Usha Ramanathan
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Supply Chain Strategies, Issues and Models

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Preface

In the twenty-first century, supply chain operations and relationships among supply chain partners have become highly challenging. This has necessitated new approaches to understand the complexities of managing supply chains, e.g., the development of new models. The literature on supply chain management has a number of such novel approaches, e.g., Vendor Managed Inventory (VMI), Quick Response, Accurate Response, Just in Time (JIT), and Lean and Agile production to improve performances of supply chains. Recently, the web-based collaborative tool Collaborative Planning Forecasting and Replenishment (CPFR) has added an extra value to information sharing between retailers and suppliers. It is hoped that new research has sought to extend this list, some of which have been explored in greater detail in this book. It is believed that contributions from academics from various geographical locations with a wide spectrum of knowledge will offer refreshing, novel, and insightful ideas.

This book features studies that have used mathematical modeling, statistical analyses, and also descriptive qualitative studies. The chapters have covered many relevant themes related to supply chains and logistics including supply chain complexity, information sharing, quality (six sigma), electronic Kanbans, inventory models, scheduling, purchasing, and contracts. To facilitate easy reading, we have organized chapters that deal with supply chain-related issues first, followed by studies on inventory, scheduling, purchasing, and logistics. The final chapter gives an assessment of supply chain strategies in the light of recession of recent years (from 2008).

This book begins with an interesting study in dealing with the increasing complexity in contemporary supply chains. The modern supply chains are characterized by different combinations of strategies, such as lean, JIT, and other collaborative arrangements, to meet the demand variability (Ramanathan & Muyldermans, 2010; Shah & Ward, 2007). In "Supply Chain Complexity and Strategy", Subramanian and Rahman provide an overview of supply chain complexity and suggest appropriate supply chain strategies based on material flow and contractual relationships, to align product and process complexities. It is essentially a qualitative study focussing on how supply chain managers can leverage product and process complexities into competitive advantage.

In the competitive market place, exchange of quality information among supply chain members plays an important role in managing competition

(Ramanathan, 2013; Forslundand & Jonsson, 2007). The next two chapters of this book provide an insight into importance of quality and value of information sharing in supply chains. In "A Systematic Approach to Analyze the Information in Supply Chain Collaboration: A Conceptual Framework", Ramanathan models supply chain information by listing all available information and then validate importance of information so as to use in various SC processes. This chapter provides a descriptive approach to information sharing, which can help managerial decision-making in two ways—managers can identify the important information based on its attached quality attributes and can revisit the supply chain collaboration for further information need. In "The Value of Information Sharing in a Multi-Stage Serial Supply Chain with Positive and Deterministic Lead Times", Kalpakam et al. study the benefit of information sharing and quantify the benefits (in terms of the reduction in the total demand variation and the reduction in inventory) in a multi-stage serial supply chain with more than three stages of positive and deterministic lead times. This chapter has developed interesting mathematical models and can appeal to students and researchers interested in modeling the impact of information sharing in supply chains.

In "Six Sigma in Supply Chain", Shokri discusses quality improvement and performance measurement practice in supply chains. This chapter specifically focuses on Six Sigma, which is a performance measurement tool, quality improvement tool, a problem solving methodology, and a business improvement strategy. It is essentially a descriptive study to understand the interrelationship between different perspectives of Six Sigma.

"A Case Study on E-Kanban Implementation: A Framework for Successful Implementation" provides generic guidelines on how Kanban can be successfully implemented across an organization in the context of an electronic supplier. In this chapter, MacKerron et al. provide a qualitative analysis using a case study conducted within a European manufacturing SME. The interesting contribution of this chapter is a simple eight-step approach for implementing an electronic supplier Kanban to help managerial decision-making.

"A Comparative Study of Periodic-Review Order-Up-To (T, S) Policy and Continuous-Review (s, S) Policy in a Serial Supply Chain Over a Finite Planning Horizon" considers a serial supply chain operating with deterministic and known customer demand, considering relevant costs (review, order, holding, and backlog) at every installation over a finite planning horizon. Using interesting mathematical programming models, Sethupathi et al. present an evaluation of two order policies: periodic-review order-up-to S policy (i.e., (T, S) policy) and (s, S) policy.

"Modeling of Scheduling Batch Processor in Discrete Parts Manufacturing" focuses on the subject of scheduling, which is a very important component of supply chain management. Using mathematical (integer) programming models, Mathirajan et al. develop strategies for efficient scheduling of batch processors in three real-life applications, namely, automobile gear manufacturing, semiconductor manufacturing, and steel casting industries. These models will help supply chain managers in identifying scheduling strategies that aim at optimizing the benefit of available resources.

Purchasing is often included in the framework of supply chain management, especially in the context of SMEs. This is a topic covered in "Cooperative Purchasing in Small and Medium-Sized Enterprises" using a qualitative perspective. In this chapter, Wantao investigates typical advantages of cooperative purchasing for SME retailers, and critical success factors for managing a purchasing group, using a case study of a purchasing group established by Chinese SME retailers. The study suggests that a successful purchasing group can help SME retailers survive in today's competitive marketplace. This study also provides practical insights for retail managers to consider when developing a purchasing group in dynamic environments, in order to achieve the benefits of cooperative purchasing.

Supply chain managers are often faced with the issues of outsourcing, with specific reference to third-party logistics or otherwise. This is the subject of "Supply Chains with Service Level Agreements", which uses mathematical modeling to model supply chain contracts. In this chapter, Dinesh Kumar studies supply chain contracts with delivery guarantees and other service level agreements and how such supply chains can be managed effectively. The author uses an array of mathematical techniques to model supply chains with service level agreements across industries.

Continuing with the theme of "Supply Chains with Service Level Agreements," "The Role of Logistics in E-Commerce Transactions: An Exploratory Study of Customer Feedback and Risk" focuses exclusively on logistics. Logistics is a very important component of supply chains and it is important to understand contributions of logistics in a wider context. In "The Role of Logistics in E-Commerce Transactions: An Exploratory Study of Customer Feedback and Risk", Ramanathan et al. focus on the role of logistics in the e-commerce context from a risk perspective. They report an exploratory study to understand how customers view logistics performance in deciding performance of sellers in e-commerce. Since it has been observed that risk plays a stronger role in online transactions compared to offline transactions, the authors study how the importance of logistics performance is influenced by risk characteristics of products sold through e-commerce websites. Data for analysis have been derived from customer feedback available in eBay. Based on Chi square tests and the Marascuilo procedure, the authors find that the importance of logistics services increase as risk characteristics of products decrease from high to low.

In the final chapter, we aim to provide some interesting strategies to supply chain managers to cope with the recent (post-2008) recessional economic issues. In "Supply Chain Strategies in Difficult Times", Bentley examines the strategic decisions taken by supply chain managers during the current (post-2008) economic recession. A longitudinal approach has been adopted, and a series of questionnaire survey rounds have been carried out in three countries. The findings can contribute to the understanding of how companies evolve their supply chain strategies when dealing with a significant change in the external environment.

In this book, the editors have sought to include a right mix of research studies dealing with various pertinent issues of supply chain management, with focus on qualitative as well as quantitative research. It is hoped that these studies provide interesting practical insights into supply chain managers across the globe and also stimulate more interesting research ideas in the minds of young and experienced researchers.

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Contents

Supply Chain Complexity and Strategy

Nachiappan Subramanian and Shams Rahman

Abstract The purpose of this chapter is to provide an overview of supply chain complexity and suggests appropriate supply chain strategies based on material flow and contractual relationships, to align product and process complexities. The material flow strategies considered for product and process alignment are lean, agile, leagile and risk hedging. The strategies considered for the contractual relationship are types of relationship, integration and preferred channel of operation. We substantiate the link between strategies and types of complexities using a case study. The discussion of this chapter is useful to supply chain managers for leveraging product and process complexities into competitive advantage.

1 Introduction

Complexity science is the study of the phenomena that emerge from a collection of interacting objects. To a certain extent, complexity could be defined as the situation in which a collection of objects are competing for some kind of limited resource. In some instances, it is difficult to exactly define complexity, in such scenarios it could be viewed in terms of its characteristics, such as when a system contains a collection of many interacting objects or “agents”, the behaviour of these objects is affected by memory or “feedback”. The objects can then adapt their strategies according to their history: whether the system is typically

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"open", appears to be "alive", or exhibits emergent phenomena which are generally surprising (and may be extreme). Emergent phenomena typically arise in the absence of any sort of "invisible hand" or central controller (Johnson 2007).

The objective of this chapter is to provide an overview about complexities and explain complexity types and measures. The focus is to understand product and process complexities in supply chain. The major contribution of this chapter is to propose an alignment model to mitigate complexities using material flow and contractual relationship strategies.

The rest of the chapter is organised as follows: Section 2 defines complexity and space of complexity. Section 3 discusses product and process complexities. Measurement of complexity at different level is discussed in Sect. 4. Different types of supply chain strategies for product flow and contractual relationship are discussed in Sect. 5. Complexity strategy alignment model is proposed in Sect. 6. Illustration of the model is done through a case study in Sect. 7. Outcome of the findings are discussed based on the two aspects viz. complexities and strategies in Sect. 8. Managerial insights of the study are outlined in Sect. 9. Finally, Sect. 10 summarises the chapter and outlines the potential scope of future work.

2 Definition of Complexity and Space of Complexity

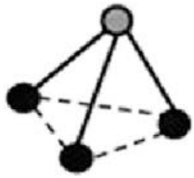
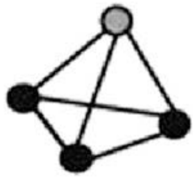
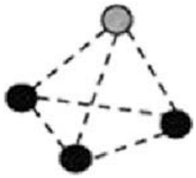
There is no agreed definition of complexity. However, researchers have attempted to explain complexity in various different ways based on numbers of structural components, its differentiation, degree of heterogeneity (relational), level of analytical sophistication (cognitive) and multiple part interactions (linear and non-linear) (Blau and Schoenher 1971; Price 1972; Price and Mueller 1986; Wang and Tunzelmann 2000; Choi and Krause 2006; Chapman 2009). For the purpose of this chapter we adopt the definition of complexity suggested by Johnson's (2007)

> *Complexity is a study of the phenomenon which emerge from a collection of interacting objects competing for limited resource.*

The space of complexity is that state which the system occupies and which lies between order and chaos. It is a state which embraces paradox; a state where both order and chaos exist simultaneously. It is also the state in which maximum creativity and possibility exist for realisation and exploration. In consideration of the space of complexity, chaos is defined as the deterministic behaviour of a dynamic system in which no system state is ever repeated (Chapman 2009; Wilding 1998).

One way to understand the different states of a given situation, from 'order' to 'chaotic', is through understanding various linkages between available resources (⬯) and competing objects (⬮) as shown in Table 1.

Table 1 Different state (*Source* Anklam, three mapping tools, theappgap.com)

State	Broad explanation	Representation
Simple (order)	Linkages exist between resources and competing objects (shown in figure with thick lines in the next column). However, there may or may not exist intra-linkages among competing objects (shown in dotted lines)	
Complicated	Both intra-linkages among competing objects and inter-linkages between resources and objects exist	
Complex (Chaos)	Intra-linkages among competing objects exist. However, inter-linkages between resources and competing objects may or may not exists	
Chaotic	Neither intra nor inter-linkages exist	

3 Complexity Types

Supply chain complexities can be classified with respect to product and process. These are discussed below:

3.1 Product Complexity

Product complexity refers to number of components, materials, process stages, technologies, performance criteria, technological difficulty in design, manufacture and assembly of a product. Heavy electrical equipment, nuclear power plants, military systems and flight simulators are considered as complex products (Walker et al. 1988; Hobday 1998; Wang and Tunzelmann 2000). We make an attempt, through a literature review, to classify the factors based on the tangible and intangible nature of both product and process. We classify tangible product complexities into the categories of numerousness and differentiations, as well as number of interacting pairs and level of inter-relationship (see Table 2). Intangible product complexities are classified based on the appearance style and comfort, safety and ease of handling (see Table 3).

Table 2 Tangible product complexity factors

Complexity factors	Description of complexity elements	Complexity level
Numerousness	• Number of components for assembly products • Number of materials for all product types, except software (number of lines in this case) • Number of process stages • Number of technologies • Number of performance criteria	• Low level of complexity = presence of lesser number of components/technologies/materials/stages/performance criteria • Moderate level of complexity = presence of average number of components/technologies/materials/stages/performance criteria • High level of complexity = presence of extensive number of components/technologies/materials/stages/performance criteria
Differentiations	Technological difficulty in design, manufacture and assembly	• Low level of complexity = presence of lesser difficulty in design, manufacture and assembly • Moderate level of complexity = presence of average difficulty in design, manufacture and assembly • High level of complexity = presence of higher difficulty in design, manufacture and assembly
Number of interacting pair and level of inter-relationships	Degree of interrelatedness or connectivity (number of interfaces among components and strength of interrelation between components)	• Low level of complexity = presence of lesser number of interacting pairs and low level of inter-relationships • Moderate level of complexity = presence of average number of interacting pairs and low level of inter-relationships • high level of complexity = presence of extensive number of interacting pairs and low level of inter-relationships

Table 3 Intangible product complexity factors

Complexity factors	Description of complexity elements	Complexity level
Appearance	• Aesthetic appearance • Flavour	• Low level of complexity = simple in appearance, and flavour • Moderate level of complexity = somewhat complex in appearance and flavour • High level of complexity = highly complex in appearance and flavour
Style and comfort	• Style • Comfort • Texture • Smell	• Low level of complexity = simple in style, comfort, texture and smell • Moderate level of complexity = somewhat complex in style, comfort, texture and smell • High level of complexity = highly complex in style, comfort, texture and smell
Safety	• Safety of product	• Low level of complexity = simple • Moderate level of complexity = somewhat critical • High level of complexity = highly critical
Ease of use	• Handle	• Low level of complexity = easy to handle • Moderate level of complexity = somewhat critical • High level of complexity = highly critical

3.2 Process Complexity

Process complexity refers to the supply base, which is made up of a number of suppliers, methods of supply, methods of cost calculation, difference in capabilities, several operational practices and different modes of connectivity. We classify tangible process complexities into the categories of numerousness and differentiations, as well as number of interacting pairs and level of inter-relationship, as shown in Table 4. (Choi and Krause 2006; Kaluza et al. 2006). Based on the sourcing characteristics suggested by Fredriksson and Jonsson (2009), intangible process complexities have been categorised as human capital, culture, infrastructure and policies and regulations. The intangible factors are shown in Table 5.

Supply chain complexity is driven by internal drivers, such as managerial decisions and external drivers, such as uncertainty and dynamics in the marketplace (Kaluza et al. 2006). It has been suggested that the competitive advantage of firms operating in global networks will increasingly be derived from their ability to manage the complex web of relationships and flows that characterise their supply chains (Christopher 2005). Aligning proper material flow and contractual relationship strategy with respect to complexity, as shown in Fig. 1, is a challenging managerial decision to be taken by top level organisations.

The aggregate representation of factors would constitute the complexity of product and process. Since the factors discussed earlier in this section include both

Table 4 Tangible process complexity factors

Complexity factors	Description of complexity elements	Complexity level
Numerousness	• Number of suppliers • Various methods/ channel of supply • Supply lead-time variations • Number of components in total landed cost • Mass production and mass customisation • Number of interfaces and systems • Proximity to supplier location	• Low level of complexity = presence of lesser number of suppliers, channel and methods of supply, components in total landed cost, interfaces and systems • Moderate level of complexity = presence of average number of suppliers, channel and methods of supply, components in total landed cost, interfaces and systems • High level of complexity = presence of extensive number of suppliers, channel and methods of supply, components in total landed cost, interfaces and systems
Differentiations	• Difference in technical capabilities • Several operational practices • Number of logistics constraints	• Low level of complexity = presence of lesser number of operational practices, logistics constraints and differences in technical capabilities • Moderate level of complexity = presence of average number of operational practices, logistics constraints and differences in technical capabilities • High level of complexity = presence of extensive number of operational practices, logistics constraints and differences in technical capabilities
Number of interacting pair and level of inter-relationships	• Different modes of connectivity • Number of inter relations	• Low level of complexity = presence of lesser number of modes of connectivity and inter relations • Moderate level of complexity = presence of average number of modes of connectivity and inter relations • high level of complexity = presence of extensive number of modes of connectivity and inter relations

qualitative and quantitative elements and it requires a framework to measure overall level of product and process complexities. Few attempts made by researchers to measure different types of complexity are discussed in the next section.

Table 5 Intangible process complexity factors

Complexity factors	Description of complexity elements	Complexity level
Human capital	• Lack of supplier skills and knowledge • Complexity of cognition	• Low level of complexity = presence of large number of knowledgeable and skilled suppliers • Moderate level of complexity = presence of average number of knowledgeable and skilled suppliers • High level of complexity = presence of less number of knowledgeable and skilled suppliers
Culture	• Criminality and corruption • Cost for exiting legacy assets and quality problems • Price erosion due to increase competition • Language and political instability • Organisational culture • Cultural difference • Prioritisation of other business initiatives	• Low level of complexity = presence of lesser level of cultural issues • Moderate level of complexity = presence of average level of cultural issues • High level of complexity = presence of extensive level of cultural issues
Infrastructure	• Increased comparative price levels • Complexity of network constellation and configuration • Pacity-sharing of information • Describing and demarcating the supply chain • Time zones	• Low level of complexity = presence of low level of infrastructural issues • Moderate level of complexity = presence of average level of infrastructural issues • High level of complexity = presence of extensive level of infrastructural issues
Policies and regulations	• Currency risks, • Intellectual property risks • Risk of supply • Rules and laws • Lack of holistic view • Different perspectives and ignorance • Volatility in demand • Dynamic customer requirements	• Low level of complexity = presence of low level of policies and regulations issues • Moderate level of complexity = presence of average level of policies and regulations issues • High level of complexity = presence of extensive number of policies and regulations issues

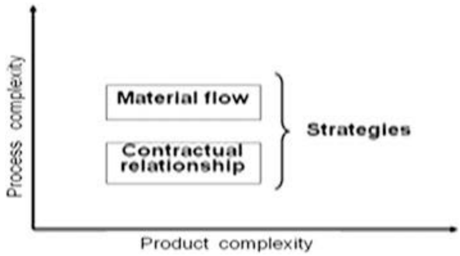


Fig. 1 Product and process complexity mapping

4 Complexity Measures

4.1 Firm-Level Complexity Measure

Mariotti (2008) proposed measure referred as complexity factor (CF) for individual firms based on products, markets, facilities, employees and customers. This measure is somewhat collectively represents the complexity of the organisation rather than isolated measures such as calculating sales and margin per stock keeping unit, sales per customer or market, sales per employee available to measure them separately. The proposed measure is a self-benchmarking measure available to relate complexity with the organisational profitability. Mariotti's (2008) measure to firm CF is given below.

$$\text{Complexity factor (CF)} = \frac{\begin{array}{r}\text{(Number of finished products (SKUs)} * \text{Number of different}\\ \text{market served}^{*} \text{ Number of company legal entities} * \text{Number of}\\ \text{significant facilities} * \text{(Number of employees + Number}\\ \text{of suppliers + Number of customers)}\end{array}}{\text{(Sales revenues)}}$$

Mariotti (2008) categorised CF into three levels based on CF value. : If the CF value is less than 1, then firms are considered to be profitable; if it is more than 50, the firms are highly complex; and, if it is between 1 and 50, then a deeper understanding of the causes of complexity is required.

4.2 Product Complexity Measure

Few attempts were made by researchers to measure product complexity. Zhuo and Qunhui (2007) proposed an indicator-based system using the grey technique to measure product complexity. The suggested indicators include the influence of technology (number and maturity of technology), physical characteristics (number of components, volume and density), organisation (people, departments, information transfer and resources allocation) and environment (number of suppliers and customers, regulations and standards and market competition). Motorola views product complexity purely based on products' physical characteristics, organisational aspects. Motorola's complexity index (CI) consists of variables such as average part per time, test time, assembly time, mechanical postponement, software postponement, use of industry standard parts and component reuse. For Motorola CI served as a gatekeeper tool for screening new product designs to prevent unnecessary and costly complexity.

4.3 Process Complexity Measure

This section describes attempts to measure and manage logistics and supply chain complexity.

4.3.1 Logistics Complexity

Specific measures of logistics complexity are not provided in the literature. Logistics complexity is expressed qualitatively using exploratory studies (e.g., Nilsson 2006) or case studies (Rao and Young 1994). Using case studies from the fashion retail industry, Masson et al. (2007) explained logistics complexity in terms of demand and supplier network complexity. He took into consideration quantity, intermediaries and geographical dispersion as constituents of supplier network complexity.

4.3.2 Supply Chain Complexity Measure

Milgate (2001) measured supply chain complexity using proxies such as the number of raw material parts, breadth of supplier base and percent of sales from exported product available in manufacturing database. However, data are firm specific and thus it is difficult to generalise. Recently, Isik (2010) attempted to measure supply chain complexity associated with uncertainty and variety. He used entropy-based statistical measures for the supply chain, which had been previously used for manufacturing. Isik (2010) argued that complexity is not only the function of the probabilities of different states, but also that each state has different complexities on its own. He defined expected value for each state and measured the deviation. His work updates that the earlier work of Frizelle and Woodcock (1995), Reiss (1993) opined that primarily there are four determinants those drive complexity. These are size, diversity, variety and uncertainty.

