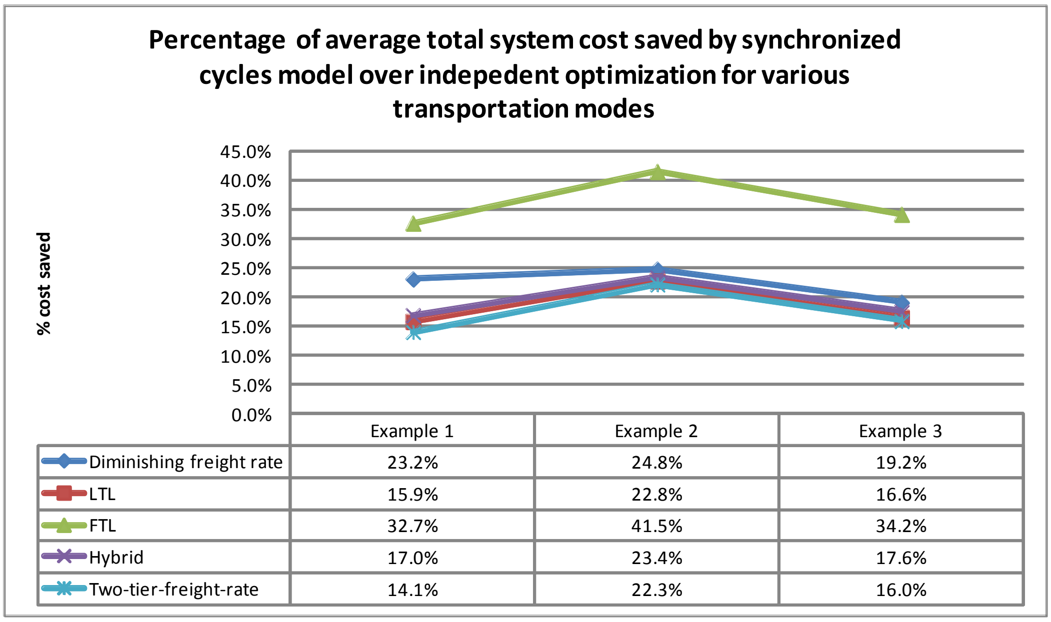
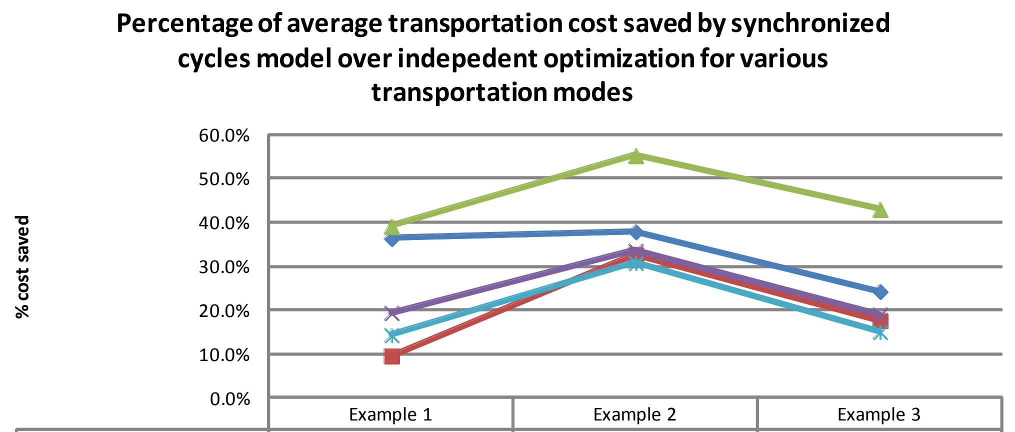


Figure 4.6: Percentage of average total system cost saved by synchronized cycles model over independent optimization for various transportation modes.



	Example 1	Example 2	Example 3
Diminishing freight rate	36.4%	37.9%	24.3%
LTL	9.7%	32.7%	17.7%
FTL	39.1%	55.3%	43.0%
Hybrid	19.4%	33.6%	19.1%
Two-tier-freight-rate	14.4%	30.8%	15.1%

Figure 4.7: Percentage of average transportation cost saved by synchronized cycles model over independent optimization for various transportation modes.

4.6.2 Sensitivity Test on the Average Percentage Saved due to Truck Sizes under Different Transportation Modes.

It is clear that the per-unit freight rate and truck capacity would affect the total system cost and transportation cost. Sensitivity tests can show how the parameters of freight rates and truck size affect the total system cost. In this section, truck sizes are varied by multiplying 50% or reducing 50% of the original truck size. Since $C^T = sQ^T$ in LTL, FTL and hybrid modes, the freight rate per-unit weight s will also be changed to keep the truck cost C^T unchanged. The percentage saving is calculated by the actual cost saved by synchronized cycles model over independent optimization in each DP ratio. Then, average percentage saving is the mean of these percentage saving with DP ratio from 0.1 to 0.9. The average percentage saving in total cost of DP ratios from 0.1 to 0.9 is shown in Table 4.3. The detailed results for each DP ratio are shown in Tables B19 to B42 of Appendix B.

In Table 4.3, when the vendor employs diminishing freight rate transportation, the percentage cost saved of synchronized cycles model over independent optimization in Example 1 is 23% when the capacity of truck is 100, 200 and 300. In Example 2 and 3, the percentage cost saved of synchronized cycles model over independent optimization remains unchanged when the capacity of truck varying from 100 to 300. When the vendor employs less-than truckload transportation, the percentage cost saved of synchronized cycles model over independent optimization in Example 1 rises from 15.8% to 19.0% if the freight rate s decreases from 0.7 to 7/15. The percentage cost saved of synchronized cycles model over independent optimization in Example 1 drops from 15.8% is 10.5% if the freight rate s increases from 0.7 to 1.4. When the vendor employs full truckload transportation, the percentage cost saved of synchronized cycles model over independent optimization in Example 1 rises from 32.7% to 36.8% if the capacity of truck Q^T increases from 200 to 300. The percentage cost saved of synchronized cycles model over independent optimization in Example 1 drops from 32.7% to 28.5% if the capacity of truck Q^T decreases from 200 to 100. When the vendor employs hybrid transportation, the percentage cost saved of synchronized cycles model over independent optimization in Example 1 rises from 16.9% to 20.5% if the capacity of truck Q^T increases from 200 to 300. The percentage cost saved of synchronized cycles model over independent optimization in Example 1 drop from 16.9% to 10.8% if the capacity of truck Q^T decreases from 200 to 100. When the vendor employs two-tier freight rate transportation, the percentage cost saved of synchronized cycles model over independent optimization in Example 1 rises from 14.2% to 16.2% if a pair of freight rates (s_1, s_2) changes from $(0.8, 0.6)$ to $(0.9, 0.5)$. The percentage cost saved of synchronized cycles model over independent optimization in Example 1 drops from 14.2% to 12.5% if a pair of freight rates (s_1, s_2) changes from $(0.8, 0.6)$ to $(0.7, 0.7)$. From the above results, It is found that the percentage cost saved of synchronized cycles model over independent optimization is significantly when the capacity of trucks Q^T is large. In general, the synchronized cycle model has a double-digit improvement over independent optimization for all truck sizes.

	The percentage of cost saved of synchronized cycles model, compared with independent optimization		
Diminishing freight rate	Q^T=100, s=1.4	Q^T=200, s=0.7	Q^T=300, s=7/15
Example 1	23.0%	23.0%	23.0%
Example 2	24.7%	24.7%	24.7%
Example 3	19.0%	19.0%	19.0%
Less-than truckload	Q^T=100, s=1.4	Q^T=200, s=0.7	Q^T=300, s=7/15
Example 1	10.5%	15.8%	19.0%
Example 2	16.8%	22.7%	26.6%
Example 3	11.3%	16.5%	19.9%
Full-truckload	Q^T=100	Q^T=200	Q^T=300
Example 1	28.5%	32.7%	36.8%
Example 2	31.2%	41.5%	48.6%
Example 3	24.7%	34.2%	41.7%
Hybrid	Q^T=100, s=1.4	Q^T=200, s=0.7	Q^T=300, s=7/15
Example 1	10.8%	16.9%	20.5%
Example 2	17.0%	23.3%	26.9%
Example 3	11.2%	17.5%	20.9%
Two-tier freight rate	s_1=0.7,s_2=0.7	s_1=0.8,s_2=0.6	s_1=0.9,s_2=0.5
Example 1	12.5%	14.2%	16.2%
Example 2	21.2%	21.9%	23.3%
Example 3	14.9%	16.1%	18.4%

Table 4.3: The percentage cost saved of synchronized cycles model, compared with independent optimization on different freight rates for three examples.

4.7 Transportation with Improvement Algorithm

In Chapter 3, some improvement algorithms such as incremental approach and inventory approach have been discussed for the synchronized cycles model in which the transportation cost is kept constant regardless of the order size or weight of the buyers. In this section, these methods are applied to the situation that LTL/FTL transportation is incorporated into the synchronized cycles model. Hybrid transportation mode is incorporated into the synchronized cycles model since hybrid transportation mode consists of LTL and FTL transportation. For comparison, four cases are considered: (1) without improvement algorithm (2) incremental approach (3) inventory approach (4) genetic algorithm. Equation (3.21) is used for case (1), and equation (3.18) is used for cases (2) - (4). The numerical results will be shown in section 4.8.

4.7.1 Algorithm of Inventory Approach

Main algorithm for the synchronized cycles model

Step 1: Set $N = 1$ and $T = 1$.

Step 2: Determine the value of k_i and j_i for fixed N and T by sub-algorithm.

Step 3: If $N < N^{max}$ where $N^{\max}$ is the maximum planning horizon, then set $N = N + 1$ and go back to step 2.

Step 4: Take the value of N^* which gives the lowest total relevant cost in equation (3.21).

Step 5: Apply inventory approach sub-algorithm to determine the value of time t such that $\delta_{i,t} = 1$.

Step 6: Calculate the total system cost by equation (3.18).

Sub-algorithm to find the value of k_i and j_i for given N and T

Step 1: Find all the factors of N.

Step 2: Consider each factor as a candidate for order cycle k_i for buyer i, calculate transportation cost $C_i(d_i k_i T)$ for each candidate of k_i such that $(j_i - 1)Q^T < d_i k_i T \leq j_i Q^T$ (each transportation mode has its own transportation cost function, i.e. equations (4.3), (4.5), (4.6), (4.8) or (4.10). Also calculate the cost function

$$f(k_i) = \frac{A_i + C_i(d_i k_i T)}{k_i T} + \left[h\left(\frac{D}{P} - \frac{1}{2} \right) - \frac{1}{2} h_i \right] d_i k_i T .$$

Step 3: Select k_i and its associated j_i which give the least value of $f(k_i)$.

Step 4: Apply inventory approach sub-algorithm for the given N, T, and k_i^* to determine t which $\delta_{i,t} = 1$.

Inventory approach sub-algorithm (to determine t for $\delta_{i,t} = 1$)

After ordering cycle k_i have been evaluated, the first order time t_i of buyer i is determined such that $\delta_{i,t} = 1$. Let $D_j^{'}$ be the assigned demand at time jT, and S_j be the inventory level available at time jT. Let D^a be a set of assigned demand $\left(D_1^{'}, D_2^{'}, ..., D_j^{'}, ..., D_N^{'}\right)$. Let ψ_j be the surplus stock at time jT and t_i be the first ordering time of buyer i.

Step 1: Start with time T, $j = 1$.

Step 2: Initialize $D_j^{'} = 0$, $t_i = 0$, and $S_j = P_j = PT$.

Step 3: Consider unassigned buyers with smallest k_i.

Step 4: If $k_i = j$, go to step 5, or else go to Step 7.

Step 5: Assign $\delta_{i,j} = 1$ for buyers with $k_i = j$ and $t_i = j$.

Update D^a and $D_j^{'}$ by $D_{j+lk_i}^{'} = D_{j+lk_i}^{'} + \sum_{i=1}^{n} \delta_{i,j} d_i k_i T$ and update

$\delta_{i,j+lk_i} = 1$ for $l = 0,1,2,..., \frac{N}{k_i} - 1$.

Update $S_j = S_j - \sum_{i=1}^{n} \delta_{i,j} d_i k_i T$.

If buyers are assigned completely, exit.

Step 6: If $S_j \geq 0$, go to step 7 , or else go to Step 9.

Step 7: If $S_j \geq \min\{d_i k_i T\}$ for unassigned buyers, go to step 8.

Else $j = j+1$, $S_j = S_{j-1} + P_j - D_j$. Go to step 3.

Step 8: Select buyer i such that $S_j = S_j - d_i k_i T$ is the least.

Assign $\delta_{i,j} = 1$ for the selected buyer i and $t_i = j$.

Update D^a and $D_j^{'}$ by $D_{j+lk_i}^{'} = D_{j+lk_i}^{'} + \sum_{i=1}^{n} \delta_{i,j} d_i k_i T$ and update

$\delta_{i,j+lk_i} = 1$ for $l = 0,1,2,..., \frac{N}{k_i} - 1$.

Update $S_j = S_j - \sum_{i=1}^{n} \delta_{i,j} d_i k_i T$.

If buyers are assigned completely, exit, or else go to step 6.

Step 9: Update surplus stock $\psi_j = -S_j$.

$j = j+1$, $S_j = S_{j-1} + P_j - D_j$.

If $S_j \geq 0$, go to step 3, or else repeat step 9.

Remarks:

The surplus stock ψ_j at time jT can be determined by equation (3.22).

4.7.2 Algorithm on Incremental Approach

Similar to Chapter 3 as mentioned, first of all, by incrementing one buyer at a time, t to $t+1$ in $\delta_{i,t}=1$, n different increments for n distinct buyers and hence n new solutions are obtained. Then, the best solution is selected from the n new solutions by comparing it with that before increment. If the new solutions cannot be improved, the process will stop and treat the best solution before the increment as the optimal solution. Otherwise, the incremental procedure will continue until the time tT in $\delta_{i,t}=1$ for all the buyers equals to their k_i's. That is, $\delta_{i,k_i}=1$ for all i.

4.7.3 Genetic Algorithm

Similar to chapter 3 as mentioned, the process of genetic algorithm is described as follows:

Step 1: Firstly, an initial population of size 20 is created by a random process. The fitness values of the strings in the initial population are also calculated.

Step 2: 1 pair of parents is chosen by using a biased roulette wheel from population.

Step 3: Their offsprings of the chosen parents are produced by crossover and by mutation. Then, reproduce two offsprings from the chosen pair of parents. If the production cycles (N) of a pair of parent are equal, then reproduce by crossover or mutation. A random number r between 0 and 1 is generated. If $r \leq p_c$, produce an offspring by a crossover process. If $r > p_c$, another random number r' is generated. If $r' \leq p_m$, mutation will be conducted; otherwise, no mutation will be started. If production cycles (N) of a pair of parents are not equal, since it is possible that no common factor k'_i can be exchanged by crossover, thus reproduce the offspring only by mutation process. A random number r'' between 0 and 1 is generated. If $r'' \leq p_m$, produce an offspring by a mutation process. If $r'' > p_m$,no mutation will be started. Note that the mutation rate p_m and crossover rate p_c are pre-determined.

Step 4: Repeat step 2 and step 3, 20 times until 20 pairs of offspring have been produced.

Step 5: Keep the top 20 strings from the combined group of population and offsprings. These 20 strings become the population for the next reproduction.

Step 6: Repeat step 2 to step 5 until the stopping criterion (200 iterations) has been reached. Choose the best (fittest) solution in the population as the “optimal” solution of the problem.

Step 7: Repeat step 1 to step 6 with 10 times (samples), select the best solution of the 10 as the final solution.

4.8 Numerical Results of Improvement Algorithms

Some numerical experiments have been carried out to investigate the performance of different improvement algorithms in synchronized cycles model. Three examples are used for the purpose of illustration and the data are shown in Tables A1 to A5 of Appendix A. By using the different algorithms, the results of the examples are found as follows:

Some improvement algorithms such as incremental approach and inventory approach to synchronized cycle model with hybrid transportation mode have also been discussed in section 4.7. Genetic algorithm has also been adopted to find the optimal solution. Now, the total costs of synchronized cycles model with hybrid transportation model under these methods are compared with the model without improvement algorithm. It is found that the total cost without improvement algorithm is the highest and the total cost under inventory approach is the least among all methods in Figure 4.8 and Figure 4.9. When DP ratio is 0.1, the total costs are close to one another as shown in Figures 4.8, 4.9 and 4.10. However, the difference of the total costs is larger as the DP ratio increases. The total costs of both incremental approach and genetic algorithm are also close to each other. However, the total cost under genetic algorithm is higher than that without improvement algorithm when DP ratio is between 0.1 and 0.6 in Figure 4.10. Also, the total cost using inventory approach is the lowerest when the DP ratio is between 0.2 and 0.9.

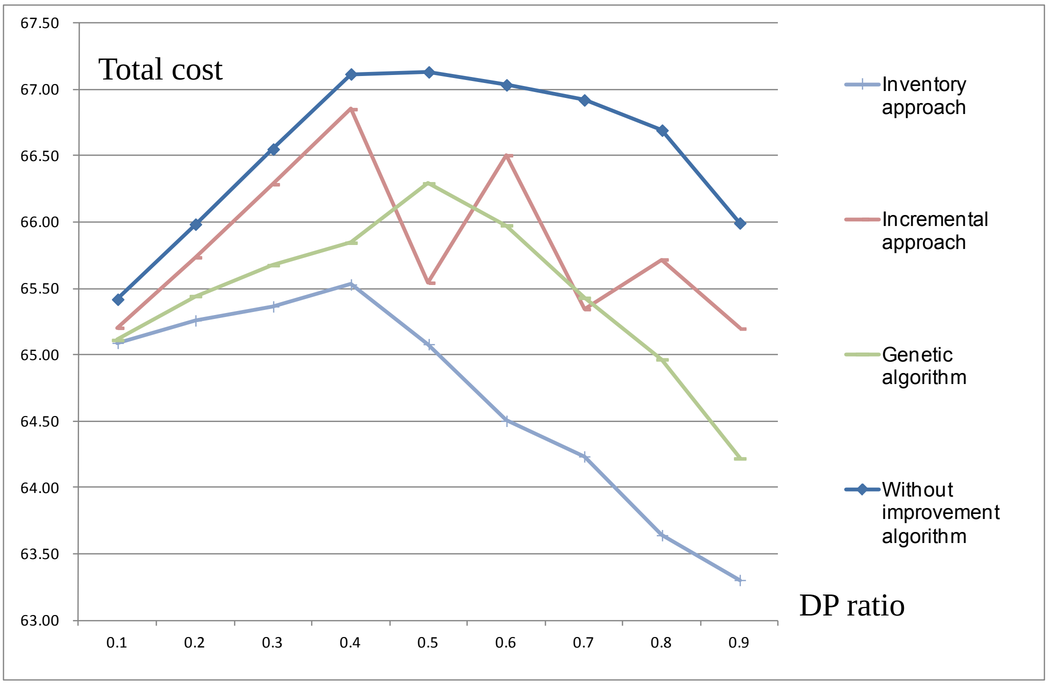


Figure 4.8 : Comparison of different improvement algorithms in Example 1.

In Figure 4.8, when DP ratio is 0.1, the total cost of syncrhonized cycles model with inventory approach, incremental approach, genetic algorithm and without improvement algorithm are 65.09, 65.2 65.11 and 65.42, respectively. It is found that the total cost without improvement algorithm is the upper bound and the total cost with inventory approach gives the lowest total costs for DP ratio from 0.1 to 0.9.

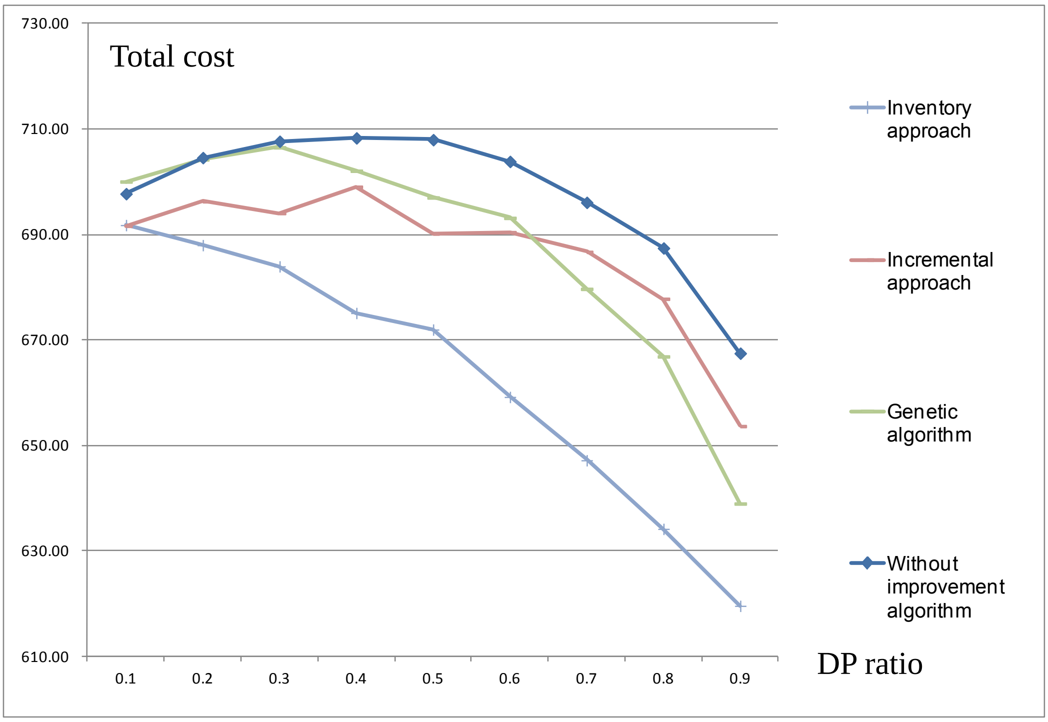


Figure 4.9: Comparison of different improvement algorithms in Example 2.

In Figure 4.9, when DP ratio is 0.1, the total cost of syncrhonized cycles model with inventory approach, incremental approach, genetic algorithm and without improvement algorithm are 691.78, 691.64, 700.03 and 697.73, respectively. It is found that the total cost without improvement algorithm is the upper bound and the total cost with inventory approach gives the lowest total costs for most of the DP ratios except 0.1. When DP ratio is 0.1, incremental approach gives the lowest total cost.

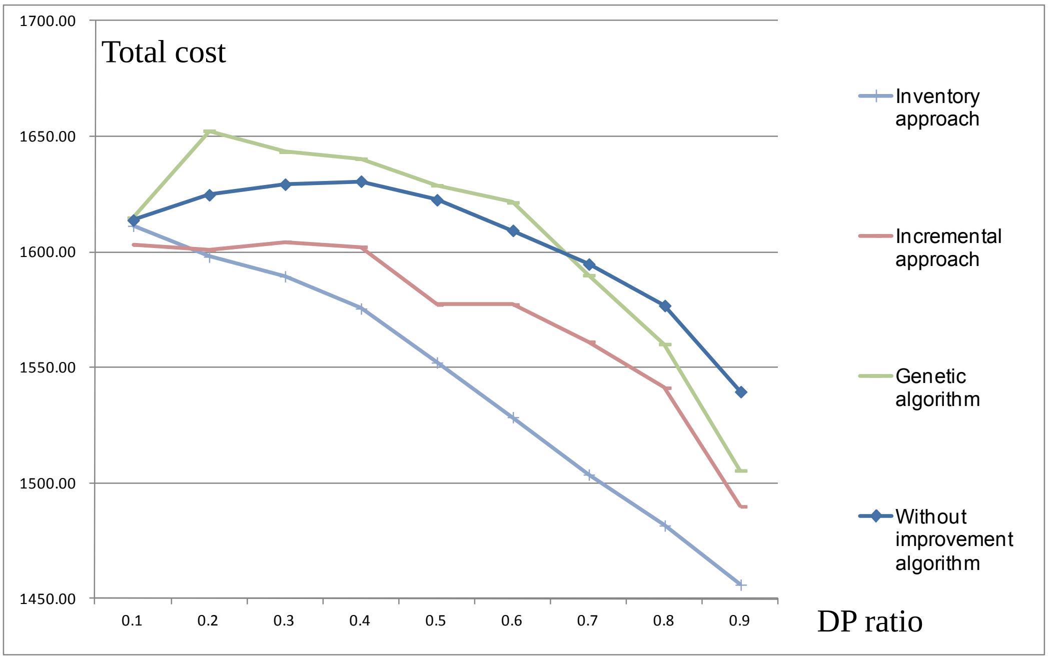


Figure 4.10 : Comparison of different improvement algorithms in Example 3.

In Figure 4.10, when DP ratio is 0.1, the total cost of syncrhonized cycles model with inventory approach, incremental approach, genetic algorithm and without improvement algorithm are 1611.36, 1603.22, 1614.91 and 1613, respectively. It is found that the total cost with inventory approach gives the lowest total costs for most of the DP ratios except 0.1. When DP ratio is 0.1, incremental approach gives the lowest total cost. From the above results, inventory approach can further reduce cost significantly for medium/large DP ratios and Incremental Approch can further reduce cost significantly for small DP ratio.

	Inventory approach			Incremental approach			Genetic algorithm			Without improvement algorithm	
DP ratio	N	Total cost	%	N	Total cost	%	N	Total cost	%	N	Total cost
0.1	39	65.09	0.50%	39	65.20	0.33%	49	65.11	0.47%	39	65.42
0.2	39	65.26	1.10%	39	65.73	0.38%	49	65.44	0.82%	39	65.98
0.3	39	65.36	1.78%	39	66.28	0.40%	49	65.68	1.31%	39	66.55
0.4	39	65.53	2.36%	39	66.85	0.39%	49	65.84	1.89%	39	67.12
0.5	78	65.08	3.05%	78	65.54	2.36%	49	66.29	1.25%	78	67.13
0.6	78	64.50	3.77%	78	66.50	0.79%	39	65.98	1.58%	78	67.03
0.7	78	64.24	4.01%	78	65.34	2.35%	78	65.43	2.23%	78	66.92
0.8	78	63.64	4.57%	78	65.72	1.46%	117	64.97	2.59%	78	66.69
0.9	156	63.30	4.07%	156	65.20	1.20%	117	64.22	2.69%	156	65.99
Time	0.4524 seconds			0.4368 seconds			24.2114 seconds			0.4056 seconds	

Table 4.4: The percentage cost saved of different algorithms compared that the total cost without improvement algorithm in Example 1.

When DP ratio is 0.1 in Table 4.4, the percentage cost saved by inventory approach in Example 1 is 0.5%, compared with the total cost without improvement alogithm. It is larger than 0.33% and 0.47% by incremental approach and genetic algorithm, respectively. When DP ratio is higher, the percentage cost saved by Inventory Appraoch will be larger. Also, in terms of computational time, the times taken by inventory approach, incremental approach and genetic algorihm are 0.4524 seconds , 0.4368 seconds and 24.2114 seconds, respectively, with the speed of computer at 2.83GHz.

When DP ratio is 0.1 in Table 4.5, the percentage cost saved by inventory approach in Example 2 is 0.85%, compared with the total cost without improvement alogithm. It is between 0.87% and -0.33% by incremental approach and genetic algorithm, respectively. When DP ratio is higher, the percentage cost saved by Inventory Appraoch will be larger. Also, in terms of computational time, the times taken by inventory approach, incremental approach and genetic algorihm are 1.1076 seconds , 0.9984 seconds and 1 minute 6.144 seconds, respectively, with the speed of computer at 2.83GHz.

	Inventory approach			Incremental approach			Genetic algorithm			Without improvement algorithm	
DP ratio	N	Total cost	%	N	Total cost	%	N	Total cost	%	N	Total cost
0.1	24	691.78	0.85%	24	691.64	0.87%	26	700.03	-0.33%	24	697.73
0.2	24	687.98	2.35%	24	696.29	1.17%	22	704.22	0.05%	24	704.56
0.3	28	683.96	3.35%	28	694.06	1.92%	24	706.51	0.16%	28	707.66
0.4	30	675.12	4.68%	30	699.05	1.31%	30	702.08	0.88%	30	708.30
0.5	30	671.99	5.08%	30	690.18	2.51%	28	697.01	1.55%	30	707.96
0.6	36	659.22	6.34%	36	690.44	1.90%	44	693.15	1.52%	36	703.84
0.7	42	647.22	7.02%	42	686.71	1.35%	42	679.70	2.35%	42	696.08
0.8	42	634.22	7.74%	42	677.82	1.40%	56	666.89	2.99%	42	687.44
0.9	84	619.64	7.17%	84	653.70	2.07%	88	639.02	4.27%	84	667.51
Time	1.1076 seconds			0.9984 seconds			1’6.144 seconds			0.5148 seconds	

Table 4.5: The percentage cost saved of different algorithms compared that the total cost without improvement algorithm in Example 2.

	Inventory approach			Incremental approach			Genetic algorithm			Without improvement algorithm	
DP ratio	N	Total cost	%	N	Total cost	%	N	Total cost	%	N	Total cost
0.1	16	1611.36	0.15%	16	1603.22	0.66%	17	1614.91	-0.07%	16	1613.84
0.2	18	1598.01	1.65%	18	1600.98	1.46%	16	1652.50	-1.71%	18	1624.78
0.3	18	1589.50	2.45%	18	1604.44	1.53%	18	1643.40	-0.86%	18	1629.37
0.4	18	1575.57	3.38%	18	1602.28	1.74%	20	1640.40	-0.60%	18	1630.66
0.5	24	1552.21	4.34%	24	1577.32	2.79%	24	1628.90	-0.39%	24	1622.62
0.6	24	1528.58	5.02%	24	1577.32	1.99%	24	1621.50	-0.75%	24	1609.38
0.7	24	1503.72	5.71%	24	1561.24	2.10%	32	1590.00	0.30%	24	1594.81
0.8	36	1481.68	6.04%	36	1541.30	2.26%	32	1560.20	1.06%	36	1576.87
0.9	36	1456.09	5.43%	36	1489.98	3.22%	49	1505.50	2.22%	36	1539.62
Time	1.5444 seconds			2.8704 seconds			4 minutes 16 seconds			0.8424 seconds	

Table 4.6: The percentage cost saved of different algorithms compared that the total cost without improvement algorithm in Example 3.

When DP ratio is 0.1 in Table 4.6, the percentage cost saved by inventory approach in Example 3 is 0.15%, compared with the total cost without improvement alogithm. It is between 0.66% and -0.07% by incremental approach and genetic algorithm, respectively. When DP ratio is higher, the percentage cost saved by inventory approach will be larger. Also, in terms of computational time, the times taken by inventory approach, incremental approach and genetic algorihm are 1.5444 seconds , 2.8704 seconds and 4 minutes 16.5904 seconds, respectively, with the speed of computer at 2.83GHz. The Intel (R) core (TM) Quad CPU Q9550 with speed of 2.83GHz is used to run the results.