Quantification and suitability of factors for measuring supply chain complexity depend on the applicable sectors and there is no unique way to represent it. Appropriate factors could be chosen for a particular sector from the factor-list provided in Tables 2, 3, 4 and 5. If a standard measure is available to capture the product and process complexities, then it would be appropriate for supply chain managers to choose the right strategies to mitigate the supply chain complexity. Supply chain strategies that would be most helpful to overcome product and process complexities are discussed in the next section.

5 Supply Chain Strategies

The fundamental objective of a typical supply chain strategy is to ensure smooth flow at minimum cost (Christopher et al. 2006). However, it is not easy to identify an appropriate strategy, based on product and process complexities. Christopher et al. (2006) argued that sourcing strategy, operations strategy and route to market need to be appropriate to specific product market conditions. Chopra and Meindl (2007) stated that supply chain strategies determine the nature of material procurement, transportation of materials, manufacture of product or creation of service and distribution of product. Fisher (1997) explained the need of different supply chain strategies for functional and innovative products with examples from a diverse range of consumer products including food, fashion apparel and automobiles. The taxonomy, suggested by Christopher et al. (2006), for selecting an appropriate supply chain strategy for material flow, is based on product uncertainty and lead time. The success of Japanese firms in the early 19980s and 1990s prompted practitioners and academics to examine their firm–supplier relationships. Firms started concentrating on methods to develop long term, close knit and cooperative relationships with suppliers (Liker and Choi 2004; Jean et al. 2010). The next section describes a few supply chain strategies based on material/service flow and contractual relationships between supplier and manufacturer.

5.1 Material Flow Strategies in Supply Chain

Material flow in a supply chain depends on the product nature (based on demand) and process (based on supply). There are four material/service flow strategies in supply chains: agility, lean thinking, leagile and risk hedging. These strategies are considered as generic strategies based on supply and demand characteristics (Christopher et al. 2006). Each is outlined briefly below and summarised in Table 6.

Table 6 Product flow strategies

Strategies	Applicability
Agile	Highly innovative product with more uncertain demand and supply
Lean	Stable demand and functional products
Leagile	Products with unpredictable demand and long lead times
Risk-hedging	Functional products and evolving process

5.1.1 Agility

Agility is primarily concerned with responsiveness—the ability to match supply and demand in turbulent and unpredictable markets. The key characteristic of agility is flexibility. Lockstrom (2007) predicted that many smaller, more agile firms would gain market share at the expense of the industry titans that find it more difficult to change with product and process requirements. Agility is a strategy most suitable for highly innovative products, with more uncertain demand and supply as it is a strategy which adapts inventory pooling, or dual sourcing, to absorb uncertainty. A good example of agility is the case of Zara, the Spanish fashion garment manufacturer and retailer (Christopher 2006).

5.1.2 Lean

The idea of lean thinking was developed by Womack and Jones (1996), among others. The focus of lean thinking has been on the elimination of waste. Christopher (2000) has suggested that the lean concept works well when demand is relatively stable, predictable and variety is very low. This minimises the cost of making and delivering the product to the customer. This strategy is most applicable to functional products with a lower uncertainty of demand and supply. A lean strategy is followed by Procter and Gamble to manage its supply chain for volume products to Wal-Mart in the USA.

5.1.3 Leagile

Leagile is a hybrid strategy that combines lean and agile principles. Lean principles are used for predicable, standard products and agile principles for unpredictable or special products. Leagile principles are used for unpredictable demand and long lead times. Leagile is used as a classic postponement strategy by Hewlett Packard for its range of desktop printers (Christopher et al. 2006).

5.1.4 Risk Hedging

Risk hedging is applicable for less demand uncertain product (functional) and high supply uncertain supply processes (evolving processes). An example given by Christopher et al. (2006) is a million plastic Christmas trees ordered each year by the UK retailer Woolworths from its numerous suppliers in China. Risk hedging is a trade-off strategy meant to gain without predominant loss and it is almost similar to lean strategy with more emphasis given towards supply uncertainty.

5.2 Contractual Relationship Strategies

To understand contractual relationship strategies one needs to be cognisant with the components: what are the relationships involved, what is supply chain integration and how do these impact type of channel preferences.

5.2.1 Relationship

A supplier's relationship varies from a transactional to a strategic one. Nordin (2008) suggested this, based on transaction cost theory claiming that a translational relationship is applicable for products with low uncertainty and large volume, and an integration or partnership type supplier relationship is when the uncertainty is higher and volumes lower. Rycroft and Kash (1999) postulated that complex technologies are innovated by equally complex innovation networks (strategic alliances, research consortia) involving firms, universities, government agencies and other organisations. Recently, Jean et al. (2010) hypothesised that there is a positive relationship between technological uncertainty and a transactional relationship. The summary of type of relationship and their applicability is shown in Table 7.

5.2.2 Supplier Integration

Supplier integration embodies various communication channels and linkages within a supply network. Integration refers to both internal (within firm) and external (outside firm) integration and this chapter refers to external integration. Supplier integration deals with the factors such as technology and knowledge integration, information sharing, trust and joint sense making (Myers and Cheung, 2008) with their first and second tier suppliers. Table 8 summaries the use of different modes of integrating a supplier and its applicability, as suggested by Myers and Cheung (2008), Selnes and Sallis (2003) and Frazier et al. (2009).

Table 7 Relationships type

Type of relationship	Applicability
Integration or partnership type supplier relationship	When the product uncertainty is high and for lower volumes
Strategic alliances with research consortia (complex innovation networks)	Complex technologies
Cooperation	To achieve global reach and to reduce time to innovate complex technologies
Positive relationship	Technological uncertainty

Table 8 Type of supplier integration

Type of supplier integration	Applicability
Use of advanced IT systems	Improving the efficiency of global business operations
Share more critical information and knowledge with a trustworthy supplier	International original equipment manufacturers (OEM) customer to improve cross-border relationship
External integration	Greater the environmental uncertainty companies will be willing to share more critical knowledge to overcome the adaptation problems
Sharing proprietary knowledge	International customers are less concerned about sharing proprietary knowledge with their OEM suppliers

5.2.3 Type of Channel Preferred

Decision on type of channel preferred depends on the mode of purchase, which can be direct purchasing from low cost country (LCC) supplier (DPS), purchasing from LCC supplier through foreign subsidiary (PFS), purchasing from LCC through a supplier's subsidiary in home country (SSH), purchasing through a third-party intermediary (P3P) or purchasing through International Procurement Office (IPO). According to Hall (1976), people in a high-context culture, such as Japan or China, rely on the communication context more than those in a low-context culture, such as the United States or Germany. People from high-context cultures mainly try to obtain information from their personal information network. In contrast, people from low-context cultures seek information from a research base or use information sources such as reports, databases and the Internet. A high-context culture that emphasises human elements and personal relationships in communication will have better trust-building processes (Rosenbloom and Larsen 2003). Summary of different types of channel preferred and its applicability is shown in Table 9.

Table 9 Type of channel preferred

Type of channel preferred	Applicability
Personal information network (DPS)	High-context culture people (e.g., Japan, China)
Research base or use information sources (SSH/P3P/PFS)	Low-context culture people (e.g., the United States, United Kingdom, Germany)
Inter-organsational relationships (IPO)	To understand inter organisational relationship and learning issues. Hall's cultural framework was tested by few researchers
Personal relationships and communication (DPS/IPO)	Trust-building processes through presence of human elements in high context culture

This section discussed the major constituents of material flow and contractual relationship strategies. The major aim of next chapter is to explore the possible alignment between supply strategies and product and process complexities.

6 Complexity Strategy Alignment

This section discusses, through literature, the nature of alignment required to minimise complexity in the supply chain. High value-added competition is based on the innovation of technologies that are knowledge intensive (supported by large investment in R and D) and complex. Examples include automobiles, aircraft and telecommunication equipment. These are the technologies that underpin the major knowledge-based economies, and provide the most prized competitive advantages and support a host of non-economic capabilities as well such as health care, national security and environmental protection (Rycroft 2007). In the literature, we found some evidence that increased relationship integration enables firms to examine, and re-examine, their own product strategies, creating more opportunities to develop new products (Chen et al. 2008). With greater technological uncertainty in the global supply chain, suppliers need more critical information from their customers (OEMs) to keep ahead of the competition. Moreover, demand–driven supply networks have forced dominant customers to outsource part of their high-level value-adding activities, including new product development, to small suppliers. In a more unpredictable technological environment, customers are willing to share knowledge with their small suppliers, to maintain their product quality and develop better new product strategies. Branded OEMs such as Apple and IBM collaborate with many original development manufacturers to develop next-generation products, mobile phones and laptops for example. These companies share much critical information about end-user preferences and market trends with their innovative original development manufacturers (Jean et al. 2010). Other examples include Boeing, which has outsourced the design of wing parts to Russia and Texas Instruments and Intel which have each outsourced the development of devices to Indian firms (Engardio et al. 2003). Nordin (2008) stated that cost could be reduced if suppliers were kept at arms length in transactional relationships and contracts awarded through competitive bidding. He also suggested transactional purchasing for simpler services bought in bulk as they have low asset specificity and uncertainty and do not directly impact on core business processes.

To explain our proposed alignments we use by way of example two products with varied product and process complexities, an aircraft and a car instrument panel. This is summarised in Fig. 2.

Aircraft could be placed under the product category of medium to high product complexity spectrum and have various sub-systems which have varied categories of process complexity, such as the engine sub-system for low to medium process complexity and fastening sub-systems (such as inserts and locknuts) could be treated as belonging to the high process product complexity category. It is assumed

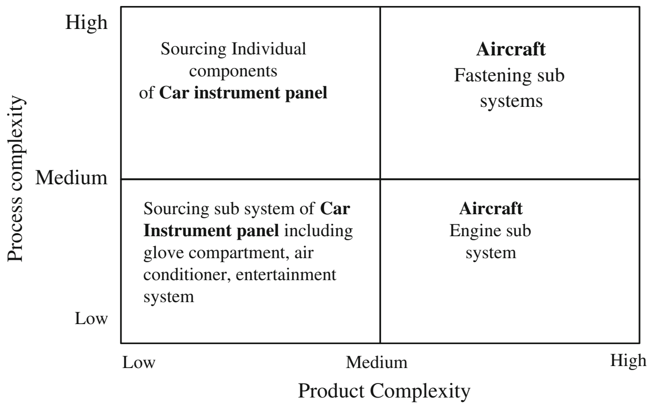
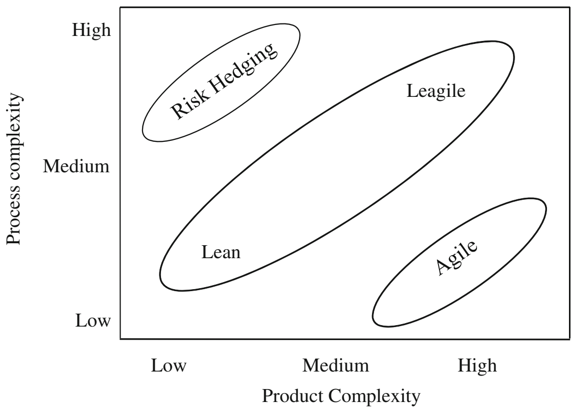


Fig. 2 Examples illustrating different process *complexity*

that an engine sub-system would sit in the low to medium process complexity category as an aircraft manufacturer (e.g. Boeing, airbus) is most likely to have only limited suppliers (e.g. Rolls Royce, Honeywell), so the number of managed interfaces would be minimal and of limited variety as there is not much difference in technical capability among suppliers and limited modes of connectivity. However, in the case of fastening sub-systems the aircraft manufacturer could procure from different suppliers (e.g. Aircraft Fasteners Ltd) with different capabilities and product systems, hence this component is assumed to be in the medium to high process complexity category.

If product complexity is from medium to high then, based on process complexity, it can be aligned using a leagile supply chain strategy (Fig. 3). If process complexity is from low to medium it can be aligned with an agile strategy. In the aircraft example, agile strategy for the engine sub-assembly is used to align low to medium process complexity. The aircraft manufacturer would be dealing with one

Fig. 3 Complexity and material flow strategies



or two suppliers and, in turn, suppliers should be responsive enough to take care of changes in demand, variety, lead time and innovation. With respect to integration, they should have full integration with suppliers (Fig. 4). This would include processes such as regular monitoring and face-to-face communication. A strategic peer-to-peer relationship is necessary for them to succeed (Fig. 5), as well as having an IPO at the supplier's location (Fig. 6). Jean et al. (2010) emphasised that in a high-context culture, firms rely more on person-to-person relationships to communicate with supply partners. They have indicated that, to augment integration, close relational bonding and ties can facilitate information sharing, and thus aid the development of innovative behaviours. Nordin (2008) emphasises the importance of close collaboration and a strategic relationship when there is greater complexity, and lower standardisation, of the products and services offered.

If the process complexity is from medium to high, then a leagile strategy would be used to align with the medium to high product complexities. In the case of fastener sub-assembly there could be many suppliers with many variations. To avoid disruptions, the manufacturer has to pool inventory to meet the uncertainties.

Fig. 4 Types of integration

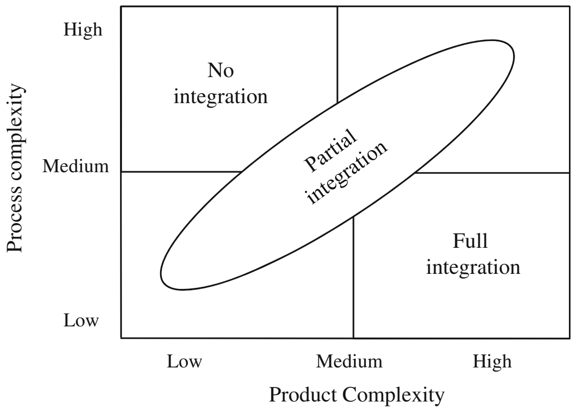


Fig. 5 Types of relationship

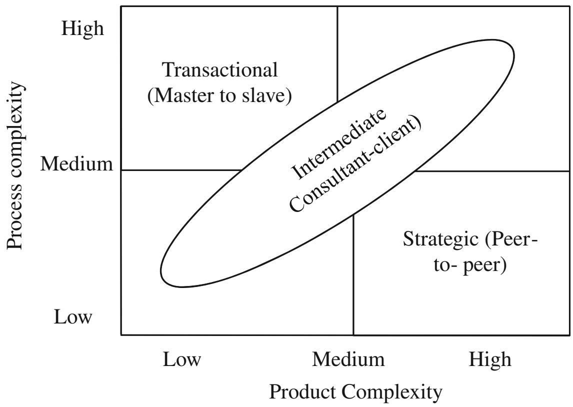
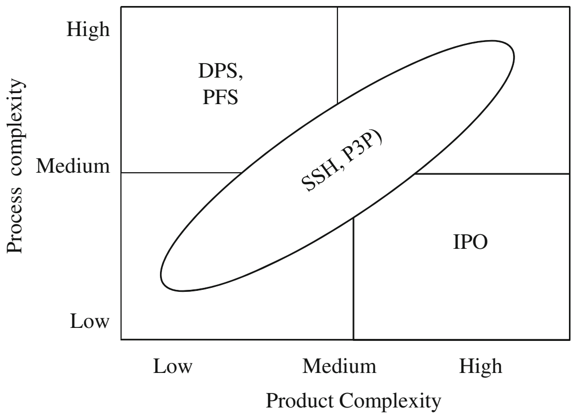


Fig. 6 Types of channel



In terms of alliance, a partial integration would be appropriate as would a consultant client relationship. When it comes to preferred channel, the most appropriate would be to purchase from LCC through a SSH or purchase through a P3P. Similarly, the sourcing of car instrument panel can be explained using Figs. 3, 4, 5 and 6.

In this section, we explained the possible strategy and complexity alignment through examples. In the following section, we examine a case study to explain proposed models.

7 Case Study

In order to confirm the above alignment and arguments, a pilot study was carried out using a company that exports automotive and engineering components to leading OEM manufacturers based in the US, Europe and Asia. Contrary to Eisenhardt's (1998) recommendation of four to ten as the number of cases that a researcher should select, other scholars showed that a smaller number of cases provide greater opportunities for depth of observations (Narasimhan and Jayaram 1998; Dyer and Wilkins 1991; Voss et al. 2002). In fact, Dyer and Wilkins (1991) argued that single case studies enable the capturing of much greater detail of the context within which the phenomena under study occur. Hence, we used a single company to capture the details in detail. The company produces fasteners, radiator caps, powder metal parts, cold extruded parts, hot forged parts, pumps and assemblies. Their Chinese facility is located in Zhejiang province and can produce thousands of varieties of fasteners, including standard and customised ones. Their present capacity is 6,000 metric tonnes of standard and specialised fasteners. If demand is higher, they can outsource from their other plants located in India, Germany, the UK and Malaysia. This product is valuable for our study because it has both product and process complexities. Product and process complexities

Table 10 Summary of case company profile

Organisation name	Respondent characteristics		Organisation characteristics			
	Position of respondent	No of years in the company	Year of operation	Accreditation	Product type	Company structure
Case company A	Manager	6	7	ISO 9000, IS 14001 and TS 16949	High tensile fasteners (standards and specials)	Flat

could be analysed as per the tangible and intangible factors listed in Tables 2, 4 and 5. The data and information were gathered through interviews and observations of the research team members during field visits to the company. Data and information were collected at the company site using a semi-structured interview questionnaire during August–September, 2011. The interview questionnaire had five sections that included respondent and organisational characteristics, product complexity factors (both tangible and intangible factors), process complexity factors (both tangible and intangible factors), material flow strategies and contractual relationship strategies. For tangible factors objective data were collected and for intangible factors, a 5-point Likert scale was used. Respondent and organisational characteristics are shown in Table 10.

The details of complexities and strategies are discussed in the following section.

7.1 Product Complexity

The case company produces different products such as fasteners, radiator caps, powder metal parts, cold extruded parts, hot forged parts, pumps and assemblies. Based on the list of factors and elements given in Tables 2 and 3, the responses with respect to product complexity are shown in Table 11. Since the factors listed

Table 11 Product complexity of case company

Tangible		In-Tangible	
Factors	Level of complexity elements	Factors	Level of complexity elements
Numerousness	• More than 10 materials would be used for all product types • 5–6 process stages • More than 5 technologies • More than 10 performance criteria	Safety	Highly complex
Differentiations	• 5–8 technological difficulty in design • 5–8 technological difficulty in manufacture		

in Tables 2 and 3 are general and applicable to all industry. The company representative felt that they have complexity elements related to numerousness and differentiation factors in tangible complexity and safety factor with respect to intangible product complexity factors. In numerousness factors, it is clear that the company has to deal with number of raw materials and performance criteria. They have high technological difficulty in design and manufacture.

7.2 Process Complexity

The case company representative felt substantial level of complexity with their supplier base. The response to individual complexity element with respect to our tangible process complexity factor classification such as numerousness, differentiations and number of interrelationship is given in Table 12. Their major concerns in terms of numerousness are related with number of suppliers, lead time variations and variety of products. On differentiation aspects, variety of production method adopted by their suppliers and difference in their technical capability matters most. Since the case company is operating in a high cultural context country they prefer to have different mode of connectivity with their suppliers. It is also interesting to note that case company suppliers have inter-relationship which adds complexity to the supply base.

Case company visualised adequate level of intangible process complexity with respect to all aspects of complexity classification factors given in Table 5. The

Table 12 Tangible process complexity of case company

Factors	Level of complexity elements
Numerousness	• 38 suppliers • 25–45 days' supply lead-time variation • Included total landed cost and it has actual procurement cost, transportation cost, duties and other taxes • Produce more than 1,000 varieties of products which include more than 50 customised products
Differentiations	• 10–15 % difference in technical capabilities of their suppliers • Case company suppliers mostly adapt different production method, transportation process, business process and different flow in network • Case company has major logistics constraint which is to meet minimum tonnage requirement, availability of trucks and road blockage during snow fall period
Number of interacting pair and level of inter-relationships	• Preferred to 9–10 different modes of connectivity such as frequent personal interaction, interaction through phone, email, fax etc • 8–11 suppliers of case company have inter-relationship among themselves

Table 13 Intangible process complexity of case company

Factors	Level of complexity elements
Human capital	High complexity in lack of supplier skills, knowledge and complexity of cognition
Culture	High complexity with respect to quality problems, price erosion due to tough competition and cultural difference
Infrastructure	High complexity in increased comparative price levels, complexity of network constellation and configuration and opacity in sharing of information
Policies and regulations	High complexity in almost all factors related to policies and regulations such as currency risks, intellectual property risks, risk of supply, rules and laws, lack of holistic view, different perspectives and ignorance, volatility in demand and dynamic customer requirements

case company's response for applicable individual complexity element is shown in Table 13. The case company is concern about policies and regulations, cultural and human capital aspects.

7.3 Supply Chain Strategies

The case company follows lean supply chain strategy for material flow. In terms of contractual relationship, they adapt peer-to-peer type of relationship even though their products are functional. They prefer to use two types of channels such as direct purchasing from low cost country (DPS) and purchasing from low cost country through foreign subsidiary (PFS). They share knowledge and information with trustworthy suppliers through quite frequent personal meetings. The major characteristics of material flow and contractual relationship strategy is shown in Table 14.

Table 14 Summary of material and contractual relationship strategies of case company

Material Flow strategy	Contractual relationship strategy			
	No of suppliers	Relationship strategy	Type of channel preferred	Supplier integration
Lean	38	Peer to peer type of relationship (Cross functional collaboration)	2(DPS, PFS)	Share more information and knowledge with a trustworthy supplier, frequent personal meetings

8 Case Company Complexity Strategy Alignment

Interpretation of pilot study based on complexity strategy alignment can be made in two ways. Using proposed alignment shown in Figs. 3, 4, 5 and 6 and the material flow and contractual relationship strategy, it is easy to identify the product and process complexity of the case company. Since we do not have standard framework to capture the composite measures of product and process complexities, our interpretation is based on Figs. 3, 4, 5 and 6 and the case company's strategies. Later, we cross examine our interpretation made earlier through Figs. 3, 4, 5 and 6 and strategies approximately with the responses obtained for various product and process complexities.

8.1 Interpretations Based on Case Company's Strategies and Proposed Alignment

The supply chain strategies adopted in the case company are "lean strategy" for material flow, "peer-to-peer" relationship for relationship, "partial integration" for type of integration and "DPS and PFS" for the type of sourcing channel. Using their material flow and contractual relationship strategies and the proposed complexity strategy alignment discussed in Sect. 5, Figs. 7, 8, 9 and 10 represent the case company's complexities strategy alignment.

Fig. 7 Case company's material flow strategies

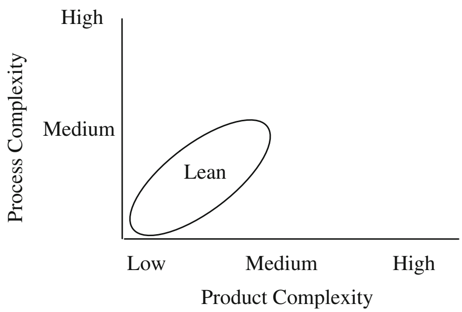
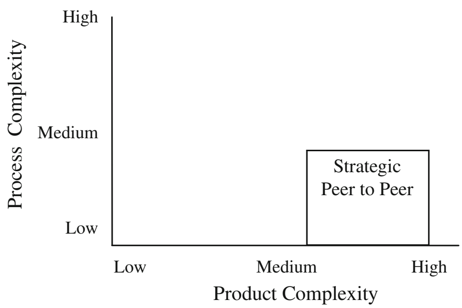


Fig. 8 Case company's relationship



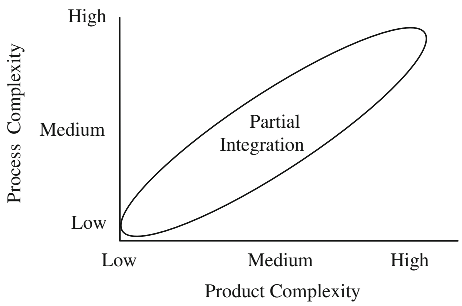


Fig. 9 Case company's integration

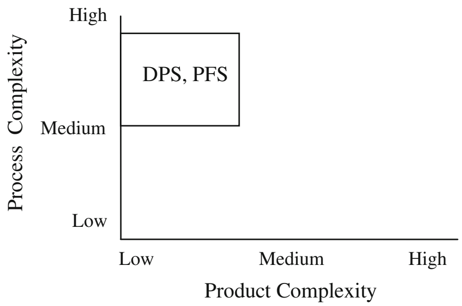


Fig. 10 Case company's preferred channel

Restructuring of Case Company's Complexity Strategy Alignment

Based on our proposed alignment discussed in Sect. 5, if the case company is using lean material strategy, then they should have a "consultant-client" type of relationship and procure through "P3P" channel instead of "DPS and PFS" channel. It is evident that they are currently practicing lean strategy, which is applicable for low process and low product complexity product. Based on their responses, we found that they have low product complexity and a somewhat higher process complexity. We would suggest that, if the firm is interested in continuing this strategy, they have to reduce their process complexity. Specifically, they need to reduce their tangible and intangible process complexities which are discussed in the managerial implication section.

8.2 Cross Examination of the Case Company's Complexity Strategy Alignment

Product and process complexities based on the response from case company are shown in Tables 10, 11 and 12. It is obvious that company's product complexity is approximately low to medium, because their tangible factors are low and intangible factor is quite high. Similarly, the company's process complexity varies from medium to high because tangible and intangible factors are from medium to high.

Using the proposed alignment discussed in Sect. 5 and their known complexity level, it is satisfactory if they adapt the following material flow and contractual relationship strategies.

Material flow strategy	:	Risk hedging material flow strategy
Type of relationship	:	Master–Slave type of relationship (Translational)
Type of integration	:	No integration is required
Type of channel preferred	:	DPS and PFS are preferred

From the above cross examination, it is obvious that there is a perfect match between the types of channel they are sourcing and there are slight deviation in material flow strategy, type of relationship and type of integration. They follow lean material strategy even though they have high process complexity. It is interesting to note the deviation, because they have standard rationalised supplier base. They have partial integration to be proactive and mitigate if there is a surge in complexity level. With respect to the type of channel they are sourcing they are very well aware about high process complexity and doing it rightly.

9 Managerial Implications

In the previous section, we examined the proposed strategy complexity alignment on two aspects i.e. For a known strategy what should be the product and process complexity of the case company, whereas on the other side we examined the suitability of chosen strategy of the company based on their response to the complexity factors. From the pilot study it is obvious that companies have to focus more on reducing tangible and intangible process complexity factors rather than product complexity factors. In this section, we discuss below the general suggestions how a firm can reduce process complexity factors with the example of case company.

Suggestions to reduce tangible process complexities in terms of numerousness, differentiation, and number of interacting pairs are given below.

Numerousness

- Companies can reduce the number of suppliers and lead time variations through proper supply base rationalisation. They could also consider real landed cost factors such as cost of delay, inventory cost, reliability cost and procurement and operations cost.
- Companies should think about reducing their varieties of products if they are interested in practicing lean strategy.

Differentiation

- Companies should come up with policies to increase the technical capability among suppliers.
- Firms should insist that suppliers to adopt quality policy and to have a suitable inventory control policy along the lines of their buyers.
- Companies must consider logistics constraints during the planning phase.

Number of Interacting Pair and Level of Inter Relationship

- Optimal number of connectivity would be appropriate for the companies and reduce different modes and numbers of connectivity, even though it is a high context cultural country. A company with low product complexity and high process complexity should maintain a consultant-client type of relationship.
- Companies should formalise their interactions with their suppliers. Most of the companies want to be proactive and trying to aim for higher level of integration. Aiming for higher level of integration is advisable at the same time they need to leverage their strategies adopted for material flow and contractual relationship.

Suggestions to reduce intangible process complexity factors in terms of human, culture, infrastructure and policies and regulation are discussed below.

Human

- In order to improve supplier skills and knowledge, companies should organise training and evaluation sessions before engaging in long-term collaborative contractual relationships.
- The suppliers' should regularly update about developments elsewhere, to improve the cognition of best practices.

Culture

- Before sharing critical information, companies should establish a formal relationship, which may include heavy penalties for deviation.
- Even though the companies adopt collaborative relationship, they must understand trust building for high context culture country.

Infrastructure

- Focal companies must educate their suppliers about the value of supply chain efficiency and its advantages.
- Focal companies should be aware of hidden costs in warehousing and transportation that could be eradicated if there was a proper network arrangement.

Policies and Regulations

- Focal companies and their suppliers should agree to share profit/loss if there is deviation due to currency risk.
- To protect intellectual property risk, firms should only engage with trustworthy suppliers with agreed penalties if something goes wrong.

10 Concluding Remarks and Future Work

This chapter analyses the complexity issues and appropriate strategies for the supply chain. The research classifies product and process complexities. A major outcome of this work is the examination of the complexities from a joint supplier and firm perspective where both product and supply process complexities have been considered. The study takes into account tangible and intangible complexity factors. We suggested alignments for the product and process complexities with material flow and contractual relationship strategies. The strategy alignment has been illustrated with simple examples. The study validated the alignment using a pilot study company based in China. The major limitation of this study is the confinement of validation to one case, and there are also challenges in evolving a quantifiable composite measure for supply chain complexity. This will be addressed in further work, where detailed case study analyses for various sectors will be carried out. Standard techniques such as Analytic Hierarchy Process or multi-attribute utility theory will be used to capture the mix of tangible and intangible complexity factors in determining weightage and ranking. A common composite score that considers tangible and intangible factors could be evolved once the weightage is known. Further, a longer term objective of this research is to analyse the impact of complexities and strategies on supply chain resilience.

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A Systematic Approach to Analyze the Information in Supply Chain Collaboration: A Conceptual Framework

Usha Ramanathan

Abstract In recent competitive business scenario, many supply chain players act together to perform well to earn profit. In this attempt, several supply chain (SC) informations are being exchanged under collaborative framework. Some information will be used for planning, production, replenishment, and forecasting; while the other information will just overload the system. Hence, it is obligatory for supply chain players to know the value of each piece of information for its role in the supply chain processes. In this chapter, first we try to model the SC information and then validate the information so as to use in the SC processes. In this approach, we suggest a framework to list and evaluate SC information. We also attach quality attributes to each of the information listed. On identifying the important information and related quality attributes, managers can decide including the information in the SC processes. This approach can help the managerial decision making in two ways—managers can identify the important information based on its attached quality attributes and can revisit the supply chain collaboration for further information need.

1 Introduction

After successful adoption of collaboration in companies like Wal-Mart and P&G, supply chain collaboration (SCC) has gained much attention from many businesses. Recent SCC framework namely Collaborative Planning Forecasting and Replenishments (CPFR) intends to improve overall performance of supply chains, having information exchange as a backbone (VICS 2002). However, the

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information exchange among players varies widely across different supply chains. For instance, retailers in the supply chain are more interested in promotional sales and hence need to know about recent price reduction and upcoming promotions. On the other hand, manufacturers are interested in knowing point of sales data and inventory levels at retail outlets for production planning, material resource planning, logistics planning, and also for avoiding excess inventory.

In collaborative SCs, both upstream and downstream members exchange information to improve overall performance of SC (Ramanathan and Muyldermans 2010). Transparent information sharing in SC helps to reduce uncertainty and avoid excess inventory (Holweg et al. 2005; Chen et al. 2000). Li and Wang (2007) asserted that the benefit of information sharing is dependent on content and use of information (Lee and Whang 1999, 2001; Lee et al. 2000; Raghunathan 2001). Improper use of important information will make no difference in the performance of SC. To ensure success in global businesses, it is essential for SC players to have right information at the right time.

However, identifying the important information, that can improve SC performance, is hard in any supply chain (Ramanathan 2012). This is mainly because every piece of SC information has some desired qualities (Forslund and Jonsson 2007). For any supply chain player, establishing an appropriate collaboration with other partners to obtain required supply chain information with the desired quality is a difficult task. With the purpose of filling this gap, our research intends to suggest a simple conceptual framework in order to identify the appropriate information before considering the same for either SC planning or forecasting or production. Rest of the chapter is organized as follows: Sect. 2 gives a brief outline on the role of information in SC collaborations. A conceptual model is developed in Sect. 3 and steps to analyze the model are also discussed. Section 4 illustrates the model and analyses through a case study. Finally, Sect. 5 summaries the contribution of this research and includes notes for future research.

2 Role of SC Information in Collaboration

The supply chain (SC) information and its role in various business performances are widely discussed in the literature by both academics and practitioners. Sharing of demand information with upstream members help reducing manufactures' supply chain cost in Collaborative Forecasting and Replenishment (Raghunathan 1999). Knowledge on demand information also reduces inventory cost of both supplier and customer (Gavirneni et al. 1999; Lee et al. 2000; Graves 1999). Meanwhile, sharing demand information along with current inventory status facilitates achieving reduction in inventory cost (Chen 1998; Cachon and Fisher 2000). Depending on capabilities (technology and manpower) of SC members, the benefit of information sharing will also range from basic inventory reduction to higher profit earning. Manufacturer could reduce variance in demand forecast if readily available historical order data is being used efficiently (Raghunathan 2001). But more update on point of sales data (POS) can improve forecast of promotions and new products (Smaros 2007; Ramanathan and Muyldermans 2010). The POS data and market-data-sharing are found influential in achieving forecast accuracy in Chang et al. (2007)'s augmented CPFR model. More detailed literature on value of information sharing in supply chains is given in Li et al. (2005). Sanders and Premus (2005) attempted to model the relationships between firms' IT capability, collaboration, and performance. However, the information sharing, planning, and forecasting have not been discussed in detail.

Most of the above-discussed literature lists the benefits of exchanging information either on POS data or inventory data but there is not enough detail on exchanging other demand-related information. Recognizing the type of information, that needs to be shared among supply chain members, to build more visibility is still a big challenge in achieving successful collaboration (Barratt and Oliveira 2001). Ryu et al. (2009) presented a simulation study on evaluation of supply chain information sharing. The authors compared the value of exchanging short-term forecast and long-term forecast among SC players. Under high demand variability, the long-term forecast performed better than the short-term forecast. Under low demand variability, the short-term forecast performed better than long-term forecast. Using store-level SKU data Ali et al. (2009) found that simple time series forecasting will be appropriate for normal sales without promotions. The authors suggested using advanced techniques for sophisticated input to improve forecast accuracy of promotional sales. Refer to Table 1 for more literature on information sharing in SCs. While most of the articles support sharing of POS data for reduction of cost or inventory, a recent paper by Nakano (2009) claimed that internal forecasting (with-in the firm) had significant impact on logistics and production performance but not external collaborative forecasting (with other supply chain players). The author using survey data from Japanese manufacturing identified a positive relationship between internal forecasting and planning, and external (upstream/downstream) collaborative forecasting and planning.

Most of the literature discussed earlier have described the information exchange among supply chain partners as a performance improvement tool (Cachon and Fisher 2000; Byrne and Heavey 2006; Lee et al. 2000). While Kulp et al. (2004) related different forms of information and knowledge integration to evaluate the supply chain performance, Steckel et al. (2004) questioned the importance of point of sale information (POS). Steckel et al. (2004) argued that the POS information may distract decision making particularly if product demand is highly fluctuating. However, Aviv (2001, 2007) supported the sharing of sales information and local forecasts between retailers and manufactures to improve the accuracy of demand forecasts. Overall performance of supply chain was proved to be higher with high quality centralized information (Forslund and Jonsson 2007). Paulraj et al. (2008) emphasized the inter-organizational communication as a relational competency in SCC. Although, many of these journal articles are focusing on different areas of supply chain, the relationship between the SC performance and characteristics of

Table 1 Some literature on SC information exchange

Authors	Information sharing (Data type)	Purpose
Bourland et al. (1996)	Inventory	Minimizing inventory cost
Cachon and Fisher (1997)	Historical data	Decision on technology investment
Chen (1998)	Demand and inventory	Minimizing total inventory cost
Gavirneni et al. (1999)	POS and inventory	Minimizing inventory cost
Cachon and Fisher (2000)	Demand and inventory	Minimizing inventory cost throughout whole SC
Lee et al. (2000)	Demand information	Minimizing inventory cost
Raghunathan (2001)	Order history	Decision on technology investment
Kulp et al. (2004)	Demand information (asymmetric)	Improve supplier benefit
Byrne and Heavey (2006)	Inventory, sales, order status, sales forecast, production/delivery schedule	Total supply chain cost saving
Chang et al. (2007)	POS and market data	Improve responsiveness to demand fluctuations
Ketzenberg (2009)	Demand, recovery yield, capacity utilization	Capacity utilization showed more value than any other information in a capacitated closed loop supply chain.
Ryu et al. (2009)	Demand information	Study changes in inventory level and service level
Ali et al. (2009)	SKU-store level data	Forecast promotions
Ramanathan (2012, 2013)	Sales data and promotion plans	Improve planning, forecasting, and replenishment

the information are not explained to a great extent. This is evident from the recent review paper on supply chain coordination (Arshinder and Deshmukh 2008; Bahinipati et al. 2009). Some previous researchers used conceptual models to design supply chain collaboration (Simatupang and Sridharan 2005; Gunasekaran et al. 2004). Similarly, in this chapter, we develop a conceptual framework for validating SC information using data from a case company. We try to achieve this in three stages (see Fig. 1).

In stage one of the information validation process, we propose to list all possible SC information. This will help to decide on whether to use or not to use the information in organizational decision making. In stage two, the selected list of information will be evaluated for its quality. This research suggests some useful steps to validate the SC information in the next section. This stage of validation process aims to guide the firms to include appropriate SC information in top management decision making. Then the information with desired quality will be included in the SC processes. Stage three will suggest the SC players to continue with the current SCC or to improve, based on the quality of the available SC

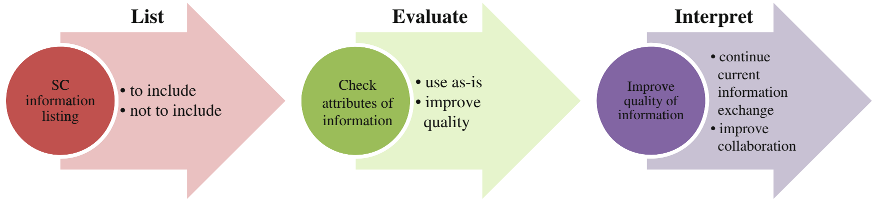

Fig. 1 Three stages of the SC information validation

information. If required, the SC members will attempt to strengthen their collaborative relationship in order to improve the quality of the SC information. The following section explains the conceptual model in detail.

3 Development of Conceptual Model

Although a lot of information related to sales, inventory, and replenishment are exchanged in almost all modern SCs, all the information is not being used by every SC member (Ramanathan 2012, 2013). As explained in Sect. 2, some of the information are used more frequently, while the others are rarely or never used. Inclusion of the information on decision making is based on the quality of the information and its impact on the performance of SCs (Forslund and Jonsson 2007; Zhao et al. 2002). Some previous researchers have used cost-benefit analysis and forecast accuracy as indicators to measure the quality of information and the performance of SC (Aviv 2007; Forslund and Jonsson 2007; Sari 2008).

Cost and benefit of obtaining and using information are acting as base lines to SC information exchange (Sari 2008). The cost involved in information exchange is measured either in terms of investment on technology and/or amount spent on obtaining the information. The benefit of information exchange can be represented through good forecast accuracy (Ramanathan and Muyldermans 2010). Although the accuracy of information is obligatory in reduction of forecast error, it is highly subjective—to the explanatory power of the partner involved in the process of information exchange and also to the accuracy of information at the time of predicting demand (Aviv 2007). The benefit can also be measured through improved inventory, production, and replenishments (Gavirneni et al. 1999).

It is also important to mention that the ability of observing any small changes in the potential market and also descriptive nature of the observer can alter the quality or accuracy of the information used for demand forecasts (Aviv 2002). For example, a sudden change in local weather such as high temperature or rain may increase the demand of umbrellas. But this information on the local weather will not help to alter any production plans, in a very short notice. However, a proper inventory deployment and good coordination among supply chain players will assist smooth replenishment. This indicates that the action-ability of the information is partially related to the performance of the supply chain. Based on the literature, in this study, we consider six major attributes of the information exchange namely—source, cost, availability, reliability, action-ability, and importance (Ramanathan 2012, 2013). These attributes aim to act as evaluation criteria for deciding the quality of the SC information.

3.1 Source of Information

Source of information indicates the parties involved in information exchange. In particular, source can help to identify who observes or owns the data. In simple terms, 'source' indicates the whereabouts of the information available.

3.2 Cost of Information

Cost of information denotes the cost incurred by the SC members to obtain information.

3.3 Availability of Information

This indicates the status of the availability of the information with specific time scale such as always, intermediate, short term, sometimes, after, and before event. Time scale is dependent on duration of special events/sales promotions in a particular company.

3.4 Reliability/Accuracy of Information

Descriptive nature of observer and market can alter the reliability of the information (Aviv 2002). Hence, it is obligatory for managers to know the accuracy of the information before using it in company's decision making.

3.5 Action-Ability of Information

The extent to which the available information can be used in forecasting, production and replenishment is represented through action-ability. Here, the action-ability represents the capability of using the available information in the SC.

3.6 Importance/Benefit

Importance of information in the supply chain processes, such as planning, forecasting, production, and replenishment, decides the need for information exchange among the supply chain members.

Of the above six attributes, the source of information and the cost of information are directly related to company top management decision making. In general, any management decisions will consider using the action-able quality information from a dependable source with premium cost in the SC processes. The capability of using the correct information at the right time will be evident through an effective supply chain performance. For example, quick transfer of sales information (such as electronic POS data) will have a positive impact on the planning and hence improve responsiveness of supply chains to any demand fluctuations (Bourland et al. 1996; Chang et al. 2007; Cachon and Fisher 2000) rather than using historical data. However, the use of technology can alter the speed of the data transfer which will affect the response to supply chain changes. If all the information available is used effectively to respond quickly to the demand, the benefit of supply chain will be in the form of forecast accuracy, inventory reduction, cost reduction, etc. (Cachon and Fisher 2000; Bourland et al. 1996).

As a first step towards developing a conceptual framework to evaluate the supply chain information, we make use of all of the above-mentioned attributes of the SC information in a single structure. This conceptual framework will suggest systematic collection of supply chain information and its analysis (refer to Fig. 2). In Fig. 2, the supply chain information 1, 2,…..n represent various information being used in a supply chain from different possible sources. By analyzing this framework, any company can understand the importance of information in its supply chain processes.