4.9 Discussions

In this research, different transportation costs are considered which comprises freight cost as well as delivery cost. The freight cost depends on the order sizes of buyers instead of using constant shipment cost. Five different transportation modes namely diminishing freight rate, less-than-truckload, full-truckload, hybrid, and two-tier freight rate transportations are considered. Diminishing freight rate transportation of synchronized cycles model, compared with that of independent optimization, gives the second best improvement, although this transportation mode was commonly used in most of the literature. Full-truckload transportation gives the best improvement, when synchronized cycles model is compared with independent optimization. The synchronized cycles model in single-vendor multi-buyer supply chain with different transportations, compared with independent optimization, gives a significant improvement in total system cost and transportation cost of a single-vendor multi-buyer supply chain system. The hybrid mode of transportation gives a lower cost compared with pure LTL or pure FTL. In the process of optimizing the system cost under synchronized cycles model, it helps to save the transportation cost over the independent optimization. It is also shown that the inventory approach works better than incremental approach in optimizing the synchronized cycles model with different kinds of transportation mode. When the DP ratio is high, the improvement is more significant.

Chapter 5

Supply Chain Models with Environmental Performance

5.1 Introduction

Can vendors and buyers coordinate for the benefit of the environment? A general result that applies in all analysis of coordinated vendor-buyer models is that, when compared with independent optimization, a coordinated model makes a significant reduction in the total system cost. Hence, most of the literature on the supply chain coordination concentrates on minimizing costs only. There is little work addressing environmental issues as an objective of vendor-buyer coordination. This research is concerned with integrating cost and environmental performance measures in a single comprehensive mathematical model so as to optimize the production and ordering policies and environmental performance at the same time.

5.2 Objectives

Supply Chain Management is one of the main industries identified by many countries and regions including the Hong Kong Special Administrative Region (HKSAR) government for accelerated development and substantial growth to support the local economy. Especially, the growth of supply chain activities in Pearl River Delta including Hong Kong, Macau and Mainland China will be enormous in the years ahead. Effective coordination plays an important role in the successful operation of supply chains. If no such coordination exists, then the vendor and the buyer will act independently to make decisions that maximize their respective profits or minimize their costs. This may not be optimal if one considers the supply chain as a whole. How best to achieve effective coordination between the suppliers and the buyers is both a current managerial concern and an important research issue. However, most of the literature on vendor-buyer coordination only concentrates on the objective of minimizing the total system costs.

With the increasing environmental awareness in the general public, many organizations are beginning to acknowledge that strategies and practices – which incorporate environmental considerations – are becoming essential to acquire a competitive advantage. In addition, the formation of many environmental organization, and the new legislations adopted in some countries have resulted in higher pressure and drivers for enterprises to improve environmental performance. Hence, taking environmental impacts into vendor-buyer coordination is of vital importance.

The objectives of this chapter are not only concerned with the economic impact of vendor-buyer coordination on the organization carrying them out, but also with the wider effects on the society, such as effects of air pollution on the environment. This research proposes to develop a single-vendor multi-buyer coordination model which includes both costs and environmental measures in its objective function. It is believed that the environmental performance of a supply chain can be improved if the performance measures are included in the objective function of a coordinated model. This is obviously desirable as environmental protection is becoming more and more important globally.

5.3 Environmental Measures

In chapter 3, the cost-minimizing models including independent optimization (or independent policy model) and synchronized cycles model in a single-vendor multi-buyer supply chain have been studied. However, existing cost-minimizing supply chain models which put stress on financial performance did not pay much attention to the environment.

In this chapter, three environmental performance measures are considered in a single-vendor multi-buyer supply chain model. The environmental performance measures include energy wastage per-unit time, raw materials wastage per-unit time and air pollution per-unit time. It may not be easy to get actual values of the above three measures directly, but they may be reflected by some other indirect. For instance, energy wastage is proportional to the number of production runs of vendor, raw materials wastage is proportional to the average inventory level of vendor, and air pollution is proportional to the total number of orders/deliveries. With the consideration of these indirect measurements, the impacts of different supply chain models on environmental performance can be compared.

5.4 Risk Attitudes and Their Utility Functions

As costs and environmental performance measures have different units of measurements, it is necessary to transform the different measurements to a common one so that all measures can be integrated into the objective function. In this research, utility measure is adopted to “generalize” the units of different measurements and more significantly, evaluate the different attitudes towards costs and environmental issues of different parties. In economics, utility is a measure of relative satisfaction of different choices. The utility functions, which show the level of satisfaction, depend on the risk attitudes of vendor and buyer. In this research, buyers and vendor are classified into three different categories of risk attitudes i.e. risk-averse, risk-neutral and risk-prone. Hence, each buyer or vendor has its own utility function on the cost and different environmental measures. For example, large buyers are risk-prone on costs because they can afford larger increase in cost whereas small buyers are risk-averse on cost as their utility value drops sharply when cost start to increase. For small to medium enterprises, they may not be willing to invest too much on environmental protection due to their financial status, these companies would prefer spending less instead of coping closely to the environmental issues. Therefore, the utility functions of the environmental measures are similar to the risk-prone (environmental insensitive) utility; while the utility function of the total system cost corresponds to the risk-averse (cost-sensitive) utility. For medium large to large enterprises, the companies has a sufficient level of capital for investment, and these companies may invest more on protecting the environment such that they can gain more goodwill from the general public, as well as the local government. These companies may have a utility function similar to the risk-averse utility on the environment measures; while the utility of the costs may look like the risk-neutral or the risk-prone utility functions.

Let x_{ij} be the real measured value on costs and environmental measurement of buyer i (of vendor, $i=0$) on the j^{th} measure in single-vendor multi-buyer supply chain. Let $x_{i1}\left(i=1,2,\ldots n\right)$ represents the total cost of buyer i and

x_{01} represents the total cost of the vendor. Let x_{i2} $\left(i = 0,1,2,...n\right)$ represents the number of production run per-unit time which measures the energy wastage. Let x_{i3} $\left(i = 0,1,2,...n\right)$ represents the average inventory holding of vendor per-unit time which measures the raw material wastage. Let x_{i4} $\left(i = 1,2,...n\right)$ represents the number of orders of buyer i per-unit time and x_{04} represents the total number of orders of all buyers per-unit time to measure the air pollution.

Since costs and environmental performance measures have different units of measurements, it is necessary to incorporate all measures into a common objective function. In this thesis, utility function is considered. Denote $U_{ij}\left(.\right)$ as the utility function of the i^{th} party on the j^{th} measure ($i = 0$ represents the vendor and $i = 1,2,...,n$ corresponding to the $\boldsymbol{i}^{\text{th}}$ buyer; $j = 1$ represents the total cost, $j = 2$ represents the energy wastage, $j = 3$ represents the raw material wastage and $j = 4$ represents the air pollution). Hence, $U_{i1}(.)$, $U_{i2}(.)$, $U_{i3}(.)$ and $U_{i4}(.)$ are the utility functions of total cost, raw material wastage, energy wastage and air pollution of the $\boldsymbol{i}^{\text{th}}$ party, respectively. Similar to Kainuma and Tawara (2006), the proposed utility values of the different measures lie between 0 and -1 inclusively. A value of -1 represents the worst situation of a measure in the system. For example, previous research showed that most of the coordination models out-perform the independent optimization in terms of total system cost. Hence, the total cost incurred under the independent optimization is assigned a utility of -1.

Let Δ_{ij} be the maximum value (worst situation) of the j[th] measure of party i such that $U_{ij}\left(\Delta_{ij}\right)=-1$. For risk-prone and risk-averse behaviour party, a utility function is assumed to be an exponential utility function, of the form

$$U_{ij}(x_{ij}) = a_{ij} + b_{ij}e^{-c_{ij}x_{ij}}\,, \quad 0 \le x_{ij} \le \Delta_{ij} \tag{5.1}$$

where a_{ij}, b_{ij}, and c_{ij} are constants for $i=0,1,2,...,n$ $j=1,2,3,4$. For risk-neutral behavior party, a linear utility function is of the form

$$U_{ij}(x_{ij}) = p_{ij} + q_{ij}x_{ij}\,, \quad 0 \le x_{ij} \le \Delta_{ij} \tag{5.2}$$

where p_{ij} and q_{ij} are constants for $i=0,1,2,...,n$ $j=1,2,3,4$.

With $U_{ij}\left(\Delta_{ij}\right)=-1$, the values of a_{ij} b_{ij}, c_{ij}, p_{ij} and q_{ij} are determined with reference to different risk attitudes of vendor and buyers. For simplicity, it is assumed that buyers and vendor do not change their attitudes throughout the whole planning horizon. Figure 5.1 illustrates the general shapes of different utility functions. When the measurement is at the best situation, usually $x_{ij}=0$, the utility is assigned to be 0, that is, $U_{ij}\left(0\right)=0$. It is assumed that different parties with different risk attitudes in a supply chain have different utility functions.

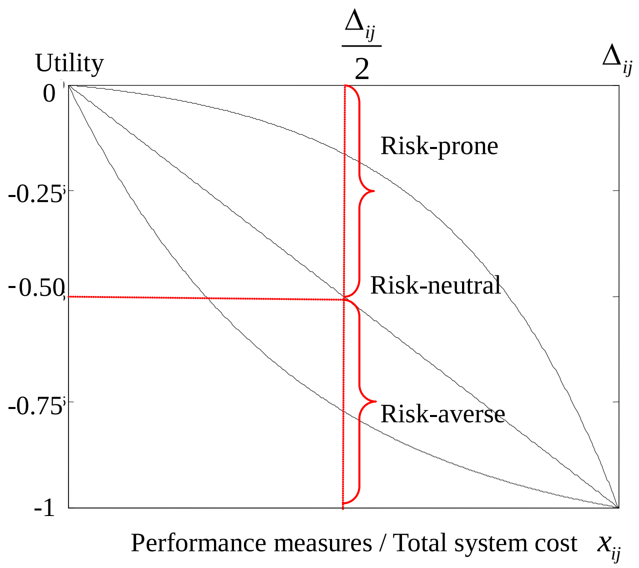


Figure 5.1 Utility functions.

When the risk measure of the i^{th} party on the j^{th} measure is $\frac{\Delta_{ij}}{2}$, the utility $U_{ij}\left(\frac{\Delta_{ij}}{2}\right)$ of the risk-prone party lies between -0.5 and 0, the utility $U_{ij}\left(\frac{\Delta_{ij}}{2}\right)$ of the risk-averse party lies between -1 and -0.5, and the utility $U_{ij}\left(\frac{\Delta_{ij}}{2}\right)$ of the risk-neutral party is -0.5 as shown in Figure 5.1.

As buyers and vendor are classified into three different categories of risk attitudes i.e. risk-averse, risk-neutral and risk-prone, each buyer and vendor has its own utility function on the cost and different environmental measures. In order to classify the risk attitudes of buyer i, demand rates d_i of buyer i are considered. The classification of risk attitude depends on the demand rate d_i of buyer i.

5.4.1 Risk-prone

It is assumed that vendor and high-demand buyers are risk-prone in financial sense since they are able to afford the cost increase as they are cost insensitive. Similarly, low-demand buyers, who have less resource to take care of the environment, are assumed to be less sensitive to the environmental measures (environmental-insensitive). They are also classified as risk-prone.

In the best situation of the j^{th} measure of party i, $x_{ij} = 0$, by equation (5.1), we have

$$U_{ij}(0) = a_{ij} + b_{ij} e^{-c_{ij}(0)} = 0,$$

$$a_{ij} = -b_{ij}. \tag{5.3}$$

In the worst situation of the j^{th} measure of party i, $x_{ij} = \Delta_{ij}$, by equation (5.1), we have

$$U_{ij}(\Delta_j) = -1,$$

$$a_{ij} + b_{ij} e^{-c_{ij}\Delta_{ij}} = -1. \tag{5.4}$$

Solving equations (5.3) and (5.4) simultaneously, we have

$$a_{ij} = \frac{1}{e^{-c_{ij}\Delta_{ij}} - 1} \tag{5.5}$$

and

$$b_{ij} = \frac{1}{1 - e^{-c_{ij}\Delta_{ij}}}. \tag{5.6}$$

By equations (5.1), (5.5) and (5.6), the utility function can be written as

$$U_{ij}(x_{ij}) = \frac{1}{e^{-c_{ij}\Delta_{ij}} - 1}\left(1 - e^{-c_{ij}x_{ij}}\right), 0 \le x_{ij} \le \Delta_{ij}. \tag{5.7}$$

When the j^{th} risk measure of the i^{th} party is $\frac{\Delta_{ij}}{2}$, the utility $U_{ij}\left(\frac{\Delta_{ij}}{2}\right)$ is sampled randomly from a uniform distribution $U\left(-0.5,0\right)$. Then, by equation (5.1), when $x_{ij}=\frac{\Delta_{ij}}{2}$, the utility value can be written as

$$U_{ij}\left(\frac{\Delta_{ij}}{2}\right)=\frac{1}{e^{-c_{ij}\Delta_{ij}}-1}\left(1-e^{-c\frac{\Delta_{ij}}{2}}\right). \tag{5.8}$$

Given the utility value $U_{ij}\left(\frac{\Delta_{ij}}{2}\right)$, the coefficient c_{ij} can be determined by equation (5.8). In order to find the value c_{ij} in equation (5.8), the worst situation is also considered such that the utility is -1 when the j^{th} measure of the i^{th} party is of the maximum value, that is, $x_{ij}=\Delta_{ij}$. Therefore, the utility value at the worst situation can be written as

$$-1=\frac{1}{e^{-c_{ij}\Delta_{ij}}-1}\left(1-e^{-c\Delta_{ij}}\right). \tag{5.9}$$

On solving equations (5.8) and (5.9) simultaneously, we have

$$c_{ij}=\frac{-2}{\Delta_{ij}}\ln\left(-1-\frac{1}{U_{ij}\left(\frac{\Delta_{ij}}{2}\right)}\right). \tag{5.10}$$

The i^{th} party on the j^{th} measure has its own value of c_{ij} in the utility function $U_{ij}(x_{ij})$, so the values of c_{ij} are obtained by equation (5.10).

If a buyer or the vendor is risk-prone, the risk parameter $c_{ij}<0$ is obtained by equation (5.10). By equations (5.7) and (5.10), the utility function of risk-prone party is written as

$$U_{ij}(x_{ij}) = \frac{1}{e^{-c_{ij}\Delta_{ij}} - 1}\left(1 - e^{-cx_{ij}}\right), 0 \le x_{ij} \le \Delta_{ij} \qquad (5.11)$$

where $c_{ij} = \frac{-2}{\Delta_{ij}} \ln\left(-1 - \frac{1}{U_{ij}\left(\frac{\Delta_{ij}}{2}\right)}\right)$ for $-0.5 < U_{ij}\left(\frac{\Delta_{ij}}{2}\right) < 0$.

5.4.2 Risk-averse

It is assumed that low-demand buyers are risk-averse in financial sense since they are not willing to afford cost increase as they are cost-sensitive. Similarly, vendor and high-demand buyers are assumed to be more concerned about and sensitive to the environmental performance (environmental sensitive) and therefore are classified as risk-averse.

Similar to the risk-prone party, as the best situation and the worst situations of the j^{th} measure of the i^{th} party who is risk-averse are considered, equations (5.3) - (5.10) can also be applied. When the j^{th} risk measure of the i^{th} party is $\frac{\Delta_{ij}}{2}$, the utility $U_{ij}\left(\frac{\Delta_{ij}}{2}\right)$ is sampled randomly from a uniform distribution $U\left(-1, -0.5\right)$.

If a buyer or the vendor is risk-averse, the risk parameter $c_{ij} > 0$ is obtained by equation (5.10). By equations (5.7) and (5.10), the utility function of risk-averse party is written as

$$U_{ij}(x_{ij}) = \frac{1}{e^{-c_{ij}\Delta_{ij}} - 1}\left(1 - e^{-cx_{ij}}\right), 0 \le x_{ij} \le \Delta_{ij} \tag{5.12}$$

where $c_{ij} = \frac{-2}{\Delta_{ij}} \ln\left(-1 - \frac{1}{U_{ij}\left(\frac{\Delta_{ij}}{2}\right)}\right)$ for $-1 < U_{ij}\left(\frac{\Delta_{ij}}{2}\right) < -0.5$.

5.4.3 Risk-neutral

Buyers with moderate demand are assumed to be risk-neutral in both financial and environmental measures. Moderate buyers are neutral towards to the costs and the environmental performance (environmental neutral) and therefore are classified as risk-neutral. Therefore, a linear utility function (5.2) is used to represent this category of buyers.

In the best situation of the j^{th} measure of party i, $x_{ij} = 0$, by (5.2), we have

$$U_{ij}(0) = p_{ij} + q_{ij}(0) = 0,$$

$$p_{ij} = 0. \tag{5.13}$$

In the worst situation of the j^{th} measure of party i, $x_{ij} = \Delta_{ij}$, by (5.2), we have

$$U_{ij}(\Delta_{ij}) = p_{ij} + q_{ij}\left(\Delta_{ij}\right) = -1,$$

$$q_{ij} = \frac{-1}{\Delta_{ij}}. \tag{5.14}$$

By equations (5.2), (5.13) and (5.14), the utility function for risk-neutral is written as

$$U_{ij}(x_{ij}) = -\frac{x_{ij}}{\Delta_{ij}}, i = 0,1,2,...,n, j = 1,2,3,4. \tag{5.15}$$

5.5 Determination of Δ_{ij} and $U_{ij}(x_{ij})$

The determination of c_{ij}, as discussed in previous sections, requires the value of Δ_{ij}, i.e., the maximum value of the j^{th} measure for the i^{th} party by equation (5.10). In this section, the way of obtaining the value of Δ_{ij} will be discussed.

5.5.1 Total Cost

Total cost is a financial performance measure in supply chain model. The 1st measurement is defined to measure the total cost. In general, the higher the total cost, the more negative the utility value. The risk attitude to cost of buyers depends on their demand rate. For high-demand buyers, they are cost insensitive, so the buyers are risk-prone. For low-demand buyers, they are cost sensitive, so the buyers are risk-averse. For moderate demand buyers, they are cost neutral, so the buyers are risk-neutral.

Let x_{i1} be the total cost of buyer i ($i = 0$ for the vendor) in a supply chain system such that $0 \le x_{i1} \le \Delta_{i1}$ where Δ_{i1} is the largest value of the total costs of i^{th} party. In order to determine the coefficients c_{i1} of utility functions, the utility $U_{i1}\left(\frac{\Delta_{i1}}{2}\right)$ is mapped with the value of c_{i1} of buyer i for risk-averse/prone parties in the 1st measurement by equation (5.10). After the coefficients c_{i1} of utility functions have been determined, the utility functions $U_{i1}(x_{i1})$ can be found by equation (5.11) and equation (5.12) for risk-prone and risk-averse parties, respectively. For risk-neutral buyers, the utility function $U_{i1}(x_{i1})$ can be found by equation (5.15). The determination of Δ_{i1} will be discussed as follows.

In order to find the value of Δ_{i1}, the cost functions of buyers and vendor are considered. Since the cost function x_{i1} of buyer i is concave upward, the total cost of buyer i is the largest when the ordering cycle $k_i T$ of buyer i is either T or $N^{\max}T$ when $N^{\max}T$ is maximum planning horizon under synchronized cycles model. Therefore, in the worst situation of buyer i, the 1st measurement $\Delta_{i1} = \max\left\{\frac{A_i}{T}+\frac{1}{2}h_i d_i T, \frac{A_i}{N^{\max}T}+\frac{1}{2}h_i d_i N^{\max}T, \sqrt{2A_i h_i d_i}\right\}$, which gives the largest total cost, has the lowest utility value of -1, that is, $U_{i1}(\Delta_{i1}) = -1$. The first term is the total cost of buyer i when the ordering cycle is T; the second term is the total cost of buyer i when the ordering cycle is $N^{\max}T$; the last term is the optimal total cost of buyer i of independent optimization. For the vendor, the total cost of vendor in independent optimization is

$$x_{01} = \frac{S_v}{T_v^*}+\frac{1}{2}\left(1-\frac{D}{P}\right)hDT_v^* + h\sum_{i=1}^{n} d_i T_i^* + \sum_{i=1}^{n}\frac{C_i}{T_i^*}. \tag{5.16}$$

The vendor cost in independent optimization is always larger than that of synchronized cycles model in a single-vendor multi-buyer supply chain. Hence, from the vendor's point of view, the total cost obtained by independent optimization gives the worst situation of the vendor in the 1st measurement, i.e. total cost, Hence, the largest total cost of vendor is computed by $\Delta_{01} = \sqrt{2S_v Dh\left(1-\frac{D}{P}\right)} + h\sum_{i=1}^{n} Q_i^* + \sum_{i=1}^{n}\frac{C_i^*}{T_i^*}$. The worst situation has the lowest utility value of -1, i.e., $U_{01}(\Delta_{01}) = -1$.

Buyer i	Risk attitude	Demand rate d_i	$\frac{A_i}{T}+\frac{1}{2}h_i d_i T$	$\frac{A_i}{N^{\max}T}+\frac{1}{2}h_i d_i N^{\max}T$	$\sqrt{2A_i h_i d_i}$	Δ_{i1}
1	Averse	8	20.0	11.7	1.88	20.0
2	Prone	15	15.1	24.7	3.37	24.7
3	Neutral	10	6.1	18.3	2.38	18.3
Vendor $i=0$	Prone	58	$\Delta_{01}=\sqrt{2S_v Dh\left(1-\frac{D}{P}\right)}+h\sum_{i=1}^{n}Q_i^*+\sum_{i=1}^{n}\frac{C_i^*}{T_i^*}$ =25.71			

Table 5.1:Risk attitudes of buyers and vendor on total cost per-unit time and Δ_{i1} in a 5-buyer example when DP ratio is 0.1.

For example, we consider a 5-buyer case when DP ratio is 0.1. To illustrate the determination of Δ_{ij}, buyers 1, 2, 3 and the vendor are considered as shown in Table 5.1. The total costs of buyer 1 are 20.0 and 11.7, respectively, when ordering cycles are T and $N^{\max}T$ where the maximum planning horizon $N^{\max}T$ is 365 T. The total cost of buyer 1 is 1.88 in the independent optimization. For buyer 1, the worst situation is when the ordering cycle is T with the total cost of 20.0. Hence, the maximum value of Δ_{11} is 20.0. For buyer 2, the total costs are 15.1 and 24.7, respectively, when ordering cycles are T and $N^{\max}T$. The total cost of buyer 2 is 3.37 in the independent optimization. For buyer 2, the worst situation is when the ordering cycle is $N^{\max}T$ with the total cost of 24.7. Hence, the maximum value of Δ_{21} is 24.7. For buyer 3, the total costs are 6.1 and 18.3, respectively, when ordering cycles are T and $N^{\max}T$. The total cost of buyer 3 is 2.38 in the independent optimization. For buyer 3, the worst situation is when the ordering cycle is

$N^{\max}T$ with the total cost of 18.3. Hence, the maximum value of Δ_{31} is 18.3. For the vendor, since the vendor cost of synchronized cycles model is much less than that of independent optimization, and hence the vendor cost of independent optimization is the worst situation for the vendor. The value of Δ_{01} is 25.71 which is the vendor cost of independent optimization.

According to the demand rates, buyers 1, 2 and 3 are classified as risk-averse, risk-prone and risk-neutral to cost, respectively, as shown in Table 5.1. After the determination of Δ_{ij}, the utility function $U_{ij}\left(x_{ij}\right)$ can be obtained as shown in Table 5.2.

Buyer i	$\frac{\Delta_{i1}}{2}$	$U_{i1}\left(\frac{\Delta_{i1}}{2}\right)$	c_{i1}	$U_{i1}\left(x_{i1}\right)$
1	10.0	-0.7979	0.13710	$U_{11}\left(x_{11}\right)=\frac{1}{e^{(-0.1371)(20)}}\left(1-e^{-0.1371x_{11}}\right)$
2	12.35	-0.3325	-0.05647	$U_{21}\left(x_{21}\right)=\frac{1}{e^{-(-0.05047)(24.7)}}\left(1-e^{-(-0.05047)x_{21}}\right)$
3	9.15	-0.5	NA	$U_{31}\left(x_{31}\right)=-\frac{x_{31}}{18.3}$
Vendor $i=0$	12.86	-0.31914	-0.05295	$U_{01}\left(x_{01}\right)=\frac{1}{e^{(-0.05295)(25.71)}}\left(1-e^{-0.05295x_{01}}\right)$

Table 5.2:Utility functions of buyers and vendor on total cost per-unit time in a 5-buyer example when DP ratio is 0.1.

For buyer 1 who is risk-averse, the utility $U_{11}(10) = -0.7979$ is sampled randomly from uniform distribution $U(-1,-0.5)$ with $\frac{\Delta_{11}}{2} = 10$. The coefficient c_{11} of utility function is 0.13710 by equation (5.10). Then, the utility function of buyer 1 $U_{11}(x_{11}) = \frac{1}{e^{(-0.1371)(20)}}\left(1 - e^{-0.1371x_{11}}\right)$ is obtained by equation (5.12) as shown in Figure 5.2.

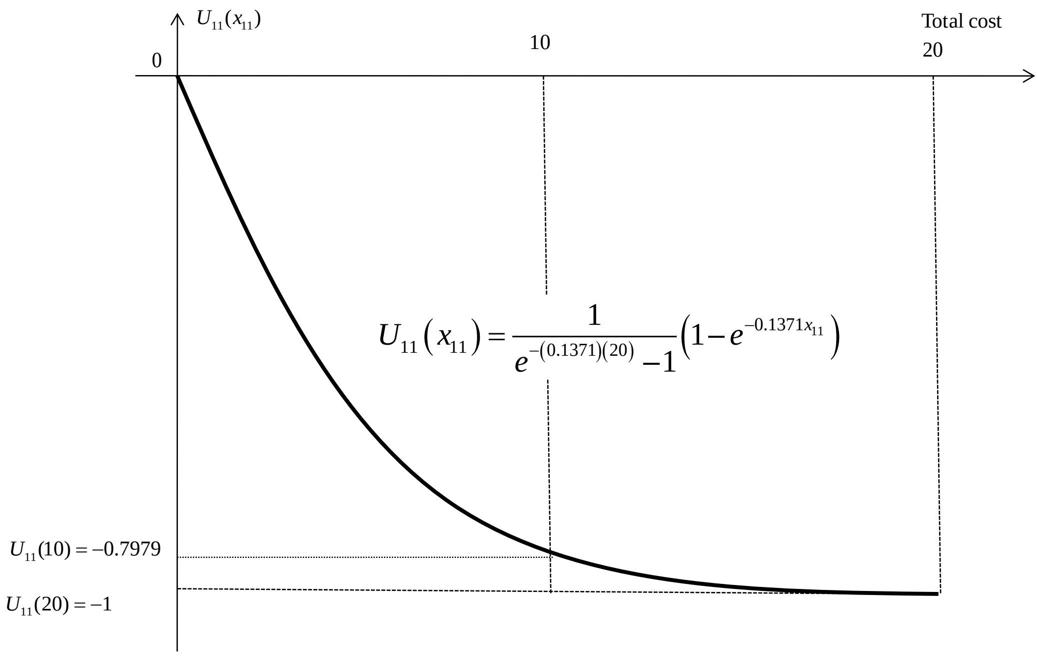


Figure 5.2: Diagram of utility function on total cost of risk-averse buyer 1.

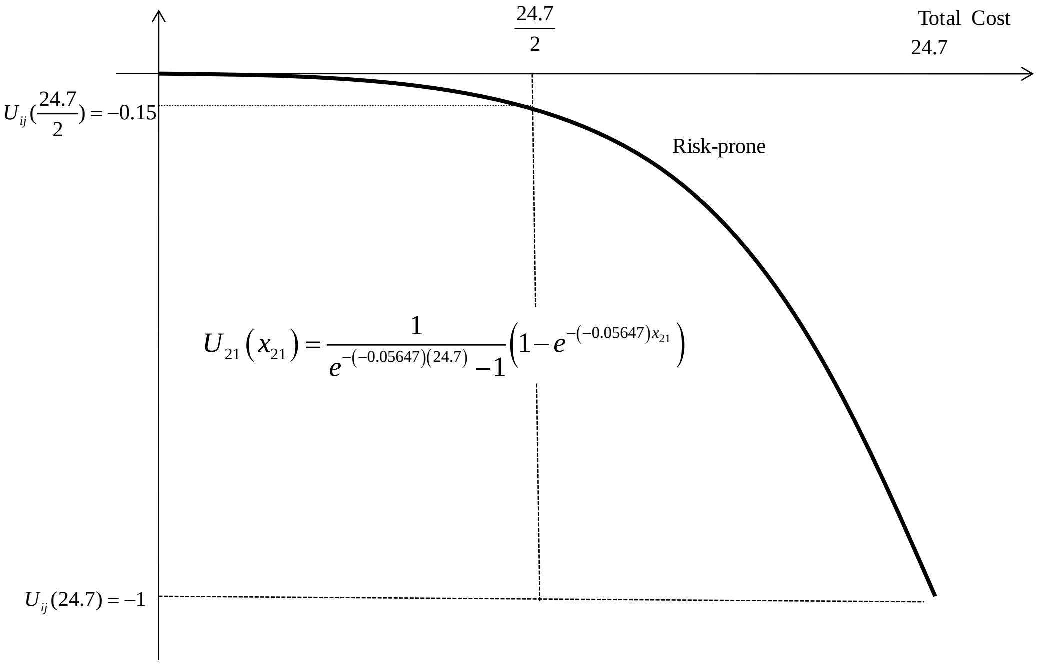


Figure 5.3: Diagram of utility function on total cost of risk-prone buyer 2.

For buyer 2 who is risk-prone as shown in Table 5.2, the utility $U_{21}\left(12.35\right) = -0.3325$ is sampled randomly from uniform distribution $U\left(-0.5, 0\right)$ with $\frac{\Delta_{21}}{2} = 12.35$. The coefficient c_{21} of utility function is -0.05647 by equation (5.10). Then, the utility function of buyer 2 $U_{21}\left(x_{21}\right) = \frac{1}{e^{-(-0.05047)(24.7)}}\left(1 - e^{-(-0.05047)x_{21}}\right)$ is obtained by equation (5.11) as shown in Figure 5.3.