As every business has a very different information requirement depending on its business objectives, it will be a good idea to set general steps to easily identify the need for any improvement in the SC information. However, earlier literature on supply chain information did not suggest any structured approach to analyze or evaluate the information. In this research, we suggest evaluating all of the SC information before including the same in the SC processes. To support this procedure, we develop a set of steps to evaluate SC information. Accordingly, every single data (information) will go through the following steps before deciding whether the particular piece of information needs more attention or not. To facilitate this analysis, we suggest some constructive iteration of analysis of the SC information to help collaborating members to decide on information exchange.

Step 1: If both or any one of 'Importance' and 'Action-ability' of information is marked low, there is no need to use the information in the SC processes. Revisit the SC information framework. Else go to step 2.

Step 2: If any one of 'Importance' or 'Action-ability' of information is marked either medium or high then perform Step 3.

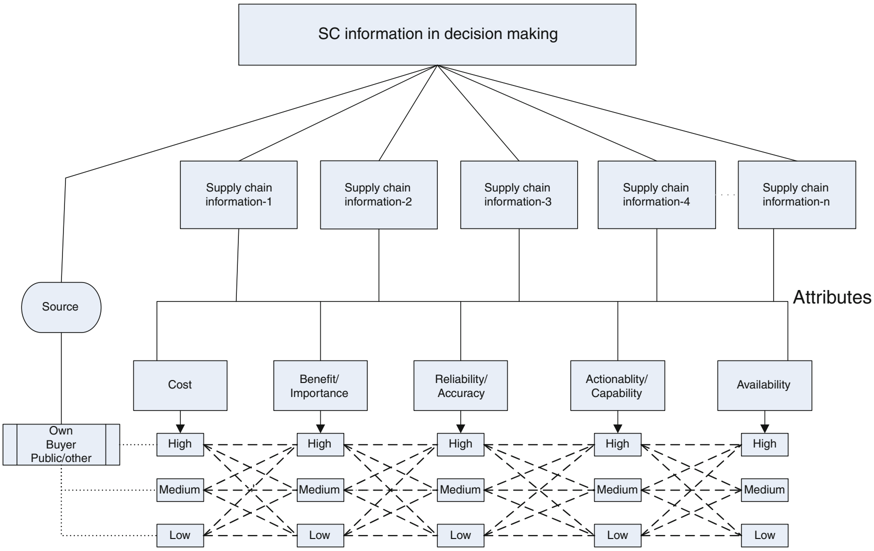

Fig. 2 Identifying important SC information—a conceptual framework

Step 3: If both 'Reliability' and 'Availability' of information are marked high, then the SC information is appropriate for decision making. Continue the information exchange (as-is). Else go to Step 4.

Step 4: If any one of 'Reliability' or 'Availability' of information is marked either medium or low then revisit the SC information framework.

Using Step1, the importance and action-ability of the SC information will be identified. Further, Steps 2 and 3 will guide the SC manager on whether to use the information or not. To better understand the given conceptual framework, we use a practical case study in the next section. Through this case, we explain the adoption of the framework and the suggested steps to evaluate the SC information.

4 Evaluation of Conceptual Framework Through a Case Study

Company-A is an established textile company operating globally. Most of the production plants of the company are located in Asian countries. Finished products (textile materials) of the company are sold around the globe. Currently, the company is trying to establish a well-connected network with all its customers.

The company considers establishing the basic communication at transactional level with new customer or relatively new customer. However, for promotional sales it communicates extensively with their retailers for planning, production, replenishment, and forecasting. Currently, the company motivates customers for a future collaboration by providing free samples. The satisfied customers plan their sales promotion in collaboration with the Company-A. During the sales promotions, both the Company-A and retailers share their plans on production and replenishments. They also share their demand forecasts. But communication between these two SC partners concentrates only on the promotional sales. This relationship is not generally extended further during normal sales. In other words, the information exchange between their customers is highly focused at the time of promotions but restricted at the other period of time. The source of information for Company-A is mainly their retailers. The cost involved in the information exchange and promotional advertisements is being shared by the Company-A and the retailers. The promotional planning, forecasting, and replenishment are jointly made by the company and the retailers.

The current collaborative arrangement of the Company-A with respect to the promotional sales looks short sighted and it needs further expansion to involve retailers in the SC processes at all the time. Our conceptual SC information model aims to help the company to identify the important supply chain information and its contribution for the SC performance improvement. As mentioned in Sect. 2, the stage one of the SC information validation process includes initial listing of all the available SC information and its characteristics. This will help the company to structurally identify the useful information.

In the stage 2 of the SC information validation, based on the present practice of the company's information exchange, we have identified two different types of information. One is internal to the SC and another is external to the SC. Here, the internal SC information refers to the information specific to particular SC that is exchanged among SC members. The external SC information refers to the information that is not normally provided within the SC, but available externally either publicly available data or through third party information providers. The internal SC information and the external SC information specific to the Company-A is given as follows:

Internal SC information. Promotional sales, sales data, order data, discount information, inventory level, trend, local forecasts

External SC information. Economic factors, competitors' information, seasonality, government policy, and regional preferences

The promotional sales plans are discussed frequently by the Company-A with their retailers, approximately, 3 months before the start of the promotions. Normally, the Company-A does not get the sales data from the retailers. However, the sales data is exchanged on daily basis during promotions. On a regular interval, say once a week, the company is being updated on the inventory at the retailers' outlet. Occasionally, the retailers offer shop discounts for some products without any prior notice to the manufacturer. In such cases, the inventory data helps the Company-A to plan their production and replenishments. Local forecast and local trend on products are regularly communicated.

In the conceptual model, the second stage of validation of the SC information is done in two phases. In the first phase, the Company has rated each of its internal and external SC information for its attributes. With reference to each attribute, all the information is rated as low or medium or high. Both the internal and the external SC information along with their corresponding rates are presented in Tables 2, 3.

In the second phase, the SC information of the case company is analyzed for its quality attributes. Using the steps suggested in Sect. 3, each data has been analyzed.

In the third stage of the SC information validation, the results of the analysis of conceptual model (see Table 2) of the company identified that the exchange of details on promotion, order, and trend was appropriate. Hence, we have suggested the company to continue using the information in the SC processes (marked as 'continue' in Table 2). This also directs the managers to continue exchanging the information in the same level (as-is). However, the other information such as sales, local forecasts, inventory, and discount details need to be updated. Currently, the Company-A uses all the available internal SC information (from customers) on sales planning, inventory planning, forecasting, and replenishments. From our analysis, it is clear that all of the SC information is not appropriate to be used in the immediate supply chain processes as it needs improvement. Hence, we have suggested the company to revisit their SC information framework. By revisiting the framework, it is possible for the Company-A to improve the quality and availability of SC information either by improving the collaboration relationships or by investing in technology.

Similarly by testing and interpreting the external SC information, decision maker can decide the level of involvement of third-party information providers in the supply chain.

From Table 3, it can be seen that the SC information related to the economic factors and seasonal factors can be used in the decision making. However, the competitors' information and the regional preferences cannot be included in the supply chain decision making as these two information lack the desired quality. This analysis gives a useful insight to the company on obtaining the competitors

Table 2 Evaluation of the internal SC information—Company A

Information Attributes	Sales	Promotions	Order	Local forecast	Inventory	Trend	Discount
Importance	High	High	Medium	High	Medium	Medium	High
Action-ability	High	High	High	High	Medium	Medium	High
Reliability	Low	High	High	Medium	Low	High	Medium
Availability	Low	High	High	Low	Low	High	Low
Step 1	× Go to step 2	× Go to step 2	× Go to step 2	× Go to step 2	× Go to step 2	× Go to step 2	× Go to Step 2
Step 2	✔ Go to step 3	✔ Go to step 3	✔ Go to step 3	✔ Go to step 3	✔ Go to step 3	✔ Go to step 3	✔ Go to Step 3
Step 3	× Go to step 4	✔ continue	✔ continue	× Go to step 4	× Go to step 4	✔ continue	× Go to Step 4
Step 4	Revisit	———	———	Revisit	Revisit	———	Revisit

Table 3 Evaluation of the external SC information—company-A

Information Attributes	Economic factors	Competitors' information	Seasonality	Regional preferences
Importance	High	High	Medium	Medium
Action-ability	Medium	Medium	Medium	Medium
Reliability	High	Medium	High	Medium
Availability	High	Low	High	Low
Step 1	× Go to step 2	× Go to step 2	× Go to step 2	× Go to step 2
Step 2	✔ Go to step 3	✔ Go to step 3	✔ Go to step 3	✔ Go to step 3
Step 3	✔ continue	× Go to step 4	✔ continue	× Go to step 4
Step 4	———	Revisit	———	Revisit

information. Currently, the company incurs an extra cost to obtain competitors information as it feels the importance and action-ability of competitors' information are high. However, the lack of good quality information impacts on overall benefits of the SC. Hence, it is important for the mangers to decide whether to obtain competitors information from the same source or do they need to explore other possible sources. Similarly, good knowledge on the preferences of local customers of the retailers is vital for the manufacturer to improve long-term planning. The company needs to improve the SC collaboration with the retailers to obtain details any such details on local customers' preferences.

Though the economic factors, competitors' information, seasonality, regional information are not directly related to the SC collaboration, the information is usually incorporated in various supply chain processes. Hence, it is necessary for the company to validate both the internal and the external SC information before including them in the decision making. Some times, the external nature of the SC information (as they are publicly available data or third-party data) needs expert judgements. In many occasions, the external SC information is not incorporated in the immediate supply chain process but in the long-term planning of the company.

5 Conclusion and Scope of Future Research

In this research, we have developed a simple framework of SC information and also have suggested steps to evaluate this framework. Six main attributes of information quality were described. This procedure was illustrated through the case of a textile company. The managerial implication of this procedure governs the top management to decide on the supply chain collaboration based on their need of information exchange. Partners of supply chain collaboration exchange information in various stages of the SC processes. Verifying the quality of the information at every stage will help the mangers to identify and improve any inappropriate information.

For instance, the managers interested in involving the SC information in forecasting can check the appropriateness of information before material resource planning and production. If needed it is also possible for them to revisit collaboration arrangement in order to strengthen the information quality. Earlier research of Forslund and Jonsson (2007) insisted the quality of information to improve performance of the supply chain. This chapter has extended the attribute of quality information into six types. This can be considered as a guideline for future work on supply chain information quality specific to the supply chain collaboration.

This research evaluated the supply chain information framework through a single case study. The supply chain information specific to the company was analyzed for its quality attributes. More case studies with details on specific role of each of the supply chain information in various processes will improve the understanding on the role of information in the supply chain collaborations.

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The Value of Information Sharing in a Multi-Stage Serial Supply Chain with Positive and Deterministic Lead Times

S. Kalpakam, Chandrasekharan Rajendran and Sunanda Saha

Abstract In traditional supply chain inventory management, orders used to be the major information that firms exchanged. Information sharing among firms within a supply chain has been a cornerstone of recent innovations in supply chain management. Lee et al. (2000) considered a two-level supply chain, consisting of a manufacturer and a retailer, with non-stationary AR(1) end demand and showed that the manufacturer benefits significantly when the retailer shares its demand information. In our work, we extend the study to quantify the value (i.e., benefit) of information sharing (in terms of demand variance reduction and inventory reduction) to a multi-stage serial supply chain with the number of stages greater than two. The lead time at every stage is positive and deterministic. Base stock levels at each installation are calculated under two scenarios—no information sharing and complete information sharing. The dependency of the benefit of information sharing on parameters like demand correlation and lead times is presented. It is seen that as the number of stages in a serial supply chain increases, the demand variance and hence the bullwhip effect increases; so is the case with an increase in the demand correlation. In addition, a comparative study of a supply chain with stages having respective lead times in decreasing order and a supply chain with stages having respective lead times in increasing order has also been carried out in order to relatively analyze the benefits of information sharing at different stages across these two supply chain settings. It is possibly for the first time in the literature that the benefit of information sharing has been studied and

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quantified (in terms of the reduction in the total demand variation and the reduction in inventory) in a multi-stage serial supply chain with more than three stages with positive and deterministic lead times.

1 Introduction

Significant work has been carried out to quantify the value of information sharing between manufacturers and retailers in a supply chain, when the demand processes are independent and identically distributed over time. Lee et al. (2000) considered a situation in which the underlying demand process is auto correlated. More specifically, they studied a two-stage model, consisting of a manufacturer and a retailer, with non-stationary AR (1) end demand and constant lead times and examined the impact of the autocorrelation and the lead time on the benefit of information sharing. It is assumed that the manufacturer also uses an AR (1) process to forecast the retailers order quantity. They showed that the manufacturer can obtain inventory reduction and cost reduction from getting information about the demand from the retailer, as it would enable the manufacturer to derive a more accurate forecast of future orders placed by the retailer. Later Raghunathan (2001) showed that the results derived by Lee et al. (LST) overestimate the benefit of demand information sharing, if the manufacturer uses the entire order history to do its forecast.

While the above models focus on the benefits of information sharing in a supply chain having two stages, in most of the real life situations, companies deal with multi-stage supply chain structure. In a serial supply chain, as the orders make their way upstream, the perceived demand is amplified and produces the bullwhip effect. In this case, sharing of the demand information with the upstream members of the supply chain is expected to reduce the bullwhip effect. Leng and Parlar (2008) studied the problem of allocating cost savings from sharing demand information in a three-level supply chain retailer, distributor, and manufacturer with deterministic unit lead time between the manufacturer and the distributor and the retailer and the manufacturer, using the concepts from cooperative game theory. Ganesh et al. (2008) studied the value of information sharing in a multi-product supply chain with product substitution and instantaneous supply at each stage. Wu and Cheng (2008) quantified the impact of information sharing on inventory and the expected cost in a three-echelon supply chain under a general end demand process. Mahajan and Venugopal (2011) considered a two-stage supply chain to study the effect of the reductions in lead time on the costs of retailer and manufacturer.

The main objective of the this work is to examine the value or benefit of information sharing (in terms of reduction in the variance of demand and inventory reduction) at each stage in an N-stage serial supply chain, as the number of stages in the chain increases. The lead time at every stage is positive and deterministic. Base stock levels at each installation are calculated under two scenarios—complete information sharing and no information sharing. The dependency of the benefit of information sharing on parameters like demand correlation, demand variance and lead times is presented. It is seen that as the number of stages in a serial supply chain increases, the demand variance and hence the bullwhip effect increases. Thus, the benefit of information sharing increases with increase in the number of installations in a supply chain. A comparative study of a supply chain with stages having respective lead times in decreasing order and a supply chain with stages having respective lead times in increasing order has also been carried out in order to relatively analyze the benefits of information sharing at different stages across these two supply chain settings. It is possibly for the first time in the literature that the benefit of information sharing has been studied and quantified (in terms of the reduction in the total demand variation and the reduction in inventory) in a multi-stage serial supply chain with more than three stages with positive and deterministic lead times.

2 Multi-Stage Supply Chain Model

Consider an N-stage serial supply chain, where $N \geq 2$. Demand D_t occurring at the retailer (stage 1) in any time period t is a simple AR (1) process given by the equation,

$$D_t(1) = d + \rho D_{t-1}(1) + \varepsilon_t , \quad t = 1, 2, 3, \ldots \tag{1}$$

where $d > 0$ is the base level of demand, $-1 < \rho < 1$, and $\{\varepsilon_t, t \geq 1\}$ are independently and identically distributed (iid) normal random variables with mean 0 and variance σ^2. Equation (1) indicates that demand D_t can also take negative values and to avoid this, we assume that $\sigma \ll d$, so that the probability of negative demand is negligible. It is also assumed that the AR (1) nature of the demand process along with its parameters d, ρ and σ is known to each member of the supply chain. All members in the supply chain adopt the order-up-to policy. At the end of period t, each site reviews its inventory level and places a replenishment order with the upstream member and receives the order quantity of the downstream member. Depending on the available inventory, part or entire order quantity is shipped to the downstream member. Excess demand is backlogged. It is assumed that the nth stage in the supply chain can seek an expedited supply to fulfill the (n-1)th stage's replenishment requirement when the stock out at the nth stage occurs. This cost of sourcing and delivering this expedited supply corresponds to the shortage or backlog cost rate for the nth stage. The supply at the Nth installation is guaranteed from a source of infinite capacity. The lead time at each stage is positive and deterministic. As the lead time is positive, shortages can occur at each installation. Let p_n and h_n respectively denote the shortage cost rate and the holding cost rate per unit per period at the nth installation, $1 \leq n \leq N$. It is also assumed that no set up costs are incurred while placing an order.

The following figure depicts a multi-stage supply chain:

We introduce following notation:

For $1 \leq n \leq N$,

$D_t(n)$ = Demand occurring at nth installation in period t, $t = 1, 2, 3, \ldots$
$T_t(n)$ = Optimal order-up-to level of the nth installation in period t
L_n = Lead time of an order at the nth installation
$B_t(n)$ = total demand over the period $t + 1$ to $t + L_n + 1$occurring at nth installation

$$M_t(n) = E(B_t(n)|\, D_t(n))$$

$$V_t(n) = Var(B_t(n)|\, D_t(n))$$

Let $Y_t(n)$ be the order quantity of the nth installation $(1 \leq n \leq N - 1)$ at the end of period t.

Note that

$D_t(n) = Y_t(n-1)$, $2 \leq n \leq N$ and the order quantity at the nth installation is given by $Y_t(n) = Y_t(n-1) + (T_t(n) - T_{t-1}(n))$.

At each stage n, the total shipment quantity $B_t(n)$, which is equal to the total orders placed over the period $t + 1$ to $t + L_n + 1$ placed by the $(n-1)$th installation, is treated as having a normal distribution with mean $M_t(n)$ and variance $V_t(n)$. Hence, the optimal order-up-to level is given by

$$T_t(n) = M_t(n) + k_n V_t(n) \tag{2}$$

where $k_n = \Phi^{-1}\left(\frac{p_n}{p_n + h_n}\right)$ with the standard normal distribution function Φ.

2.1 Results from the LST Model

Lee et al. (2000), called LST in this paper, considered a simple two-level supply chain model that consists of a retailer (stage 1) and a manufacturer (stage 2).

The retailer's optimal order-up-to level is given by

$$T_t(1) = M_t(1) + k_1 \sigma \sqrt{V_1} \tag{3}$$

where

$$M_t(1) = \frac{d}{1-\rho}\left\{(L_1 + 1) - \sum_{i=1}^{L_1+1} \rho^i\right\} + \frac{\rho(1-\rho^{L_1+1})}{1-\rho} D_t$$

$$V_t(1) = \frac{1}{(1-\rho)^2}\left(\sum_{j=1}^{L_1+1} (1-\rho^j)^2\right)$$

Further, the retailer's order quantity Y_t, at the end of period t is given by

$$Y_t(1) = d + \rho Y_{t-1}(1) + \frac{(1-\rho^{L_1+2})}{1-\rho}\varepsilon_t - \frac{\rho(1-\rho^{L_1+1})}{1-\rho}\varepsilon_{t-1} \tag{4}$$

When there is no information sharing, the manufacturer receives only retailer's order quantity $Y_t(1)$ from the retailer and the manufacturer's optimal order-up-to level $T_t(2)$ is given by

$$T_t(2) = M_t(2) + k_2\,\sigma\sqrt{V_2} \tag{5}$$

where

$$M_t(2) = \frac{d}{1-\rho}\left((L_2+1) - \frac{\rho(1-\rho^{L_2+1})}{1-\rho}\right) + \frac{\rho(1-\rho^{L_2+1})}{1-\rho}Y_t$$

$$V_t(2) = \frac{1}{(1-\rho)^2}\left(\left(1-\rho^{L_1+2}\right)^2 + \sum_{i=1}^{L_2}\left(1-\rho^{L_2+L_1+3-i}\right)^2 + \frac{\rho^2\left(1-\rho^{L_2+1}\right)^2\left(1-\rho^{L_1+1}\right)^2}{(1-\rho)^2}\right)$$

The complexity of analysis increases with an increase in the number of stages of a serial supply chain. In the next section, we deal with the multi-stage serial supply chain having N stages and study the benefits of information sharing in terms of reduction in average on-hand inventory at each installation of the supply chain. We limit our discussion to the two scenarios of information sharing, namely, no information sharing and complete information sharing.

3 Ordering Decisions at the $(\mathbf{n+1})$th Stage

At installation $n+1$, after receiving the order of nth stage at the end of time period t, immediately an order is placed with its supplier at the next stage at the end of time period t, so as to bring the inventory position to an order-up-to level $T_t(n+1)$. This order will arrive at the beginning of period $t + L_{n+1} + 1$. To determine the order-up-to-level $T_t(n+1)$, it is necessary to anticipate the total demand (or shipment quantity) $B_t(n+1) = \sum_{i=1}^{L_{n+1}+1} Y_{t+i}(n)$ over the lead time at that stage. To determine the conditional mean $M_t(n+1)$ and conditional variance $V_t(n+1)$, we develop an expression of $B_t(n+1)$ in terms of $Y_t(n)$.

$$\text{Let } a_n = \frac{\rho(1-\rho^{L_n+1})}{1-\rho} \text{ and } b_n = \frac{1-\rho^{L_n+2}}{1-\rho}, \qquad 1 \le n \le N \tag{6}$$

Induction hypothesis: For $1 \le n \le N-1$,

$$Y_{t+1}(n) = d + \rho Y_t(n) + \sum_{i=0}^{n}\alpha_i(n)\varepsilon_{t+1-i} \tag{7}$$

with

$$\alpha_0(n) = b_1 b_2 \ldots b_n$$
$$\alpha_n(n) = (-1)^n a_1 a_2 \ldots a_n$$
$$\alpha_i(n) = (-1)^i \sum_{k_1, k_2, \ldots, k_i} a_{k_1} a_{k_2} \ldots a_{k_i} b_{k_{i+1}} b_{k_{i+2}} k_n$$

where $k_1, k_2, \ldots, k_i, k_{i+1}, \ldots k_n$ are distinct and the indices in the sum range from 1 to n without ordering.