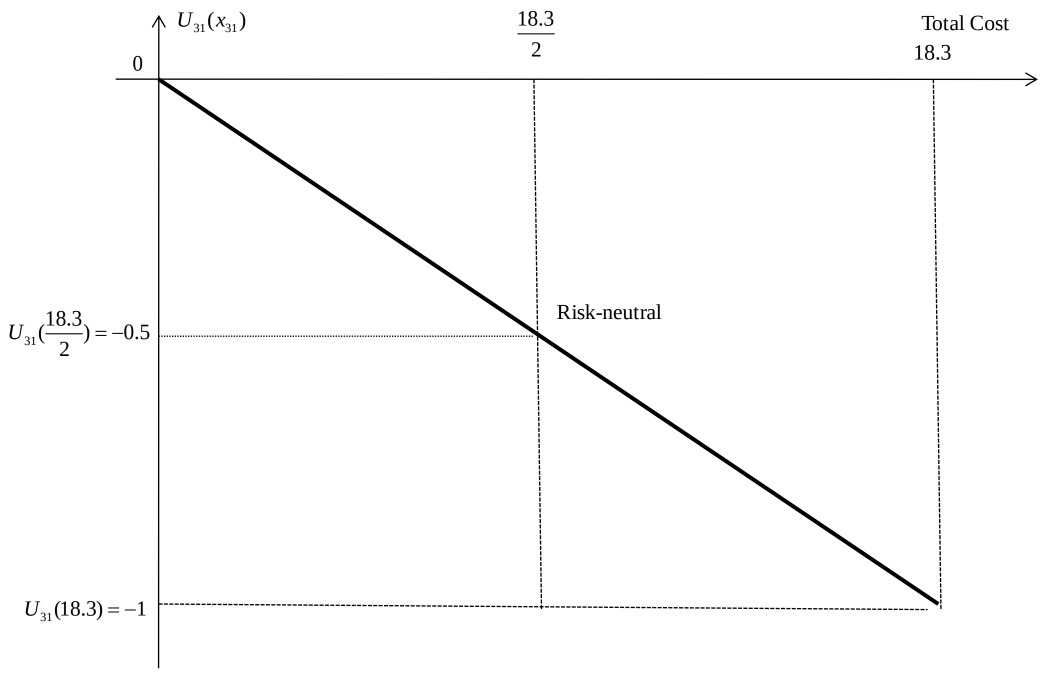


Figure 5.4: Diagram of utility function on total cost of risk-neutral buyer 3.

For risk-neutral buyer 3, since the utility $U_{31}(9.15) = -0.5$, the determination of c_{31} is not applicable as shown in Table 5.2. The value of Δ_{31} is 18.3. Then, the utility function of buyer 3 $U_{31}(x_{31}) = -\frac{x_{31}}{18.3}$ is obtained by equation (5.15) as shown in Figure 5.4.

For the vendor, the utility $U_{01}(12.86) = -0.31914$ is sampled randomly from uniform distribution $U(-0.5, 0)$ since the vendor is risk-prone. The largest total cost Δ_{01} of vendor is 25.71. The coefficient c_{01} of utility function is -0.05295 by equation (5.10). Then, the utility function of vendor $U_{01}(x_{01}) = \frac{1}{e^{(-0.05295)(25.71)}}\left(1 - e^{-0.05295 x_{01}}\right)$ can be obtained by equation (5.11) as shown in Figure 5.5.

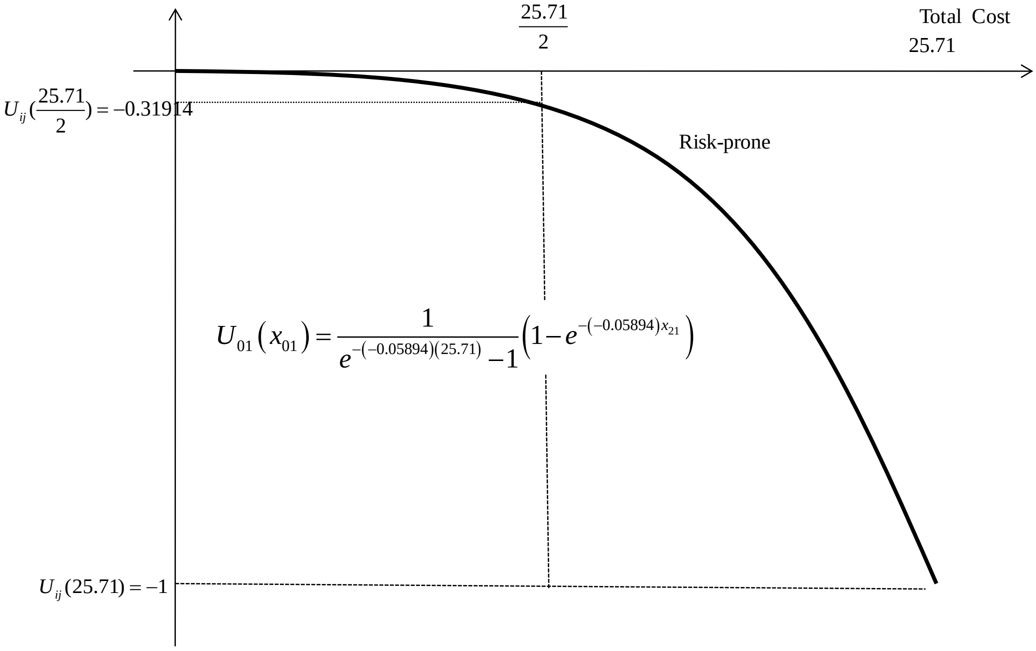


Figure 5.5: Diagram of utility function on total cost of risk-prone vendor.

5.5.2 Energy Wastage per Unit Time

Energy wastage occurs during each production run. For example, a machine needs to be warmed up before a production run can be started. The 2nd measurement is defined to measure the energy wastage. Energy wastage is proportional to the number of production runs. Hence, the number of production run per unit time can be employed to represent the energy wastage. Generally, the higher the number of production runs per unit time, the lower the environmental performance and hence the more negative the utility value. The risk attitude to energy wastage of buyers depends on their demand rate. For high-demand buyers, they are environmental sensitive, so the buyer is risk-averse to energy wastage. For low-demand buyers, they are environmental insensitive, so the buyer is risk-prone to energy wastage. For moderate demand buyers, they are environmental neutral, so the buyer is risk-neutral to energy wastage.

Let x_{i2} be the number of production run per unit time in a supply chain system which represents the 2nd measurement of the i^{th} party to measure the energy wastage in a supply chain system where Δ_{i2} is the largest value of the number of production run of vendor. In order to determine the coefficients c_{i2} of utility functions, the utility $U_{i2}\left(\frac{\Delta_{i2}}{2}\right)$ is mapped with the value of c_{i2} of buyer i for risk-averse/prone parties in the 2nd measurement by equation (5.10). After the coefficients c_{i2} of utility functions have been determined, the utility functions $U_{i2}(x_{i2})$ can be found by equation (5.11) and equation (5.12) for risk-prone and risk-averse parties, respectively. For risk-neutral buyers, the utility function $U_{i2}(x_{i2})$ can be found by equation (5.15).

The number of production run per unit time of vendor is $\frac{1}{NT}$. Since the production cycle of vendor can be less than 1 by independent optimization and the smallest integer of the production cycle NT of vendor is 1, hence the largest value in the 2nd measurement Δ_{i2} of the i^{th} party is $\Delta_{i2} = \max\left\{1, \frac{1}{T_v^*}\right\}$ for all i. In other words, the worst situation is that there is a production run every day.

For example, we consider a 5-buyer case when DP ratio is 0.1. Buyers 1, 2 and 3 are classified as risk-prone, risk-averse and risk-neutral to energy wastage, respectively, as shown in Table 5.3 as the risk attitude to energy wastage depends on the demand rate of buyers. Since the production cycle of vendor by independent optimization is 43.77 which is larger than 1, the maximum value $\Delta_{i2} = \max\left\{1, \frac{1}{43.77}\right\}$ is 1 as shown in Table 5.3.

Buyer i	Risk attitude	Demand rate d_i	T_v^*	$\Delta_{i2} = \max\left\{1, \frac{1}{T_v^*}\right\}$
1	Prone	8	43.77	1
2	Averse	15	43.77	1
3	Neutral	10	43.77	1
Vendor $i=0$	Averse	58	43.77	1

Table 5.3:Risk attitudes of buyers and vendor on energy wastage per unit time and Δ_{i2} in a 5-buyer example when DP ratio is 0.1.

Buyer i	$\frac{\Delta_{i2}}{2}$	$U_{i2}\left(\frac{\Delta_{i2}}{2}\right)$	c_{i2}	$U_{i2}(x_{i2})$
1	0.5	-0.26420	-2.0485	$U_{12}(x_{12}) = \frac{1}{e^{2.0485}-1}\left(1-e^{2.0485x_{12}}\right)$
2	0.5	-0.92053	4.89915	$U_{22}(x_{22}) = \frac{1}{e^{-4.89915}-1}\left(1-e^{-4.89915x_{22}}\right)$
3	0.5	-0.5	NA	$U_{32}(x_{32}) = -x_{32}$
Vendor	0.5	-0.84197	3.34587	$U_{02}(x_{02}) = \frac{1}{e^{-3.34587}-1}\left(1-e^{-3.34587x_{02}}\right)$

Table 5.4:Utility functions of buyers and vendor on total cost per unit time in a 5-buyer example when DP ratio is 0.1.

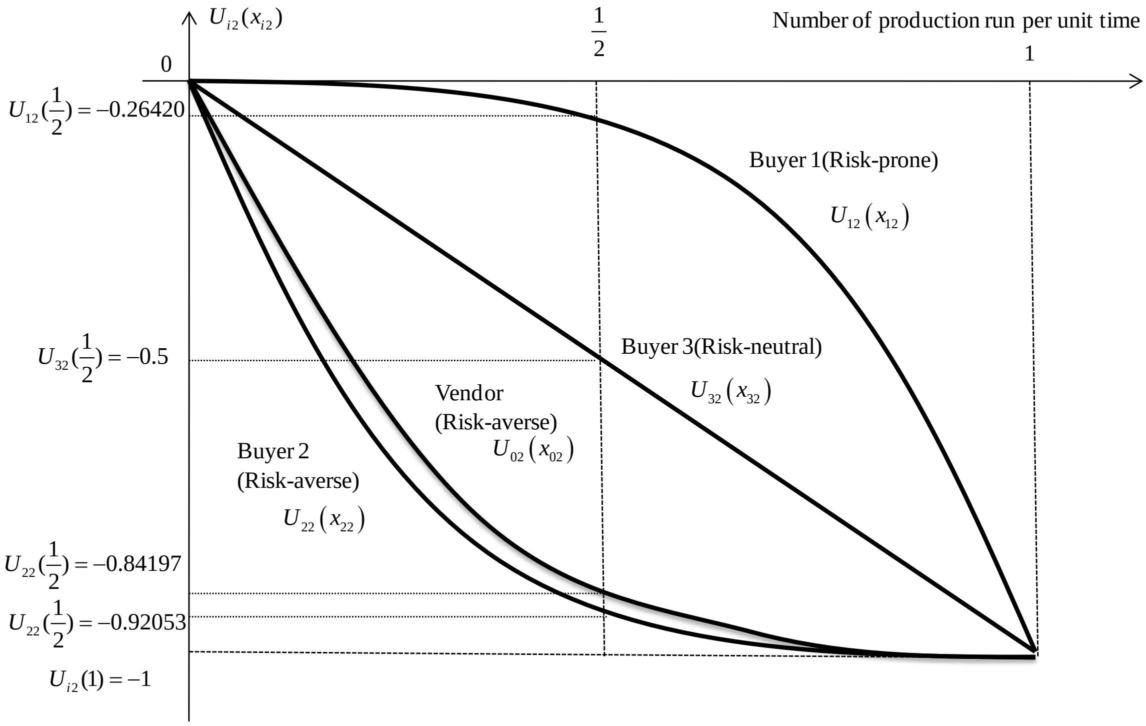


Figure 5.6: Diagram of utility functions on energy wastage per unit time of buyers 1, 2 ,3 and vendor in a 5-buyer example when DP ratio is 0.1.

For risk-prone buyer 1, the utility $U_{12}\left(\frac{1}{2}\right) = -0.26420$ is sampled randomly from uniform distribution $U(-0.5, 0)$ as shown in Table 5.4. The coefficient c_{12} of utility function is -2.04853 by equation (5.10). The utility function of buyer 1 $U_{12}(x_{12}) = \frac{1}{e^{2.0485} - 1}\left(1 - e^{2.0485 x_{12}}\right)$ is obtained by equation (5.11) as shown in Figure 5.6. For risk-averse buyer 2, the utility $U_{22}\left(\frac{1}{2}\right) = -0.92053$ is sampled randomly from uniform distribution $U(-1, -0.5)$ as shown in Table 5.4. The coefficient c_{22} of utility function is 4.89915 by equation (5.10). The utility function of buyer 2 $U_{22}(x_{22}) = \frac{1}{e^{-4.89915} - 1}\left(1 - e^{-4.89915 x_{22}}\right)$ is obtained by equation (5.11) as shown in

Figure 5.6. For risk-neutral buyer 3, since the utility, $U_{32}\left(\frac{1}{2}\right)=-0.5$, the determination of c_{32} is not applicable as shown in Table 5.4. Then, the utility function of buyer 3 $U_{32}\left(x_{32}\right)=-x_{32}$ is obtained by equation (5.15) as shown in Figure 5.6. For the vendor who is risk-averse, the utility $U_{02}\left(\frac{1}{2}\right)=-0.84197$ is sampled randomly from uniform distribution $U\left(-0.5,0\right)$ as shown in Table 5.4. The largest total cost Δ_{02} of vendor is 1. The coefficient c_{02} of utility function is 3.34587 by equation (5.12). Then, the utility function of vendor $U_{02}\left(x_{02}\right)=\frac{1}{e^{-3.34587}-1}\left(1-e^{-3.34587x_{02}}\right)$ can be obtained by equation (5.12) as shown in Figure 5.6. Note that the measurements, x_{02} x_{12}, x_{22}, and x_{32} are all equal to the number of production run per unit time $\frac{1}{NT}$ of vendor in a single-vendor multi-buyer supply chain system.

5.5.3 Raw Material Wastage per Unit Time

Raw materials wastage is another measure of environmental performance considered by this research. Raw material wastage occurs during inventory. The 3rd measurement is defined to measure the raw materials wastage. Raw materials wastage is proportional to the average inventory level of the vendor. The higher the average inventory level of the vendor, the more raw material wastage creates during production. The risk attitude to raw material wastage depends on the demand rate of buyers. For high-demand buyers, they are environmental sensitive, so the buyer is risk-averse to raw material wastage. For low-demand buyers, they are environmental insensitive, so the buyer is risk-prone to raw material wastage. For moderate demand buyers, they are environmental neutral, so the buyer is risk-neutral to raw material wastage.

Let x_{i3} be the average inventory of the vendor in a single-vendor multi-buyer supply chain system such that $0 \le x_{i3} \le \Delta_{i3}$ where Δ_{i3} represents the largest average inventory level of vendor per unit time. In order to determine the coefficients c_{i3} of utility functions, the utility $U_{i3}\left(\frac{\Delta_{i3}}{2}\right)$ is mapped with the value of c_{i3} of buyer i for risk attitude in the 3rd measurement by equation (5.10). After the coefficients c_{i3} of utility functions have been determined, the utility functions $U_{i3}(x_{i3})$ can be found by equation (5.11) and equation (5.12) for risk-prone and risk-averse parties, respectively. For risk-neutral buyers, the utility function $U_{i3}(x_{i3})$ can be found by equation (5.15).

Let I^{SYN} and I^{IND} be the average inventory level of the vendor in the synchronized cycles model and independent optimization in a single-vendor multi-buyer supply chain, respectively, where Δ_{i3} is the largest average inventory level of vendor per unit time, i.e., $\Delta_{i3} = \max\left\{I^{SYN}, I^{IND}\right\}$. The average inventory levels of vendor per unit time are $I^{IND} = \frac{1}{2}D\left(1-\frac{D}{P}\right)T_v^* + \sum_{i=1}^{n} Q_i^*$ and $I^{SYN} = \frac{1}{2}D\left(1-\frac{D}{P}\right)NT + \sum_{i=1}^{n}\left(\frac{D}{P}-\frac{1}{2}\right)d_i k_i T$ by independent optimization and by synchronized cycles model, respectively. In general, it is found that $I^{IND} > I^{SYN}$ because safety stocks are held under independent optimization. The utility value of largest average inventory level of vendor per unit time Δ_{i3}, i.e. $U_{i3}\left(\Delta_{i3}\right)$, is assigned as -1, that is, $U_{i3}\left(\Delta_{i3}\right)=-1$.

Buyer i	Demand rate d_i	Risk attitude	I^{SYN}	I^{IND}	$\Delta_{i3}=\max\left\{I^{SYN},I^{IND}\right\}$
1	8	Prone	130.5	2096.23	2096.23
2	15	Averse	130.5	2096.23	2096.23
3	10	Neutral	130.5	2096.23	2096.23
Vendor $i=0$	58	Averse	130.5	2096.23	2096.23

Table 5.5:Risk attitudes of buyers and vendor on raw material wastage per unit time and Δ_{i3} in a 5-buyer example when DP ratio is 0.1.

For example, we consider a 5-buyer case when DP ratio is 0.1. Buyers 1, 2 and 3 are classified as risk-prone, risk-averse and risk-neutral to raw material wastage, respectively, as shown in Table 5.5, according to their demand rates. It is also shown that the largest average inventory level of vendor Δ_{i3} is 2096.23 calculated by $\Delta_{i3}=\max\left\{I^{SYN},I^{IND}\right\}$ since $I^{SYN}=130.5$ and $I^{IND}=2096.23$ in Table 5.5.

Buyer i	$\frac{\Delta_{i3}}{2}$	$U_{i3}\left(\frac{\Delta_{i3}}{2}\right)$	c_{i3}	$U_{i3}(x_{i3})$
1	1048.12	-0.07858	-0.00235	$U_{13}(x_{13}) = \frac{1}{e^{(0.00235)(2096.23)}-1}\left(1-e^{0.00235x_{13}}\right)$
2	1048.12	-0.82986	0.00151	$U_{23}(x_{23}) = \frac{1}{e^{-(0.00151)(2096.23)}-1}\left(1-e^{-0.00151x_{23}}\right)$
3	1048.12	-0.5	NA	$U_{33}(x_{33}) = -\frac{x_{33}}{2096.23}$
Vendor	1048.12	-0.62401	0.00048	$U_{03}(x_{03}) = \frac{1}{e^{-(0.00048)(2096.23)}-1}\left(1-e^{-0.00048x_{03}}\right)$

Table 5.6: Utility functions of buyers and vendor on raw material wastage per unit time in a 5-buyer example when DP ratio is 0.1.

In Table 5.6 for risk-prone buyer 1, the utility $U_{13}(1048.12) = -0.07858$ is sampled randomly from uniform distribution $U(-0.5, 0)$. The coefficient c_{13} of utility function is -0.00235 which is calculated by equation (5.10). The utility function of buyer 1 $U_{13}(x_{13}) = \frac{1}{e^{(0.00235)(2096.23)}-1}\left(1-e^{0.00235x_{13}}\right)$ is obtained by equation (5.11) as shown in Figure 5.7. For risk-averse buyer 2, the utility $U_{23}(1048.12) = -0.829896$ is sampled randomly from uniform distribution $U(-1, -0.5)$. The coefficient c_{23} of utility function is 0.00151 which is calculated by equation (5.10). As shown in Figure 5.7, the utility function of buyer 1 $U_{23}(x_{23}) = \frac{1}{e^{-(0.00151)(2096.23)}-1}\left(1-e^{-0.00151x_{23}}\right)$ is obtained by equation (5.12). For risk-neutral buyer 3, since the utility $U_{33}(1048.12) = -0.5$, the determination of c_{33} is not applicable. Then, the utility function of buyer 3

$U_{33}\left(x_{33}\right)=-\dfrac{x_{33}}{2096.23}$ is obtained by equation (5.15) as shown in Figure 5.7. For the vendor who is risk-averse, the utility $U_{03}\left(1048.12\right)=-0.62401$ is sampled randomly from uniform distribution $U\left(-0.5,0\right)$. The coefficient c_{03} of utility function is 0.00048 by equation (5.11). Then, the utility function of vendor $U_{03}\left(x_{03}\right)=\dfrac{1}{e^{-(0.00048)(2096.23)}-1}\left(1-e^{-0.00048x_{03}}\right)$ can be obtained by equation (5.12) as shown in Figure 5.7. Note that the measurements, x_{03}, x_{13}, x_{23}, and x_{33} are all equal to the average inventory level of vendor per unit time in a single-vendor multi-buyer supply chain system.

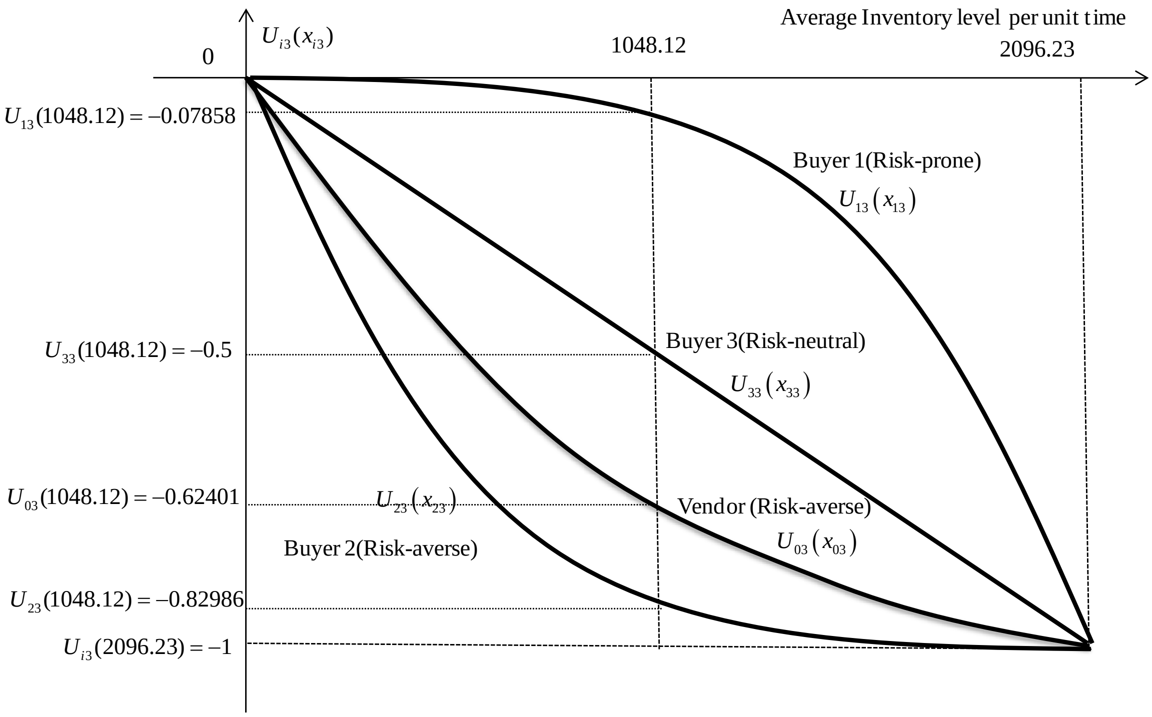


Figure 5.7: Diagram of utility functions on raw material wastage per unit time of buyers 1, 2 ,3 and vendor in a 5-buyer example when DP ratio is 0.1.

5.5.4 Air Pollution per Unit Time

Air pollution is a major concern of environmental performance in recent years.

Deliveries of goods in a supply chain will produce air pollution. The 4th measurement is defined to measure air pollution. Air pollution is proportional to the total number of orders/deliveries. The more frequent the delivery, the more air pollution will be produced. Hence, the number of orders delivered per unit time measures air pollution per unit time. The risk attitude to air pollution depends on the demand rate of buyers. For high-demand buyers, they are environmental sensitive, so the buyer is risk-averse to air pollution. For low-demand buyers, they are environmental insensitive, so the buyer is risk-prone to air pollution. For moderate demand buyers, they are environmental neutral, so the buyer is risk-neutral to air pollution.

Let x_{i4} be the number of order per unit time of buyer i in a supply chain system where Δ_{i4} is the largest value of the number of delivery per unit time of buyer i. In order to determine the coefficients c_{i4} of utility functions, the utility $U_{i4}\left(\frac{\Delta_{i4}}{2}\right)$ is mapped with the value of c_{i4} of buyer i for risk attitude in the 4th measurement by equation (5.10). After the coefficients c_{i4} of utility functions have been determined, the utility functions $U_{i4}(x_{i4})$ can be found by equation (5.11) and equation (5.12) for risk-prone and risk-averse parties, respectively. For risk-neutral buyers, the utility function $U_{i4}(x_{i4})$ can be found by equation (5.15).

Let $\frac{1}{k_i^* T}$ and $\frac{1}{T_i^*}$ be the number of order per unit time in synchronized cycles model and independent optimization, respectively. Since the smallest integer of the production cycle NT of vendor is 1 and the optimal ordering cycle T_i^* of buyer i in independent optimization can be less than 1 in a single-vendor multi-buyer supply chain, the largest value Δ_{i4} of the number of order per unit time of buyer i is the maximum of 1 and $\frac{1}{T_i^*}$, i.e. $\Delta_{i4} = \max\left(1, \frac{1}{T_i^*}\right)$ for all i. This is the worst situation in term of air pollution so the utility value of Δ_{i4} is $U_{i4}\left(\Delta_{i4}\right) = -1$. Moreover, since the vendor handles all the deliveries of buyers, the aggregate number of order per unit time of vendor x_{04} is the sum of the number of order per unit time of all buyers, i.e. $x_{04} = \sum_{i=1}^{n} x_{i4}$. Then, the largest number of order per unit time Δ_{04} is the sum of Δ_{i4} for all i, that is, $\Delta_{04} = \sum_{i=1}^{n} \max\left(1, \frac{1}{T_i^*}\right)$. It is the worst situation in term of air pollution when $x_{i4} = \Delta_{i4}$, the utility value of Δ_{i4} is $U_{i4}\left(\Delta_{i4}\right) = -1$.

Buyer i	Risk attitude	Demand rate d_i	$\frac{1}{T_i^*}$	Δ_{i4}
1	Prone	8	0.04	1
2	Averse	15	0.0671	1
3	Neutral	10	0.0913	1
Vendor $i = 0$	Averse	58	0.3107	5

Table 5.7:Risk attitudes of buyers and vendor on air pollution per unit time and Δ_{i4} in a 5-buyer example when DP ratio is 0.1.

For example, we consider a 5-buyer case when DP ratio is 0.1. According to the demand rates, buyers 1, 2 and 3 are classified as risk-prone, risk-averse and risk-neutral to air pollution, respectively, as shown in Table 5.7. The number of order per unit time of buyers 1, 2, and 3 are 0.04, 0.0671, and 0.0913, respectively. Since the numbers of order per unit time of buyers 1, 2, and 3 are less than 1, so their maximum values Δ_{i4} are 1 as shown in Table 5.7. For the vendor, the total number of order per unit time is $\sum_{i=1}^{5} \max\left(1, \frac{1}{T_i^*}\right) = 0.3107$ which is less than $n=5$, so the maximum value Δ_{04} is 5.

Buyer i	Δ_{i4}	$U_{i4}\left(\frac{\Delta_{i4}}{2}\right)$	c_{i4}	$U_{i4}(x_{i4})$
1	1	-0.35509	-1.19349	$U_{14}(x_{14}) = \frac{1}{e^{1.19349}-1}\left(1-e^{1.19349x_{14}}\right)$
2	1	-0.97564	7.38045	$U_{24}(x_{24}) = \frac{1}{e^{-7.38045}-1}\left(1-e^{-7.38045x_{24}}\right)$
3	1	NA	NA	$U_{34}(x_{34}) = -x_{34}$
Vendor $i=0$	5	-0.75389	0.44779	$U_{04}(x_{04}) = \frac{1}{e^{-0.44779}-1}\left(1-e^{-0.44779x_{24}}\right)$

Table 5.8: Utility functions of buyers and vendor on air pollution per unit time in a 5-buyer example when DP ratio is 0.1.

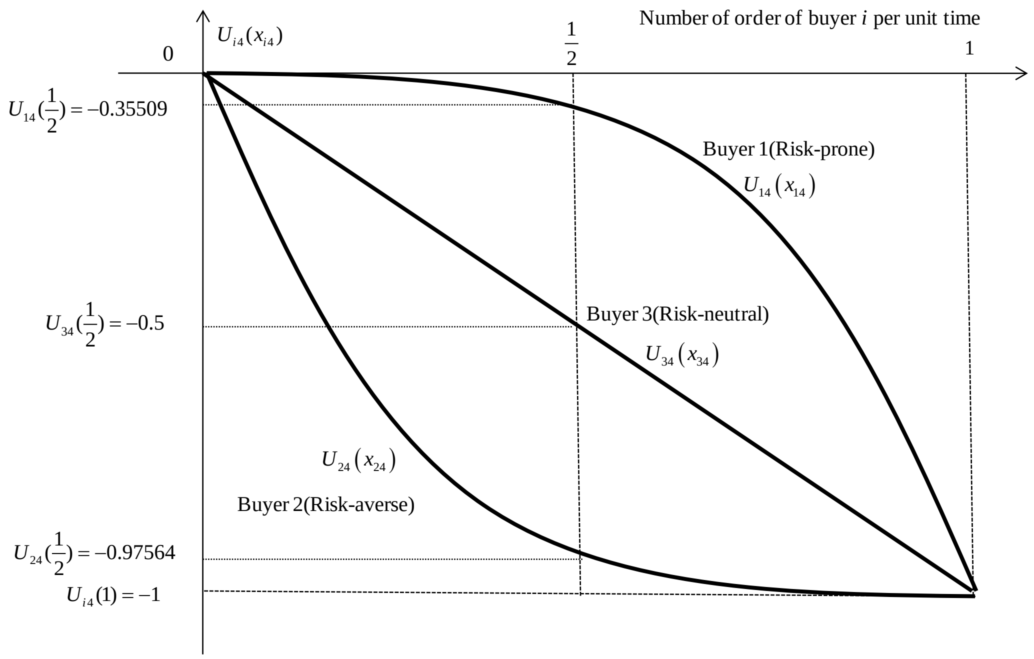


Figure 5.8: Diagram of utility functions on air pollution per unit time of buyers 1, 2 and 3 in a 5-buyer example when DP ratio is 0.1.

In Table 5.8, the utility $U_{14}\left(\frac{1}{2}\right) = -0.35509$ is sampled randomly from uniform distribution $U(-0.5, 0)$ for risk-prone buyer 1. The coefficient c_{14} of utility function is -1.19349 by equation (5.10). The utility function of buyer 1 is $U_{14}(x_{14}) = \frac{1}{e^{1.19349} - 1}\left(1 - e^{1.19349 x_{14}}\right)$ by equation (5.11) as shown in Figure 5.8. For risk-averse buyer 2, the utility $U_{24}\left(\frac{1}{2}\right) = -0.97564$ is sampled randomly from uniform distribution $U(-1, -0.5)$ as shown in Table 5.8. The coefficient c_{24} of utility function is 7.38045 by equation (5.10). The utility function of buyer 2 is $U_{24}(x_{24}) = \frac{1}{e^{-7.38045} - 1}\left(1 - e^{-7.38045 x_{24}}\right)$ by equation (5.12) as shown in Figure 5.8. For risk-neutral buyer 3, since the utility

$U_{34}\left(\frac{1}{2}\right) = -0.5$, the determination of c_{34} is not applicable. The utility function of buyer 3 is $U_{34}\left(x_{34}\right) = -x_{34}$ by equation (5.15) as shown in Figure 5.8. For risk-averse vendor, the utility $U_{04}\left(\frac{5}{2}\right) = -0.75389$ is sampled randomly from uniform distribution $U\left(-1,-0.5\right)$ as shown in Table 5.8. The coefficient c_{04} of utility function is 0.44779 by equation (5.10). The utility function of vendor is $U_{04}\left(x_{04}\right) = \frac{1}{e^{-0.44779}-1}\left(1-e^{-0.44779x_{24}}\right)$ by equation (5.12) as shown in Figure 5.9.