Proof: From Eq. (4), the result is true for $r = 1$.

Let the hypothesis (7) be true for $r < N$.

The anticipated total demand at $r + 1$th installation with respect to the lead time L_{r+1} is given by $\sum_{i=1}^{L_{r+1}+1} Y_{t+i}(r)$.

Let $\xi_{t+i}(r) = \alpha_0(r)\varepsilon_{t+i} + \alpha_1(r)\varepsilon_{t+i-1} + \alpha_2(r)\varepsilon_{t+i-2} + \cdots + \alpha_r(r)\varepsilon_{t+i-r}$.

From (7) we define

$$Y_{t+1}(r) = d + \rho Y_t(r) + \xi_{t+1}(r) \tag{8}$$

Repeated use of (8) gives

$$Y_{t+i}(r) = d\frac{1-\rho^i}{1-\rho} + \rho^i Y_t(r) + \xi_{t+i}(r) + \rho\xi_{t+i-1}(r) + \rho^2\xi_{t+i-2}(r) + \cdots + \rho^{i-1}\xi_{t+1}(r)$$

Since $B_t(r+1) = \sum_{i=1}^{L_{r+1}+1} Y_{t+i}(r)$, we get

$$B_t(r+1) = \frac{d}{1-\rho}\left((L_{r+1}+1) - \sum_{i=1}^{L_{r+1}+1} \rho^i\right) + a_{r+1}Y_t(r) + \sum_{i=1}^{L_{r+1}+1}\left(\sum_{j=0}^{i-1} \rho^j \xi_{t+i-j}(r)\right) \tag{9}$$

Since $E(\varepsilon_t) = 0 \, \forall t$, from Eq. (9), we get

$$M_t(r+1) = \frac{d}{1-\rho}\left((L_{r+1}+1) - \sum_{i=1}^{L_{r+1}+1} \rho^i\right) + a_{r+1}Y_t(r) \tag{10}$$

Also, as the coefficients of the error terms are independent of time t, we have

$$V_t(r+1) = \sigma^2 V_{r+1} \tag{11}$$

where V_{r+1} is independent of t and is to be determined.

The corresponding order-up-to level and the order quantity of the $r + 1$th installation is given by

$$T_t(r+1) = M_t(r+1) + k_{r+1}\sigma\sqrt{V_{r+1}} \tag{12}$$

Therefore, the order quantity of the $r+1$th installation is

$$Y_t(r+1) = Y_t(r) + (T_t(r+1) - T_{t-1}(r+1))$$

Hence, we get

$$\begin{aligned} Y_{t+1}(r+1) &= Y_{t+1}(r) + a_{r+1}(Y_{t+1}(r) - Y_t(r)) \\ &= (1+a_{r+1})Y_{t+1}(r) - a_{r+1}Y_t(r) \\ &= b_{r+1}Y_{t+1}(r) - a_{r+1}Y_t(r) \end{aligned} \tag{13}$$

Using the induction hypothesis in (13), we obtain

$$\begin{aligned} Y_{t+1}(r+1) &= d(b_{r+1} - a_{r+1}) + \rho(b_{r+1}Y_t(r) - a_{r+1}Y_{t-1}(r)) \\ &\quad + b_{r+1}\sum_{i=0}^{r}\alpha_i(r)\varepsilon_{t+1-i} - a_{r+1}\sum_{i=1}^{r+1}\alpha_{i-1}(r)\varepsilon_{t+1-i} \\ &= d + \rho Y_t(r+1) + b_{r+1}\alpha_0(r)\varepsilon_{t+1} \\ &\quad + \sum_{i=1}^{r}(b_{r+1}\alpha_i(r) - a_{r+1}\alpha_{i-1}(r))\varepsilon_{t+1-i} \\ &\quad + (-1)a_{r+1}\alpha_r(r)\varepsilon_{t+1-(r+1)} \end{aligned} \tag{14}$$

We note that

$$b_{r+1}\alpha_0(r) = b_{r+1}b_r\cdots b_1 = \alpha_0(r+1)$$

$$\begin{aligned} & b_{r+1}\alpha_i(r) - a_{r+1}\alpha_{i-1}(r) \\ &\quad = (-1)^i b_{r+1}\sum_{k_1,k_2,\ldots,k_i} a_{k_1}a_{k_2}\ldots a_{k_i}b_{k_{i+1}}b_{k_{i+2}}\ldots b_{k_r} - (-1)^{i-1}a_{r+1}\sum_{k_1,k_2,\ldots,k_i} a_{k_1}a_{k_2}\ldots a_{k_{i-1}}b_{k_i}b_{k_{i+1}}\ldots b_{k_r} \\ &\quad = (-1)^i\sum_{k_1,k_2,\ldots,k_i} a_{k_1}a_{k_2}\ldots a_{k_i}b_{k_{i+1}}b_{k_{i+2}}\ldots b_{k_{r+1}} = \alpha_i(r+1),\ 1\le i\le r, \text{ and} \end{aligned}$$

$$(-1)a_{r+1}\alpha_r(r) = (-1)^{r+1}a_{r+1}a_r\cdots a_1 = \alpha_{r+1}(r+1)$$

Thus, from (14), we get

$$Y_{t+1}(r+1) = d + \rho\,Y_t(r+1) + \sum_{i=0}^{r+1}\alpha_i(r+1)\,\varepsilon_{t+1-i} \tag{15}$$

Hence the hypothesis.

We note that, at each stage n, the demand process is an AR(1) process given by

$$Y_{t+1}(n) = d + \rho\,Y_t(n) + \xi_{t+1}(n)$$

with identically distributed but non-independent error terms.

Now repeated use of (7) yields

$$
\begin{aligned}
Y_{t+i}(n) &= d\left(\frac{1-\rho^i}{1-\rho}\right) + \rho^i Y_t(n) + \sum_{j=0}^{i-1} \left(\alpha_j(n) + \rho\alpha_{j-1}(n) + \cdots + \rho^j \alpha_0(n)\right)\varepsilon_{t+i-j} \\
&\quad + \sum_{j=i-1}^{n-1} \left(\alpha_j(n) + \rho\alpha_{j-1}(n) + \cdots + \rho^{i-1}\alpha_{j-(i-1)}(n)\right)\varepsilon_{t+i-j} \\
&\quad + \sum_{j=n}^{n+i-1} \left(\rho^{j-n}\alpha_n(n) + \rho^{j+1-n}\alpha_{n-1}(n) + \cdots + \rho^{i-1}\alpha_{j-(i-1)}(n)\right)\varepsilon_{t+1-j}, \quad 1 \le i \le n
\end{aligned}
$$

$$
\begin{aligned}
Y_{t+i}(n) &= d\left(\frac{1-\rho^i}{1-\rho}\right) + \rho^i Y_t(n) + \sum_{j=0}^{n} \left(\alpha_j(n) + \rho\alpha_{j-1}(n) + \cdots + \rho^j \alpha_0(n)\right)\varepsilon_{t+i-j} \\
&\quad + \sum_{j=n+1}^{i-1} \left(\rho^{j-n}\alpha_n(n) + \rho^{j-n+1}\alpha_{n-1}(n) + \cdots + \rho^j\alpha_0(n)\right)\varepsilon_{t+i-j} \\
&\quad + \sum_{j=i}^{n+i-1} \left(\rho^{j-n}\alpha_n(n) + \rho^{j+1-n}\alpha_{n-1}(n) + \cdots + \rho^{i-1}\alpha_{j-(i-1)}(n)\right)\varepsilon_{t+i-j}, \; > \; n
\end{aligned}
$$

The above can be written as follows.

$$
\begin{aligned}
Y_{t+i}(n) &= d\left(\frac{1-\rho^i}{1-\rho}\right) + \rho^i Y_t(n) + \sum_{j=0}^{i-2} \left(\sum_{k=0}^{j} \rho^{j-k}\alpha_k(n)\right)\varepsilon_{t+i-j} \\
&\quad + \sum_{j=i-1}^{n-1} \left(\sum_{k=0}^{i-1} \rho^k \alpha_{j-k}(n)\right)\varepsilon_{t+i-j} + \sum_{j=n}^{n+i-1} \left(\sum_{k=j}^{n+i-1} \rho^{k-n}\alpha_{n-(k-j)}(n)\right)\varepsilon_{t+1-j}, \qquad 1 \le i \le n
\end{aligned}
$$

$$
\begin{aligned}
Y_{t+i}(n) = {} & d\left(\frac{1-\rho^i}{1-\rho}\right) + \rho^i Y_t(n) + \sum_{j=0}^{n} \left(\sum_{k=0}^{j} \rho^{j-k}\alpha_k(n)\right)\varepsilon_{t+i-j} \\
& + \sum_{j=n+1}^{i-1} \left(\sum_{k=0}^{n} \rho^{j-n-k}\alpha_{n-k}(n)\right)\varepsilon_{t+i-j} + \sum_{j=i}^{n+i-1} \left(\sum_{k=j}^{n+i-1} \rho^{k-n}\alpha_{n-(k-j)}(n)\right)\varepsilon_{t+i-j}, \qquad i > n
\end{aligned}
$$

In our work, we have

$$
\sum_{a}^{b} = 0 \text{ if } a > b \tag{16}
$$

Using the above, the total shipment quantity $B_t(n+1) = \sum_{i=1}^{L_{n+1}+1} Y_{t+i}(n)$ over the lead time, on simplification, is obtained as:

$$\begin{aligned} B_t(n+1) = {} & \frac{d}{1-\rho}\{(L_{n+1}+1)-a_{n+1}\} + a_{n+1}Y_t(n) \\ & + \sum_{i=0}^{n}\left\{\sum_{j=0}^{i}\alpha_j(n)\left(\sum_{k=0}^{i-j}\rho^k\right)\right\}\varepsilon_{t+L_{n+1}+1-i} \\ & + \sum_{i=n+1}^{L_{n+1}}\left\{\sum_{j=0}^{n}\alpha_j(n)\left(\sum_{k=0}^{i-j}\rho^k\right)\right\}\varepsilon_{t+L_{n+1}+1-i} \\ & + \sum_{i=L_{n+1}+1}^{L_{n+1}+n}\left\{\sum_{j=i-L_{n+1}}^{n}\alpha_j(n)\left(\sum_{k=0}^{i-j}\rho^k\right)\right\}\varepsilon_{t+L_{n+1}+1-i}, \quad \text{if } n < L_{n+1} \end{aligned}$$

$$\begin{aligned} B_t(n+1) = {} & \frac{d}{1-\rho}\{(L_{n+1}+1)-a_{n+1}\} + a_{n+1}Y_t(n) + \sum_{i=0}^{L_{n+1}}\left\{\sum_{j=0}^{i}\alpha_j(n)\left(\sum_{k=0}^{i-j}\rho^k\right)\right\}\varepsilon_{t+L_{n+1}+1-i} \\ & + \sum_{i=L_{n+1}+1}^{L_{n+1}+n}\left\{\sum_{j=i-L_{n+1}}^{n}\alpha_j(n)\left(\sum_{k=0}^{i-j}\rho^k\right)\right\}\varepsilon_{t+L_{n+1}+1-i}, \text{if} n \geq L_{n+1} \end{aligned}$$

The above can be written in a compact form as:

$$\begin{aligned} B_t(n+1) = {} & \frac{d}{1-\rho}\{(L_{n+1}+1)-a_{n+1}\} + a_{n+1}Y_t(n) \\ & + \sum_{i=0}^{\min(n,L_{n+1})}\left\{\sum_{j=0}^{i}\alpha_j(n)\left(\sum_{k=0}^{i-j}\rho^k\right)\right\}\varepsilon_{t+L_{n+1}+1-i} \\ & + \sum_{i=n+1}^{L_{n+1}}\left\{\sum_{j=0}^{n}\alpha_j(n)\left(\sum_{k=0}^{i-j}\rho^k\right)\right\}\varepsilon_{t+L_{n+1}+1-i} \\ & + \sum_{i=1}^{n}\left\{\sum_{j=i}^{n}\alpha_j(n))\left(\sum_{k=0}^{L_{n+1}+i-j}\rho^k\right)\right\}\varepsilon_{t+1-i} \end{aligned}$$

where

$$\sum_{a}^{b} = 0 \text{ if a } > \text{b.} \tag{17}$$

In all the above, $\alpha_i(n) = 0$ for $i > n$.

Special case: when the lead times are identical at each installation, $L_i = L, \ 1 \leq i \leq N$, and Eq. (7) reduces to:

$$Y_{t+1}(n) = d + \rho Y_t(n) + \sum_{i=0}^{n}(-1)^i\left({}^nC_i\, b^{n-i}a^i\right)\varepsilon_{t+1-i}$$

where

$$a = \frac{\rho(1 - \rho^{L+1})}{1-\rho} \quad \text{and} \quad b = \frac{1 - \rho^{L+2}}{1-\rho} \tag{18}$$

4 Benefits of Information Sharing

In this section, we consider two scenarios—no information sharing and complete information sharing, and determine the value or benefit of information sharing in terms of (1) reduction in variance of total demand and (2) inventory reduction.

4.1 Reduction in the Variance of Total Demand

When there is no information sharing, each installation receives only its order quantity from the previous installation and the demand D_t realized at the retailer (first installation) is not shared with any member of the supply chain. In this case the error terms $\varepsilon_t, \varepsilon_{t-1}, \ldots, \varepsilon_{t+1-n}$ have already been realized, but unknown to the members at stage $(n+1)$ when the order-up-to level $T_t(n+1)$ is determined at the end of period t. Thus, at this stage, the supplier would treat $B_t(n+1)$ as having a normal distribution with mean $M_t(n+1)$ and variance $V_t(n+1) = \sigma^2 V_{n+1}$. We have

$$M_t(n+1) = \frac{d}{1-\rho}\{(L_{n+1}+1) - a_{n+1}\} + a_{n+1} Y_t(n) \tag{19}$$

$$V_{n+1} = \sum_{i=0}^{\min(n,L_{n+1})} \left\{ \sum_{j=0}^{i} \alpha_j(n) \left(\sum_{k=0}^{i-j} \rho^k \right) \right\}^2 + \sum_{i=n+1}^{L_{n+1}} \left\{ \sum_{j=0}^{n} \alpha_j(n) \left(\sum_{k=0}^{i-j} \rho^k \right) \right\}^2 + \sum_{i=1}^{n} \left\{ \sum_{j=i}^{n} \alpha_j(n) \left(\sum_{k=0}^{L_{n+1}+i-j} \rho^k \right) \right\}^2. \tag{20}$$

In this case, the optimal order-up-to level is given by

$$T_t(n+1) = M_t(n+1) + k_{n+1}\sigma\sqrt{V_{n+1}} \tag{21}$$

With complete information sharing, each installation knows both the order quantity and the information about the realized demand D_t in every time period t. Hence, at the $(n+1)$th installation, information about $\varepsilon_t, \varepsilon_{t-1}, \ldots, \varepsilon_{t+1-n}$ is known (through information about all the previous demands $D_t, D_{t-1}, \ldots, D_{t+1-n}$). In this case, the supplier would treat $B_t(n+1)$ as having a normal distribution with mean $M'_t(n+1)$ and variance $V'_t(n+1) = \sigma^2 V'_{n+1}$ where $M'_t(n+1)$ and $V'_t(n+1)$ are given by

$$M_t'(n+1) = M_t(n+1) + \sum_{i=1}^{n}\left\{\sum_{j=i}^{n}\alpha_j(n)\left(\sum_{k=0}^{L_{n+1}+i-j}\rho^k\right)\right\}\varepsilon_{t+1-i}$$

$$V_{n+1}' = V_{n+1} - \sum_{i=1}^{n}\left\{\sum_{j=i}^{n}\alpha_j(n)\left(\sum_{k=0}^{L_{n+1}+i-j}\rho^k\right)\right\}^2.$$

In this case, the optimal order-up-to level is given by

$$T_t'(n+1) = M_t'(n+1) + k_{n+1}\sigma\sqrt{V_{n+1}'} \tag{22}$$

We therefore note that $V_t'(n+1) \le V_t(n+1)$ for all n.

It is also evident that as ρ increases, both $V_t'(n+1)$ and $V_t(n+1)$ increase.

We now present numerical illustrations to determine the reduction in the variance of total demand under no information sharing and complete information sharing. Let us assume that for the sake of simplicity, $\sigma^2 = 1$, and that there are six installations with the first installation being the retailer. Let us assume the following cases:

1. lead times at all stages = 1 (see Table 1 for results);
2. lead times at all stages = 3 (see Table 2 for results);
3. lead times at all stages = 6 (see Table 3 for results);
4. lead times at stages 1, 2, 3, 4, 5, and 6 = 1, 2, 3, 4, 5, and 6, respectively (see Table 4 for results); and
5. lead times at stages 1, 2, 3, 4, 5, and 6 = 6, 5, 4, 3, 2, and 1, respectively (see Table 5 for results).

The results of the computational evaluation of the variance of total demand over lead time (without and with information sharing) and the reduction in the variance of the total demand over lead time are shown in Tables 1–5. The results indicate that the total demand variance increases as the number of stages in the supply chain increases. Thus, it is seen that information about the realized demand is more crucial for the upstream members. Further, it is also observed that the variance decreases when there is information sharing across all stages of the supply chain which in turn reduces the approximate expected on-hand inventory. In particular, the reduction obtained is larger when either the underlying demand process is highly correlated or the lead time at each installation is high or both.

A comparative study of a supply chain with stages having respective lead times in a decreasing order from the right end of the supply chain (divergent supply chain as seen from the left end of the supply chain) and a supply chain with stages having respective lead times in an increasing order from the right end of the supply chain (convergent supply chain as seen from the left end of the supply chain) has revealed (see Table 5 concerning the results for the former supply chain, and Table 4 concerning the results for the latter supply chain) that the former supply chain has a larger variance of the total demand over lead time and a larger

Table 1 Variance of total demand (without and with information sharing) at various stages, with lead times at all stages = 1

Stage\\ρ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
2	2.48	5.66	9.86	15.54	23.39	34.32	49.63	71.01	100.74
	2.47	5.56	9.50	14.57	21.15	29.73	40.94	55.61	74.78
3	2.82	7.18	14.57	27.99	53.35	101.97	194.84	369.66	692.08
	2.75	6.68	12.45	21.13	34.38	54.82	86.47	135.53	211.42
4	3.24	9.57	24.20	61.83	162.84	433.99	1144.94	2945.51	7331.19
	3.08	8.11	16.83	32.75	62.79	120.45	231.31	442.53	838.66
5	3.78	13.49	45.45	164.57	621.16	2331.68	8453.47	29197.40	95602.60
	3.45	10.05	24.42	59.54	151.55	397.44	1045.20	2696.49	6738.24
6	4.47	20.13	95.41	503.86	2730.46	14316.00	70682.10	325376.00	1393940.00
	3.88	12.94	40.14	138.81	519.53	1959.27	7121.15	24507.40	79520.70
Reduction in total demand variance due to information sharing									
2	0.01	0.10	0.35	0.97	2.23	4.59	8.69	15.41	25.96
3	0.07	0.50	2.12	6.86	18.96	47.14	108.36	234.13	480.66
4	0.17	1.47	7.37	29.08	100.05	313.54	913.63	2502.99	6492.54
5	0.34	3.44	21.02	105.03	469.62	1934.24	7408.27	26500.91	88864.36
6	0.59	7.19	55.26	365.05	2210.93	12356.73	63560.95	300868.60	1314419.30

reduction in the total demand over lead time at respective stages than those for the latter supply chain, and this observation holds true only up to five stages in the supply chain in most cases of varying levels of ρ; however, at stage 6, the variance of the total demand and the reduction in the variance of the total demand over lead time are larger in the latter supply chain.

4.2 *Inventory Reduction at Stage* $(n+1)$

When the demand process is auto-correlated over time, it is difficult to derive an exact expression for the average inventory level. We use the following approximation given in Silver and Peterson (1985) and derive expression for approximate on-hand inventory. For any order-up-to $T_t(n+1)$ system with $Y_t(n)$ being demand in period t and $\sum_{i=1}^{L_{n+1}+1} Y_{t+i}(n)$ being the total demand from period $(t+1)$ to period $(t+L_{n+1}+1)$, the average (on-hand) inventory level can be approximated by

$$\left\{T_t(n+1) - E\left(\sum_{i=1}^{L_{n+1}} Y_{t+i}(n)\right) + E(Y_t(n))/2\right\} \tag{23}$$

From the recursive Eq. (7) we get,

$$\lim_{t\to\infty} E\left(Y_t(n)\right) = \frac{d}{1-\rho}$$

Table 2 Variance of total demand (without and with information sharing) at various stages, with lead times at all stages = 3

Stage\\ρ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
2	4.95	11.30	19.81	31.94	50.57	81.58	137.32	243.76	455.44
	4.94	11.19	19.34	30.36	45.89	68.83	104.40	162.24	260.62
3	5.30	12.92	25.38	49.55	106.16	262.02	741.42	2309.04	7564.01
	5.23	12.35	22.60	38.34	64.42	111.28	202.39	392.58	814.80
4	5.73	15.52	37.61	106.19	382.02	1686.54	8419.92	44568.80	240143.00
	5.55	13.86	27.69	54.36	115.39	279.56	778.02	2404.44	7886.69
5	6.28	20.00	68.26	324.68	2067.11	15605.80	128563.00	1099460.00	9438910.00
	5.93	16.01	37.62	101.37	354.18	1566.05	7950.83	42838.80	234022.00
6	7.01	28.18	152.52	1260.64	13477.00	165477.00	2188790.00	29846000.00	405581000.00
	6.38	19.40	61.14	279.26	1814.38	14229.10	120991.00	1057480.00	9207360.00
Reduction in total demand variance due to information sharing									
2	0.02	0.11	0.48	1.59	4.68	12.75	32.92	81.52	194.82
3	0.07	0.57	2.78	11.21	41.74	150.74	539.04	1916.46	6749.21
4	0.17	1.66	9.92	51.82	266.63	1406.99	7641.90	42164.36	232256.31
5	0.35	3.99	30.64	223.31	1712.93	14039.75	120612.17	1056621.20	9204888.00
6	0.62	8.79	91.38	981.38	11662.62	151247.90	2067799.00	28788520.00	396373640.00

Table 3 Variance of total demand (without and with information sharing) at various stages, with lead times at all stages = 6

Stage\ ρ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
2	8.66	19.69	34.35	55.02	86.83	142.63	259.45	559.20	1485.30
	8.64	19.58	33.86	53.30	81.24	124.48	198.42	342.14	668.20
3	9.00	21.32	40.00	73.63	152.09	405.31	1530.96	8035.48	53634.00
	8.93	20.75	37.16	61.52	101.27	175.27	339.07	783.74	2275.21
4	9.43	23.93	52.50	135.40	505.88	2920.55	24459.70	275126.00	3890370.00
	9.26	22.26	42.32	78.42	160.94	419.84	1550.31	8057.10	53837.30
5	9.99	28.43	84.10	381.64	2865.25	32490.10	524660.00	11631000.00	335493000.00
	9.64	24.41	52.46	129.79	469.50	2723.16	23348.10	268114.00	3840140.00
6	10.71	36.65	171.70	1470.77	20243.90	412746.00	12355700.00	531722000.00	31073400000.00
	10.09	27.81	76.72	331.16	2534.75	30022.00	501831.00	11364200.00	331658000.00
Reduction in total demand variance due to information sharing									
2	0.02	0.11	0.49	1.71	5.59	18.14	61.04	217.06	817.10
3	0.07	0.57	2.85	12.12	50.82	230.05	1191.89	7251.74	51358.79
4	0.17	1.67	10.18	56.98	344.94	2500.71	22909.39	267068.90	3836532.70
5	0.35	4.01	31.64	251.85	2395.75	29766.94	501311.90	11362886.00	331652860.00
6	0.62	8.84	94.98	1139.61	17709.15	382724.00	11853869.00	520357800.00	30741742000.00

Table 4 Variance of total demand (without and with information sharing) at various stages, with lead times at stages = 1, 2, 3, 4, 5, and 6 equal to 1, 2, 3, 4, 5, and 6, respectively

Stage\\ρ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
2	3.72	8.46	14.73	23.28	35.34	52.77	78.46	116.78	174.19
	3.70	8.36	14.33	22.12	32.45	46.35	65.25	91.22	127.16
3	5.29	12.85	24.80	46.17	89.35	185.65	414.70	977.17	2368.77
	5.22	12.31	22.31	37.04	59.70	95.96	156.19	259.74	443.78
4	6.96	18.20	41.14	102.82	312.00	1133.97	4624.62	19940.80	87421.00
	6.79	16.60	32.03	59.04	112.04	227.43	498.57	1165.60	2844.74
5	8.74	25.39	74.72	300.55	1657.31	11146.00	83911.40	673488.00	5570590.00
	8.40	21.51	46.28	107.77	308.20	1093.81	4470.58	19483.10	86306.30
6	10.70	36.20	158.65	1136.08	11256.00	135485.00	1882810.00	29205300.00	487627000.00
	10.08	27.64	73.26	270.88	1483.34	10289.60	79892.80	654996.00	5487090.00
Reduction in total demand variance due to information sharing									
2	0.01	0.10	0.40	1.16	2.88	6.42	13.22	25.56	47.04
3	0.07	0.54	2.49	9.13	29.65	89.68	258.51	717.43	1924.99
4	0.17	1.60	9.10	43.78	199.95	906.54	4126.05	18775.20	84576.26
5	0.35	3.88	28.44	192.78	1349.12	10052.19	79440.82	654004.90	5484283.70
6	0.62	8.56	85.39	865.20	9772.66	125195.40	1802917.20	28550304.00	482139910.00

Table 5 Variance of total demand (without and with information sharing) at various stages, with lead times at stages = 1, 2, 3, 4, 5, and 6 equal to 6, 5, 4, 3, 2, and 1, respectively

Stage\ ρ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
2	7.42	16.90	29.51	47.40	75.15	124.23	226.86	483.74	1234.34
	7.41	16.78	29.03	45.69	69.63	106.63	169.60	290.47	557.06
3	6.53	15.72	30.32	58.25	126.90	348.40	1255.85	5710.88	30488.70
	6.46	15.15	27.48	46.27	77.90	138.56	275.06	640.29	1794.23
4	5.73	15.53	37.89	110.43	435.83	2312.40	15412.40	121098.00	1065550.00
	5.56	13.87	27.79	55.39	123.98	344.46	1244.36	5671.33	30441.90
5	5.05	17.21	63.69	325.35	2248.51	19448.80	199384.00	2326610.00	29708800.00
	4.70	13.22	33.00	97.24	389.11	2114.91	14472.40	116161.00	1037440.00
6	4.51	21.64	126.40	1008.88	10259.80	125084.00	1757980.00	27515000.00	462303000.00
	3.90	13.55	49.42	251.35	1752.19	15064.70	150277.00	1685800.00	20667000.00
Reduction in total demand variance due to information sharing									
2	0.02	0.11	0.49	1.71	5.52	17.60	57.26	193.27	677.28
3	0.07	0.57	2.84	11.98	49.00	209.84	980.79	5070.59	28694.47
4	0.17	1.66	10.09	55.04	311.85	1967.94	14168.04	115426.67	1035108.10
5	0.35	3.99	30.69	228.11	1859.40	17333.89	184911.60	2210449.00	28671360.00
6	0.61	8.08	76.98	757.53	8507.61	110019.30	1607703.00	25829200.00	441636000.00

$$\lim_{t\to\infty} E\left(\sum_{i=1}^{L_{n+1}+1} Y_{t+i}(n)\right) = \frac{(L_{n+1}+1)d}{1-\rho} \tag{24}$$

Let

$$\boldsymbol{\varepsilon_t}(n) = (\varepsilon_t, \varepsilon_{t-1}, \ldots, \varepsilon_{t-n+1})$$

Since $E(\varepsilon_t(n)) = 0$, we get

$$\lim_{t\to\infty} E_{Y_{t(n)}} E_{\varepsilon_t(n)} (T_t(n+1)) = \frac{(L_{n+1}+1)d}{1-\rho} + k_{n+1}\sigma\sqrt{V_{n+1}}$$

$$\lim_{t\to\infty} E_{Y_{t(n)}} E_{\varepsilon_t(n)} \left(T'_t(n+1)\right) = \frac{(L_{n+1}+1)d}{1-\rho} + k_{n+1}\sigma\sqrt{V'_{n+1}} \tag{25}$$

Let $I(n+1)$ and $I'(n+1)$ respectively denote the average on hand inventory at the $(n+1)$th installation when information is not shared and when information is shared. Since the demand process at each installation is an AR(1) process, using the approximation given in Eq. (23), the expressions for the average on-hand inventory are given by

$$I(n+1) = \frac{d}{2(1-\rho)} + k_{n+1}\,\sigma\sqrt{V_{n+1}} \tag{26}$$

$$I'(n+1) = \frac{d}{2(1-\rho)} + k_{n+1}\,\sigma\sqrt{V'_{n+1}} \tag{27}$$

Since $V'_t(n+1) \le V_t(n+1)$, from Eqs. (26) and (27), it is clear that $I'(n+1) \le I(n+1)$. Thus complete information sharing is beneficial at each installation of the supply chain in terms of inventory reduction and

$$I(n+1) - I'(n+1) = k_{n+1}\sigma\left(\sqrt{V_{n+1}} - \sqrt{V'_{n+1}}\right). \tag{28}$$

This reduction in inventory is similar to that of the reduction in the variance of total demand, as presented earlier. When $\rho = 0$, we have $\sqrt{V_{n+1}} = \sqrt{V'_{n+1}}$ and $I(n+1) = I'(n+1)$. Hence, when the demands are uncorrelated over time, there is no benefit through the information about the realized demand.

5 Conclusion

In this work, we extended the analysis of LST to a multi-stage model with deterministic but non-identical lead times and studied the value of information sharing at each stage. More specifically, we obtained explicit expressions for the mean and variance of the total demand over the lead time for the two cases—no information sharing and complete information sharing, and showed that the demand variance is less in the case of complete information sharing. We also quantified the value or benefit of information sharing in terms of average inventory reduction.

As for managerial implications, we showed that the variance of the total demand over lead time increases as the number of stages in the supply chain increases. Thus, it is seen that information about the realized demand is more crucial for the upstream members. Further, it is observed that the variance decreases when there is information sharing across all stages of the supply chain which in turn reduces the approximate expected on-hand inventory. In particular, the reduction obtained is larger when either the underlying demand process is highly correlated or the lead time at each installation is high or both. A comparative study of a supply chain with stages having respective lead times in a decreasing order from the right end of the supply chain (divergent supply chain as seen from the left end of the supply chain) and a supply chain with stages having respective lead times in an increasing order from the right end of the supply chain (convergent supply chain as seen from the left end of the supply chain) has revealed that the former supply chain has a larger variance of the total demand over lead time and a larger reduction in the total demand over lead time at respective stages than those for the latter supply chain, and this observation has held true only up to five stages in the supply chain in most cases of varying levels of ρ; however, at stage 6, the variance of the total demand and the reduction in the variance of the total demand over lead time are larger in the latter supply chain for all values of ρ. It is possibly for the first time in the literature that the benefit of information sharing has been studied and quantified (in terms of the reduction in the total demand variation and the reduction in inventory) in a multi-stage serial supply chain with more than three stages with positive and deterministic lead times.

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Six Sigma in Supply Chain

Alireza Shokri

1 Introduction

Customer satisfaction and competitiveness are in the centre of attention for any quality improvement and performance measurement practice in integration with supply chain (SC). The new perspective of quality improvement in SC demands improvement in profitability besides the customer satisfaction and competitiveness. Enhancing both customer satisfaction and profitability through having a customer- and profit-focussed corporate vision is required to perceive the strength of supply chain management (SCM) (Sila et al. 2006; Lado et al. 2011). The necessity of a dynamic, systematic and reliable process-based performance measurement tool to improve SC and logistics measures as future requirement in SC (Thakkar et al. 2009), and a more rigorous and less complicated quality improvement tool in logistics and SCM (Forslund et al. 2009 and Shams-ur-Rehman 2006); and acknowledgement of versatility between Six Sigma and SCM (Yang et al. 2007 and Dasgupta 2003) have already been indicated by researchers. In other words, Six Sigma projects can be indicated as the performance measurement toolset for any SC process, while it could be used as an entire inter- and intra-business improvement strategy through cultural change. This means that Six Sigma has ability to be integrated with SCM as more straightforward performance measurement tool, a clear and rigorous quality and business improvement methodology and more reliable business strategy in relation to SC to promote profitability and customer satisfaction. But, there is unlikely to find a single research output to capture the real benefits of Six Sigma programme in different perspectives as a performance measurement tool, quality improvement and problem solving methodology and finally a potential business strategy in relation to actual SC and logistics measures in one single and structured output.

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The purpose of this chapter is to instigate the reality of inter-relationship between different perspectives of Six Sigma (performance measurement tool, quality improvement and problem solving methodology and business improvement strategy) and practical SC measures through one single resource, which could be used for both research and pedagogical purposes in higher education and also in practical projects. This would reduce the gap between Six Sigma principles and SC research, while introducing an organised source of integration between SC and Six Sigma in performance measurement, quality and performance improvement and business strategy perspectives. The practical aspect of implementing Six Sigma in SC and methodology and examples related to them are not in the centre of attention for this paper.

It was decided to initially present the role of performance measurement and quality management in SC in the following two sections. This would potentially prepare a platform to review the role of Six Sigma in SCM after briefly introducing the Six Sigma programme. It was decided to present some practical and research-based findings through quantitative and qualitative data analysis in Sect. 5 to indicate the practical implications of this research article. These findings were obtained through conducting a PhD research programme in a specific SC and logistics industry (food distribution) to evaluate the role of Six Sigma in SC and logistics.

2 Performance Measurement in SC

Performance measurement in SC is a complicated practice, whilst it is highly recommended to trace back its performance and commit to the customer satisfaction. The essence of performance measurement in supplier evaluation and supplier development (Lo and Yeung 2006) and also planning to deal with deviation (Tummala et al. 2006) in any SCM practice to improve performance more effectively and proactively was highlighted in research studies. It was highly recommended that good quality performance measurement systems with high effectiveness should be simple, practical, focussed, relevant and reliable to provide the right feedback (Gunasekaran et al. 2007 and Morgan et al. 2007).

The criteria of balanced score card (BSC) and supply chain operation reference (SCOR) model as two common performance measurement models in SC was presented in different research outputs (Shepherd et al. 2006 and Aramayan et al. 2007). These two models were criticised by some researchers in respect to complexity and difficulty to implement especially for organisations with less resources (Barber 2008 and Thakkar et al. 2009). It was highlighted by other researchers that performance measurement system in SC should provide signals, followed by innovative set of actions, which are based on strong planning (Gunasekaran et al. 2007 and Morgan et al. 2007). Therefore, adopting a more contemporary performance measurement tool with more systematic and comprehensive approach towards strategic problem solving and improvement could be considered. It is highly beneficial to select a tool or methodology, which can satisfy the potential users in SC in terms of focusing on performance dimensions, nature of measures (financial or non-financial) and levels of decision making.

Implementing Six Sigma methodology addresses a comprehensive and systematic performance measurement toolset through which different SC and logistics measures can be targeted and evaluated by various tools and techniques in more scientific and reliable way. Six Sigma toolset is a comprehensive and simple-structured methodology with reliable and flexible tools with focused and practical purposes, which can target all types of quantified SC and logistical measures (financial, non-financial, organisational, functional…). The great news here is that this performance measurement practice will not be abandoned or relied on other practices for SC improvement, and has ability to expand its focus to identify the gaps in performance, solve them and sustainably improve the performance. It means that unlike SCOR and BSC models Six Sigma methodology also has ability to improve the quality of performance measures in SC and logistics. In fact, any Six Sigma project starts with defect identification and performance measurement, and continues with quality improvement and finalised as a business strategy as part of the business culture. Therefore, it is essential to review the impacts of quality improvement in SC in next section to highlight the benefits of the Six Sigma in SC through more fundamental fashion.

3 Quality Improvement in SC

The impact of the customer satisfaction on improving the demand chain (Camra-Fierro and Polo-Redondo 2008) and supplier selection (Lo et al. 2006); and consequently, increasing the value in SC was proposed in research studies. It means that the buyer in a modern SC considers the level of effort by the supplier to improve the customer satisfaction (Lo and Yeung 2006). In this respect, the significant role of quality management (QM) to improve the customer satisfaction in SC was acknowledged (Sila et al. 2006 and Kuei et al. 2008).

The importance of integration between SC and QM as operational efficiency (Kuei et al. 2008) and strategic decision making (Carmignani 2009) was a major breakthrough in promoting the adoption of any QM initiative in SC. This means that QM initiatives could impact on the change management in SC and logistics. For instance, the value adding effect of QM in adoption of purchasing strategies (Fung 1999 and Shokri et al. 2010) and logistics (Ballou 2007 and Barber 2008) was highlighted. Key benefits of integrating QM in SC are presented as “more value adding” (Kuei et al. 2008), “increasing customer satisfaction” (Kuei et al. 2008 and Carmignani 2009), “improving competitiveness” (Sila et al. 2006), “improving down-stream and up-stream performance” (Sila et al. 2006) and “reducing process variation and waste” (Flynne 2005). This would potentially demonstrate more profit and quality-oriented values of quality improvement in SC rather than just cost-oriented benefit.

The integration and coordination of QM and SCM in a series of processes, such as measuring, analysing and continually improving the performance and product resulted in large transformation towards quality improvement and was called the supply chain quality management (SCQM) (Vanichinchai 2009). Figure 1 depicts the key quality-related dimensions of the route map to SCQ. Quality-related dimensions are within four different drivers of the successful SCQM. This means that QM can be integrated with SCM to deliver more effective and efficient SC activities and practices.

The Six Sigma methodology can be considered as a perfect quality improvement methodology by which the four quality management dimensions presented in Fig. 1 and also key benefits of QM integration in SC will be addressed. It is a systematic quality improvement methodology with customer satisfaction, continuous improvement and profitability focus. It can substantially and systematically improve the customer experience and supplier performance in all quality dimensions of SC and logistics. This will make Six Sigma more distinctive with other quality improvement initiatives such as TQM, lean and ISO9000. It is essential to generate some aspects of Six Sigma programme in next section before reviewing some actual benefits of Six Sigma in SC and logistics.

4 Six Sigma Programme

Six Sigma is a top–down approach that can be described in business perspective as a customer-driven (Nakhai and Neves 2009) and project-driven (Kwak and Anbari 2006 and Assarlind et al. 2012) approach, a business-driven (Savolanainen and Haikonen 2007) methodology, or a business improvement strategy to improve profitability and efficiency of all operations (Anbari and Kwak 2004), which focusses on decision making based on quantitative data (De Koning and De Mast 2006)

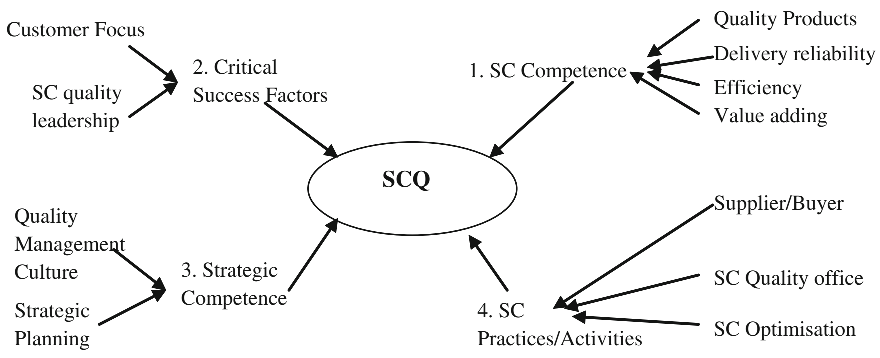

Fig. 1 Route map to supply chain quality (quality management-related dimensions) (Kuei et al. 2008)

and meet or exceed customer satisfaction. This will lead to improving the organisation's product, process and service (Kwak and Anbari 2006) financial performance of the organisation (Nakhai and Neves 2009) or generally business strategies continuously by focussing on eliminating the variables (Saolainen and Haikonen 2007). Numbers represent features and characteristics of processes in Six Sigma and therefore data availability and statistical tools and techniques in Six Sigma is key, as it focuses on opportunities of defects not just defects. In statistical term, Six Sigma is about reducing the sigma level as representation of variation in process by reducing the gap between target and mean value in normal distribution and approaching to 99.99997 % perfection. The complementary application of statistical and business aspects of the Six Sigma was expressed as a necessity in successful project executions (Kwak and Anbari 2006 and Kumar et al. 2009a, b).

Six Sigma is an ever-increasing integration of quality and business strategy (McAdam and Lafferty 2004), which its growing interest in the UK and globally has been acknowledged (Grigg and Walls 2007). The competitive nature of the market in SC is demanding quality and perfection in both production and service and Six Sigma could be an attempt to manage global competitive market to pursue continuous improvement (Kumar et al. 2008). There are numerous studies to describe Six Sigma as a tool, methodology or strategy. It was once described as a top–down managerial strategy, methodological improvement programme, and as a set of quality tools or techniques (Johannsen and Leist 2009). It was also accepted as a business strategy to bring excellence (Antony et al. 2007) or a vision and philosophy (Naslund 2008). Six Sigma is characterised by its customer-driven approach, by its emphasise on data-driven decision making, priority on profitability, systematic training, effective utilisation of knowledge and focussing on relevant measures (De Mast 2006).

Six Sigma was established in mid 1980s by some engineers in Motorola, a leading manufacturer of electronic devices, as a comprehensive quality programme (Naslund 2008 and Chakrabary and Chuan 2009). It was then established by so many big national and multi-national organisations, including General Electric (GE), Honeywell (Allied Signal), Polaroid, Sony, Honda, American Express, Ford (Chakrabary and Chuan 2009), Caterpillar, Nissan, Kraft Foods. There are many more organisations around the world, which have implemented Six Sigma successfully, and it is a significant part of their business strategy. Six Sigma has already been introduced as a process-focussed strategy in operational level, which focusses on projects, processes, deliverables and problems (Haikonen et al. 2004 and McAdam and Lafferty 2004). It focuses on "customer satisfaction" (Kumar et al. 2008), "cultural change" (Raisinghani et al. 2005), "quality improvement" (Wessel and Burcher 2004), "enhancing financial performance" (Kumar et al. 2008) and "systematic projects" (Andersson et al. 2006) to tackle the problems with unknown solutions (Kumar et al. 2009a, b). The level of focus by Six Sigma programme is depicted in Fig. 2 as a summary of understanding from literatures. It was stated in this figure that cultural change or business transformation is the first stage of Six Sigma to be focused followed by operational aspects and finally focus on strategic level.