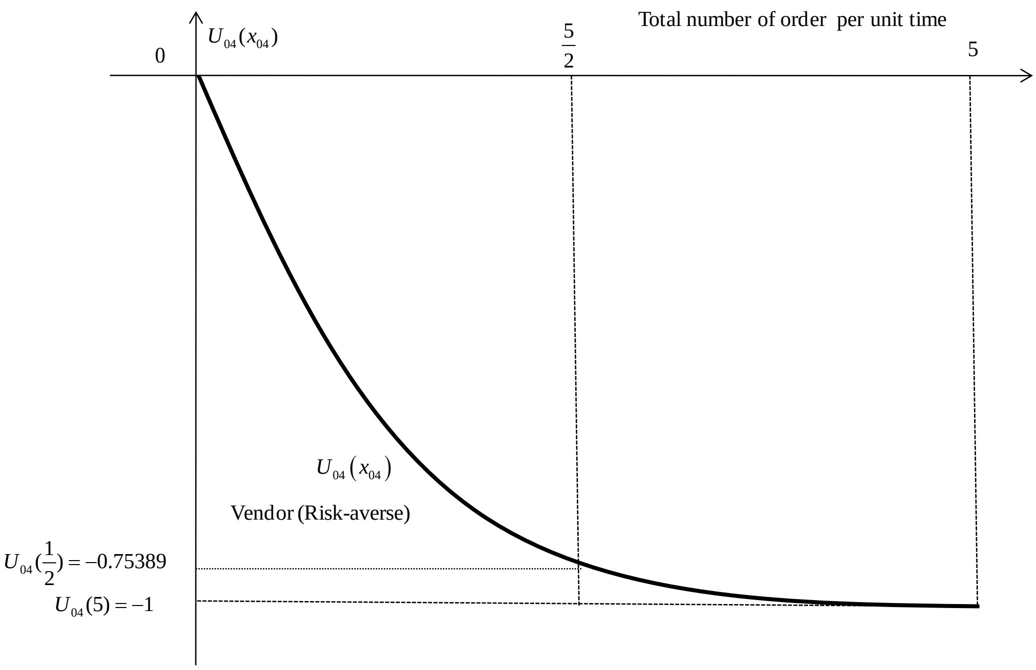


Figure 5.9: Diagram of utility functions on air pollution per unit time of vendor in a 5-buyer example when DP ratio is 0.1.

5.5.5 The Model

The utility functions with different financial measurements and environmental measurement as discussed in sections 5.51 to 5.54 are integrated into a weighted utility function. It is proposed that another coordinated model involving green components and utility components, called the green utility optimization, can be addressed and it can be considered as a utility maximization problem with weighted utility functions, i.e.

$$\underset{k'_i,N'}{Max}\,TU=\alpha_1\sum_{i=0}^{n}U_{i1}\left(x_{i1}\right)+\alpha_2\sum_{i=0}^{n}U_{i2}\left(x_{i2}\right)+\alpha_3\sum_{i=0}^{n}U_{i3}\left(x_{i3}\right)+\alpha_4\sum_{i=0}^{n}U_{i4}\left(x_{i4}\right). \tag{5.17}$$

Where x_{ij} represents the j th performance measure of buyer i, x_{0j} represents the j th performance measure of vendor and α_j are the weight associated with the j th measure with $\sum_{j=1}^{4}\alpha_j=1$.

There are four components in equation (5.17), the first component, $\sum_{i=0}^{n}U_{i1}\left(x_{i1}\right)$, shows the total utility value of vendor and buyer to the total cost. The second component, $\sum_{i=0}^{n}U_{i2}\left(x_{i2}\right)$, shows the total utility value of vendor and buyer to the energy wastage. The third component, $\sum_{i=0}^{n}U_{i3}\left(x_{i3}\right)$, shows the total utility value of vendor and buyer to the raw materials wastage. The fourth component, $\sum_{i=0}^{n}U_{i3}\left(x_{i3}\right)$, shows the total utility value of vendor and buyer to the air pollution.

The total utility of the cost component for best the vendor and all buyers is represented by $\sum_{i=0}^{n}U_{i1}\left(x_{i1}\right)$, where

$$U_{01}(x_{01}) = \frac{1}{e^{-c_{01}\Delta_{01}}-1} + \frac{1}{1-e^{-c_{01}\Delta_{01}}} e^{-c_{01}x_{01}} \quad \text{for vendor}$$

and

$$U_{i1}(x_{i1}) = \begin{cases} \dfrac{1}{e^{-c_{i1}\Delta_{i1}}-1} + \dfrac{1}{1-e^{-c_{i1}\Delta_{i1}}} e^{-c_{i1}x_{i1}} & \text{for risk averse/prone buyers} \\ \dfrac{x_{i1}}{\Delta_{i1}} & \text{for risk neutral buyers} \end{cases}$$

and

$$x_{i1} = \begin{cases} \dfrac{A_i}{k_i^* T} + \dfrac{1}{2} d_i h_i k_i^* T & \text{synchronized cycles model} \\ \dfrac{A_i}{T_i^*} + \dfrac{1}{2} d_i h_i T_i^* & \text{indepedent optimization} \quad \forall i = 1,2,...,n \\ \dfrac{A_i}{k_i' T} + \dfrac{1}{2} d_i h_i k_i' T & \text{green utility optimization} \end{cases}$$

and

$$x_{01} = \begin{cases} \dfrac{S_v}{N^* T} + \dfrac{1}{2}\left(1-\dfrac{D}{P}\right) hDN^* T + h\sum_{i=1}^{n}\left(\dfrac{D}{P}-\dfrac{1}{2}\right) d_i k_i^* T + \sum_{i=1}^{n}\dfrac{C_i}{k_i^* T} & \text{synchronized cycles model} \\ \dfrac{S_v}{T_v^*} + \dfrac{1}{2}\left(1-\dfrac{D}{P}\right) hDT_v^* + \sum_{i=1}^{n} d_i T_i^* + \sum_{i=1}^{n}\dfrac{C_i}{T_i^*} & \text{indepedent optimization} \\ \dfrac{S_v}{N' T} + \dfrac{1}{2}\left(1-\dfrac{D}{P}\right) hDN' T + h\sum_{i=1}^{n}\left(\dfrac{D}{P}-\dfrac{1}{2}\right) d_i k_i' T + \sum_{i=1}^{n}\dfrac{C_i}{k_i' T} & \text{green utility optimization.} \end{cases} \tag{5.18}$$

Similarly, the total utilities of energy wastage per unit time, raw material wastage per unit time , and air pollution per unit time for the vendor and buyers are represented by $\sum_{i=0}^{n} U_{i2}(x_{i2})$, $\sum_{i=0}^{n} U_{i3}(x_{i3})$, and $\sum_{i=0}^{n} U_{i4}(x_{i4})$, respectively.

For the component of energy wastage per unit time, the variables and utility functions are expressed as follows:

$$x_{i2} = \begin{cases} \dfrac{1}{N^{*}T} & \text{synchronized cycles model} \\ \dfrac{1}{T_v^{*}} & \text{indepedent optimization} \\ \dfrac{1}{N^{'}T} & \text{green utility optimization} \end{cases} \quad \forall i = 0,1,2,...,n;$$

and

$$U_{02}(x_{02}) = \frac{1}{e^{-c_{02}\Delta_{02}} - 1} + \frac{1}{1 - e^{-c_{02}\Delta_{02}}} e^{-c_{02}x_{02}} \quad \text{for vendor}$$

and

$$U_{i2}(x_{i2}) = \begin{cases} \dfrac{1}{e^{-c_{i2}\Delta_{i2}} - 1} + \dfrac{1}{1 - e^{-c_{i2}\Delta_{i2}}} e^{-c_{i2}x_{i2}} & \text{for risk averse/prone buyers} \\ \dfrac{x_{i2}}{\Delta_{i2}} & \text{for risk neutral buyers} \end{cases}.$$

(5.19)

For the component of raw materials wastage per unit time, the variables and utility functions are expressed as follows:

$$U_{03}(x_{03}) = \frac{1}{e^{-c_{03}\Delta_{03}} - 1} + \frac{1}{1 - e^{-c_{03}\Delta_{03}}} e^{-c_{03}x_{03}} \quad \text{for vendor}$$

and

$$U_{i3}(x_{i3}) = \begin{cases} \dfrac{1}{e^{-c_{i3}\Delta_{i3}} - 1} + \dfrac{1}{1 - e^{-c_{i3}\Delta_{i3}}} e^{-c_{i3}x_{i3}} & \text{for risk averse/prone buyers} \\ \dfrac{x_{i3}}{\Delta_{i3}} & \text{for risk neutral buyers} \end{cases}$$

and

$$x_{i3} = \begin{cases} \dfrac{1}{2}\left(1 - \dfrac{D}{P}\right) DN^{*}T + \displaystyle\sum_{i=1}^{n}\left(\dfrac{D}{P} - \dfrac{1}{2}\right) d_i k_i^{*} T & \text{synchronized cycles model} \\ \dfrac{1}{2}\left(1 - \dfrac{D}{P}\right) DT_v^{*} + \displaystyle\sum_{i=1}^{n} d_i T_i^{*} & \text{indepedent optimization} \\ \dfrac{1}{2}\left(1 - \dfrac{D}{P}\right) DN'T + \displaystyle\sum_{i=1}^{n}\left(\dfrac{D}{P} - \dfrac{1}{2}\right) d_i k_i^{'} T & \text{green utility optimization} \end{cases}$$

$\forall i = 0,1,2,...,n$. (5.20)

For the component of air pollution per unit time, the variables and utility functions are expressed as follows:

$$U_{04}(x_{04}) = \frac{1}{e^{-c_{04}\Delta_{04}} - 1} + \frac{1}{1 - e^{-c_{04}\Delta_{04}}} e^{-c_{04}x_{04}} \quad \text{for vendor}$$

and

$$U_{i4}(x_{i4}) = \begin{cases} \dfrac{1}{e^{-c_{i4}\Delta_{i4}} - 1} + \dfrac{1}{1 - e^{-c_{i4}\Delta_{i4}}} e^{-c_{i4}x_{i4}} & \text{for risk averse/prone buyers} \\ \dfrac{x_{i4}}{\Delta_{i4}} & \text{for risk neutral buyers} \end{cases}$$

and

$$x_{i4} = \begin{cases} \dfrac{1}{k_i^* T} & \text{synchronized cycles model} \\ \dfrac{1}{T_i^*} & \text{indepedent optimization} \quad \forall i = 1, 2, \ldots, n \\ \dfrac{1}{k_i^{'} T} & \text{green utility optimization} \end{cases}$$

and

$$x_{04} = \begin{cases} \sum_{i=1}^{n} \dfrac{1}{k_i^* T} & \text{synchronized cycles model} \\ \sum_{i=1}^{n} \dfrac{1}{T_i^*} & \text{indepedent optimization} \\ \sum_{i=1}^{n} \dfrac{1}{k_i^{'} T} & \text{green utility optimization} \end{cases} . \tag{5.21}$$

However, the total utility of the system by cost minimization models is expressed as

$$TU = \alpha_1 \sum_{i=0}^{n} U_{i1}(x_{i1}) + \alpha_2 \sum_{i=0}^{n} U_{i2}(x_{i2}) + \alpha_3 \sum_{i=0}^{n} U_{i3}(x_{i3}) + \alpha_4 \sum_{i=0}^{n} U_{i4}(x_{i4})$$

subject to $\sum_{j=1}^{4} \alpha_j = 1$.

(5.22)

As mentioned before, the objectives of this chapter are concerned with the economic impact of vendor-buyer coordination on the organization carrying them out. Hence, the first objective in this research is to analyze the impacts of the environmental performance by the cost-minimizing models of the supply chain by equation (5.22). The utility values of financial and environmental components are compared. The second objective of this research is to maximize the total utility of the weight utility function, given by equation (5.17), by determining the ordering cycle $k_i^{'}T$ of buyer i and production cycle $N'T$ of vendor.

In general, the total utility TU, given by equation (5.22), is calculated by the utility functions (equations (5.18) - (5.21)) given the weights $(\alpha_1, \alpha_2, \alpha_3, \alpha_4)$ for the independent optimization and synchronized cycles model. However, for the green utility optimization, the objective is to determine the value of N' and k_i' in order to maximize equation (5.17). Since the ordering cycles $k_i^{'}T$ of buyers should be an integer factor of production cycle $N'T$ of vendor. It is difficult to find the "real" optimal solution analytically by equation (5.17) since $U_{ij}(x_{ij})$ are function of k_i' and N' and k_i' also depends on N'. Therefore, exhaustive enumeration is applied to find the real optimal solution in a 5-buyer example. Since the sets of feasible solutions are very large in 30-buyer and 50-buyer examples, it is difficult to obtain the real optimal solution by exhaustive enumeration in term of computational time. Therefore, genetic algorithms are applied to search the near optimal solution.

5.6 Genetic Algorithm

Similar to Chapter 3, the genes (entries) of a string are coded with non-negative number. The first entry of the string denotes the total utility value which represents the fittest value for the string. A high total utility value ranks high in population. The total utility value is a weighted average of utilities on different measures U_{ij}. Then, U_{i1} is the utility value of total cost of the party i, U_{i2} is the utility value of energy wastage of the party i, U_{i3} is the utility value of raw material wastage of the party i, and U_{i4} is the utility value of air pollution of the party i. Hence, U_1 denotes the sum of the utility value of total cost for all parties which are calculated by equation (5.18), U_2 denotes the sum of the utility value of energy wastage for all parties which are calculated by equation (5.19), U_3 denotes the sum of the utility value of raw material wastage for all parties which are calculated by equation (5.20) and U_4 denotes the sum of the utility value of air pollution for all parties which are calculated by equation (5.21). Given the weights $(\alpha_1, \alpha_2, \alpha_3, \alpha_4)$ of utility functions, the total utility value TU is the sum of the weighted utilities, i.e. $TU = \sum_{i=0}^{n} (\alpha_1 U_{i1} + \alpha_2 U_{i2} + \alpha_3 U_{i3} + \alpha_4 U_{i4})$ which is calculated by equation (5.22). Then the next entry is the production cycle of vendor N'. Then, TC represents the total cost per unit time of the system. Lastly, the values of k'_i are coded to represent the ordering cycles of buyer i. The string is shown in Figure 5.10.

TU	U_1	U_2	U_3	U_4	TC	N'	k'_1	k'_2				k'_n

Figure 5.10: A string in genetic algorithm in utility maximization.

The process of genetic algorithm is described as follows:

Step 1: Firstly, an initial population of size 20 is created by a random process. The fitness values of the strings in the initial population are also calculated.

Step 2: 1 pair of parents are chosen by using a biased roulette wheel from population.

Step 3: Their offsprings of the chosen parents are produced by crossover and by mutation. Then, reproduce two offsprings from the chosen pair of parents. If the production cycles (N') of a pair of parent are equal, then reproduce by crossover and mutation. A random number r between 0 and 1 is generated. If $r \leq p_c$, produce an offspring by a crossover process. If $r > p_c$, another random number r' is generated. If $r' \leq p_m$ mutation will be conducted; otherwise, no mutation will be started. If production cycles (N') of a pair of parents are not equal, since it is possible that no common factor k'_i can be exchanged by crossover, thus reproduce the offspring only by the mutation process. A random number r'' between 0 and 1 is generated. If $r'' \leq p_m$, produce an offspring by a mutation process. If $r > p_m$, no mutation will be started. Note that the mutation rate p_m and crossover rate p_c are pre-determined.

Step 4: Repeat step 2 and step 3, 20 times until 20 pairs of offspring have been produced.

Step 5: Keep the top 20 strings from the combined group of population and offsprings. These 20 strings become the population for next reproduction.

Step 6: Repeat step 2 to step 5 until the stopping criterion has been reached. Choose the best (fittest) solution in the population as the "optimal" solution of the problem.

Step 7: Repeat step 1 to step 6 with 5 times (samples), select the best solution of the 5 as the final solution.

5.6.1 Crossover

A random numbers r between 0 and 1 are generated. If the random number r of a string is smaller than or equal to the pre-determined crossover rate p_c, crossover will be applied to the chosen strings (parents). During crossover, if the production cycles N' of vendor of two strings (parents) are the same, crossover operator will randomly select two genes of the parents that the genes between two selected genes of the strings are swapped between two parents. Then, the utility values of 4 measures and total utility value are calculated again with the new k_i. If the random number r of a string is larger than the pre-determined crossover rate p_c, usually $p_c = 0.8$, mutation will be carried out. However, if the production cycles N' of vendor of two strings (parents) are different, no crossover will be started. The offsprings will be the same as the parents.

For example, two strings are randomly selected from the population as shown in

Figure 5.11. Two random numbers are selected, e.g. 2 and 4. If the production cycles (N^1, N^2) of vendor of two strings (parents) are the same, the genes $\left(k_2^1, k_3^1, k_4^1\right)$ and $\left(k_2^2, k_3^2, k_4^2\right)$ are swapped between string 1 and string 2. All utility values ($TU^1, TU^2, U^1{}_j$ and $U^2{}_j$, $j = 1, 2, 3, 4$) and total cost (TC^1 and TC^2) in the two strings are shown in Figure 5.11. After crossover, All utility values ($\underline{TU}^1, \underline{TU}^2$, $\underline{U}^1{}_j$ and $\underline{U}^2{}_j$, $j = 1, 2, 3, 4$) and total cost ($\underline{TC}^1$ and $\underline{TC}^2$) of the strings are computed again shown as Figure 5.12 .

String 1:

TU^1	$U^1{}_1$	$U^1{}_2$	$U^1{}_3$	$U^1{}_4$	TC^1	N^1	k_1^1	k_2^1		k_4^1		k_n^1

String 2:

TU^2	$U^2{}_1$	$U^2{}_2$	$U^2{}_3$	$U^2{}_4$	TC^2	N^2	k_1^2	k_2^2		k_4^2		k_n^2

Figure 5.11: Two randomly selected strings before crossover.

String 1:

$\underline{TU}^1$	$\underline{U}^1{}_1$	$\underline{U}^1{}_2$	$\underline{U}^1{}_3$	$\underline{U}^1{}_4$	$\underline{TC}^1$	N^1	k_1^1	k_2^2	k_3^2	k_4^2		k_n^1

String 2:

$\underline{TU}^2$	$\underline{U}^2{}_1$	$\underline{U}^2{}_2$	$\underline{U}^2{}_3$	$\underline{U}^2{}_4$	$\underline{TC}^2$	N^2	k_1^2	k_2^1	k_3^1	k_4^1		k_n^2

Figure 5.12: Two randomly selected strings after crossover if the production cycles of two strings are the same.

5.6.2 Mutation

A random numbers r between 0 and 1 are assigned to each gene of the string. If the random number r of a gene of the string is smaller than or equal to the pre-determined mutation rate p_m, usually $p_m = 0.2$, mutation will be applied to the chosen gene of the string. During mutation, a random ordering cycle from a list of factors of production cycles N of the string is generated and assigned to the chosen gene. The utility values of 4 different performance measures and total utility value are calculated again with the new sets of N' and k'_i.

For example, a string is randomly selected from the population as shown in Figure 5.13. A random number between 0 and 1 is generated to each gene of the string. The random numbers of gene 1 and 3 are below the pre-determined mutation rate p_m. Then, the new genes (k'_1 and k'_3) are randomly regenerated from a list of factors of N'. Suppose that k'_1 is mutated to k'_3 and k'_3 is mutated to k'_2 after random generation. All utility values (TU, U_1, U_2, U_3 and U_4) and total cost TC in the string are computed again. After mutation, the new string is shown in Figure 5.14.

TU	U_1	U_2	U_3	U_4	TC	N'	k'_1	k'_2	k'_3			k'_n

Figure 5.13: A string before mutation.

TU'	U'_1	U'_2	U'_3	U'_4	TC'	N'	k'_3	k'_2	k'_2			k'_n

Figure 5.14: A string after mutation.

5.6.3 Stopping Criterion

The stopping criterion for the problem is important in the genetic algorithm. This is a limit of number of iteration to stop the process when the solution is settled down. If this value is too small, the process will stop before convergence. However, if it is too large, it wastes of times. In this research, the stopping criterion is determined as follows. For example, when DP ratio is 0.5 and $(\alpha_1, \alpha_2, \alpha_3, \alpha_4) = \left(0.9, \frac{0.1}{3}, \frac{0.1}{3}, \frac{0.1}{3}\right)$, for a 5-buyer case as shown in Figure 5.15, when the number of iterations is 20, the total utility values with 5 random samples are -1.0017, -0.9749, -0.9749, -0.9749, and -0.9749,which are converged to the real optimal solution of -0.975 obtained by exhaustive enumeration, and then there is no significant improvement after that. The stopping criterion for a 5-buyer case is 100 iterations. Moreover, for a 30-buyer case as shown in Figure 5.16, the total utility values with 5 random samples are -2.9197, -2.9197, -2.9201, -2.9197, and -2.9204, which converge (with maximum error of 0.024%) and become stable when the number of iterations is 1500, and then there is no significant improvement after that. The stopping criterion for a 30-buyer case is 1500 iterations. For a 50-buyer case as shown in Figure 5.17, the total utility values with 5 random samples are -5.302, -5.306, -5.307, -5.316, and -5.295 which converge (with maximum error of 0.39%) and become stable when the number of iterations is 2500, and it would not be improved significantly after that. The stopping criterion for a 50-buyer case is 2500 iterations.

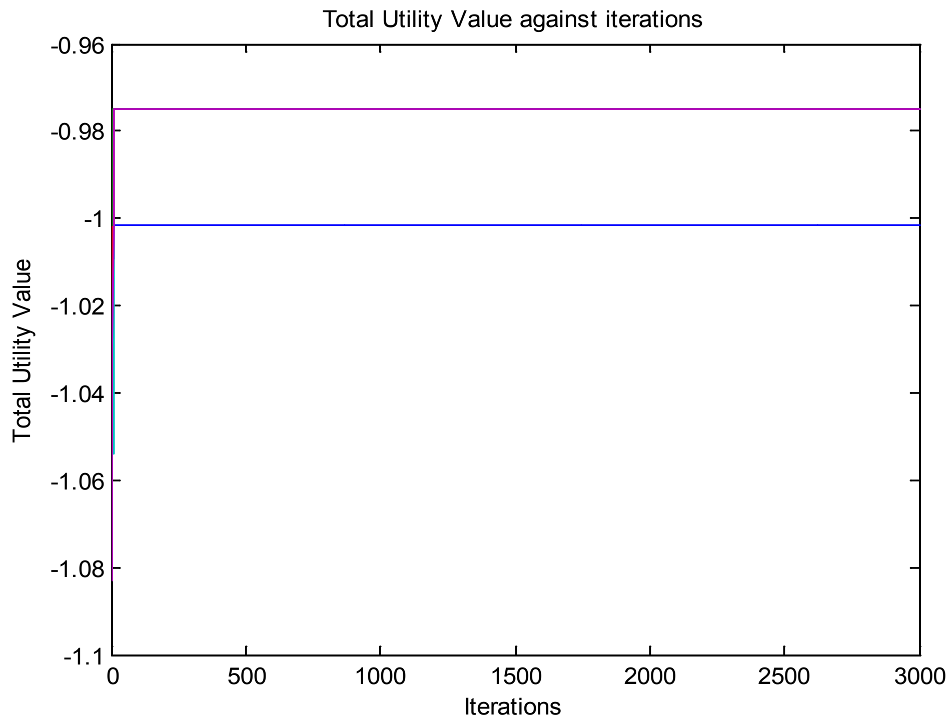


Figure 5.15: Total utility value for a 5-buyer example with DP ratio 0.5.

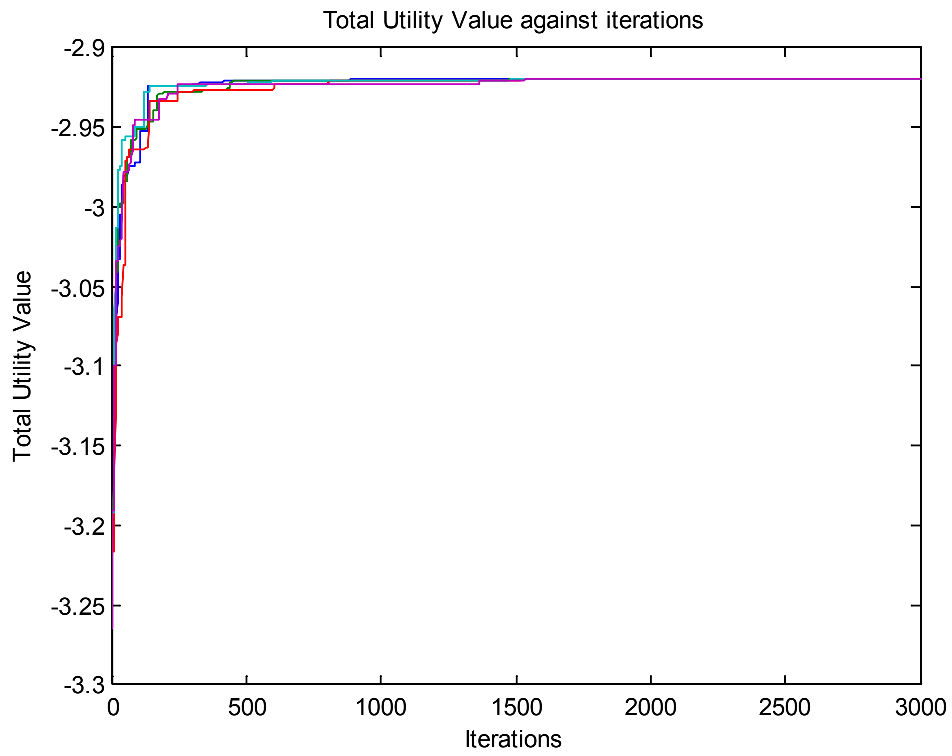


Figure 5.16: Total utility value for a 30-buyer example with DP ratio 0.5.

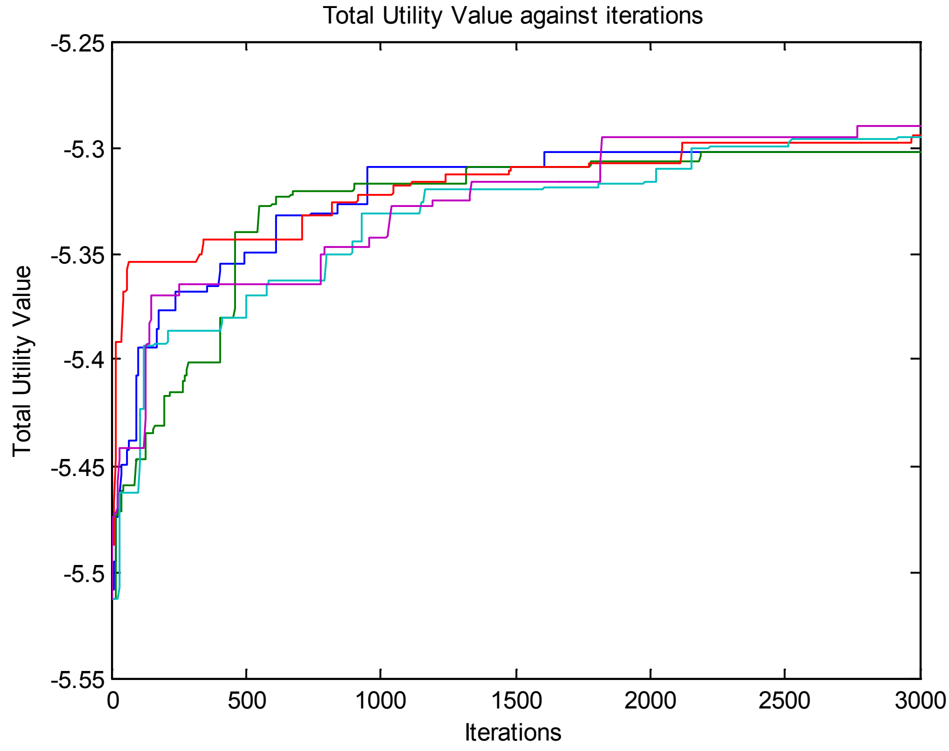


Figure 5.17: Total utility value for a 50-buyer example with DP ratio 0.5.

After running the 3,000 iterations for each example with 5 runs, it is recommended that the stopping criteria are to stop at 100, 1500, and 2500 iterations for Example 1, Example 2 and Example 3, respectively, to obtain near optimal solution.

5.7 Results

Three examples with 5-buyer, 30-buyer and 50-buyer are illustrated in this section as Example 1, Example 2, and Example 3, respectively. The data are obtained in Tables A1 to A3 of Appendix A. The Intel (R) core (TM) Quad CPU Q9550 with speed of 2.83GHz is used to run the results. If the maximum planning horizon $N^{max}T$ is 365, there are totally 45,169,525 combinations of ordering cycles $\left(k'_1, k'_2, k'_3, k'_4, k'_5\right)$ of buyers in Example 1 (5-buyer case), it takes 3 hours 22 minutes 56 seconds to list out all feasible solutions and to obtain the optimal solution (k'^*_i and N'^*) by exhaustive enumeration with DP ratios from 0.1 to 0.9. However, in the cases of 30-buyer and 50-buyer, the numbers of combinations are too large to obtain the optimal solution. Therefore, Genetic algorithm is applied to obtain a near optimal solution. If the cross-over rate and mutation rate are 0.8 and 0.2, respectively, and the number of iterations per run and number of samples (runs) are 1000 and 5, respectively, the time taken by genetic algorithm is only around 11 minutes in Example 1. Hence, in order to obtain the result efficiently, Genetic algorithm is applied in 30-buyer and 50-buyer examples.

First of all, in order to determine the risk attitudes to financial and environmental performance, a random number is generated and assigned to each buyer and vendor. Since there are four measurements for a single-vendor *n*-buyer supply chain, namely, total cost, energy wastage, raw materials wastage and air pollution, $4(n+1)$ random numbers are generated totally. In this thesis, the utility values run by three sets random numbers are produced for each example as shown in Tables A6 to A8 of Appendix A.

The total cost, production cycle of vendor, and ordering cycles of buyers for the synchronized cycles model and independent optimization are obtained in Chapter 3. Then, by above information, environmental measures such as number of production run per unit time, average inventory level of vendor and number of orders per unit time, are produced and shown in Tables B43 to B48 of Appendix B.

5.7.1 Utilities under Cost-minimizing Synchronized Cycles Model and Independent Optimization

When DP ratios ranges from 0.1 to 0.9, the utility values on cost, energy wastage, raw material wastage, and air pollution of synchronized cycles model and independent optimization are obtained for 5-buyer, 30-buyer and 50-buyer examples. The average values of Utility and total cost are calculated. Also, three different sets of random numbers in 5-buyer example are used. One of them is shown in Table 5.9 and the results by other two sets are shown in Tables B49 to B54 of Appendix B.