Business transformation is required to promote Six Sigma (Al-Mishari and Suliman 2008) as the first step followed by a project-by-project process improvement, strategic performance measurement and problem solving practices with clear responsibilities and boundaries. There is also a new modern approach of Six Sigma, which is its application in small to medium-sized enterprises (SMEs) (Kumar et al. 2011 and Kaushik et al. 2012), which their role in any SC improvement is substantial. The Six Sigma approaches in successful application are presented in Fig. 3. It indicates that the outlier approach is necessary to exercise the insider layer. It means that focusing on mind-set components is a prerequisite for any Six Sigma implementation, which includes project set-up and execution through road map or methodology and tool-set.

Principles of Six Sigma

There are some constructing elements of any Six Sigma project that are necessary to formulate the Six Sigma programme. Attention to customer's needs, solving a variety of problems and devising a "project" to improve operations are the main principles of the Six Sigma programme. The problem must be strategically critical for both the organisation and the customer and it is necessary to select the right project to solve the right problem. The results from research analysis identified project selection as the most critical and most commonly mishandled activity in launching Six Sigma (Antony et al. 2007 and Kumar et al. 2009a, b). Six Sigma is a toolset and needs to focus on a single measure within a period of time. In this respect, criteria prioritisation was recommended by some authors (Kumar et al. 2009a, b) to select the right projects in Six Sigma. Selecting the right criteria or project in Six Sigma needs resources; voice of the customer (VOC) is the most common resource followed by voice of the business (VOB) (Antony et al. 2007), which then could be used to set up a Six Sigma project. Duration, customer

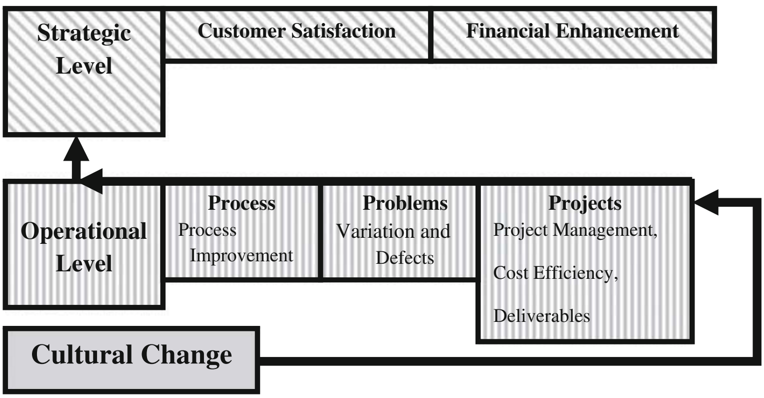

Fig. 2 Six Sigma focus in different levels

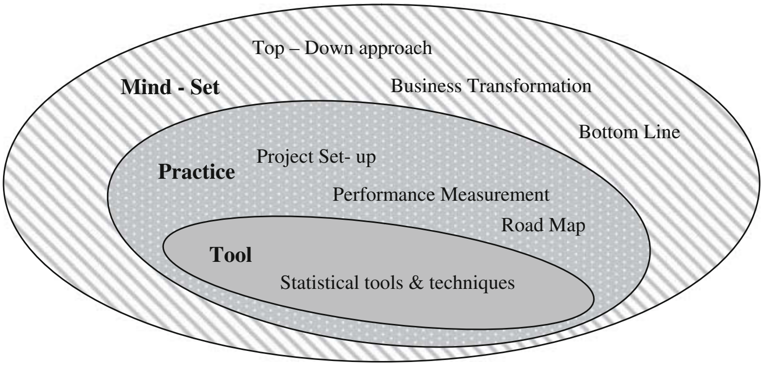

Fig. 3 The Six Sigma approaches

requirement, business strategy and feasibility could be the most common prioritisation aspects for any Six Sigma project. Analytical hierarchy process (AHP) (Kumar et al. 2009a, b), failure mode and effect analysis (FMEA) (Kumar et al. 2008) and quality function deployment (QFD) (Kumar et al. 2008) alongside brainstorming and Pareto Analysis are some common tools and techniques that could be used in Six Sigma programme to select the right project.

Key Success Factors in Six Sigma

Six Sigma is not a magic bullet that solves problems automatically. It needs good people who can communicate, think well and work together. It also needs managerial support, resources, training, leadership skills, methodology and organisational focus. The result of a secondary data analysis amongst many Six Sigma-related articles, which is presented in Fig. 4, indicates that there are some human resource or leadership factors that have the most significant impact on Six Sigma success or failure. It was understood as part of the author's research review that "top management commitment", "training", "leadership" and "project selection" are the most common key success factors (KSFs) in Six Sigma projects (Fig. 4). Furthermore, it was suggested by one of the most recent articles through studying the Six Sigma evolution that top management support could be the most critical success factors in first few years, and then it is established the project selection would play the biggest role in Six Sigma success (Firka 2010). Training and education is another key factor that could be including in-house training or any outside training that is provided by training organisations. The extend and criticality of training for a small organisation to implement Six Sigma is not as big as for bigger organisations, since it could cover the basic required training for smaller organisations.

Benefits of Six Sigma

It is indicated from Fig. 5 that process and people as two key elements of the organisation can benefit from a Six Sigma programme. Systematic data collection and methodology of Six Sigma promotes a more scientific approach and easier

Fig. 4 Most common literature recommended KSFs for Six Sigma projects

decision making (Grigg and Walls 2007). The utilisation of different sets of statistical tools and techniques, besides managerial and problem-solving tools, will enable the people who are involved in the Six Sigma project to experience better results. Management involvement in training and project utilisation results in management development. This in turn addresses more opportunities for employee training and development in the project team and increases their job satisfaction and loyalty. Systematic team building and task delegation in Six Sigma projects could also have positive impact on employee empowerment. Then, defects could be detected in more professional manner, and this results in product and service improvement. The first financial benefits of the Six Sigma programme appear within the processes by reducing the cost of poor quality (COPQ) and cycle time. This will result in net profit increase. Six Sigma utilisation also promotes effectiveness and efficiency together by promoting both quality and value for customer. Therefore, customer satisfaction will increase as a result; this will promote sales, market share and profit growth.

Limitations in Six Sigma

Maintaining customer satisfaction and profitability in the real world through Six Sigma is unlikely to be an easy job and there could be many problems. Six Sigma is a complex and time-consuming exercise (Chakrabary and Chuan 2009) and therefore it was reported that it cannot be recognised as a "quick fix" (Dahlgaard 2006). Over-focusing in two elements, including "cost down" approach (Bendell 2006) and Infrastructure-based training (De Mast 2006) is a challenging factor which could happen in any Six Sigma project and must be avoided as much as is possible. Ambiguity in purpose (Raisinghani et al. 2005) and certification (Laureani A. and Antony J. 2012), difficulty in data collection (Chakrabary and

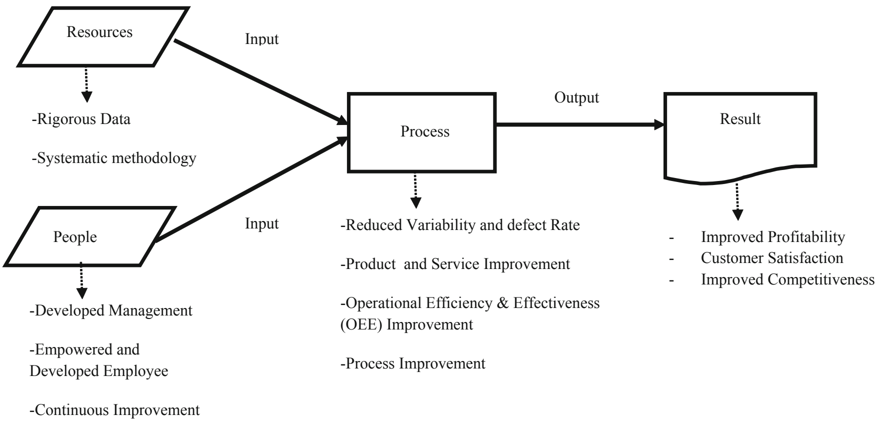

Fig. 5 Six Sigma benefits associated with people, processes and results

Chuan 2009), application in service organisations (Antony 2006), lack of theoretical understanding behind Six Sigma concept (Kumar et al. 2008) and lack of unified standard training (Antony 2008) are other challenges in Six Sigma application. Ignorance to process-based business (Swinney 2006), complexity in tools and techniques (Chakrabary and Chuan 2009), refusal to change (Swinney 2006), lack of interest (Fotopoulos and Psomas 2009) and internal Limited resources (Antony and Desai 2009), lack of knowledge (Chakrabary 2009), significant start up investment (Antony 2006), lack of process understanding (Kwak and Anbari 2006), lack of tangible result (Antony and Desai 2009) and poor project management skills (Miguel and Anderietta 2009) are more technical barriers which could happen before, during and even after any Six Sigma implementation. These barriers are also subject to the size and type of the organisation and there are plenty of opportunities to minimise or remove these barriers in any organisation. It is believed that all of these challenging elements could be tackled through consideration of Six Sigma KSFs, applying required and sometimes simpler tools or application of some supportive tools and techniques to practice technical Six Sigma tools.

Infrastructure Team Deployment and training in Six Sigma

Infrastructured team building in Six Sigma programme might be one of its distinguishing elements in comparison with other quality initiatives (Manville et al. 2012; Hilton and Sohal 2012 and Brun 2011). However, this factor is also not solid and may be changed based on the size of the industry. There are some elements that must be considered in deployment elements. Number of employees, methodology and criteria of selection, level of involvement, content and number of projects (Thomas 2006) and the capabilities of the involved people in deployment (Pfeifer et al. 2004) are critical elements in team building. Team infrastructure in Six Sigma programme is normally based on the “Belt System”. The constructing belt members of this deployment and their roles and characteristics are described in Table 1. It is believed that BBs (full-time project managers) and GBs (part-time project managers) are the most critical members of any Six Sigma project in any size.

Training in the six sigma initiative is critical for productivity improvement, cultural change and organisational modification and must be team-based, practical, purposeful and effective for all top managers and relevant employees. It could be tailored to specific industry, process or problem (Raisinghani et al. 2005). Six Sigma training could be provided in three different tool sets: team tools, process tools and statistical tools (Antony et al. 2007). It is important to have an effective blend of all these tools in any type of organisation with any size. There is no evidence for massive training sessions by training providers under different trading names for every organisation that wants to implement a Six Sigma programme. For instance, the level, amount and even structure of training for smaller organisations are not the same as bigger counterparts and it is in lower profile.

Six Sigma Methodology

The Six Sigma methodology can be presented as a systematic structure with the configuration of various flexible tools and techniques. The Six Sigma methodology is linked to continuous improvement due to the systematic selection and continuous implementation of improvement projects (Savolainen and Haikonen 2007 and Antony et al. 2012) and formulates the main body of Six Sigma programme. The most common methodologies are: Define, Measure, Analyse, Improve, Control (DMAIC), Define, Measure, Analyse, Design, Verify (DMADV) and Design for Six Sigma (DFSS). DMAIC is the most common and popular Six Sigma methodology, which has systematic, rigorous, cost effectiveness, disciplined and scientific approach towards problem solving and process improvement. DMADV and DFSS are mainly used for innovations and in any project that a new process or product design is required. The summary of key activities and tools of each phase in DMAIC road map are depicted in Fig. 6.

Table 1 The Six Sigma team deployment and their roles based on the belt system

Six Sigma team member	Role	Responsibilities
Executive	Senior management	Strategic decision making and setting up the objectives
Champion	Process owner	Sponsorship, leading the deployment, removing road blocks, providing resources, project selection
Master black belt (MBB)	Black belt support	Mentoring, coaching and consulting
Black belt (BB)	Project leader	Methodology execution, project management
Green belt and yellow belt (GB and YB)	Team member/ Project leader	Methodology execution, project management and support

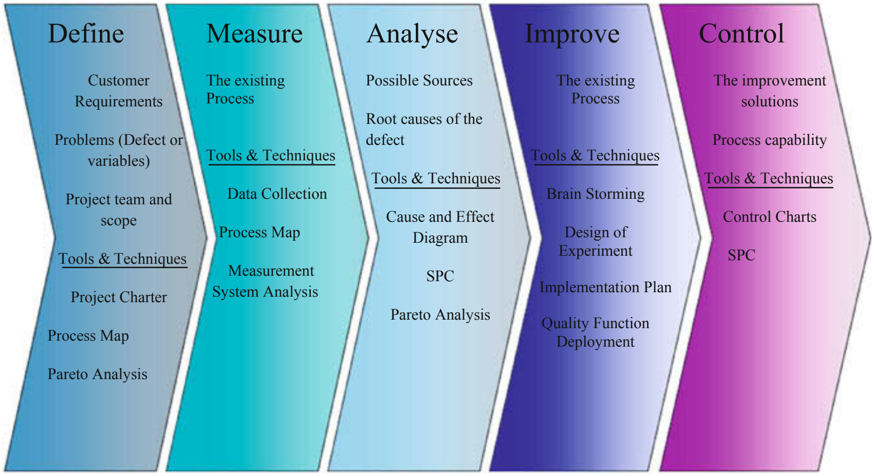

Fig. 6 Key activities, tools and techniques of five phases in DMAIC methodology

5 Six Sigma Methodology in SC

Fung (1999) and Sila et al. (2006) stated that QM initiatives can lead to dramatic changes in SC through analysis of upstream. Six Sigma is not limited to the downstream and can be adopted in a proactive approach by any organisation to identify any defect or variability of the supplier, which might affect the overall performance of the customer or whole SC. Six Sigma can add value to order processing, storage, transport, purchasing, sales and lean operation as SC practices. The continuous improvement is one of the principles of Six Sigma programme for any company in any size. The presence of control stage in DMAIC methodology, which promotes the sustainability of improvement strategies, can guarantee the continuous improvement philosophy in undertaking any Six Sigma project. Flynn (2005) put emphasis on reducing the process variation in any SC process as the result of implementing any QM programme. Variation within any SC process or activity could be related to the quality of service, speed, flexibility and dependability, which results in higher COPQ. Six Sigma aims to reduce the variability within any manufacturing and service processes.

In regards to logistics management, Mentzer et al. (2008) suggested the new set of conceptual dimensions of a contemporary logistics era as the result of logistics evolution. Cost efficiency, customer satisfaction and competitiveness, which were indicated as these important conceptual dimensions, could carry various measures in any business within SC. Six Sigma methodology of DMAIC can be stated as an appropriate approach towards improvement in these dimensions since these dimensions were theoretically capsulated in Six Sigma programme. Six Sigma programme aims to focus on key SC and logistical measures with dramatic strategic and financial impact. This means that Six Sigma projects must focus on key metrics or critical-to-quality (CTQ) metrics, which represent the strategic objectives of the business improvement in SC and logistics. Sum et al. (2001) stated the key logistical objectives or CTQs as “meeting customer special requests”, “reduced delivery lead time”, “low cost operation” and “value adding to the service”. In respect to project selection in Six Sigma application, any defect or measure associated with these strategic objectives will be desirable, since small improvement in these measures could result to significant impact of overall financial and strategic performance of the logistics and SC.

The Six Sigma integration with SC and logistics can be studied through four different perspectives. In respect to the Six Sigma principles, methodology and tools and techniques, which are utilised, it could be applied as a performance measurement tool or problem solving methodology and quality improvement programme in starting point and then it could change the whole culture of the organisation or SC and can be established as the business strategy (Fig. 7). This depends on the level of profile that Six Sigma is practiced and the experience of any organisation or SC that is practicing Six Sigma. Moreover, if any organisation is practicing Six Sigma in either of these perspectives, the business partners in upstream and downstream can also be affected and experience this practice. It is intended to introduce the impact of Six Sigma in SC through these four different perspectives separately by providing some information including case studies, which were conducted in food SC and logistics as an example of a complicated and competitive SC with various quality improvement, and customer satisfaction requirements in a sustainable and systematic way in recent years.

There are various SC measures and practices that can be targeted by Six Sigma as a performance measurement tool, problem solving methodology and quality improvement programme. These measures and practices are mainly quantitative and process based, which have opportunity to produce products and services with variability and defect. Figure 8 represents some of these SC measures.

The role of Six Sigma methodology will be specifically evaluated in regards to four different perspectives as following to indicate the real benefits of Six Sigma into SC. In fact, the conducted qualitative research methodology, which is a series of case studies has been summarised as the following to provide some findings as benefits of applying Six Sigma into food SC and logistics.

The methodology, which was used in this study, was a triangulation approach of research methodology through using both case studies and questionnaires. The following sections have been provided as the result of implementing five different case studies and seven questionnaires to promote adoption of Six Sigma in food distribution SC within 3.5 years. However, the purpose of this study is not just to present the result of any case study or questionnaire specifically and it is rather to present the role of Six Sigma aspects in dealing with issues and problems in food SC. Therefore, the methodology of this research output here is a secondary data analysis on a PhD thesis to present Six Sigma application and its benefits to logistics and SC via different perspectives.

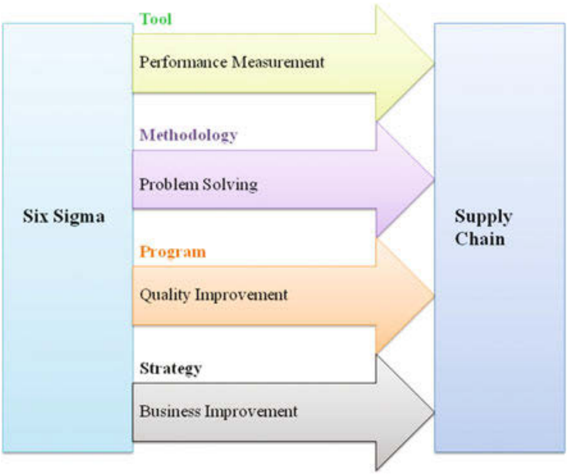

Fig. 7 Holistic view of Six Sigma roles in supply chain through different approaches

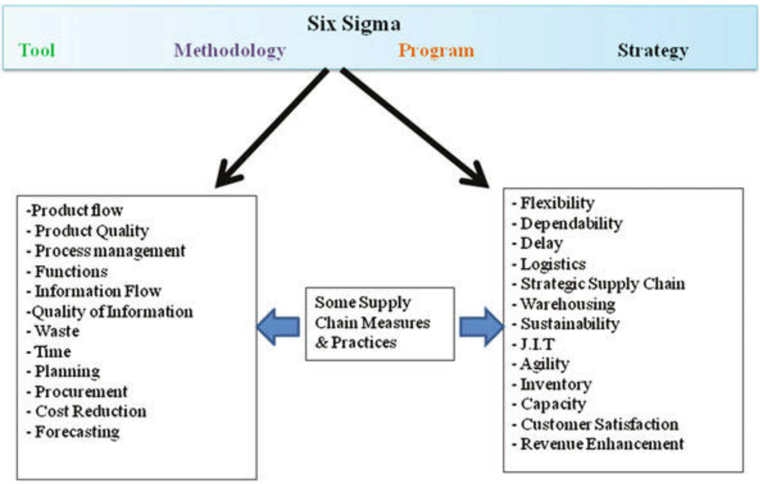

Fig. 8 Six Sigma role in some supply chain measures and practices

5.1 Six Sigma as a Performance Measurement Tool in SC

The continuous performance measurement practice of the Six Sigma implementation could be considered as one of the most common activities that could be undertaken in any organisation. This practice does not oblige organisations to follow the Six Sigma principles. It means that measurement tools and practices in DMAIC methodology can be undertaken by any organisation; as the starting point of Six Sigma journey, or the practical stage of the Six Sigma project or even as a performance measurement process isolated from any Six Sigma programme.

Performance measurement role of Six Sigma is mainly associated with methodology stage of the Six Sigma. There are many activities, tools and techniques that are undertaken to measure the existing performance of the organisation and performance after the implementation of the project. It means that performance measurement in Six Sigma is one of the most critical and fundamental tasks during the project utilisation. Data collection and benchmarking are two major performance measurement activities in Six Sigma methodology, which can indicate the current performance of any SC measure. This could include the target setting and gap analysis. Performance measurement in SC is difficult and complicated in terms of data collection and benchmarking. If the specific SC measure is an internal or inter-departmental measure, the data collection and benchmarking will be easier than data collection and benchmarking for inter-organisational SC measures. This would also depend on the level of SC measure; if the measure is strategic and data is required from top managers and senior executives, the data collection is difficult in terms of availability and willingness to share the information with other SC network firms. Data for tactical and operational measures can be collected in connection with medium level managers or shop floor employees. This would increase the availability, but can also increase the bias, which results in less precision and accuracy. The repeatability and reproducibility of data in data collection of SC measures is another issue, which can be more problematic in collecting the inter-organisational or even national and international SC measures.

Data collection can happen in all five stages of the DMAIC or any other Six Sigma methodologies. Identifying the most critical defects in “Define” stage, measuring the current performance of the organisation in relation to that defect in “Measure” stage, identifying the most important cause or source of the defect in “Analyse” stage and finally monitoring the improved performance in “Control” stage needs the set of rigorous data collection.

There are some examples of different tools or techniques that have been used in “Measure” or “Define” stage of the DMAIC for different purposes. Some examples of using these tools and techniques in measuring SC activities or processes will be presented as follows. However, these tools and techniques could also be used in any performance measurement practice isolated from Six Sigma methodology.