The total utilities of cost, energy wastage per unit time, raw material wastage per unit time , and air pollution per unit time for the vendor and buyers, which are represented by $\sum_{i=0}^{n} U_{i1}\left(x_{i1}\right)$, $\sum_{i=0}^{n} U_{i2}\left(x_{i2}\right)$, $\sum_{i=0}^{n} U_{i3}\left(x_{i3}\right)$, and $\sum_{i=0}^{n} U_{i4}\left(x_{i4}\right)$, respectively, are shown in the columns 2, 3, 4 and 5 in Table 5.9, Table 5.10, and Table 5.11. The average values of total cost and utility values are shown in the last row in Table 5.9, Table 5.10, and Table 5.11.

In Table 5.9, the average utility value of cost by synchronized cycles model is -1.0202, which is higher than -1.5032 by independent optimization. Also, the average utility value of energy wastage by synchronized cycles model is -0.2449, which is higher than -0.25 by independent optimization. Besides, the average utility value of raw materials wastage by synchronized cycles model is -0.28377, which is higher than -6 by independent optimization. Finally, the average utility value of air pollution by synchronized cycles model is -0.4113, which is higher than -0.7745 by independent optimization. In general, synchronized cycle model produces a higher satisfaction on cost, energy wastage, raw materials wastage, and air pollution in 5-buyer example.

	Independent optimization					Synchronized cycles model				
DP ratio	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost
0.1	-1.5032	-0.3460	-6	-0.7745	36.58	-0.9092	-0.3370	-0.5413	-0.2862	23.19
0.2	-1.5032	-0.3271	-6	-0.7745	35.92	-0.9297	-0.3443	-1.0301	-0.2924	23.83
0.3	-1.5032	-0.3068	-6	-0.7745	35.23	-1.0270	-0.2732	-2.5467	-0.4186	24.25
0.4	-1.5032	-0.2849	-6	-0.7745	34.48	-1.0469	-0.2732	-2.7197	-0.4186	24.43
0.5	-1.5032	-0.2610	-6	-0.7745	33.67	-1.0700	-0.2732	-2.9096	-0.4186	24.61
0.6	-1.5032	-0.2343	-6	-0.7745	32.77	-1.0249	-0.1982	-3.7373	-0.4582	24.60
0.7	-1.5032	-0.2037	-6	-0.7745	31.75	-1.0403	-0.1982	-3.7528	-0.4582	24.31
0.8	-1.5032	-0.1672	-6	-0.7745	30.54	-1.0635	-0.1982	-3.8086	-0.4582	24.02
0.9	-1.5032	-0.1190	-6	-0.7745	28.96	-1.0705	-0.1086	-4.4931	-0.4929	23.15
Average	-1.5032	-0.2500	-6	-0.7745	33.32	-1.0202	-0.2449	-2.8377	-0.4113	24.04

Table 5.9:Comparison of utility values and total cost between synchronized cycles model and independent optimization for various DP ratios in Example 1.

	Independent optimization					Synchronized cycles model				
DP ratio	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost
0.1	-2.8423	-1.9041	-31	-7.5397	567.03	-2.7808	-1.8302	-10.2693	-3.0388	374.15
0.2	-2.8423	-1.7995	-31	-7.5397	554.61	-2.7305	-1.8302	-12.1280	-3.5508	378.10
0.3	-2.8423	-1.6877	-31	-7.5397	541.39	-2.9099	-1.5780	-15.6130	-3.5909	378.80
0.4	-2.8423	-1.5669	-31	-7.5397	527.18	-2.7863	-1.4763	-17.5650	-3.6793	378.09
0.5	-2.8423	-1.4348	-31	-7.5397	511.74	-2.7543	-1.4763	-17.9946	-4.0824	375.62
0.6	-2.8423	-1.2877	-31	-7.5397	494.65	-2.7295	-1.2370	-20.6466	-4.2638	369.10
0.7	-2.8423	-1.1195	-31	-7.5397	475.26	-2.7290	-1.2370	-20.3441	-4.3259	361.76
0.8	-2.8423	-0.9183	-31	-7.5397	452.26	-2.7685	-0.9343	-23.1736	-4.5446	349.08
0.9	-2.8423	-0.6533	-31	-7.5397	422.28	-2.6519	-0.6273	-25.3827	-4.7040	329.53
Average	-2.8423	-1.3746	-31	-7.5397	505.16	-2.7601	-1.3585	-18.1241	-3.9756	366.02

Table 5.10:Comparison of utility values and total cost between synchronized cycles model and independent optimization for various DP ratios in Example 2.

In Table 5.10, the average utility value of cost by synchronized cycles model is -2.7601, which is higher than -2.8423 by independent optimization. Also, the average utility value of energy wastage by synchronized cycles model is -1.3585, which is higher than -1.3746 by independent optimization. Besides, the average utility value of raw materials wastage by synchronized cycles model is -18.1241, which is higher than -31 by independent optimization. Finally, the average utility value of air pollution by synchronized cycles model is -3.9756, which is higher than -7.5397 by independent optimization. In general, synchronized cycle model produces a higher satisfaction on cost, raw materials wastage and air pollution in 30-buyer example.

	Independent optimization					Synchronized cycles model				
DP ratio	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost
0.1	-4.9880	-4.8894	-51	-14.9283	1025.54	-4.8873	-4.8340	-11.8950	-7.7714	714.84
0.2	-4.9880	-4.6292	-51	-14.9283	1000.73	-4.7823	-4.2686	-19.8548	-9.2450	722.37
0.3	-4.9880	-4.3498	-51	-14.9283	974.31	-4.7276	-4.2686	-21.5171	-9.9855	723.68
0.4	-4.9880	-4.0469	-51	-14.9283	945.92	-4.6439	-3.8217	-24.8790	-10.1358	720.04
0.5	-4.9880	-3.7141	-51	-14.9283	915.06	-4.6408	-3.8217	-25.1294	-11.1289	713.27
0.6	-4.9880	-3.3420	-51	-14.9283	880.92	-4.6770	-2.9087	-30.5935	-11.4131	701.31
0.7	-4.9880	-2.9142	-51	-14.9283	842.16	-4.6827	-2.9087	-29.1104	-12.0020	681.41
0.8	-4.9880	-2.3992	-51	-14.9283	796.20	-4.7617	-2.3480	-30.8609	-12.2325	657.76
0.9	-4.9880	-1.7152	-51	-14.9283	736.29	-4.6654	-1.4878	-33.3108	-12.5775	617.57
Average	-4.9880	-3.5556	-51	-14.9283	901.90	-4.7188	-3.4075	-25.2390	-10.7213	694.69

Table 5.11:Comparison of utility values and total cost between synchronized cycles model and independent optimization for various DP ratios in Example 3.

In Table 5.11, the average utility value of cost by synchronized cycles model is -4.7188, which is higher than -4.988 by independent optimization. Also, the average utility value of energy wastage by synchronized cycles model is -3.4075, which is higher than -3.5556 by independent optimization. Besides, the average utility value of raw materials wastage by synchronized cycles model is -25.239, which is higher than -51 by independent optimization. Finally, the average utility value of air pollution by synchronized cycles model is -10.7213, which is higher than -14.9283 by independent optimization. In general, Synchronized cycle model produces a higher satisfaction on cost, raw materials wastage and air pollution in 50-buyer example.

By the above three examples, synchronized cycle model produces a higher satisfaction on cost, raw materials wastage and air pollution, but not always for energy wastage on average.

5.7.2 Comparison of Green Utility Optimization with Cost Minimization

As the total utility value depends on the weights of utility $(\alpha_1, \alpha_2, \alpha_3, \alpha_4)$ and total cost is an important factor in supply chain, the total utility with different weights of total cost α_1 are studied for a particular DP ratio. As various DP ratios have similar results, it is considered that DP ratio is 0.5 for simplicity. Moreover, the utility values with three sets of random numbers are shown. The ten weight of cost α_1 from 0.1 to 1.0 and other weights $(\alpha_2, \alpha_3, \alpha_4)$ are equally weights.

Given that DP ratio is equal to 0.5, it takes 121 minutes 32 seconds for a 5-buyer example by exhaustive enumerative search for ten different weights of utility. However, by genetic algorithm, it takes only 9 minutes 1 second for a 30-buyer example with 1500 runs and 19 minutes 42 second with 2500 runs for a 50-buyer example.

The weights of utilities are shown in Table 5.12 where α_1, α_2, α_3, and α_4 denote the weight of measurements of cost, energy wastage, raw materials wastage and air pollution, respectively. With the information in Table 5.12, the total costs and total utilities values for 5-buyer, 30-buyer and 50-buyer examples are computed by equation (5.17).

Case	α_1	α_2	α_3	α_4
1	1.000	0.000	0.000	0.000
2	0.900	0.033	0.033	0.033
3	0.800	0.067	0.067	0.067
4	0.700	0.100	0.100	0.100
5	0.600	0.133	0.133	0.133
6	0.500	0.167	0.167	0.167
7	0.400	0.200	0.200	0.200
8	0.300	0.233	0.233	0.233
9	0.200	0.267	0.267	0.267
10	0.100	0.300	0.300	0.300

Table 5.12: The weights of the four measurements.

The results of utility values and total costs for Example 1, 2, and 3 are shown in Table 5.13, Table 5.14, and Table 5.15, respectively. The utility value of green utility optimization is shown in column 3. Columns 4 and 5 show the percentage of improvement of total utility of green utility optimization over synchronized cycles model and independent optimization, respectively. Column 6 represents the total cost of green utility optimization. Columns 7 and 8 show the percentage of improvement of total cost of green utility optimization over synchronized cycles model and independent optimization, respectively. The last row shows the average total utility, average total cost and their average percentage improvement over synchronized cycles model and independent optimization.

5.7.2.1 5-buyer Example

DP ratio	α_1	Total utility	Improved over SYN	Improved over IND	Total cost	Improved over SYN	Improved over IND
0.5	1.0	-0.9465	11.54%	37.03%	25.95	-5.46%	22.91%
0.5	0.9	-0.9743	10.04%	38.62%	25.91	-5.29%	23.03%
0.5	0.8	-0.9935	9.36%	40.57%	26.68	-8.39%	20.77%
0.5	0.7	-0.9959	10.20%	43.28%	25.92	-5.34%	23.00%
0.5	0.6	-0.9873	12.02%	46.34%	26.04	-5.83%	22.64%
0.5	0.5	-0.9770	13.94%	49.23%	26.36	-7.13%	21.69%
0.5	0.4	-0.9642	16.03%	51.99%	26.57	-7.96%	21.08%
0.5	0.3	-0.9485	18.33%	54.67%	27.09	-10.08%	19.53%
0.5	0.2	-0.9288	20.91%	57.33%	27.78	-12.89%	17.48%
0.5	0.1	-0.9031	23.94%	60.06%	28.69	-16.56%	14.80%
Average		-0.9619	14.63%	47.91%	26.70	-8.49%	20.69%

Table 5.13:Comparison of total utility and total cost of green utility optimization over synchronized cycles model and independent optimization on various weight of cost in Example 1 when DP ratio is 0.5.

For example, when DP ratio is 0.5 in Table 5.13, the average total utility value of green utility optimization is -0.9619, which is 14.63% higher than that of synchronized cycles model and 47.91% higher than that of independent optimization. Also, the average total cost of green utility optimization is 26.70, which is 8.49% more than that of synchronized cycles model and is 20.69% lower than that of independent optimization.

5.7.2.2 30-buyer Example

For example, when DP ratio is 0.5 in Table 5.14, the average total utility value of green utility optimization is -4.5124, which is 10.36% higher than that of synchronized cycles model and 36.48% higher than that of independent optimization. Also, the total cost of green utility optimization is 429.49, which is 14.34% more than that of synchronized cycles model and is 16.07% lower than that of independent optimization.

DP ratio	α_1	Total utility	Improved over SYN	Improved over IND	Total cost	Improved over SYN	Improved over IND
0.5	1.0	-2.3708	13.92%	16.59%	402.10	-7.05%	21.42%
0.5	0.9	-2.9197	10.55%	24.95%	408.86	-8.85%	20.10%
0.5	0.8	-3.4448	8.71%	30.25%	413.30	-10.03%	19.24%
0.5	0.7	-3.9524	7.73%	33.98%	416.86	-10.98%	18.54%
0.5	0.6	-4.4477	7.20%	36.78%	421.01	-12.09%	17.73%
0.5	0.5	-4.9321	6.99%	38.99%	422.56	-12.50%	17.43%
0.5	0.4	-5.4055	7.00%	40.81%	441.63	-17.58%	13.70%
0.5	0.3	-5.8658	7.22%	42.38%	458.51	-22.07%	10.40%
0.5	0.2	-5.1124	25.17%	54.47%	429.42	-14.32%	16.09%
0.5	0.1	-6.6727	9.11%	45.65%	480.66	-27.97%	6.07%
Average		-4.5124	10.36%	36.48%	429.49	-14.34%	16.07%

Table 5.14:Comparison of total utility and total cost of green utility optimization over synchronized cycles model and independent optimization on various weight of cost in Example 2 when DP ratio is 0.5.

5.7.2.3 50-buyer Example

DP ratio	α_1	Total utility	Improved over SYN	Improved over IND	Total cost	Improved over SYN	Improved over IND
0.50	1.0	-4.5060	2.90%	9.66%	753.35	-5.62%	17.67%
0.50	0.9	-5.2900	4.04%	22.33%	796.63	-11.69%	12.94%
0.50	0.8	-6.0092	5.88%	30.39%	835.59	-17.15%	8.68%
0.50	0.7	-6.7258	7.31%	35.67%	850.57	-19.25%	7.05%
0.50	0.6	-7.4048	8.90%	39.69%	869.91	-21.96%	4.93%
0.50	0.5	-8.1068	9.93%	42.51%	870.40	-22.03%	4.88%
0.50	0.4	-8.7508	11.36%	45.05%	896.23	-25.65%	2.06%
0.50	0.3	-9.3919	12.59%	47.08%	900.04	-26.19%	1.64%
0.50	0.2	-10.0015	13.90%	48.89%	910.46	-27.65%	0.50%
0.50	0.1	-10.6095	15.04%	50.40%	909.54	-27.52%	0.60%
Average		-7.6796	9.19%	37.17%	859.27	-20.47%	6.10%

Table 5.15:Comparison of total utility and total cost of green utility optimization over synchronized cycles model and independent optimization on various weight of cost in Example 3 when DP ratio is 0.5.

For example, when DP ratio is 0.5 in Table 5.15, the average total utility value of green utility optimization is -7.6796, which is 9.19% higher than that of synchronized cycles model and 37.17% higher than that of independent optimization. Also, the total cost of green utility optimization is 859.27, which is 20.47% more than that of synchronized cycles model and is 6.10% lower than that of independent optimization.

5.7.3 Comparison of Environmental Performance

The environmental performances of energy wastage, raw materials wastage and air pollution are computed in terms of utility values with various weights of cost in Table 5.12. Then, they are compared between cost-minimization model and utility maximization model when DP ratio is 0.5. Three sets of random numbers are generated and their results are consistent. The results by the first set of random numbers are shown in the following sections 5.7.3.1 to 5.7.3.3, and the results produced by other two sets of random numbers are shown in Tables B55 to B60 of Appendix B.

5.7.3.1 5-buyer Example

In Table 5.16, the effect on different weights of cost α_1 is considered, so the weights of energy wastage α_2, raw material wastage α_3 and air pollution α_4 are equally weighted. The average total utility value of energy of green utility optimization is -0.428, which is 56.6% lower than that of synchronized cycles model and 63.9% lower than that of independent optimization. Also, the average total utility value of raw materials wastage of green utility optimization is -2.140, which is 26.5% higher than that of synchronized cycles model and

64.3% higher than that of independent optimization. Besides, the average total utility value of air pollution of green utility optimization is -0.402, which is 4.05% higher than that of synchronized cycles model and 48.1% higher than that of independent optimization.

α_1	N	Energy Wastage	Improved over SYN	Improved over IND	Raw Materials wastage	Improved over SYN	Improved over IND	Air Pollution	Improved over SYN	Improved over IND
1.0	60	-0.256	6.4%	2.1%	-3.064	-5.3%	48.9%	-0.379	9.5%	51.1%
0.9	58	-0.264	3.3%	-1.2%	-2.987	-2.7%	50.2%	-0.391	6.7%	49.5%
0.8	50	-0.305	-11.5%	-16.7%	-2.672	8.2%	55.5%	-0.320	23.5%	58.7%
0.7	35	-0.428	-56.6%	-63.9%	-2.029	30.3%	66.2%	-0.363	13.3%	53.1%
0.6	34	-0.440	-60.9%	-68.4%	-1.983	31.9%	67.0%	-0.373	10.9%	51.9%
0.5	32	-0.465	-70.3%	-78.3%	-1.889	35.1%	68.5%	-0.395	5.7%	49.0%
0.4	31	-0.479	-75.5%	-83.7%	-1.841	36.7%	69.3%	-0.406	2.9%	47.5%
0.3	29	-0.510	-86.7%	-95.5%	-1.744	40.1%	70.9%	-0.432	-3.3%	44.2%
0.2	27	-0.545	-99.6%	-108.9%	-1.645	43.5%	72.6%	-0.462	-10.3%	40.4%
0.1	25	-0.585	-114.3%	-124.3%	-1.543	47.0%	74.3%	-0.496	-18.4%	36.0%
Average		-0.428	-56.6%	-63.9%	-2.140	26.5%	64.3%	-0.402	4.05%	48.1%

Table 5.16:Comparison of utility values of energy wastage, raw materials wastage and air pollution of green utility optimization over synchronized cycles model and independent optimization on various weight of cost in Example 1 when DP ratio is 0.5.

However, when the weight of cost α_1 is 0.9, the total utility value of energy of green utility optimization is -0.264, which is 3.3% higher than that of synchronized cycles model and 1.2% lower than that of independent optimization. Also, the total utility value of raw materials wastage of green utility optimization is -2.987, which is 2.7% lower than that of synchronized cycles model and 50.2% higher than that of independent optimization.

In general, green utility optimization can raw material wastage and air pollution but cannot improve energy wastage, compared with synchronized cycle model and independent optimization in 5-buyer case.

5.7.3.2 30-buyer example

In Table 5.17, the average total utility value of energy of green utility optimization is -1.569, which is 6.3% lower than that of synchronized cycles model and 9.4% lower than that of independent optimization. Also, the average total utility value of raw materials wastage of green utility optimization is -17.41, which is 3.3% higher than that of synchronized cycles model and 43.9% higher than that of independent optimization. Besides, the average total utility value of air pollution of green utility optimization is -2.83, which is 30.6% higher than that of synchronized cycles model and 62.4% higher than that of independent optimization.

α_1	N	Energy Wastage	Improved over SYN	Improved over IND	Raw Materials wastage	Improved over SYN	Improved over IND	Air Pollution	Improved over SYN	Improved over IND
1.0	30	-1.4763	0.0%	-2.9%	-17.99	0.0%	42.0%	-4.32	-5.9%	42.7%
0.9	30	-1.4763	0.0%	-2.9%	-17.99	0.0%	42.0%	-3.78	7.5%	49.9%
0.8	30	-1.4763	0.0%	-2.9%	-17.99	0.0%	42.0%	-3.31	19.0%	56.1%
0.7	30	-1.4763	0.0%	-2.9%	-17.99	0.0%	42.0%	-2.90	28.9%	61.5%
0.6	30	-1.4763	0.0%	-2.9%	-17.99	0.0%	42.0%	-2.65	35.1%	64.9%
0.5	30	-1.4763	0.0%	-2.9%	-17.99	0.0%	42.0%	-2.54	37.9%	66.4%
0.4	30	-1.4763	0.0%	-2.9%	-17.99	0.0%	42.0%	-2.34	42.7%	69.0%
0.3	30	-1.4763	0.0%	-2.9%	-17.99	0.0%	42.0%	-2.22	45.7%	70.6%
0.2	18	-2.4077	-63.1%	-67.8%	-12.10	32.8%	61.0%	-2.59	36.6%	65.7%
0.1	30	-1.4763	0.0%	-2.9%	-17.99	0.0%	42.0%	-1.67	59.0%	77.8%
Average		-1.569	-6.3%	-9.4%	-17.41	3.3%	43.9%	-2.83	30.6%	62.4%

Table 5.17:Comparison of utility values of energy wastage, raw materials wastage and air pollution of green utility optimization over synchronized cycles model and independent optimization on various weights of cost in Example 2 when DP ratio is 0.5.

However, as shown in Table 5.17 except the weight of cost α_1 is 0.2, the total utility value of energy of green utility optimization is -1.4763, which is equal to that of synchronized cycles model and 2.9% lower than that of independent optimization. Also, the total utility value of raw materials wastage of green utility optimization is -17.99, which is equal to that of synchronized cycles model and 42.0% higher than that of independent optimization.

In general, green utility optimization can improve raw material wastage and air pollution but cannot improve energy wastage, compared with independent optimization in 30-buyer case. Besides, compared with synchronized cycles model, green utility optimization give the same satisfaction in energy wastage and air material wastage but can further improve air pollution.

5.7.3.3 50-buyer example

α_1	N	Energy Wastage	Improved over SYN	Improved over IND	Raw Materials wastage	Improved over SYN	Improved over IND	Air Pollution	Improved over SYN	Improved over IND
1.0	18	-3.82	0.0%	-2.9%	-25.13	0.0%	50.7%	-9.45	15.1%	36.7%
0.9	18	-3.82	0.0%	-2.9%	-25.13	0.0%	50.7%	-7.41	33.4%	50.3%
0.8	18	-3.82	0.0%	-2.9%	-25.13	0.0%	50.7%	-6.26	43.8%	58.1%
0.7	18	-3.82	0.0%	-2.9%	-25.13	0.0%	50.7%	-5.89	47.1%	60.6%
0.6	18	-3.82	0.0%	-2.9%	-25.13	0.0%	50.7%	-5.59	49.8%	62.6%
0.5	18	-3.82	0.0%	-2.9%	-25.13	0.0%	50.7%	-5.47	50.8%	63.3%
0.4	18	-3.82	0.0%	-2.9%	-25.13	0.0%	50.7%	-5.17	53.5%	65.4%
0.3	18	-3.82	0.0%	-2.9%	-25.13	0.0%	50.7%	-5.00	55.0%	66.5%
0.2	18	-3.82	0.0%	-2.9%	-25.13	0.0%	50.7%	-4.81	56.8%	67.8%
0.1	18	-3.82	0.0%	-2.9%	-25.13	0.0%	50.7%	-4.66	58.1%	68.8%
Average		-3.82	0.0%	-2.9%	-25.13	0.0%	50.7%	-5.97	46.3%	60.0%

Table 5.18:Comparison of utility values of energy wastage, raw materials wastage and air pollution of green utility optimization over synchronized cycles model and independent optimization on various weights of cost in Example 3 when DP ratio is 0.5.

In Table 5.18, the average total utility value of energy of green utility optimization is -3.82, which is equal to that of synchronized cycles model and 2.9% lower than that of independent optimization. Also, the average total utility value of raw materials wastage of green utility optimization is -25.13, which is equal to that of synchronized cycles model and 50.7% higher than that of independent optimization. Besides, the average total utility value of air pollution of green utility optimization is -5.97, which is 46.3% higher than that of synchronized cycles model and 60% higher than that of independent optimization.

In general, green utility optimization can improve raw material wastage and air pollution but cannot improve energy wastage, compared with independent optimization in 50-buyer case. Besides, compared with synchronized cycles model, green utility optimization give the same satisfaction in energy wastage and air material wastage but can further improve air pollution.

Also, the environmental performance of raw material wastage of green utility optimization is the same as that of synchronized cycles model in the 30- and the 50-buyer examples. In the 5-buyer example, when the weight of cost α_1 is lower than 0.9, the raw material wastage of green utility optimization is better than that of synchronized cycles model. However, the environmental performance of raw material wastage of green utility optimization is always better than that of independent optimization. Finally, the environmental performance of air pollution of green utility optimization is better than that of synchronized cycles model and independent optimization in most of the time in three examples.

5.8 Discussions

This research has contribution in modeling and assessing environmental performance into a single-vendor multi-buyer supply chain model. The model integrates ordering policy, delivery and shipping schedules, and environmental measures in a multi-buyer supply chain system with heterogeneous buyers and different ordering cycles. As the total cost and the other three environmental performance measures have different units of measurements, this thesis transforms the different measurements into a common measurement in terms of utility value by utility functions $U_{ij}\left(x_{ij}\right)$ $i = 0,1,2,...,n$ $j = 1,2,3,4$ with weights $\left(\alpha_1, \alpha_2, \alpha_3, \alpha_4\right)$. The optimal solution can be obtained by utility maximization. Also, as weighting of utility functions affects performance, different data sets have been considered and the results are consistent among different data sets. In cost minimization model, the synchronized cycles model gives a higher utility of the system in financial and environmental terms, compared with independent optimization. After taking environmental performance into account, the total utility can be maximized by determining the optimal production cycle of vendor and optimal ordering cycles of buyers in order to reduce energy wastage, raw material wastage, air pollution and total cost simultaneously. Also, the total cost of green utility optimization is higher than that of synchronized cycles model for all weight of cost α_1. In 30- and 50-buyer examples, the production cycle of vendor and the average inventory level of vendor of green utility optimization are equal to that of synchronized cycles model, the environmental performance of energy wastage and raw material wastage of green utility optimization cannot improve, compared with synchronized cycles model. In general, when the production cycle $N'T$ of vendor of green utility optimization is smaller than that of cost-minimization models, the performance of energy wastage is worse off but the performance of overall utility is better off. Since the order cycles $k_i^{'}T$ of buyers depend on the production cycle $N'T$ of vendor, the utility values of energy wastage and air pollution are in the same direction but in a reverse direction with raw material wastage. In other words, when the utility values of raw material wastage increase, the utility values of energy wastage and air pollution decrease. Hence, there is a tradeoff between energy wastage/air pollution and raw material wastage. Moreover, the environmental performance of synchronized cycles model is better than that of independent optimization, the environmental performance of green utility optimization is also better than that of independent optimization for 5-buyer, 30-buyer, and 50-buyer examples.

Chapter 6

Concluding Remarks and Future Research Directions

This thesis further investigates possible applications and enhancements regarding the synchronized cycles model. Chapter 3 improves the quality of the solutions, as compared with the improvement sub-algorithm in Chan and Kingsman (2007), by developing the inventory approach algorithm. Chapter 4 explores different modes of transportation to be incorporated into the synchronized inventory-transportation model. Chapter 5 combines the supply chain model with environmental measures.

In Chapter 3, the inventory approach algorithm is developed as an alternative to the incremental sub-algorithm presented in Chan and Kingsman (2007). Inventory approach is a heuristic method that the assignment of the first ordering time based on the inventory of vendor. The inventory approach algorithm simply adopts two dispatching rules: select the buyers with the least ordering cycle k_i and if there is any ties, select the buyers (with the same ordering cycle) in descending order based upon their order size $d_i k_i T$. Such simple rules allow the near-optimal solution to be found in polynomial time. With numerous numerical examples, results on incremental approach, inventory approach and genetic algorithm are compared. Based upon the results, it is found that the inventory approach outperforms the incremental approach both in terms of computational effort and total system cost. In addition, the inventory approach also further reduces the average inventory of the vendor, as compared with the incremental approach. The effectiveness of the approach is more significant for DP ratios larger than 0.5. Moreover, when the buyer size is large (i.e. 50

buyers), the inventory approach works better than genetic algorithm with less computational time to produce a near-optimal solution.

Most of the literature, which considered single-vendor multi-buyer supply chain, assumed that the transportation cost is fixed regardless of order size. Further, truck cost and truck size were not taken into consideration. In Chapter 4 of this thesis, the fixed transportation cost C_i is modified into a function in terms of truck cost and truck size. The freight cost component depends on the order sizes (weights) of buyers, truck cost and truck size, and the delivery cost component depends on the locations of buyers. The mode of delivering the items to the buyers greatly affects the transportation cost. In this thesis, five different transportation modes are investigated. The five modes are diminishing freight rate, LTL, FTL, combinations of LTL and FTL (hybrid mode), and two-tier freight rate transportations. The results of the numerical example reveal that, no matter the choice of the five transportation modes, the synchronized cycles model outperforms the results under independent optimization both in terms of total system cost and transportation cost. Moreover, full-truckload transportation gives the best improvement when synchronized cycles model is compared with independent optimization. While less-than truckload (LTL) and full-truckload (FTL) transportation modes are commonly considered in single-vendor single-buyer supply chain models, hybrid transportation mode is considered in this thesis. Adopting the hybrid mode, the vendor may select either FTL or LTL mode of transportation which gives the lower transportation cost. It is anticipated that the hybrid transportation mode gives a better transportation cost as compared with the pure LTL or pure FTL in both independent optimization and coordinated models. By incorporating the inventory approach, the transportation cost and the total system cost can be further reduced. It is also shown that the inventory approach as an improvement algorithm works better than the incremental approach with different modes of transportation. Sensitivity analysis are also conducted with different truck sizes and cost parameters.

This research can be extended to a third party logistics which delivers orders for buyer i with a time interval of $k_i T$, the delivery cost C_i of a third party logistics to deliver the items to buyer i is reduced by a discount factor β_i due to the economy of scales. Hence, the delivery cost $(1-\beta_i)C_i$ of buyer i can be considered for further development.

Chapter 5 of the thesis considers environmental awareness. A general result that applies in all analysis of coordinated vendor-buyer models is that, when compared with independent optimization, a coordinated model makes a significant reduction in the total system cost. Hence, most of the literature on the supply chain coordination concentrates on minimizing total costs only. There is little work addressing environmental issues as an objective of vendor-buyer coordination. Since the awareness of environment is raised, this chapter integrates total cost and environmental performance measures in a single comprehensive mathematical model so as to optimize the production and ordering policies and environmental performance at the same time. In this chapter, the supply chain model is formulated by considering ordering policies, delivery and shipping schedules, and environmental measures. As costs and environmental performance measures have different units of measurements, it is necessary to transform the different measurements to a common one so that all measures can be integrated into the objective function. Three environmental performance measures are considered, namely, energy wastage, raw material wastage and air pollution. As the three measures and the cost are quantified with different units, utility measures are adopted to unify the units. Different attitudes (risk-averse or risk-prone or risk-neutral) towards costs and environmental issues are taken into consideration. For different industries, the degrees of awareness of different environmental measures may vary. As a result, weightings (denoted by α_i) are assigned to each utility function and hence, the objective function is a combination of the weighted utility functions. The goal of formulating the environmental model is to determine simultaneously the optimal solution of the vendor's production cycle N and the buyer's ordering cycles k_i such that the weighted utility function is maximized. From the results, the synchronized cycles model outperforms the independent optimization both in cost minimization model and utility maximization model. Using the utility maximization model, the three environmental measures are significantly better than the one obtained under cost minimization model, but the total cost incurred is inevitably increased. This is the tradeoff between cost and environmental awareness.

It is believed that the environmental supply chain model considered in Chapter 5 is one of the pioneer works that combine both supply chain coordination and environmental performances. Results show that some kinds of coordination should be feasible for both reducing total system cost and increasing the satisfaction of environmental measures. For further research directions, it is promising to explore the different kinds of coordination mechanisms in environmental supply chain industry.

There are many future directions arising from this research. A general result that applies in all the analysis of vendor-buyer supply chain model is that the coordinated model reduce the total system cost significantly, compared with independent optimization with any one of the five transportation modes. This research can be extended to the situation that more than one transportation mode or a combination of the transportation modes can be freely employed by each buyer. Thus, a third-party logistics can be introduced to allocate a proper transportation to minimize the total system cost.

Furthermore, in the environmental supply chain, total cost, energy wastage per unit time, raw material per unit time and air pollution per unit time are considered as the key measurements of financial and environmental performance. The environmental performance also depends on transportation mode. For example, air pollution by airplanes is more severe than that by high-speed railways despite the former is more efficiently. Hence, the mode of transportation can also be incorporated into the environmental supply chain model.

For another direction of the future research, an equitable sharing of system saving is essential because the costs of buyer increase but the cost of vendor reduces through coordination despite the total system cost reduced. Some mechanisms such as price discount, quantity discount and trade credit are needed to motivate the buyers to change their policies to join coordination. Recently, a delayed payment method is proposed by Chan et.al. (2010) in coordinating a single-vendor multi-buyer supply chain. These mechanisms can induce the buyers to participate in co-ordination.

The supply chain model is this thesis is limited to deliver homogeneous items from vendor to buyers. This model can be extended to deliver heterogeneous items in the supply chains.

Appendix A: Data

Example 1:5-buyer case			
Buyer i	d_i	A_i	h_i
1	8	20	0.008
2	15	15	0.009
3	10	6	0.01
4	5	10	0.01
5	20	18	0.007
S_v=250 and h=0.005			

Table A1: Data of 5 buyers in Example 1.

Example 2: 30-buyer case							
Buyer i	d_i	A_i	h_i	Buyer i	d_i	A_i	h_i
1	8	21	0.0504	16	13	9	0.0344
2	15	14	0.0344	17	7	10	0.0297
3	10	7	0.0557	18	15	18	0.0367
4	5	15	0.0512	19	23	17	0.0516
5	20	6	0.0507	20	9	17	0.0451
6	31	2	0.0431	21	26	18	0.0305
7	5	10	0.0353	22	19	8	0.0552
8	14	15	0.0286	23	3	10	0.0451
9	12	7	0.0409	24	18	16	0.0378
10	9	6	0.0370	25	5	6	0.0538
11	20	9	0.0412	26	11	3	0.0328
12	4	12	0.0372	27	5	2	0.0473
13	5	7	0.0395	28	27	7	0.0308
14	28	12	0.0549	29	33	8	0.0479
15	2	11	0.0512	30	17	17	0.0493
S_v=2500 and h=0.025							

Table A2: Data of 30 buyers in Example 2.

Example 3: 50-buyer case											
Buyer i	d_i	A_i	h_i	Buyer i	d_i	A_i	h_i	Buyer i	d_i	A_i	h_i
1	26	8	0.0512	18	2	1	0.0686	35	14	10	0.0341
2	6	19	0.0358	19	20	5	0.0294	36	20	39	0.0546
3	49	7	0.0560	20	31	18	0.0467	37	16	22	0.0490
4	3	26	0.0380	21	29	11	0.0649	38	24	14	0.0394
5	11	22	0.0543	22	24	19	0.0672	39	37	26	0.0478
6	15	24	0.0590	23	7	12	0.0641	40	45	20	0.0616
7	26	21	0.0397	24	21	22	0.0680	41	2	4	0.0394
8	48	20	0.0355	25	22	15	0.0344	42	37	16	0.0691
9	33	1	0.0627	26	21	17	0.0459	43	16	29	0.0613
10	24	4	0.0540	27	1	26	0.0518	44	34	23	0.0394
11	18	11	0.0554	28	31	14	0.0305	45	47	20	0.0414
12	20	27	0.0414	29	48	5	0.0397	46	15	17	0.0568
13	16	22	0.0355	30	48	22	0.0333	47	33	10	0.0697
14	30	17	0.0585	31	4	28	0.0512	48	31	18	0.0492
15	32	2	0.0492	32	13	8	0.0411	49	35	27	0.0473
16	1	10	0.0518	33	7	11	0.0428	50	20	5	0.0554
17	7	5	0.0537	34	42	6	0.0476				
S_v=3000 and h=0.03											

Table A3: Data of 50 buyers in Example 3.

Truck capacity	Q^T	200
Full load cost	C^T	140
Freight cost per unit	s	0.7
Minimum cost	$C_{\min}$	20
Base cost	C_b	50

Table A4: Data for transportation.

Initial population	20
Iteration	100
Sample size	10

Table A5: Data for genetic algorithm.

			Set 1				Set 2				Set 3			
Buyer	i	Attitude	j=1	j=2	j=3	j=4	j=1	j=2	j=3	j=4	j=1	j=2	j=3	j=4
1	1	averse	-0.7979	-0.2642	-0.0786	-0.3551	-0.7618	-0.1761	-0.2581	-0.0103	-0.8271	-0.2136	-0.3682	-0.0347
2	2	prone	-0.3325	-0.9205	-0.8299	-0.9756	-0.3873	-0.9660	-0.7208	-0.5272	-0.2771	-0.7668	-0.6815	-0.6208
3	3	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
4	4	averse	-0.7037	-0.3579	-0.3254	-0.1358	-0.5761	-0.3643	-0.0959	-0.4493	-0.5187	-0.0494	-0.2876	-0.1898
5	5	prone	-0.0189	-0.9431	-0.7920	-0.6944	-0.0721	-0.9577	-0.7681	-0.8794	-0.0548	-0.9833	-0.9890	-0.9178
vendor	0	prone	-0.3191	-0.8420	-0.6240	-0.7539	-0.1112	-0.5420	-0.9504	-0.8784	-0.4152	-0.9495	-0.9250	-0.8920

Table A6: The value of U_{ij} for five buyers and one vendor in Example 1.

			Set 1				Set 2				Set 3			
Buyer	i	Attitude	j=1	j=2	j=3	j=4	j=1	j=2	j=3	j=4	j=1	j=2	j=3	j=4
1	1	averse	-0.6036	-0.0199	-0.4813	-0.3171	-0.5507	-0.3501	-0.3895	-0.4504	-0.5405	-0.4160	-0.4754	-0.2751
2	2	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
3	3	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
4	4	averse	-0.7345	-0.2780	-0.3492	-0.4774	-0.9428	-0.1609	-0.4552	-0.0575	-0.6920	-0.1863	-0.2063	-0.0498
5	5	prone	-0.4180	-0.8012	-0.6137	-0.6010	-0.4816	-0.6239	-0.7277	-0.7426	-0.2504	-0.8780	-0.5808	-0.9333
6	6	prone	-0.1068	-0.7115	-0.8779	-0.7067	-0.4814	-0.9397	-0.9558	-0.8263	-0.1632	-0.8315	-0.7420	-0.6105
7	7	averse	-0.5985	-0.4175	-0.0775	-0.0914	-0.9962	-0.1484	-0.3919	-0.0551	-0.8874	-0.4120	-0.4758	-0.1645
8	8	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
9	9	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
10	10	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Continued			Set 1				Set 2				Set 3			
Buyer	i	Attitude	j=1	j=2	j=3	j=4	j=1	j=2	j=3	j=4	j=1	j=2	j=3	j=4
11	11	prone	-0.0552	-0.9218	-0.8101	-0.9437	-0.1024	-0.8260	-0.5717	-0.6572	-0.4843	-0.9718	-0.6831	-0.6255
12	12	averse	-0.7580	-0.2238	-0.1805	-0.2995	-0.8800	-0.1168	-0.3644	-0.1210	-0.9874	-0.0870	-0.3038	-0.0793
13	13	averse	-0.9255	-0.3103	-0.1575	-0.3740	-0.5446	-0.2485	-0.2090	-0.3761	-0.8482	-0.2603	-0.1604	-0.3414
14	14	prone	-0.4934	-0.7574	-0.5408	-0.6060	-0.4391	-0.9130	-0.9106	-0.6357	-0.1705	-0.7723	-0.9059	-0.6242
15	15	averse	-0.9697	-0.3845	-0.4414	-0.2401	-0.9723	-0.0340	-0.0014	-0.1338	-0.7634	-0.1148	-0.4770	-0.0915
16	16	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
17	17	averse	-0.5504	-0.0659	-0.4484	-0.4395	-0.9507	-0.1727	-0.2734	-0.1821	-0.8377	-0.0046	-0.1715	-0.3493
18	18	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
19	19	prone	-0.2038	-0.7428	-0.9659	-0.7729	-0.1563	-0.5754	-0.8950	-0.8454	-0.0247	-0.9986	-0.8377	-0.5615
20	20	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
21	21	prone	-0.3939	-0.8542	-0.9830	-0.6059	-0.2135	-0.8388	-0.5199	-0.5490	-0.0254	-0.8649	-0.8703	-0.8687
22	22	prone	-0.4504	-0.7910	-0.9359	-0.7482	-0.1656	-0.9280	-0.7664	-0.6370	-0.3405	-0.5884	-0.7362	-0.7266
23	23	averse	-0.6492	-0.1117	-0.3254	-0.0428	-0.5424	-0.2011	-0.0082	-0.1441	-0.7411	-0.3188	-0.1009	-0.3230
24	24	prone	-0.4195	-0.5202	-0.5448	-0.9953	-0.3853	-0.7266	-0.7227	-0.5636	-0.4173	-0.5159	-0.8526	-0.7029
25	25	averse	-0.5681	-0.4308	-0.2040	-0.2828	-0.6827	-0.4991	-0.0100	-0.3858	-0.5980	-0.4507	-0.3218	-0.2472
26	26	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
27	27	averse	-0.6426	-0.4482	-0.2822	-0.0281	-0.5307	-0.3016	-0.3512	-0.4416	-0.9902	-0.1118	-0.4982	-0.3212
28	28	prone	-0.0703	-0.8101	-0.6727	-0.5751	-0.1858	-0.9481	-0.8400	-0.8474	-0.0118	-0.5494	-0.6472	-0.9813
29	29	prone	-0.4606	-0.9074	-0.6799	-0.6862	-0.4124	-0.8922	-0.6688	-0.9840	-0.4878	-0.5365	-0.5011	-0.6361
30	30	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
vendor	0	prone	-0.3097	-0.6225	-0.8064	-0.9569	-0.2691	-0.9977	-0.5630	-0.9895	-0.0721	-0.9819	-0.5942	-0.8541

Table A7: The value of U_{ij} for 30 buyers and one vendor in Example 2.

			Set 1				Set 2				Set 3			
Buyer	i	Attitude	j=1	j=2	j=3	j=4	j=1	j=2	j=3	j=4	j=1	j=2	j=3	j=4
1	1	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2	2	averse	-0.8413	-0.3726	-0.4944	-0.1654	-0.5816	-0.1528	-0.0461	-0.1104	-0.6920	-0.4190	-0.3311	-0.2941
3	3	prone	-0.2284	-0.9380	-0.6400	-0.7396	-0.3756	-0.6385	-0.9059	-0.6275	-0.2913	-0.6232	-0.5165	-0.8993
4	4	averse	-0.9100	-0.3920	-0.4874	-0.3404	-0.8766	-0.3554	-0.2701	-0.2472	-0.8212	-0.0513	-0.3976	-0.2201
5	5	averse	-0.6702	-0.0694	-0.3158	-0.1253	-0.8454	-0.2081	-0.3270	-0.4510	-0.6007	-0.0651	-0.1656	-0.4731
6	6	averse	-0.9384	-0.3304	-0.3283	-0.3687	-0.9268	-0.0746	-0.4981	-0.0340	-0.9288	-0.4528	-0.0697	-0.4109
7	7	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
8	8	prone	-0.2098	-0.5116	-0.5003	-0.6447	-0.2256	-0.9551	-0.5283	-0.8010	-0.4302	-0.9091	-0.7573	-0.6749
9	9	prone	-0.2627	-0.6101	-0.5878	-0.5670	-0.3713	-0.5911	-0.5733	-0.8543	-0.0855	-0.9633	-0.7743	-0.7055
10	10	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	11	averse	-0.8364	-0.1803	-0.0167	-0.3048	-0.8057	-0.1820	-0.2005	-0.1482	-0.6904	-0.4747	-0.3227	-0.3994
12	12	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
13	13	averse	-0.8218	-0.1090	-0.4866	-0.0733	-0.6438	-0.1171	-0.2954	-0.3466	-0.9406	-0.4264	-0.0893	-0.0247
14	14	prone	-0.1366	-0.5745	-0.9510	-0.9545	-0.3582	-0.9758	-0.8545	-0.6078	-0.2932	-0.8328	-0.7396	-0.5601
15	15	prone	-0.3063	-0.8473	-0.9244	-0.7000	-0.2305	-0.7893	-0.5036	-0.7966	-0.3856	-0.6988	-0.9094	-0.5821
16	16	averse	-0.8517	-0.3305	-0.1346	-0.4164	-0.8327	-0.4937	-0.3005	-0.0017	-0.9670	-0.4249	-0.4479	-0.0734
17	17	averse	-0.5389	-0.2456	-0.2791	-0.3088	-0.7317	-0.1863	-0.0420	-0.2306	-0.6320	-0.4051	-0.0362	-0.1267
18	18	averse	-0.5315	-0.2428	-0.4429	-0.2411	-0.8079	-0.1362	-0.2735	-0.2835	-0.8013	-0.3002	-0.2978	-0.0496
19	19	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
20	20	prone	-0.0818	-0.7147	-0.7389	-0.7227	-0.1140	-0.5760	-0.6360	-0.5118	-0.2311	-0.7113	-0.9401	-0.6394

Continued			Set 1				Set 2				Set 3			
Buyer	i	Attitude	j=1	j=2	j=3	j=4	j=1	j=2	j=3	j=4	j=1	j=2	j=3	j=4
21	21	prone	-0.1333	-0.8192	-0.6045	-0.5156	-0.1286	-0.6369	-0.7081	-0.6362	-0.4129	-0.9152	-0.5517	-0.6695
22	22	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
23	23	averse	-0.6995	-0.4506	-0.4327	-0.3443	-0.6417	-0.3018	-0.4134	-0.0013	-0.9321	-0.0227	-0.0031	-0.2472
24	24	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
25	25	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
26	26	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
27	27	averse	-0.9921	-0.3935	-0.0870	-0.0364	-0.7833	-0.4008	-0.3470	-0.1585	-0.8481	-0.2539	-0.0635	-0.4421
28	28	prone	-0.1290	-0.7314	-0.6035	-0.8452	-0.0791	-0.8819	-0.7329	-0.9685	-0.3730	-0.8472	-0.9616	-0.9492
29	29	prone	-0.0009	-0.9038	-0.8588	-0.8617	-0.4769	-0.8449	-0.5171	-0.8214	-0.4745	-0.5888	-0.7766	-0.7602
30	30	prone	-0.2490	-0.7394	-0.9431	-0.9682	-0.4226	-0.6789	-0.8089	-0.7410	-0.3657	-0.6086	-0.7218	-0.9132
31	31	averse	-0.8611	-0.2846	-0.2716	-0.1394	-0.9412	-0.1757	-0.0481	-0.1041	-0.6899	-0.3188	-0.4821	-0.1407
32	32	averse	-0.9422	-0.4621	-0.4971	-0.2840	-0.9932	-0.1374	-0.0356	-0.3722	-0.9118	-0.1424	-0.0223	-0.4246
33	33	averse	-0.9092	-0.0909	-0.1837	-0.0448	-0.5537	-0.1669	-0.4645	-0.4544	-0.6494	-0.0135	-0.0968	-0.0945
34	34	prone	-0.3572	-0.8015	-0.5923	-0.9996	-0.0638	-0.8616	-0.9555	-0.9339	-0.4523	-0.7161	-0.8446	-0.5432
35	35	averse	-0.8602	-0.0297	-0.2346	-0.1928	-0.8687	-0.2364	-0.0554	-0.2498	-0.5587	-0.1878	-0.3474	-0.0904
36	36	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
37	37	averse	-0.9522	-0.1629	-0.3002	-0.3324	-0.9675	-0.3896	-0.1680	-0.3036	-0.8632	-0.4468	-0.2688	-0.0161
38	38	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
39	39	prone	-0.4818	-0.5202	-0.8865	-0.8301	-0.2764	-0.7402	-0.5721	-0.8652	-0.0678	-0.6974	-0.6238	-0.5129
40	40	prone	-0.2931	-0.6118	-0.8831	-0.9446	-0.4368	-0.9184	-0.5884	-0.9475	-0.2813	-0.6284	-0.8363	-0.6349

Continued			Set 1				Set 2				Set 3			
buyer	i	Attitude	j=1	j=2	j=3	j=4	j=1	j=2	j=3	j=4	j=1	j=2	j=3	j=4
41	41	averse	-0.9945	-0.0332	-0.1610	-0.0554	-0.5364	-0.2720	-0.1422	-0.1370	-0.8043	-0.3368	-0.1053	-0.0325
42	42	prone	-0.2685	-0.5195	-0.8522	-0.6267	-0.3118	-0.5096	-0.8685	-0.9377	-0.4135	-0.7902	-0.8199	-0.7123
43	43	averse	-0.7248	-0.3204	-0.1857	-0.3451	-0.9840	-0.3054	-0.2152	-0.4831	-0.9585	-0.4194	-0.4330	-0.1609
44	44	prone	-0.1493	-0.7555	-0.7586	-0.9734	-0.1866	-0.5490	-0.6028	-0.9560	-0.1494	-0.6080	-0.9779	-0.8816
45	45	prone	-0.3196	-0.5659	-0.7990	-0.5720	-0.3295	-0.5953	-0.9612	-0.6484	-0.2598	-0.9946	-0.8489	-0.9379
46	46	averse	-0.5238	-0.2673	-0.0134	-0.4994	-0.5109	-0.3665	-0.0124	-0.1111	-0.8934	-0.4938	-0.3238	-0.1042
47	47	prone	-0.1823	-0.7348	-0.5043	-0.6817	-0.2294	-0.5710	-0.8799	-0.6185	-0.0530	-0.6688	-0.6853	-0.6102
48	48	prone	-0.0960	-0.9192	-0.5455	-0.5745	-0.3951	-0.5989	-0.5040	-0.5199	-0.2402	-0.9362	-0.7710	-0.6384
49	49	prone	-0.1161	-0.9122	-0.9541	-0.7111	-0.0744	-0.6626	-0.9262	-0.7635	-0.4208	-0.8028	-0.5148	-0.7391
50	50	neutral	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
vendor	0	prone	-0.2542	-0.9132	-0.6353	-0.7684	-0.1172	-0.7150	-0.6480	-0.7192	-0.1841	-0.5542	-0.9061	-0.8346

Table A8: The value of U_{ij} for 50 buyers and one vendor in Example 3.

Appendix B: Results

DP ratio	k_1	k_2	k_3	k_4	k_5	t_1	t_2	t_3	t_4	t_5
0.1	45	45	45	45	45	2	3	1	3	5
0.2	44	44	44	44	44	2	6	4	1	10
0.3	56	28	28	56	28	11	4	2	8	7
0.4	56	28	28	56	28	14	5	2	11	9
0.5	56	28	28	56	28	18	7	3	14	11
0.6	39	26	26	39	26	18	7	3	15	13
0.7	39	26	26	39	26	21	8	4	17	15
0.8	39	26	26	39	26	24	9	4	19	17
0.9	36	24	24	36	24	25	10	4	20	17

Table B1: Ordering cycles and first ordering time on various DP ratios by synchronized cycles model and independent optimization in Example 1.

DP ratio	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	DP ratio	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
k_{1}	24	24	28	30	15	18	18	16	18	t_{1}	2	3	4	5	6	6	7	9	9
k_{2}	12	12	14	10	10	9	9	8	8	t_{2}	1	2	3	2	2	1	3	2	3
k_{3}	12	12	14	10	10	9	9	8	8	t_{3}	1	2	3	2	2	2	3	3	3
k_{4}	24	24	28	30	30	18	18	24	18	t_{4}	2	3	4	5	6	7	8	9	12
k_{5}	8	8	7	6	6	6	6	6	6	t_{5}	1	1	1	1	1	1	1	1	1
k_{6}	6	4	4	5	3	4	4	3	3	t_{6}	1	1	1	1	1	1	1	1	1
k_{7}	24	24	28	30	30	18	18	24	24	t_{7}	2	3	5	6	7	7	8	11	12
k_{8}	24	24	28	15	15	18	12	12	12	t_{8}	2	3	4	4	5	6	6	8	8
k_{9}	12	8	7	10	6	6	6	6	6	t_{9}	1	3	1	2	1	1	1	1	1
k_{10}	24	24	14	15	15	12	12	12	12	t_{10}	2	2	3	5	3	5	3	6	8
k_{11}	24	24	14	15	15	12	12	12	12	t_{11}	1	2	2	3	3	4	4	5	5
k_{12}	24	24	28	30	30	36	36	24	24	t_{12}	2	2	4	6	6	8	9	9	14
k_{13}	24	24	28	15	15	18	18	16	12	t_{13}	2	3	5	3	6	8	8	9	9
k_{14}	8	8	7	6	6	6	6	6	6	t_{14}	1	1	1	1	1	1	1	1	1
k_{15}	24	24	28	30	15	36	36	48	36	t_{15}	2	3	5	6	7	8	9	12	15
k_{16}	24	12	14	15	15	12	12	12	9	t_{16}	2	2	3	4	5	2	7	8	4
k_{17}	24	24	28	30	30	18	18	16	18	t_{17}	2	3	4	5	6	7	8	9	11
k_{18}	24	24	14	15	15	12	12	12	12	t_{18}	2	3	3	4	4	5	6	4	5
k_{19}	12	12	14	15	10	12	12	12	9	t_{19}	1	1	2	3	2	3	4	4	4
k_{20}	24	24	28	15	15	18	18	16	12	t_{20}	2	3	4	5	5	6	8	8	9
k_{21}	12	12	14	10	10	9	9	8	8	t_{21}	1	1	2	1	2	2	2	2	2
k_{22}	12	12	14	15	15	12	12	12	12	t_{22}	1	1	2	2	4	4	5	5	6
k_{23}	24	24	28	15	15	18	18	16	18	t_{23}	1	3	5	3	5	6	9	8	9
k_{24}	24	12	14	15	15	12	12	12	12	t_{24}	1	1	3	3	4	4	5	6	6
k_{25}	12	12	14	15	15	12	12	12	12	t_{25}	1	1	4	5	6	3	4	5	9
k_{26}	24	12	14	15	10	12	9	8	9	t_{26}	2	2	2	4	2	5	1	3	5
k_{27}	12	12	14	15	15	12	12	12	12	t_{27}	1	2	4	5	6	6	5	7	9
k_{28}	24	24	14	15	15	12	12	12	9	t_{28}	1	2	1	2	3	3	3	3	3
k_{29}	12	12	14	10	10	9	9	8	8	t_{29}	1	1	1	1	1	2	2	2	2
k_{30}	12	12	14	15	15	12	12	12	12	t_{30}	1	2	3	4	5	5	6	6	8

Table B2:Ordering cycles and first ordering time on various DP ratios by synchronized cycles model and independent optimization in Example 2.

DP ratio	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	DP ratio	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
k_1	7	8	8	6	6	6	4	5	4	t_1	1	1	2	2	2	1	1	2	2
k_2	14	16	16	18	18	12	12	10	12	t_2	2	2	3	3	4	4	4	5	6
k_3	7	8	4	6	6	4	4	5	4	t_3	1	1	1	1	1	1	1	1	1
k_4	14	16	16	18	18	24	24	30	24	t_4	2	2	3	3	4	4	6	6	7
k_5	14	16	16	18	9	12	12	10	12	t_5	1	2	3	3	2	4	5	4	7
k_6	14	16	8	9	9	8	8	10	8	t_6	1	2	2	3	3	4	4	5	6
k_7	14	8	8	9	9	8	8	6	6	t_7	1	1	2	2	3	2	3	3	4
k_8	14	8	8	6	6	6	6	5	6	t_8	1	1	1	1	1	1	2	1	2
k_9	7	4	4	3	3	3	3	3	3	t_9	1	1	1	1	1	1	1	1	1
k_{10}	7	8	8	6	6	6	6	5	4	t_{10}	1	1	2	2	2	2	3	2	1
k_{11}	14	8	8	9	9	8	8	6	6	t_{11}	1	12	2	3	3	3	4	4	3
k_{12}	14	16	16	9	9	12	8	10	8	t_{12}	1	2	2	3	3	4	4	5	6
k_{13}	14	16	16	9	9	12	12	10	8	t_{13}	1	2	3	3	3	4	5	5	5
k_{14}	7	8	8	6	6	6	4	5	4	t_{14}	1	1	2	1	2	2	1	2	2
k_{15}	7	4	4	6	3	4	4	3	3	t_{15}	1	1	1	1	1	1	1	1	1
k_{16}	14	16	16	18	18	24	24	30	24	t_{16}	1	2	3	3	4	4	6	5	7
k_{17}	14	16	8	9	9	8	8	10	8	t_{17}	2	2	1	3	4	4	3	5	6
k_{18}	14	16	16	18	18	12	12	10	12	t_{18}	2	2	3	3	4	4	5	4	6
k_{19}	14	16	8	9	9	8	6	6	6	t_{19}	1	2	2	3	3	3	3	4	5
k_{20}	14	8	8	9	6	6	6	6	6	t_{20}	1	1	1	2	2	2	2	3	3
k_{21}	7	8	8	6	6	6	6	6	6	t_{21}	1	1	2	1	2	2	2	3	3
k_{22}	7	8	8	9	6	8	6	6	6	t_{22}	1	1	2	2	2	3	3	3	4
k_{23}	14	8	8	9	9	8	8	10	8	t_{23}	2	1	2	3	4	4	4	5	6
k_{24}	7	8	8	9	6	6	6	6	6	t_{24}	1	1	2	3	2	2	3	4	4
k_{25}	14	16	16	9	9	8	8	10	8	t_{25}	1	2	2	3	3	3	3	5	5
k_{26}	14	8	8	9	9	8	8	6	6	t_{26}	1	1	2	3	3	3	4	4	4
k_{27}	14	16	16	18	18	24	24	30	24	t_{27}	2	2	3	3	4	5	6	6	7
k_{28}	14	16	8	9	9	8	8	6	6	t_{28}	1	2	2	2	3	3	3	3	3
k_{29}	7	4	4	3	3	3	3	3	3	t_{29}	1	1	1	1	1	1	1	1	1
k_{30}	14	8	8	6	6	6	4	5	4	t_{30}	1	1	1	1	1	1	1	1	1
k_{31}	14	16	16	18	18	24	24	15	16	t_{31}	2	2	3	3	4	4	6	5	7
k_{32}	14	8	8	9	9	8	8	6	6	t_{32}	2	2	2	3	4	4	4	4	4
k_{33}	14	16	16	9	9	12	12	10	8	t_{33}	2	2	3	3	4	4	6	5	6
k_{34}	7	4	4	6	3	4	4	3	3	t_{34}	1	1	1	1	1	1	1	1	1
k_{35}	14	8	8	9	9	8	6	6	6	t_{35}	1	2	2	3	4	4	3	4	5
k_{36}	14	16	16	9	9	8	8	10	8	t_{36}	1	2	3	3	3	3	4	5	6
k_{37}	14	16	16	9	9	8	8	10	8	t_{37}	1	2	3	3	3	3	3	5	6
k_{38}	14	8	8	9	6	6	6	6	6	t_{38}	1	1	2	2	2	2	2	3	4
k_{39}	7	8	8	9	6	6	6	6	6	t_{39}	1	1	1	2	1	2	2	2	3
k_{40}	7	8	8	6	6	6	6	5	6	t_{40}	1	1	1	1	1	2	6	2	2
k_{41}	14	16	16	18	18	24	24	30	24	t_{41}	2	2	3	3	4	5	1	6	7
k_{42}	7	4	4	6	3	4	4	3	4	t_{42}	1	1	1	1	1	1	4	1	1
k_{43}	14	8	8	9	9	8	8	6	6	t_{43}	1	2	2	3	3	4	3	4	2
k_{44}	14	16	8	9	9	8	8	6	6	t_{44}	1	2	1	2	2	3	2	3	3
k_{45}	14	8	8	9	6	6	6	6	6	t_{45}	1	1	1	2	1	2	4	2	2
k_{46}	14	8	8	9	9	8	8	6	8	t_{46}	1	2	2	3	3	4	1	2	6
k_{47}	7	4	4	6	6	4	4	5	4	t_{47}	1	1	1	1	2	1	1	2	1

DP ratio	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	DP ratio	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
k_{48}	7	8	8	6	6	4	4	5	4	t_{48}	1	1	2	1	2	1	1	2	2
k_{49}	14	8	8	9	9	8	6	6	6	t_{49}	1	1	1	2	2	3	2	3	3
k_{50}	7	4	4	3	3	3	3	3	3	t_{50}	1	1	1	1	1	1	1	1	1

Table B3:Ordering cycles and first ordering time on various DP ratios by synchronized cycles model and independent optimization in Example 3.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	7.953	66.114	74.067	7.953	43.585	51.538	69	49.921	29.044
0.2	7.953	65.460	73.413	7.953	44.566	52.519	67	49.921	29.433
0.3	7.953	64.765	72.718	7.953	45.521	53.474	65	49.921	29.846
0.4	7.953	64.017	71.970	7.953	46.454	54.407	63	49.921	30.286
0.5	7.953	63.205	71.158	7.953	47.224	55.177	53	49.921	32.357
0.6	7.953	62.306	70.259	7.953	47.992	55.945	53	49.921	32.357
0.7	7.953	61.286	69.238	7.953	47.999	55.952	90	49.921	33.207
0.8	7.953	60.075	68.028	7.953	47.704	55.657	90	49.921	34.763
0.9	7.953	58.498	66.451	7.953	47.118	55.071	135	49.921	34.505
Average	7.953	62.858	70.811	7.953	46.462	54.415		49.921	31.755

Table B4 Total cost and shipment cost between independent optimization and synchronized cycles model in Example 1 using diminishing freight rate.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	97.389	803.950	901.339	97.389	530.310	627.699	24	528.144	303.133
0.2	97.389	791.533	888.922	97.389	539.037	636.427	24	528.144	310.925
0.3	97.389	778.313	875.702	97.389	545.345	642.734	30	528.144	312.567
0.4	97.389	764.109	861.499	97.389	547.485	644.874	30	528.144	325.967
0.5	97.389	748.664	846.053	97.389	546.243	643.632	36	528.144	326.994
0.6	97.389	748.664	846.053	97.389	546.243	643.632	36	528.144	326.994
0.7	97.389	731.579	828.969	97.389	542.329	639.718	36	528.144	340.556
0.8	97.389	689.186	786.575	97.389	525.077	622.467	48	528.144	347.225
0.9	97.389	659.209	756.598	97.389	507.629	605.018	72	528.144	356.347
Average	97.389	746.134	843.523	97.389	536.633	634.022		528.144	327.856

Table B5: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 2 using diminishing freight rate.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	266.717	1629.457	1896.17	266.717	1145.511	1412.23	16	1027.880	721.913
0.2	266.717	1604.644	1871.36	266.717	1165.871	1432.59	16	1027.880	739.500
0.3	266.717	1578.224	1844.94	266.717	1182.349	1449.07	16	1027.880	754.663
0.4	266.717	1549.840	1816.56	266.717	1194.343	1461.06	18	1027.880	772.600
0.5	266.717	1518.974	1785.69	266.717	1187.684	1454.40	24	1027.880	782.842
0.6	266.717	1484.833	1751.55	266.717	1177.857	1444.57	24	1027.880	793.908
0.7	266.717	1446.082	1712.80	266.717	1166.767	1433.48	24	1027.880	796.717
0.8	266.717	1400.115	1666.83	266.717	1154.465	1421.18	24	1027.880	811.475
0.9	266.717	1340.210	1606.93	266.717	1117.147	1383.86	48	1027.880	826.446
Average	266.717	1505.820	1772.54	266.717	1165.777	1432.494		1027.880	777.785

Table B6: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 3 using diminishing freight rate.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	7.953	75.437	83.390	7.953	57.971	65.924	49	53.444	46.722
0.2	7.953	74.784	82.736	7.953	58.671	66.624	48	53.444	46.850
0.3	7.953	74.088	82.041	7.953	59.352	67.305	46	53.444	47.122
0.4	7.953	73.341	81.293	7.953	59.803	67.756	62	53.444	48.342
0.5	7.953	72.528	80.481	7.953	60.005	67.958	62	53.444	48.342
0.6	7.953	71.629	79.582	7.953	60.204	68.157	60	53.444	48.600
0.7	7.953	70.609	78.562	7.953	60.098	68.051	90	53.444	49.267
0.8	7.953	69.398	77.351	7.953	59.761	67.714	90	53.444	49.267
0.9	7.953	67.821	75.774	7.953	59.128	67.081	135	53.444	49.933
Average	7.953	72.181	80.134	7.953	59.444	67.396		53.444	48.272

Table B7: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 1 using less-than-truckload transportation.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	97.389	875.905	973.294	97.389	603.543	700.933	24	600.098	379.092
0.2	97.389	863.488	960.877	97.389	610.942	708.331	24	600.098	386.842
0.3	97.389	850.268	947.657	97.389	614.495	711.884	30	600.098	392.700
0.4	97.389	836.064	933.453	97.389	615.194	712.583	30	600.098	397.267
0.5	97.389	820.619	918.008	97.389	614.952	712.342	30	600.098	403.767
0.6	97.389	803.534	900.924	97.389	612.411	709.801	36	600.098	410.800
0.7	97.389	784.143	881.532	97.389	607.071	704.461	36	600.098	418.689
0.8	97.389	761.140	858.530	97.389	596.049	693.439	48	600.098	421.071
0.9	97.389	731.164	828.553	97.389	578.277	675.667	72	600.098	423.189
Average	97.389	814.036	911.425	97.389	605.882	703.271		600.098	403.713

Table B8: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 2 using Less-than-truckload transportation.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	266.717	1810.624	2077.34	266.717	1355.420	1622.14	16	1209.047	959.075
0.2	266.717	1785.811	2052.53	266.717	1369.739	1636.46	16	1209.047	968.013
0.3	266.717	1759.391	2026.11	266.717	1379.435	1646.15	16	1209.047	972.825
0.4	266.717	1731.007	1997.72	266.717	1382.956	1649.67	18	1209.047	987.200
0.5	266.717	1700.142	1966.86	266.717	1383.040	1649.76	18	1209.047	1003.311
0.6	266.717	1666.001	1932.72	266.717	1374.578	1641.29	24	1209.047	1002.542
0.7	266.717	1627.249	1893.97	266.717	1361.374	1628.09	24	1209.047	1009.500
0.8	266.717	1581.282	1848.00	266.717	1343.220	1609.94	30	1209.047	1020.833
0.9	266.717	1521.377	1788.09	266.717	1308.676	1575.39	48	1209.047	1027.629
Average	266.717	1686.987	1953.70	266.717	1362.049	1628.77		1209.047	994.548

Table B9: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 3 using Less-than-truckload transportation.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	7.953	95.846	103.799	7.953	58.533	66.486	39	79.653	48.205
0.2	7.953	95.193	103.146	7.953	59.098	67.051	39	79.653	48.205
0.3	7.953	94.498	102.450	7.953	59.664	67.617	39	79.653	48.205
0.4	7.953	93.750	101.703	7.953	60.229	68.182	39	79.653	48.205
0.5	7.953	92.938	100.890	7.953	60.245	68.198	78	79.653	48.718
0.6	7.953	92.039	99.991	7.953	60.147	68.100	78	79.653	48.718
0.7	7.953	91.018	98.971	7.953	60.050	68.003	78	79.653	48.718
0.8	7.953	89.808	97.761	7.953	59.952	67.905	78	79.653	48.718
0.9	7.953	88.231	96.184	7.953	59.383	67.336	156	79.653	48.718
Average	7.953	92.591	100.54	7.953	59.700	67.653		79.653	48.490

Table B10: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 1 using Full-truckload transportation.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	97.389	1219.371	1316.761	97.389	647.000	744.390	36	943.565	402.583
0.2	97.389	1206.954	1304.344	97.389	648.649	746.038	36	943.565	408.500
0.3	97.389	1193.734	1291.123	97.389	649.281	746.671	36	943.565	413.556
0.4	97.389	1179.531	1276.920	97.389	647.066	744.456	36	943.565	424.306
0.5	97.389	1164.085	1261.474	97.389	643.549	740.938	36	943.565	431.250
0.6	97.389	1147.001	1244.390	97.389	639.190	736.579	36	943.565	433.639
0.7	97.389	1127.609	1224.998	97.389	634.615	732.004	36	943.565	433.639
0.8	97.389	1104.607	1201.996	97.389	619.134	716.523	60	943.565	418.400
0.9	97.389	1074.630	1172.020	97.389	598.626	696.015	72	943.565	434.042
Average	97.389	1157.502	1254.892	97.389	636.345	733.735		943.565	422.213

Table B11: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 2 using Full-truckload transportation.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	266.71	2417.836	2684.55	266.717	1465.600	1732.32	24	1816.259	1011.417
0.2	266.71	2393.022	2659.74	266.717	1462.695	1729.41	24	1816.259	1017.333
0.3	266.71	2366.603	2633.32	266.717	1454.415	1721.13	24	1816.259	1040.708
0.4	266.71	2338.219	2604.94	266.717	1442.517	1709.23	24	1816.259	1040.708
0.5	266.71	2307.353	2574.07	266.717	1429.472	1696.19	24	1816.259	1049.708
0.6	266.71	2273.212	2539.93	266.717	1414.557	1681.27	24	1816.259	1052.042
0.7	266.71	2234.460	2501.18	266.717	1398.926	1665.64	24	1816.259	1055.667
0.8	266.71	2188.493	2455.21	266.717	1366.175	1632.89	36	1816.259	1041.222
0.9	266.71	2128.588	2395.31	266.717	1327.309	1594.03	48	1816.259	1007.750
Average	266.717	2294.198	2560.92	266.717	1417.963	1684.68		1816.259	1035.173

Table B12: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 3 using Full-truckload transportation.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	7.953	75.437	83.390	7.953	57.466	65.419	39	59.244	47.139
0.2	7.953	74.784	82.736	7.953	58.032	65.985	39	59.244	47.139
0.3	7.953	74.088	82.041	7.953	58.597	66.550	39	59.244	47.139
0.4	7.953	73.341	81.293	7.953	59.163	67.116	39	59.244	47.139
0.5	7.953	72.528	80.481	7.953	59.178	67.131	78	59.244	47.651
0.6	7.953	71.629	79.582	7.953	59.081	67.034	78	59.244	47.651
0.7	7.953	70.609	78.562	7.953	58.967	66.920	78	59.244	48.574
0.8	7.953	69.398	77.351	7.953	58.739	66.692	78	59.244	48.574
0.9	7.953	67.821	75.774	7.953	58.040	65.993	156	59.244	48.574
Average	7.953	72.181	80.134	7.953	58.585	66.538		59.244	47.731

Table B13: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 1 using Hybrid transportation.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	97.389	875.515	972.904	97.389	600.344	697.733	24	599.709	376.525
0.2	97.389	863.098	960.487	97.389	607.174	704.564	24	599.709	385.025
0.3	97.389	849.878	947.267	97.389	610.274	707.664	28	599.709	391.964
0.4	97.389	835.674	933.063	97.389	610.910	708.299	30	599.709	395.100
0.5	97.389	820.229	917.618	97.389	610.573	707.963	30	599.709	399.367
0.6	97.389	803.144	900.534	97.389	606.450	703.839	36	599.709	402.939
0.7	97.389	783.753	881.142	97.389	598.695	696.085	42	599.709	408.157
0.8	97.389	760.751	858.140	97.389	590.051	687.440	42	599.709	410.014
0.9	97.389	730.774	828.163	97.389	570.119	667.508	84	599.709	416.102
Average	97.389	813.646	911.035	97.389	600.510	697.899		599.709	398.355

Table B14: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 2 using Hybrid transportation.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	266.717	1803.81	2070.53	266.717	1347.128	1613.84	16	1202.237	952.075
0.2	266.717	1779.00	2045.72	266.717	1358.062	1624.78	18	1202.237	952.667
0.3	266.717	1752.58	2019.30	266.717	1362.655	1629.37	18	1202.237	968.689
0.4	266.717	1724.19	1990.91	266.717	1363.942	1630.66	18	1202.237	975.311
0.5	266.717	1693.33	1960.05	266.717	1355.899	1622.62	24	1202.237	967.800
0.6	266.717	1659.19	1925.91	266.717	1342.666	1609.38	24	1202.237	978.050
0.7	266.717	1620.43	1887.15	266.717	1328.089	1594.81	24	1202.237	985.225
0.8	266.717	1574.47	1841.19	266.717	1310.156	1576.87	36	1202.237	987.611
0.9	266.717	1514.56	1781.28	266.717	1272.904	1539.62	36	1202.237	990.778
Average	266.717	1680.17	1946.89	266.717	1337.945	1604.66		1202.237	973.134

Table B15: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 3 u using Hybrid transportation.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	7.953	71.201	79.154	7.953	56.182	64.135	40	55.008	45.800
0.2	7.953	70.547	78.500	7.953	56.762	64.715	40	55.008	45.800
0.3	7.953	69.852	77.805	7.953	57.342	65.295	40	55.008	45.800
0.4	7.953	69.104	77.057	7.953	57.772	65.724	54	55.008	47.215
0.5	7.953	68.292	76.245	7.953	57.947	65.900	54	55.008	47.215
0.6	7.953	67.393	75.346	7.953	57.941	65.894	84	55.008	47.705
0.7	7.953	66.373	74.325	7.953	57.591	65.544	84	55.008	47.705
0.8	7.953	65.162	73.115	7.953	57.184	65.136	84	55.008	47.705
0.9	7.953	63.585	71.538	7.953	56.292	64.245	120	55.008	48.900
Average	7.953	67.945	75.898	7.953	57.224	65.176		55.008	47.094

Table B16: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 1 using the two-tier freight rate transportation.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	97.389	827.938	925.328	97.389	578.581	675.971	24	552.132	366.542
0.2	97.389	815.522	912.911	97.389	583.513	680.902	28	552.132	371.279
0.3	97.389	802.301	899.691	97.389	584.543	681.933	28	552.132	372.693
0.4	97.389	788.098	885.487	97.389	584.930	682.320	30	552.132	375.233
0.5	97.389	772.652	870.042	97.389	583.450	680.839	30	552.132	382.533
0.6	97.389	755.568	852.957	97.389	578.223	675.613	36	552.132	387.456
0.7	97.389	736.176	833.566	97.389	572.007	669.396	36	552.132	390.611
0.8	97.389	713.174	810.564	97.389	559.674	657.063	48	552.132	393.646
0.9	97.389	683.197	780.587	97.389	540.614	638.003	72	552.132	398.436
Average	97.389	766.070	863.459	97.389	573.948	671.338		552.132	382.048

Table B17: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 2 using the two-tier freight rate transportation.

Cost	Independent optimization			Synchronized cycles model				Shipment cost	
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N	IND	SYN
0.1	266.717	1692.431	1959.15	266.717	1294.664	1561.38	16	1090.854	908.663
0.2	266.717	1667.617	1934.33	266.717	1301.519	1568.24	16	1090.854	918.488
0.3	266.717	1641.198	1907.91	266.717	1302.901	1569.62	18	1090.854	920.100
0.4	266.717	1612.814	1879.53	266.717	1300.064	1566.78	18	1090.854	926.611
0.5	266.717	1581.948	1848.66	266.717	1294.896	1561.61	24	1090.854	919.983
0.6	266.717	1547.807	1814.52	266.717	1279.046	1545.76	24	1090.854	926.108
0.7	266.717	1509.055	1775.77	266.717	1262.130	1528.85	24	1090.854	929.842
0.8	266.717	1463.088	1729.81	266.717	1240.607	1507.32	30	1090.854	937.967
0.9	266.717	1403.183	1669.90	266.717	1202.053	1468.77	36	1090.854	946.800
Average	266.717	1568.793	1835.51	266.717	1275.320	1542.037		1090.854	926.062

Table B18: Total cost and shipment cost between independent optimization and synchronized cycles model in Example 3 using the two-tier freight rate transportation.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	7.953	116.037	123.990	7.953	98.571	106.524	49
0.2	7.953	115.384	123.336	7.953	99.271	107.224	48
0.3	7.953	114.688	122.641	7.953	99.952	107.905	46
0.4	7.953	113.941	121.893	7.953	100.403	108.356	62
0.5	7.953	113.128	121.081	7.953	100.605	108.558	62
0.6	7.953	112.229	120.182	7.953	100.804	108.757	60
0.7	7.953	111.209	119.162	7.953	100.698	108.651	90
0.8	7.953	109.998	117.951	7.953	100.361	108.314	90
0.9	7.953	108.421	116.374	7.953	99.728	107.681	135
Average	7.953	112.781	120.734	7.953	100.044	107.996	

Table B19: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 1 using Less-than-truckload transportation with Q^T=100.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	7.953	61.904	69.856	7.953	44.437	52.390	49
0.2	7.953	61.250	69.203	7.953	45.138	53.091	48
0.3	7.953	60.555	68.507	7.953	45.818	53.771	46
0.4	7.953	59.807	67.760	7.953	46.270	54.223	62
0.5	7.953	58.995	66.947	7.953	46.471	54.424	62
0.6	7.953	58.096	66.049	7.953	46.670	54.623	60
0.7	7.953	57.075	65.028	7.953	46.565	54.518	90
0.8	7.953	55.865	63.818	7.953	46.227	54.180	90
0.9	7.953	54.288	62.241	7.953	45.595	53.548	135
Average	7.953	58.648	66.601	7.953	45.910	53.863	

Table B20: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 1 using Less-than-truckload transportation with Q^T=300.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	97.389	1163.636	1261.025	97.389	896.843	994.233	24
0.2	97.389	1151.219	1248.608	97.389	904.242	1001.631	24
0.3	97.389	1137.998	1235.388	97.389	907.795	1005.184	30
0.4	97.389	1123.795	1221.184	97.389	908.494	1005.883	30
0.5	97.389	1108.349	1205.739	97.389	908.252	1005.642	30
0.6	97.389	1091.265	1188.654	97.389	905.711	1003.101	36
0.7	97.389	1071.873	1169.263	97.389	900.371	997.761	36
0.8	97.389	1048.871	1146.261	97.389	889.349	986.739	48
0.9	97.389	1018.894	1116.284	97.389	871.577	968.967	72
Average	97.389	1101.767	1199.156	97.389	899.182	996.571	

Table B21: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 2 using Less-than-truckload transportation with Q^T=100.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	97.389	791.450	888.839	97.389	506.093	603.483	24
0.2	97.389	779.033	876.423	97.389	513.401	610.791	26
0.3	97.389	765.813	863.202	97.389	516.795	614.184	30
0.4	97.389	751.609	848.999	97.389	517.494	614.883	30
0.5	97.389	736.164	833.553	97.389	517.252	614.642	30
0.6	97.389	719.079	816.469	97.389	514.720	612.109	36
0.7	97.389	699.688	797.077	97.389	509.514	606.904	36
0.8	97.389	676.686	774.075	97.389	498.282	595.672	48
0.9	97.389	646.709	744.098	97.389	480.511	577.900	72
Average	97.389	729.581	826.971	97.389	508.229	605.619	

Table B22: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 2 using Less-than-truckload transportation with Q^T=300.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	266.717	2611.947	2878.66	266.717	2166.470	2433.19	16
0.2	266.717	2587.134	2853.85	266.717	2180.789	2447.51	16
0.3	266.717	2560.714	2827.43	266.717	2190.485	2457.20	16
0.4	266.717	2532.330	2799.05	266.717	2194.423	2461.14	18
0.5	266.717	2501.464	2768.18	266.717	2194.506	2461.22	18
0.6	266.717	2467.323	2734.04	266.717	2186.878	2453.59	24
0.7	266.717	2428.572	2695.29	266.717	2173.674	2440.39	24
0.8	266.717	2382.605	2649.32	266.717	2155.787	2422.50	30
0.9	266.717	2322.700	2589.42	266.717	2121.859	2388.58	40
Average	266.717	2488.310	2755.03	266.717	2173.875	2440.59	

Table B23: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 3 using Less-than-truckload transportation with Q^T=100.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	266.717	1556.714	1823.43	266.717	1086.170	1352.89	16
0.2	266.717	1531.900	1798.62	266.717	1100.489	1367.21	16
0.3	266.717	1505.481	1772.20	266.717	1110.129	1376.85	18
0.4	266.717	1477.097	1743.81	266.717	1113.490	1380.21	18
0.5	266.717	1446.231	1712.95	266.717	1113.573	1380.29	18
0.6	266.717	1412.090	1678.81	266.717	1104.545	1371.26	24
0.7	266.717	1373.338	1640.06	266.717	1091.341	1358.06	24
0.8	266.717	1327.372	1594.09	266.717	1072.686	1339.40	30
0.9	266.717	1267.466	1534.18	266.717	1038.493	1305.21	48
Average	266.717	1433.077	1699.79	266.717	1092.324	1359.04	

Table B24: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 3 using Less-than-truckload transportation with Q^T=300.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	7.953	148.079	156.032	7.953	99.176	107.129	59
0.2	7.953	147.426	155.379	7.953	100.031	107.984	59
0.3	7.953	146.730	154.683	7.953	100.887	108.840	59
0.4	7.953	145.983	153.936	7.953	101.742	109.695	59
0.5	7.953	145.170	153.123	7.953	102.006	109.958	78
0.6	7.953	144.271	152.224	7.953	102.064	110.017	78
0.7	7.953	143.251	151.204	7.953	102.123	110.075	78
0.8	7.953	142.041	149.994	7.953	102.181	110.134	78
0.9	7.953	140.463	148.416	7.953	101.198	109.151	312
Average	7.953	144.824	152.777	7.953	101.267	109.220	

Table B25: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 1 using Full truckload transportation with Q^T=100.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	7.953	80.855	88.808	7.953	44.599	52.552	59
0.2	7.953	80.202	88.155	7.953	45.442	53.395	58
0.3	7.953	79.506	87.459	7.953	45.848	53.801	58
0.4	7.953	78.759	86.712	7.953	46.254	54.207	58
0.5	7.953	77.946	85.899	7.953	46.660	54.613	58
0.6	7.953	77.047	85.000	7.953	47.057	55.009	58
0.7	7.953	76.027	83.980	7.953	46.927	54.880	108
0.8	7.953	74.816	82.769	7.953	46.223	54.176	108
0.9	7.953	73.239	81.192	7.953	45.476	53.429	108
Average	7.953	77.600	85.553	7.953	46.054	54.007	

Table B26: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 1 using Full truckload transportation with Q^T=300.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	97.389	1474.749	1572.138	97.389	952.889	1050.278	32
0.2	97.389	1462.332	1559.721	97.389	957.114	1054.503	36
0.3	97.389	1449.112	1546.501	97.389	957.618	1055.007	36
0.4	97.389	1434.908	1532.297	97.389	956.409	1053.799	36
0.5	97.389	1419.463	1516.852	97.389	949.650	1047.040	42
0.6	97.389	1402.378	1499.768	97.389	941.405	1038.794	42
0.7	97.389	1382.987	1480.376	97.389	932.916	1030.306	42
0.8	97.389	1359.984	1457.374	97.389	924.014	1021.403	42
0.9	97.389	1330.008	1427.397	97.389	895.808	993.197	90
Average	97.389	1412.880	1510.269	97.389	940.869	1038.258	

Table B27: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 2 using Full truckload transportation with Q^T=100.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	97.389	1219.371	1316.761	97.389	558.180	655.569	30
0.2	97.389	1206.954	1304.344	97.389	557.357	654.747	36
0.3	97.389	1193.734	1291.123	97.389	555.506	652.895	36
0.4	97.389	1179.531	1276.920	97.389	553.301	650.690	36
0.5	97.389	1164.085	1261.474	97.389	551.076	648.465	36
0.6	97.389	1147.001	1244.390	97.389	548.263	645.652	36
0.7	97.389	1127.609	1224.998	97.389	545.451	642.840	36
0.8	97.389	1104.607	1201.996	97.389	539.694	637.084	60
0.9	97.389	1074.630	1172.020	97.389	520.462	617.851	90
Average	97.389	1157.502	1254.892	97.389	547.699	645.088	

Table B28: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 2 using Full truckload transportation with Q^T=300.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	266.717	3202.865	3469.58	266.717	2285.048	2551.76	18
0.2	266.717	3178.051	3444.77	266.717	2294.115	2560.83	24
0.3	266.717	3151.632	3418.35	266.717	2286.167	2552.88	24
0.4	266.717	3123.248	3389.96	266.717	2276.385	2543.10	24
0.5	266.717	3092.382	3359.10	266.717	2265.425	2532.14	24
0.6	266.717	3058.241	3324.96	266.717	2251.303	2518.02	24
0.7	266.717	3019.489	3286.21	266.717	2235.435	2502.15	24
0.8	266.717	2973.522	3240.24	266.717	2209.605	2476.32	42
0.9	266.717	2913.617	3180.33	266.717	2157.674	2424.39	72
Average	266.717	3079.227	3345.94	266.717	2251.240	2517.96	

Table B29: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 3 using Full truckload transportation with Q^T=100.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	266.717	2305.559	2572.28	266.717	1191.873	1458.59	18
0.2	266.717	2280.746	2547.46	266.717	1194.338	1461.05	24
0.3	266.717	2254.327	2521.04	266.717	1185.962	1452.68	24
0.4	266.717	2225.943	2492.66	266.717	1176.572	1443.29	24
0.5	266.717	2195.077	2461.79	266.717	1167.182	1433.90	24
0.6	266.717	2160.936	2427.65	266.717	1157.792	1424.51	24
0.7	266.717	2122.184	2388.90	266.717	1148.402	1415.12	24
0.8	266.717	2076.217	2342.93	266.717	1126.983	1393.70	36
0.9	266.717	2016.312	2283.03	266.717	1088.399	1355.12	48
Average	266.717	2181.922	2448.64	266.717	1159.722	1426.44	

Table B30: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 3 using Full truckload transportation with Q^T=300.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	7.953	116.037	123.990	7.953	98.269	106.222	49
0.2	7.953	115.384	123.336	7.953	98.979	106.932	49
0.3	7.953	114.688	122.641	7.953	99.690	107.643	49
0.4	7.953	113.941	121.893	7.953	100.070	108.023	66
0.5	7.953	113.128	121.081	7.953	100.285	108.238	66
0.6	7.953	112.229	120.182	7.953	100.333	108.286	78
0.7	7.953	111.209	119.162	7.953	100.105	108.058	78
0.8	7.953	109.998	117.951	7.953	99.878	107.831	78
0.9	7.953	108.421	116.374	7.953	99.179	107.132	156
Average	7.953	112.781	120.734	7.953	99.643	107.596	

Table B31: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 1 using Hybrid transportation with Q^T=100, s=0.7/0.5.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	7.953	62.070	70.023	7.953	43.926	51.879	59
0.2	7.953	61.417	69.370	7.953	44.693	52.646	58
0.3	7.953	60.721	68.674	7.953	44.973	52.926	58
0.4	7.953	59.974	67.927	7.953	45.161	53.114	58
0.5	7.953	59.161	67.114	7.953	45.350	53.303	58
0.6	7.953	58.262	66.215	7.953	45.538	53.491	58
0.7	7.953	57.242	65.195	7.953	45.727	53.680	58
0.8	7.953	56.032	63.985	7.953	45.442	53.395	116
0.9	7.953	54.454	62.407	7.953	44.777	52.730	116
Average	7.953	58.815	66.768	7.953	45.065	53.018	

Table B32: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 1 using Hybrid transportation with Q^T=300, s=0.7/1.5.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	97.389	1161.311	1258.700	97.389	893.750	991.140	24
0.2	97.389	1148.894	1246.283	97.389	901.028	998.418	24
0.3	97.389	1135.673	1233.063	97.389	905.132	1002.521	28
0.4	97.389	1121.470	1218.859	97.389	906.362	1003.751	30
0.5	97.389	1106.024	1203.414	97.389	905.075	1002.464	36
0.6	97.389	1088.940	1186.329	97.389	900.127	997.517	36
0.7	97.389	1069.548	1166.938	97.389	894.339	991.728	36
0.8	97.389	1046.546	1143.936	97.389	884.207	981.597	48
0.9	97.389	1016.569	1113.959	97.389	862.543	959.932	72
Average	97.389	1099.442	1196.831	97.389	894.729	992.119	

Table B33: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 2 using Hybrid transportation with Q^T=100, s=0.7/0.5.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	97.389	791.450	888.839	97.389	504.413	601.802	26
0.2	97.389	779.033	876.423	97.389	511.278	608.668	26
0.3	97.389	765.813	863.202	97.389	514.062	611.451	30
0.4	97.389	751.609	848.999	97.389	514.961	612.350	30
0.5	97.389	736.164	833.553	97.389	514.786	612.175	30
0.6	97.389	719.079	816.469	97.389	511.043	608.433	36
0.7	97.389	699.688	797.077	97.389	506.207	603.597	36
0.8	97.389	676.686	774.075	97.389	496.465	593.855	48
0.9	97.389	646.709	744.098	97.389	477.711	575.100	72
Average	97.389	729.581	826.971	97.389	505.658	603.048	

Table B34: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 2 using Hybrid transportation with Q^T=300, s=0.7/1.5.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	266.717	2587.965	2854.68	266.717	2156.873	2423.59	16
0.2	266.717	2563.151	2829.87	266.717	2170.298	2437.01	16
0.3	266.717	2536.732	2803.45	266.717	2176.777	2443.49	18
0.4	266.717	2508.348	2775.06	266.717	2179.000	2445.72	18
0.5	266.717	2477.482	2744.20	266.717	2176.680	2443.40	24
0.6	266.717	2443.341	2710.06	266.717	2163.415	2430.13	24
0.7	266.717	2404.589	2671.31	266.717	2148.556	2415.27	24
0.8	266.717	2358.622	2625.34	266.717	2131.922	2398.64	36
0.9	266.717	2298.717	2565.43	266.717	2092.396	2359.11	48
Average	266.717	2464.327	2731.04	266.717	2155.102	2421.82	

Table B35: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 3 using Hybrid transportation with Q^T=100, s=0.7/0.5.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	266.717	1556.714	1823.43	266.717	1076.696	1343.41	18
0.2	266.717	1531.900	1798.62	266.717	1086.022	1352.74	18
0.3	266.717	1505.481	1772.20	266.717	1091.164	1357.88	18
0.4	266.717	1477.097	1743.81	266.717	1093.496	1360.21	18
0.5	266.717	1446.231	1712.95	266.717	1093.575	1360.29	18
0.6	266.717	1412.090	1678.81	266.717	1085.260	1351.98	24
0.7	266.717	1373.338	1640.06	266.717	1072.254	1338.97	24
0.8	266.717	1327.372	1594.09	266.717	1058.102	1324.82	24
0.9	266.717	1267.466	1534.18	266.717	1020.846	1287.56	48
Average	266.717	1433.077	1699.79	266.717	1075.268	1341.99	

Table B36: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 3 using Hybrid transportation with Q^T=100, s=0.7/1.5.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	7.953	73.528	81.481	7.953	56.382	64.335	40
0.2	7.953	72.875	80.827	7.953	56.962	64.915	40
0.3	7.953	72.179	80.132	7.953	57.542	65.495	40
0.4	7.953	71.432	79.384	7.953	58.122	66.075	40
0.5	7.953	70.619	78.572	7.953	58.477	66.430	80
0.6	7.953	69.720	77.673	7.953	58.327	66.280	80
0.7	7.953	68.700	76.653	7.953	57.994	65.947	84
0.8	7.953	67.489	75.442	7.953	57.422	65.375	100
0.9	7.953	65.912	73.865	7.953	56.592	64.545	120
Average	7.953	70.272	78.225	7.953	57.536	65.489	

Table B37: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 1 using two-tier freight rate transportation with s_1=0.9 ands_2=0.5.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	7.953	69.222	77.175	7.953	55.835	63.788	45
0.2	7.953	68.569	76.522	7.953	56.487	64.440	44
0.3	7.953	67.873	75.826	7.953	56.892	64.845	56
0.4	7.953	67.126	75.079	7.953	57.074	65.027	56
0.5	7.953	66.313	74.266	7.953	57.256	65.209	56
0.6	7.953	65.414	73.367	7.953	57.249	65.202	78
0.7	7.953	64.394	72.347	7.953	56.956	64.909	78
0.8	7.953	63.184	71.137	7.953	56.664	64.617	78
0.9	7.953	61.606	69.559	7.953	55.800	63.753	144
Average	7.953	65.967	73.920	7.953	56.690	64.643	

Table B38: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 1 using two-tier freight rate transportation with s_1=0.7 ands_2=0.7.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	97.389	867.056	964.445	97.389	592.576	689.966	24
0.2	97.389	854.639	952.028	97.389	599.253	696.643	24
0.3	97.389	841.419	938.808	97.389	602.779	700.168	28
0.4	97.389	827.215	924.605	97.389	605.083	702.473	28
0.5	97.389	811.770	909.159	97.389	605.385	702.774	30
0.6	97.389	794.685	892.075	97.389	601.341	698.731	36
0.7	97.389	775.294	872.683	97.389	591.736	689.125	48
0.8	97.389	752.292	849.681	97.389	579.673	677.062	48
0.9	97.389	722.315	819.704	97.389	563.898	661.287	72
Average	97.389	805.187	902.576	97.389	593.525	690.914	

Table B39: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 2 using two-tier freight rate transportation with s_1=0.9 ands_2=0.5.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	97.389	803.950	901.339	97.389	570.824	668.213	24
0.2	97.389	791.533	888.922	97.389	574.890	672.279	28
0.3	97.389	778.313	875.702	97.389	575.235	672.624	28
0.4	97.389	764.109	861.499	97.389	574.298	671.688	30
0.5	97.389	748.664	846.053	97.389	571.941	669.330	30
0.6	97.389	731.579	828.969	97.389	566.140	663.529	36
0.7	97.389	712.188	809.577	97.389	558.997	656.386	36
0.8	97.389	689.186	786.575	97.389	545.603	642.993	48
0.9	97.389	659.209	756.598	97.389	526.672	624.061	72
Average	97.389	742.081	839.470	97.389	562.733	660.123	

Table B40: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 2 using two-tier freight rate transportation with s_1=0.7 ands_2=0.7.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	266.717	1816.981	2083.70	266.717	1322.809	1589.53	16
0.2	266.717	1792.167	2058.88	266.717	1335.712	1602.43	16
0.3	266.717	1765.748	2032.46	266.717	1346.445	1613.16	16
0.4	266.717	1737.364	2004.08	266.717	1355.186	1621.90	16
0.5	266.717	1706.498	1973.21	266.717	1352.985	1619.70	24
0.6	266.717	1672.357	1939.07	266.717	1342.678	1609.39	24
0.7	266.717	1633.605	1900.32	266.717	1331.258	1597.97	30
0.8	266.717	1587.639	1854.36	266.717	1308.612	1575.33	30
0.9	266.717	1527.734	1794.45	266.717	1271.091	1537.81	40
Average	266.717	1693.344	1960.06	266.717	1329.642	1596.36	

Table B41: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 3 using two-tier freight rate transportation with s_1=0.9 ands_2=0.5.

Cost	Independent optimization			Synchronized cycles model			
DP ratio	Buyer	Vendor	Total Cost	Buyer	Vendor	Total Cost	N
0.1	266.717	1641.064	1907.78	266.717	1273.854	1540.57	14
0.2	266.717	1616.251	1882.97	266.717	1278.809	1545.53	16
0.3	266.717	1589.832	1856.55	266.717	1279.673	1546.39	18
0.4	266.717	1561.448	1828.16	266.717	1275.942	1542.66	18
0.5	266.717	1530.582	1797.30	266.717	1269.007	1535.72	20
0.6	266.717	1496.441	1763.16	266.717	1252.910	1519.63	24
0.7	266.717	1457.689	1724.41	266.717	1233.315	1500.03	24
0.8	266.717	1411.722	1678.44	266.717	1208.958	1475.67	30
0.9	266.717	1351.817	1618.53	266.717	1168.783	1435.50	48
Average	266.717	1517.427	1784.14	266.717	1249.028	1515.74	

Table B42: Buyer cost, vendor cost and total costs between independent optimization and synchronized cycles model in Example 3 using two-tier freight rate transportation with s_1=0.7 ands_2=0.7.

	Total cost		Number of production run		Average Inventory level	
DP ratio	TC^{SYN}	TC^{IND}	$\frac{1}{N^*}$	$\frac{1}{T_v^*}$	I^{SYN}	I^{IND}
0.1	23.19	36.58	0.0222	0.0228	130.50	2096.23
0.2	23.83	35.92	0.0227	0.0215	255.20	2030.90
0.3	24.25	35.23	0.0179	0.0201	739.20	1961.34
0.4	24.43	34.48	0.0179	0.0187	775.60	1886.60
0.5	24.61	33.67	0.0179	0.0170	812.00	1805.33
0.6	24.60	32.77	0.0128	0.0152	1072.50	1715.44
0.7	24.31	31.75	0.0128	0.0132	1014.00	1613.41
0.8	24.02	30.54	0.0128	0.0108	955.50	1492.38
0.9	23.15	28.96	0.0069	0.0076	1036.80	1334.65

Table B43: Total cost, number of production run per unit time and average inventory of synchronized cycles model (SYN) and independent optimization (IND) for 5 buyers.

DP ratio	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
k_1	0.021	0.024	0.022	0.016	0.018	0.018	0.022	0.019	0.028
k_2	0.021	0.024	0.043	0.032	0.036	0.036	0.033	0.038	0.042
k_3	0.021	0.024	0.022	0.032	0.036	0.036	0.033	0.038	0.042
k_4	0.021	0.024	0.022	0.016	0.018	0.018	0.022	0.019	0.028
k_5	0.021	0.024	0.022	0.032	0.036	0.036	0.033	0.038	0.042

Table B44: number of orders per unit time of synchronized cycles model (SYN) and independent optimization (IND) for 5 buyers.

DP ratio	Total cost TC^{SYN}	Total cost TC^{IND}	Number of production run $\frac{1}{N^*}$	Number of production run $\frac{1}{T_v^*}$	Average Inventory level I^{SYN}	Average Inventory level I^{IND}
0.1	374.15	567.03	0.0417	0.0434	1825.20	6690.02
0.2	378.10	554.61	0.0417	0.0409	2181.60	6441.68
0.3	378.80	541.39	0.0357	0.0383	2905.40	6177.27
0.4	378.09	527.18	0.0333	0.0355	3218.20	5893.20
0.5	375.62	511.74	0.0333	0.0324	3142.50	5584.29
0.6	369.10	494.65	0.0278	0.0289	3481.60	5242.61
0.7	361.76	475.26	0.0278	0.0251	3168.80	4854.77
0.8	349.08	452.26	0.0208	0.0205	3324.30	4394.73
0.9	329.53	422.28	0.0139	0.0145	3158.40	3795.19

Table B45: Total cost, number of production run per unit time and average inventory of synchronized cycles model (SYN) and independent optimization (IND) for 30 buyers.

DP ratio	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
k_1	0.04	0.04	0.04	0.03	0.07	0.06	0.06	0.06	0.06
k_2	0.08	0.08	0.07	0.10	0.10	0.11	0.11	0.13	0.13
k_3	0.08	0.08	0.07	0.10	0.10	0.11	0.11	0.13	0.13
k_4	0.04	0.04	0.04	0.03	0.03	0.06	0.06	0.04	0.06
k_5	0.13	0.13	0.14	0.17	0.17	0.17	0.17	0.17	0.17
k_6	0.17	0.25	0.25	0.20	0.33	0.25	0.25	0.33	0.33
k_7	0.04	0.04	0.04	0.03	0.03	0.06	0.06	0.04	0.04
k_8	0.04	0.04	0.04	0.07	0.07	0.06	0.08	0.08	0.08
k_9	0.08	0.13	0.14	0.10	0.17	0.17	0.17	0.17	0.17
k_{10}	0.04	0.04	0.07	0.07	0.07	0.08	0.08	0.08	0.08
k_{11}	0.04	0.04	0.07	0.07	0.07	0.08	0.08	0.08	0.08
k_{12}	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.04
k_{13}	0.04	0.04	0.04	0.07	0.07	0.06	0.06	0.06	0.08
k_{14}	0.13	0.13	0.14	0.17	0.17	0.17	0.17	0.17	0.17
k_{15}	0.04	0.04	0.04	0.03	0.07	0.03	0.03	0.02	0.03
k_{16}	0.04	0.08	0.07	0.07	0.07	0.08	0.08	0.08	0.11
k_{17}	0.04	0.04	0.04	0.03	0.03	0.06	0.06	0.06	0.06
k_{18}	0.04	0.04	0.07	0.07	0.07	0.08	0.08	0.08	0.08
k_{19}	0.08	0.08	0.07	0.07	0.10	0.08	0.08	0.08	0.11
k_{20}	0.04	0.04	0.04	0.07	0.07	0.06	0.06	0.06	0.08
k_{21}	0.08	0.08	0.07	0.10	0.10	0.11	0.11	0.13	0.13
k_{22}	0.08	0.08	0.07	0.07	0.07	0.08	0.08	0.08	0.08
k_{23}	0.04	0.04	0.04	0.07	0.07	0.06	0.06	0.06	0.06
k_{24}	0.04	0.08	0.07	0.07	0.07	0.08	0.08	0.08	0.08
k_{25}	0.08	0.08	0.07	0.07	0.07	0.08	0.08	0.08	0.08
k_{26}	0.04	0.08	0.07	0.07	0.10	0.08	0.11	0.13	0.11
k_{27}	0.08	0.08	0.07	0.07	0.07	0.08	0.08	0.08	0.08
k_{28}	0.04	0.04	0.07	0.07	0.07	0.08	0.08	0.08	0.11
k_{29}	0.08	0.08	0.07	0.10	0.10	0.11	0.11	0.13	0.13
k_{30}	0.08	0.08	0.07	0.07	0.07	0.08	0.08	0.08	0.08

Table B46: number of orders per unit time of synchronized cycles model (SYN) and independent optimization (IND) for 30 buyers.

DP ratio	Total cost		Number of production run		Average Inventory level	
	TC^{SYN}	TC^{IND}	$\frac{1}{N^*}$	$\frac{1}{T_v^*}$	I^{SYN}	I^{IND}
0.1	714.84	1025.54	0.0714	0.0723	2384.20	12821.38
0.2	722.37	1000.73	0.0625	0.0682	4370.80	12407.82
0.3	723.68	974.31	0.0625	0.0638	4673.60	11967.50
0.4	720.04	945.92	0.0556	0.0590	5404.80	11494.43
0.5	713.27	915.06	0.0556	0.0539	5229.00	10980.00
0.6	701.31	880.92	0.0417	0.0482	6327.50	10410.98
0.7	681.41	842.16	0.0417	0.0417	5588.20	9765.12
0.8	657.76	796.20	0.0333	0.0341	5526.60	8999.01
0.9	617.57	736.29	0.0208	0.0241	5373.20	8000.59

Table B47: Total cost, number of production run per unit time and average inventory of synchronized cycles model (SYN) and independent optimization (IND) for 50 buyers.

DP ratio	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	DP ratio	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
k_1	0.14	0.13	0.13	0.17	0.17	0.17	0.25	0.20	0.25	k_{26}	0.07	0.13	0.13	0.11	0.11	0.13	0.13	0.17	0.17
k_2	0.07	0.06	0.06	0.06	0.06	0.08	0.08	0.10	0.08	k_{27}	0.07	0.06	0.06	0.06	0.06	0.04	0.04	0.03	0.04
k_3	0.14	0.13	0.25	0.17	0.17	0.25	0.25	0.20	0.25	k_{28}	0.07	0.06	0.13	0.11	0.11	0.13	0.13	0.17	0.17
k_4	0.07	0.06	0.06	0.06	0.06	0.04	0.04	0.03	0.04	k_{29}	0.14	0.25	0.25	0.33	0.33	0.33	0.33	0.33	0.33
k_5	0.07	0.06	0.06	0.06	0.11	0.08	0.08	0.10	0.08	k_{30}	0.07	0.13	0.13	0.17	0.17	0.17	0.25	0.20	0.25
k_6	0.07	0.06	0.13	0.11	0.11	0.13	0.13	0.10	0.13	k_{31}	0.07	0.06	0.06	0.06	0.06	0.04	0.04	0.07	0.06
k_7	0.07	0.13	0.13	0.11	0.11	0.13	0.13	0.17	0.17	k_{32}	0.07	0.13	0.13	0.11	0.11	0.13	0.13	0.17	0.17
k_8	0.07	0.13	0.13	0.17	0.17	0.17	0.17	0.20	0.17	k_{33}	0.07	0.06	0.06	0.11	0.11	0.08	0.08	0.10	0.13
k_9	0.14	0.25	0.25	0.33	0.33	0.33	0.33	0.33	0.33	k_{34}	0.14	0.25	0.25	0.17	0.33	0.25	0.25	0.33	0.33
k_{10}	0.14	0.13	0.13	0.17	0.17	0.17	0.17	0.20	0.25	k_{35}	0.07	0.13	0.13	0.11	0.11	0.13	0.17	0.17	0.17
k_{11}	0.07	0.13	0.13	0.11	0.11	0.13	0.13	0.17	0.17	k_{36}	0.07	0.06	0.06	0.11	0.11	0.13	0.13	0.10	0.13
k_{12}	0.07	0.06	0.06	0.11	0.11	0.08	0.13	0.10	0.13	k_{37}	0.07	0.06	0.06	0.11	0.11	0.13	0.13	0.10	0.13
k_{13}	0.07	0.06	0.06	0.11	0.11	0.08	0.08	0.10	0.13	k_{38}	0.07	0.13	0.13	0.11	0.17	0.17	0.17	0.17	0.17
k_{14}	0.14	0.13	0.13	0.17	0.17	0.17	0.25	0.20	0.25	k_{39}	0.14	0.13	0.13	0.11	0.17	0.17	0.17	0.17	0.17
k_{15}	0.14	0.25	0.25	0.17	0.33	0.25	0.25	0.33	0.33	k_{40}	0.14	0.13	0.13	0.17	0.17	0.17	0.17	0.20	0.17
k_{16}	0.07	0.06	0.06	0.06	0.06	0.04	0.04	0.03	0.04	k_{41}	0.07	0.06	0.06	0.06	0.06	0.04	0.04	0.03	0.04
k_{17}	0.07	0.06	0.13	0.11	0.11	0.13	0.13	0.10	0.13	k_{42}	0.14	0.25	0.25	0.17	0.33	0.25	0.25	0.33	0.25
k_{18}	0.07	0.06	0.06	0.06	0.06	0.08	0.08	0.10	0.08	k_{43}	0.07	0.13	0.13	0.11	0.11	0.13	0.13	0.17	0.17
k_{19}	0.07	0.06	0.13	0.11	0.11	0.13	0.17	0.17	0.17	k_{44}	0.07	0.06	0.13	0.11	0.11	0.13	0.13	0.17	0.17
k_{20}	0.07	0.13	0.13	0.11	0.17	0.17	0.17	0.17	0.17	k_{45}	0.07	0.13	0.13	0.11	0.17	0.17	0.17	0.17	0.17
k_{21}	0.14	0.13	0.13	0.17	0.17	0.17	0.17	0.17	0.17	k_{46}	0.07	0.13	0.13	0.11	0.11	0.13	0.13	0.17	0.13
k_{22}	0.14	0.13	0.13	0.11	0.17	0.13	0.17	0.17	0.17	k_{47}	0.14	0.25	0.25	0.17	0.17	0.25	0.25	0.20	0.25
k_{23}	0.07	0.13	0.13	0.11	0.11	0.13	0.13	0.10	0.13	k_{48}	0.14	0.13	0.13	0.17	0.17	0.25	0.25	0.20	0.25
k_{24}	0.14	0.13	0.13	0.11	0.17	0.17	0.17	0.17	0.17	k_{49}	0.07	0.13	0.13	0.11	0.11	0.13	0.17	0.17	0.17
k_{25}	0.07	0.06	0.06	0.11	0.11	0.13	0.13	0.10	0.13	k_{50}	0.14	0.25	0.25	0.33	0.33	0.33	0.33	0.33	0.33

Table B48: number of orders per unit time of synchronized cycles model (SYN) and independent optimization (IND) for 50 buyers.

	Independent optimization					Synchronized cycles model				
DP ratio	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost
0.1	-1.4324	-0.3408	-6	-0.6522	36.58	-0.6747	-0.3320	-0.6772	-0.2369	23.19
0.2	-1.4324	-0.3224	-6	-0.6522	35.92	-0.6787	-0.3391	-1.2369	-0.2421	23.83
0.3	-1.4324	-0.3026	-6	-0.6522	35.23	-0.7167	-0.2698	-2.7443	-0.3336	24.25
0.4	-1.4324	-0.2812	-6	-0.6522	34.48	-0.7288	-0.2698	-2.9027	-0.3336	24.43
0.5	-1.4324	-0.2578	-6	-0.6522	33.67	-0.7438	-0.2698	-3.0755	-0.3336	24.61
0.6	-1.4324	-0.2316	-6	-0.6522	32.77	-0.6993	-0.1962	-3.8289	-0.3723	24.60
0.7	-1.4324	-0.2017	-6	-0.6522	31.75	-0.7116	-0.1962	-3.8432	-0.3723	24.31
0.8	-1.4324	-0.1657	-6	-0.6522	30.54	-0.7310	-0.1962	-3.8947	-0.3723	24.02
0.9	-1.4324	-0.1181	-6	-0.6522	28.96	-0.7372	-0.1079	-4.5381	-0.4016	23.15

Table B49:Comparison of utility values and total cost between synchronized cycles model and independent optimization for various DP ratios in 5-buyer example (random number set 2).

	Independent optimization					Synchronized cycles model				
DP ratio	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost
0.1	-1.4293	-0.3823	-6	-0.6991	36.58	-0.8913	-0.3725	-0.9359	-0.2543	23.19
0.2	-1.4293	-0.3618	-6	-0.6991	35.92	-0.9185	-0.3804	-1.6210	-0.2598	23.83
0.3	-1.4293	-0.3398	-6	-0.6991	35.23	-1.0165	-0.3031	-3.2061	-0.3691	24.25
0.4	-1.4293	-0.3159	-6	-0.6991	34.48	-1.0375	-0.3031	-3.3636	-0.3691	24.43
0.5	-1.4293	-0.2897	-6	-0.6991	33.67	-1.0616	-0.3031	-3.5352	-0.3691	24.61
0.6	-1.4293	-0.2605	-6	-0.6991	32.77	-1.0346	-0.2208	-4.2766	-0.4066	24.60
0.7	-1.4293	-0.2269	-6	-0.6991	31.75	-1.0496	-0.2208	-4.2904	-0.4066	24.31
0.8	-1.4293	-0.1866	-6	-0.6991	30.54	-1.0719	-0.2208	-4.3398	-0.4066	24.02
0.9	-1.4293	-0.1332	-6	-0.6991	28.96	-1.0806	-0.1217	-4.9273	-0.4382	23.15

Table B50:Comparison of utility values and total cost between synchronized cycles model and independent optimization for various DP ratios in 5-buyer example (random number set 3).

	Independent optimization					Synchronized cycles model				
DP ratio	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost
0.1	-3.4720	-2.4541	-31	-7.7186	567.03	-3.4732	-2.3637	-9.5971	-3.3584	374.15
0.2	-3.4720	-2.3260	-31	-7.7186	554.61	-3.4192	-2.3637	-11.4312	-3.7177	378.10
0.3	-3.4720	-2.1882	-31	-7.7186	541.39	-3.6301	-2.0521	-14.8526	-3.7533	378.80
0.4	-3.4720	-2.0383	-31	-7.7186	527.18	-3.6254	-1.9253	-16.7403	-3.9331	378.09
0.5	-3.4720	-1.8733	-31	-7.7186	511.74	-3.5962	-1.9253	-17.1522	-4.3831	375.62
0.6	-3.4720	-1.6882	-31	-7.7186	494.65	-3.3736	-1.6242	-19.6704	-4.4741	369.10
0.7	-3.4720	-1.4747	-31	-7.7186	475.26	-3.3730	-1.6242	-19.3848	-4.5371	361.76
0.8	-3.4720	-1.2167	-31	-7.7186	452.26	-3.4588	-1.2373	-22.0587	-4.7883	349.08
0.9	-3.4720	-0.8723	-31	-7.7186	422.28	-3.3485	-0.8381	-24.2064	-4.9835	329.53

Table B51:Comparison of utility values and total cost between synchronized cycles model and independent optimization for various DP ratios in 30-buyer example (random number set 2).

	Independent optimization					Synchronized cycles model				
DP ratio	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost
0.1	-3.2005	-2.3380	-31	-7.2917	567.03	-3.0811	-2.2527	-9.6880	-2.9690	374.15
0.2	-3.2005	-2.2171	-31	-7.2917	554.61	-3.0091	-2.2527	-11.6394	-3.3009	378.10
0.3	-3.2005	-2.0869	-31	-7.2917	541.39	-3.2041	-1.9583	-15.3324	-3.4373	378.80
0.4	-3.2005	-1.9453	-31	-7.2917	527.18	-3.1112	-1.8383	-17.3932	-3.6213	378.09
0.5	-3.2005	-1.7891	-31	-7.2917	511.74	-3.0752	-1.8383	-17.8445	-3.9602	375.62
0.6	-3.2005	-1.6137	-31	-7.2917	494.65	-2.9218	-1.5529	-20.6092	-4.1209	369.10
0.7	-3.2005	-1.4110	-31	-7.2917	475.26	-2.9161	-1.5529	-20.2959	-4.1813	361.76
0.8	-3.2005	-1.1655	-31	-7.2917	452.26	-2.8964	-1.1851	-23.2046	-4.4073	349.08
0.9	-3.2005	-0.8370	-31	-7.2917	422.28	-2.8198	-0.8044	-25.4416	-4.5893	329.53

Table B52:Comparison of utility values and total cost between synchronized cycles model and independent optimization for various DP ratios in 30-buyer example (random number set 3).

	Independent optimization					Synchronized cycles model				
DP ratio	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost
0.1	-4.5161	-4.7438	-51	-14.5405	1025.54	-4.3292	-4.6902	-10.9686	-7.4690	714.84
0.2	-4.5161	-4.4923	-51	-14.5405	1000.73	-4.1512	-4.1436	-18.4385	-9.0818	722.37
0.3	-4.5161	-4.2222	-51	-14.5405	974.31	-4.0677	-4.1436	-20.0174	-9.7901	723.68
0.4	-4.5161	-3.9292	-51	-14.5405	945.92	-4.0113	-3.7114	-23.2362	-9.8723	720.04
0.5	-4.5161	-3.6073	-51	-14.5405	915.06	-3.9909	-3.7114	-23.4775	-11.1154	713.27
0.6	-4.5161	-3.2471	-51	-14.5405	880.92	-3.9650	-2.8274	-28.8126	-11.2145	701.31
0.7	-4.5161	-2.8328	-51	-14.5405	842.16	-3.9692	-2.8274	-27.3496	-11.7638	681.41
0.8	-4.5161	-2.3335	-51	-14.5405	796.20	-4.0009	-2.2838	-29.0779	-12.1897	657.76
0.9	-4.5161	-1.6696	-51	-14.5405	736.29	-3.9573	-1.4487	-31.5300	-12.5033	617.57

Table B53:Comparison of utility values and total cost between synchronized cycles model and independent optimization for various DP ratios in 50-buyer example (random number set 2).

	Independent optimization					Synchronized cycles model				
DP ratio	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost	Cost	Energy wastage	Raw materials wastage	Air pollution	Total cost
0.1	-4.5557	-5.4921	-51	-13.4891	1025.54	-4.4175	-5.4315	-12.1414	-6.3605	714.84
0.2	-4.5557	-5.2073	-51	-13.4891	1000.73	-4.2579	-4.8113	-19.8745	-7.9195	722.37
0.3	-4.5557	-4.9006	-51	-13.4891	974.31	-4.1844	-4.8113	-21.4541	-8.6909	723.68
0.4	-4.5557	-4.5671	-51	-13.4891	945.92	-4.1225	-4.3186	-24.6220	-8.7316	720.04
0.5	-4.5557	-4.1997	-51	-13.4891	915.06	-4.1209	-4.3186	-24.8569	-9.8720	713.27
0.6	-4.5557	-3.7871	-51	-13.4891	880.92	-4.1132	-3.3047	-29.9741	-10.0617	701.31
0.7	-4.5557	-3.3109	-51	-13.4891	842.16	-4.1190	-3.3047	-28.5837	-10.6102	681.41
0.8	-4.5557	-2.7344	-51	-13.4891	796.20	-4.1832	-2.6769	-30.2253	-10.9113	657.76
0.9	-4.5557	-1.9633	-51	-13.4891	736.29	-4.1169	-1.7055	-32.5377	-11.2631	617.57

Table B54:Comparison of utility values and total cost between synchronized cycles model and independent optimization for various DP ratios in 50-buyer example (random number set 3).

α_1	N	Energy wastage	% over SYN	% over IND	Raw materials wastage	% over SYN	% over IND	Air pollution	% over SYN	% over IND
1.0	60	-0.25	6.4%	2.0%	-3.22	-4.6%	46.4%	-0.31	8.4%	53.2%
0.9	54	-0.28	-3.5%	-8.3%	-3.00	2.3%	49.9%	-0.31	8.1%	53.0%
0.8	52	-0.29	-7.3%	-12.3%	-2.93	4.7%	51.1%	-0.32	4.7%	51.3%
0.7	34	-0.43	-60.0%	-67.4%	-2.21	28.0%	63.1%	-0.31	7.0%	52.4%
0.6	32	-0.46	-69.2%	-77.1%	-2.12	31.0%	64.6%	-0.33	1.4%	49.6%
0.5	31	-0.47	-74.2%	-82.3%	-2.08	32.5%	65.4%	-0.34	-1.6%	48.0%
0.4	30	-0.48	-79.6%	-87.9%	-2.03	34.0%	66.2%	-0.35	-4.9%	46.4%
0.3	29	-0.50	-85.2%	-93.8%	-1.98	35.6%	67.0%	-0.36	-8.3%	44.6%
0.2	27	-0.53	-97.7%	-106.9%	-1.88	38.8%	68.6%	-0.39	-15.9%	40.7%
0.1	24	-0.59	-119.9%	-130.1%	-1.73	43.9%	71.2%	-0.43	-29.6%	33.7%

Table B55:Comparison of utility values of energy wastage, raw materials wastage and air pollution of green utility optimization over synchronized cycles model and independent optimization on various weights of cost in 5-buyer example when DP ratio is 0.5. (random number set 2).

α_1	N	Energy wastage	% over SYN	% over IND	Raw materials wastage	% over SYN	% over IND	Air pollution	% over SYN	% over IND
1.0	62	-0.28	9.2%	5.0%	-3.74	-5.9%	37.6%	-0.28	23.9%	59.8%
0.9	60	-0.28	6.3%	2.0%	-3.67	-3.9%	38.8%	-0.29	21.5%	58.5%
0.8	52	-0.33	-7.3%	-12.2%	-3.39	4.0%	43.4%	-0.29	21.8%	58.7%
0.7	36	-0.46	-51.2%	-58.2%	-2.76	21.8%	53.9%	-0.31	14.7%	55.0%
0.6	35	-0.47	-55.2%	-62.3%	-2.72	23.1%	54.7%	-0.32	12.4%	53.7%
0.5	33	-0.50	-63.8%	-71.3%	-2.63	25.6%	56.2%	-0.34	7.4%	51.1%
0.4	31	-0.53	-73.4%	-81.4%	-2.53	28.3%	57.8%	-0.36	1.7%	48.1%
0.3	28	-0.58	-90.1%	-98.9%	-2.38	32.6%	60.3%	-0.40	-8.2%	42.9%
0.2	26	-0.62	-103.2%	-112.5%	-2.28	35.6%	62.0%	-0.43	-15.9%	38.8%
0.1	22	-0.71	-135.5%	-146.4%	-2.05	42.1%	65.9%	-0.50	-35.4%	28.5%

Table B56:Comparison of utility values of energy wastage, raw materials wastage and air pollution of green utility optimization over synchronized cycles model and independent optimization on various weights of cost in 5-buyer example when DP ratio is 0.5. (random number set 3).

α_1	N	Energy wastage	% over SYN	% over IND	Raw materials wastage	% over SYN	% over IND	Air pollution	% over SYN	% over IND
1.0	30	-1.93	0.0%	-2.8%	-17.15	0.0%	44.7%	-4.75	-8.3%	38.5%
0.9	30	-1.93	0.0%	-2.8%	-17.15	0.0%	44.7%	-3.95	9.8%	48.8%
0.8	30	-1.93	0.0%	-2.8%	-17.15	0.0%	44.7%	-3.44	21.6%	55.5%
0.7	30	-1.93	0.0%	-2.8%	-17.15	0.0%	44.7%	-2.89	34.0%	62.5%
0.6	30	-1.93	0.0%	-2.8%	-17.15	0.0%	44.7%	-2.69	38.6%	65.1%
0.5	30	-1.93	0.0%	-2.8%	-17.15	0.0%	44.7%	-2.55	41.8%	67.0%
0.4	30	-1.93	0.0%	-2.8%	-17.15	0.0%	44.7%	-2.29	47.7%	70.3%
0.3	30	-1.93	0.0%	-2.8%	-17.15	0.0%	44.7%	-2.17	50.5%	71.9%
0.2	30	-1.93	0.0%	-2.8%	-17.15	0.0%	44.7%	-1.72	60.7%	77.7%
0.1	30	-1.93	0.0%	-2.8%	-17.15	0.0%	44.7%	-1.65	62.4%	78.6%

Table B57:Comparison of utility values of energy wastage, raw materials wastage and air pollution of green utility optimization over synchronized cycles model and independent optimization on various weights of cost in 30-buyer example when DP ratio is 0.5. (random number set 2).

α_1	N	Energy wastage	% over SYN	% over IND	Raw materials wastage	% over SYN	% over IND	Air pollution	% over SYN	% over IND
1.0	30	-1.84	0.0%	-2.7%	-17.84	0.0%	42.4%	-3.84	3.0%	47.3%
0.9	30	-1.84	0.0%	-2.7%	-17.84	0.0%	42.4%	-3.39	14.4%	53.5%
0.8	30	-1.84	0.0%	-2.7%	-17.84	0.0%	42.4%	-2.92	26.2%	59.9%
0.7	16	-3.22	-75.4%	-80.2%	-10.51	41.1%	66.1%	-3.25	17.8%	55.4%
0.6	30	-1.84	0.0%	-2.7%	-17.84	0.0%	42.4%	-2.57	35.1%	64.8%
0.5	30	-1.84	0.0%	-2.7%	-17.84	0.0%	42.4%	-2.28	42.5%	68.8%
0.4	18	-2.91	-58.3%	-62.6%	-11.61	34.9%	62.5%	-2.53	36.1%	65.3%
0.3	30	-1.84	0.0%	-2.7%	-17.84	0.0%	42.4%	-2.06	48.1%	71.8%
0.2	21	-2.54	-38.1%	-41.9%	-13.22	25.9%	57.4%	-2.09	47.3%	71.4%
0.1	30	-1.84	0.0%	-2.7%	-17.84	0.0%	42.4%	-1.57	60.5%	78.5%

Table B58:Comparison of utility values of energy wastage, raw materials wastage and air pollution of green utility optimization over synchronized cycles model and independent optimization on various weights of cost in 30-buyer example when DP ratio is 0.5. (random number set 3).

α_1	N	Energy wastage	% over SYN	% over IND	Raw materials wastage	% over SYN	% over IND	Air pollution	% over SYN	% over IND
1.0	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-10.12	9.0%	30.4%
0.9	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-7.45	33.0%	48.8%
0.8	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-6.64	40.2%	54.3%
0.7	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-5.72	48.5%	60.7%
0.6	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-5.29	52.4%	63.6%
0.5	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-4.87	56.2%	66.5%
0.4	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-4.66	58.1%	68.0%
0.3	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-4.67	57.9%	67.9%
0.2	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-4.43	60.2%	69.5%
0.1	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-4.24	61.9%	70.9%

Table B59:Comparison of utility values of energy wastage, raw materials wastage and air pollution of green utility optimization over synchronized cycles model and independent optimization on various weights of cost in 50-buyer example when DP ratio is 0.5. (random number set 2).

α_1	N	Energy wastage	% over SYN	% over IND	Raw materials wastage	% over SYN	% over IND	Air pollution	% over SYN	% over IND
1.0	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-10.12	9.0%	30.4%
0.9	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-7.45	33.0%	48.8%
0.8	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-6.64	40.2%	54.3%
0.7	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-5.72	48.5%	60.7%
0.6	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-5.29	52.4%	63.6%
0.5	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-4.87	56.2%	66.5%
0.4	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-4.66	58.1%	68.0%
0.3	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-4.67	57.9%	67.9%
0.2	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-4.43	60.2%	69.5%
0.1	18	-3.71	0.0%	-2.9%	-23.48	0.0%	54.0%	-4.24	61.9%	70.9%

Table B60:Comparison of utility values of energy wastage, raw materials wastage and air pollution of green utility optimization over synchronized cycles model and independent optimization on various weights of cost in 50-buyer example when DP ratio is 0.5. (random number set 3).

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