“Target setting” is one of the common activities in “Measure” and “Define” stage of the Six Sigma methodology in which the required measures from customer or management team are set in order to identify the defect and the gap. These target values are used to monitor the performance and effectiveness of the Six Sigma methodology and also the performance of the organisation or department in relation to the specific performance measure. Table 2 represents a “measuring criteria” in logistics as part of “Define” stage of one of the Six Sigma case studies that was conducted in relevant research programme. It was designed by a UK-based food wholesaler to increase the awareness of the supplier’s performance in global logistics and transport. This model was produced through this case study in a UK-based food wholesaler as the result of monitoring the performance of the third party logistics and to increase the awareness of the global packaging manufacturer as a supplier. Containers of palletised goods have been delivered by cargo ships from outside the Europe to the UK-based food wholesaler with more concern in quality transport and shipment. This table can provide the customer's requirement in terms of what the very good or very poor performance in each category means.

The packaging manufacturer could simply measure its performance in packing, palletising, wrapping, loading and transport to the customer by receiving the feedback from customer based on this measuring target, which is used as the measuring criteria for quality of service and product.

Performance measurement also happens in "Control" stage of any Six Sigma methodology to check the impact of the solutions to reduce the defect level. Data will be collected from the same measure or performance to indicate the effectiveness of the methodology to reduce the level of the defect within the same number of opportunities. This data could be processed in the Excel to provide the graphic version of the effectiveness, and there would be no requirement of more complicated data analysis tools.

Figure 9 represents the effect of the Six Sigma methodology as a case study on performance of that packaging manufacturer in a global SC network. This figure indicates the delivery performance of the logistics aspects of the packaging products before and after implementing Six Sigma methodology in integration with supplier development practice with the packaging manufacturer. It is evident from this figure that Six Sigma project helped the food distribution company and the packaging manufacturer to remove the causes of the problems in five different logistics aspects and improve their performance. It is clear from this figure that the overall performance on delivery has transformed from poor and very poor to good and very good condition as the result of Six Sigma implementation. The rest of the Six Sigma methodology stages were applied as the result of identifying the key areas of the defect and also the level of non-conformance through this performance measurement practice. The first set of data was collected from a certain number of inward containers before implementing the Six Sigma methodology and the second set of the data was collected from exactly the same number of containers after implementing Six Sigma. It is clear that performance of the manufacturer could be measured in different stages of the methodology to ensure about the effectiveness of the solutions and also check them against the targets.

The performance related to any product or process in Six Sigma methodology needs to be translated in Six Sigma language, in which the Sigma level value indicates how the performance is. It means, the closer the Sigma value to six, the better the performance. This Sigma value can also be calculated after implementing the solutions from the new sets of data from the same product or process to evaluate the effect of the Six Sigma methodology on the product or process.

Figure 10 represents the process Sigma calculation for an "order taking" process as one of the SC activities. This Sigma calculation has happened during the "measure" stage of another case study in the relevant research programme in

Table 2 The measuring criteria for a packaging supplier using 3rd party logistics

	Very good	Good	Average	Poor	Very poor
Pallet condition	Impressive	No poor quality	≤10 % Poor quality	10–30 % Poor	≥30 % Poor quality
Wrapping of the pallet	Impressive tight and multi layered wrap	No loose, damaged or poor wrap	≤10 % loose, damaged or poor wrap	10–30 % loose, damaged or poor wrap	≥30 % loose, damaged or poor wrap
Stacking condition	Strong, straight and top level stacking	No poor or leaning stacking	≤10 % poor or leaning Stacking	10–30 % poor or leaning stacking	≥30 % poor or leaning stacking
Packaging	Tight, strong and perfect packs	Not tight but no obvious damages or holes on packs	Not tight and very few obvious damages or holes on packs	Not tight and few obvious damages or holes on packs	Not tight and many obvious damages or holes on packs
Product quality	Perfect and impressive quality in every issue	Less than 5 obvious damages on the pizza boxes	5–10 cases obvious damages to discarded the products	Few uncommon obvious damages to discard the products	Too many uncommon obvious damages to discard the products

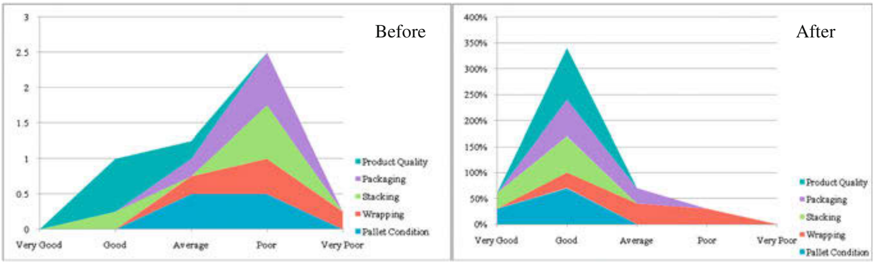

Fig. 9 Measurement of the logistics performance before and after implementing Six Sigma

which the defective order processing in a UK-based food wholesaler and distributor had been analysed through Six Sigma project. The number of processed units indicates the number of samples or collected data. The number of defect opportunities per unit has indicated as one opportunity for one invoice. The total number of defects per collected sample, defect per million opportunities (DPMO) and finally Sigma value were also presented in this tool. It is indicated in Fig. 10 that process sigma level for the current process (order processing) is 4.42 and target value must be a figure more than that. The gap between target and existing sigma value depends on process and number of units in the process. The processes with less samples or less units have lower jump on sigma value than more complicated processes with more units. This tool can simultaneously indicate the performance of the product or process with different languages. But, Six Sigma practitioners are usually concentrating on Sigma value. This tool is available online and can be used in both Six Sigma projects and any other complicated project to review the performance.

Benchmarking is another performance measurement activity that can be undertaken in different stages of any Six Sigma methodology. It can be applied in

Process Sigma Calculator - Discrete Data		
Number of Units Processed	**N**	692
Total Number of Defects	**D**	1.21
Number of Defect Opportunities per Unit	**O**	1
Defects per million opportunities	**dpmo**	1748.6
Defects as percentage		0.17%
Process Sigma Level	**Sigma**	4.42

Fig. 10 Process sigma level for the existing process of the order taking referred to the defect

"Measure" stage, where the gap between current performance and best-in-class target or an internal or external target is calculated. It can also be applied in "Define" and "Improve" stages, where inter- or intra-focused SC measures can be compared with others in terms of meeting the customer requirements or VOC. House of quality or QFD is one of the most common Six Sigma tools that can be used for benchmarking. It is usually used to translate the most critical VOC to the most critical VOB or technical requirements in the customisation and benchmarking context. This will be embedded with benchmarking process in which the performance of the organisation will be compared with a few other organisations in the same SC and for the same product or service. Project prioritisation matrix is a key component of the QFD in which the relationship between customer requirements and technical requirements alongside to presenting the most critical requirements will be presented.

Figure 11 is the example of project prioritisation matrix of a house of quality which represents the QFD analysis in a food SC. Key customer attributes of a UK-based food distributor and wholesaler have been collected through data collection and affinity process in another Six Sigma case study relevant to the PhD research programme. Then, the technical requirements of voice of business were identified and the relationship between these two sets of data was analysed to measure the level of relationship and finally identify the most critical customer and technical requirements. The benchmarking process was carried out based on studying the performance of two other organisations and scoring their performance. This process can be recognised in Fig. 11.

There are some other tools that could be used to monitor the performance of any Six Sigma project for any SC measure or process. Control or monitoring charts are used to monitor the performance of the Six Sigma project or capability of the product or process. Figure 12 represents an example of monitoring chart for the reverse logistics in a food distributor and wholesaler, which was part of another Six Sigma case study. This case study was conducted to identify the reasons for significant number of quality-related reverse logistics or rejects in that organisation. This tool is to indicate the occasions that the process went out of control in the logistics process, when the number of returned goods was more than the upper limit. This tool was used in a reverse logistics process of SC and can be used in any SC process or activity.

Failure mode and effect analysis (FMEA) is another tool that can be used to measure the severity of any problem, defect or even cause of the defect in Six Sigma project. This tool could be used to measure the SC risks in relation to quality improvement and customisation and in order to focus on the most significant risk. Table 3 represents an example of assessing the severity of different potential failure modes of a food supplier in food SC in relation to the reverse logistics case study based on the level of impact and effect that they can generate for the process failure.

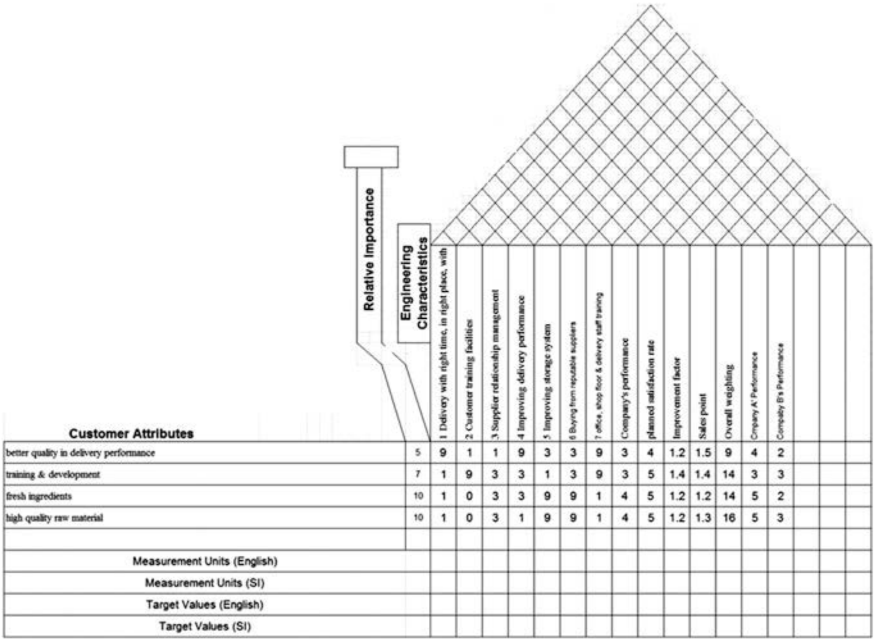

Fig. 11 The QFD analysis to benchmark the performance of the company in a food SC

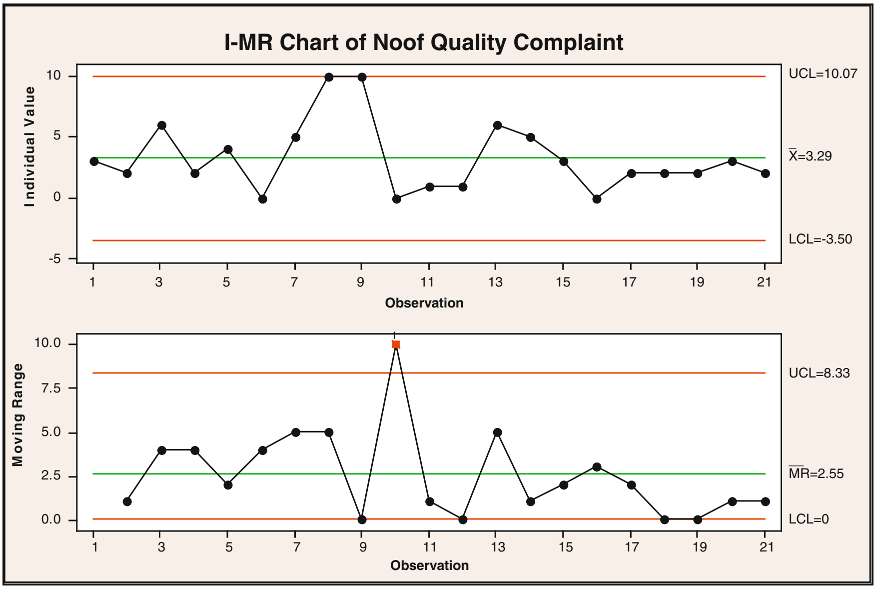

Fig. 12 Monitoring chart for a reverse logistics process

5.2 Six Sigma as a Problem Solving Methodology in SC

The Six Sigma methodology is one of the few quality improvement tools that has the ability to practically drill the problems through systematic, rigorous and data-driven approach. Six Sigma project can be applied in both proactive and reactive approaches and problem solving is the key task of the reactive approach (Shokri et al. 2010). There are various problem indicators in any process or product, which could be targeted by the Six Sigma methodology. These indicators in any SC process, sub-process or activity could be associated to time, quality, reliability, dependability and cost.

There are many SC issues that could be dealt with as the defect or variability. These issues will generate problem, if happen in any SC network; and Six Sigma methodology has ability to remove or minimise these problems. Some common SC-related problems with drastic effect on SC performance, which could be resolved by the Six Sigma methodology are presented in Table 4. It is clear from these examples that many of these problems have multi-effects on the SC performance in any organisation. It is also indicated that most of the problems have impacts on cost, while they can improve other performance indicators.

Figures 13 and 14 depict two practical examples in relation to one of the previous case studies stressing problems generated by third party logistics, hired by the packaging manufacturer to supply the UK-based food distributor and wholesaler. Figure 13 represents the poor warehousing within SC network in which the pallet of the whole product batch was damaged. This could happen in storage, loading, off loading or transport processes in warehousing. Figure 14 represents an example of poor transport, in which the pallet was tipped over as the result of poor planning in freight transport of the 40 ft container. These two problems are amongst the series of problems that have been raised and transferred to the supplier through designed measurement criteria (Table 2) resulting in rework and increased process cycle time. Here, the connection of two aspects of the Six Sigma methodology as performance measurement and problem solving tool can be identified. This would also highlight the mutual interaction between supplier development practices and Six Sigma project, in which Six Sigma project can improve supplier development practices by removing strategic problems with financial impact, while supplier development activities could also facilitate any Six Sigma project to be implemented for upstream side of the SC.

The general systematic approach of the Six Sigma methodology from performance measurement towards problem solving and improvement in any SC process, sub-process or activity is depicted in Fig. 15.

Six Sigma is identified as a process-based methodology to solve any problem. It means that if there is any intention to carry out the Six Sigma project to solve any SC problem, the process must be studied as the very first stage. If any defect or variability is observed in any SC process as the result of performance measurement tool, process mapping is a wise step to understand the current situation of the

Table 3 FMEA analysis to assess the severity of the SC risks

Process steps or product functions	Potential failure mode	Potential effects of failure	Severity (1–10)	Potential cause(s) of failure	Occurence (1–10)	Current controls	Detection(1–10)	Risk priority number(RPN)
Gods return	Irregular product failure	Recalling, customer complaint, food poisoning, customer loss	8	Machine, environment, personal, material, sudden cause	9	Data base, traceability system, monitoring, stock control, rotation	10	720
Gods return	Supplier function failure	Recalling, customer complaint, food poisoning, customer loss	8	Machine, environment, personal, material, sudden and common causes	9	Data base, traceability system, monitoring, stock control, rotation	10	720
Gods return	Live products	Recalling, customer complaint	5	Material common cause	10	Rotation, stock control monitoring, temperature control	10	500
Gods return	In consistency	Recalling, customer complaint	5	Material sudden cause	9	Supplier development, sampling, customer feedback	10	450
Gods return	Buying from inreputable supplier	Recalling, customer complaint, customer loss, malfunction	8	Personal, method, environment material, common cause	8	Supplier selection, supplier assessment, supplier development	1	64

Table 4 Examples of SC problems and their performance indicators

SC problem	Performance indicator				
	Time	Cost	Quality	Dependability	Flexibility
Logistics transfer Cost		√			
Forecasting inaccuracy	√			√	√
Excess and obsolete inventory		√			
Damaged and returned products		√	√		
Inaccurate bill of material		√		√	√
Excess of cycle time	√	√		√	
Lead tim	√	√		√	
Shipping errors		√	√	√	
Billing errors		√	√	√	√
Handling time	√		√		
Scrap and rework		√	√		
Energy cost		√			
Distribution cost		√	√	√	√
Line-item unavailability	√	√		√	√
Poor scheduling	√	√		√	√
Poor storage			√		
Poor delivery performance			√		

Fig. 13 Poor warehousing quality

process and also identify the potential steps that could have possible effect to occurrence of the defect or variability.

Process Map could be adopted as the very first step of the DMAIC methodology after identifying the defect. This would help to generate more idea for next steps. Figure 16 depicts a process map of a “Delivery” process in the food SC as part of previous presented case studies in the PhD research programme, where the “Delivery Lead Time” as one of the key SC problems is reported as the critical measure and reason of many customer complaints. This activity was carried out in

Fig. 14 Poor transport quality

the "measure" stage of a Six Sigma project as another research case study to reduce the delivery lead time in the UK-based food distributor and wholesaler.

The Six Sigma methodology was carried out as a problem solving project in a food distribution organisation to reduce the number of customer complaints related to the late delivery. The process steps that could be associated to the "Delivery Lead Time" were assessed in order to identify the defect. The average of delivery lead time for different delivery routes was calculated as the result of data collection and data analysis for the period of time. Then, any delivery lead time more than average were indicated as the defect. This would present the quantitative measure as the defect in which its reduction can represent the reduction of number of complaints in the delivery process. So, the problem identification, defect identification and data collection were carried out during two stages of the "Define" and "Measure" in the DMAIC methodology.

Then, the defect was analysed to identify the key sources or causes of this defect. The result of carrying out a statistical process control (SPC) analysis for all routes with recorded delivery lead time of certain amount of time indicated whether the routs are under control or not. The normal distribution and also high process capability of the process can allow the project team to rule out any possibility of sudden or special causes. This will also oblige the project team to look for the source of the defect within the processes of the organisation. Brainstorming will provide number of potential sources of the defect, which need refinery to select the most critical sources. The prioritisation strategy can be adopted in this stage in order to strategically select the most critical sources of the defect. "Pareto Analysis" will enable the project team to select these critical sources through prioritisation practice. Figure 17 presents a "Pareto Chart", in which the most counted sources of the defect were prioritised in order to focus on the most important options.

The Pareto Analysis indicated that the first three sources of the defect (spent loading time, late afternoon loading and too many shops) count for 61 % of total

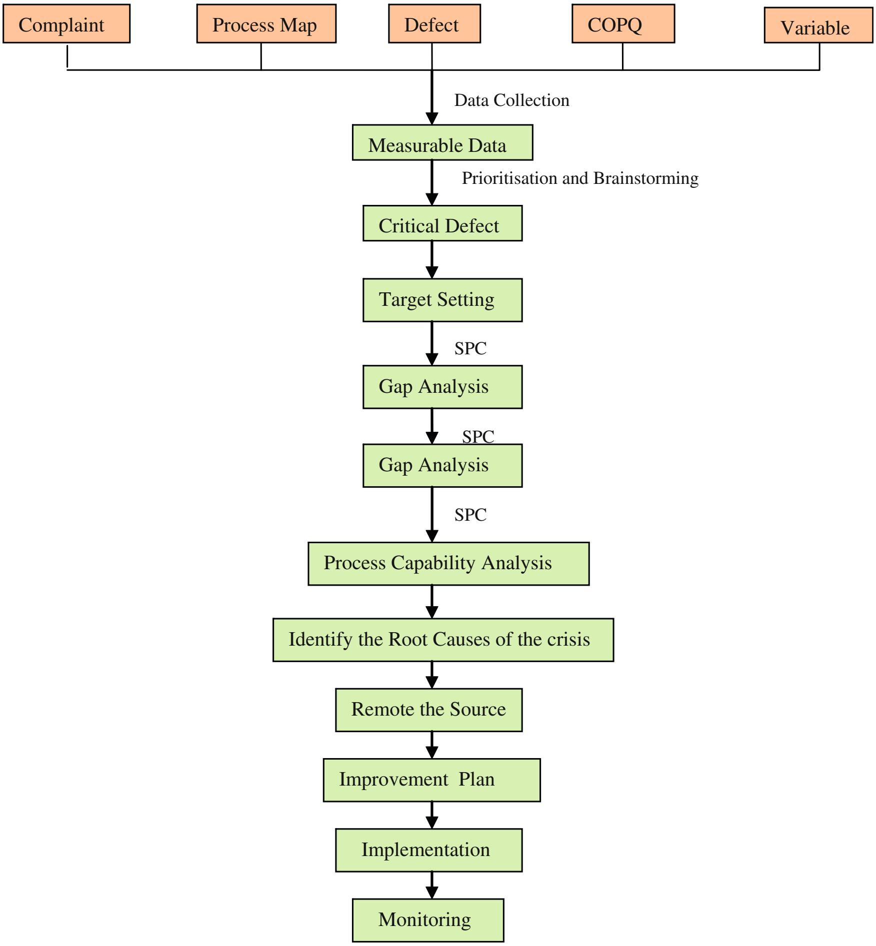

Fig. 15 Six Sigma systematic approach towards any crisis

number of sources as the result of brainstorming and data analysis, and therefore can be selected as the key variables, which need further investigation. This means that other variables would be avoided to be investigated at this time as the purpose of strategically focusing on critical measures, although they cannot be ruled out as the sources of the defect. However, if any changes happen to these variables, it means that the number of defects and ultimately number of customer complaints in delivery must be reduced significantly.

Then, it is important to deploy the further analysis in order to identify the critical causes of these variables. In fact, it is the distinguishing characteristic of the Six Sigma programme to dig to deeper sources and identify the most critical causes of the defect, which their removal or minimisation would provide significant improvement to the process. Therefore, a more quantitative tool can be

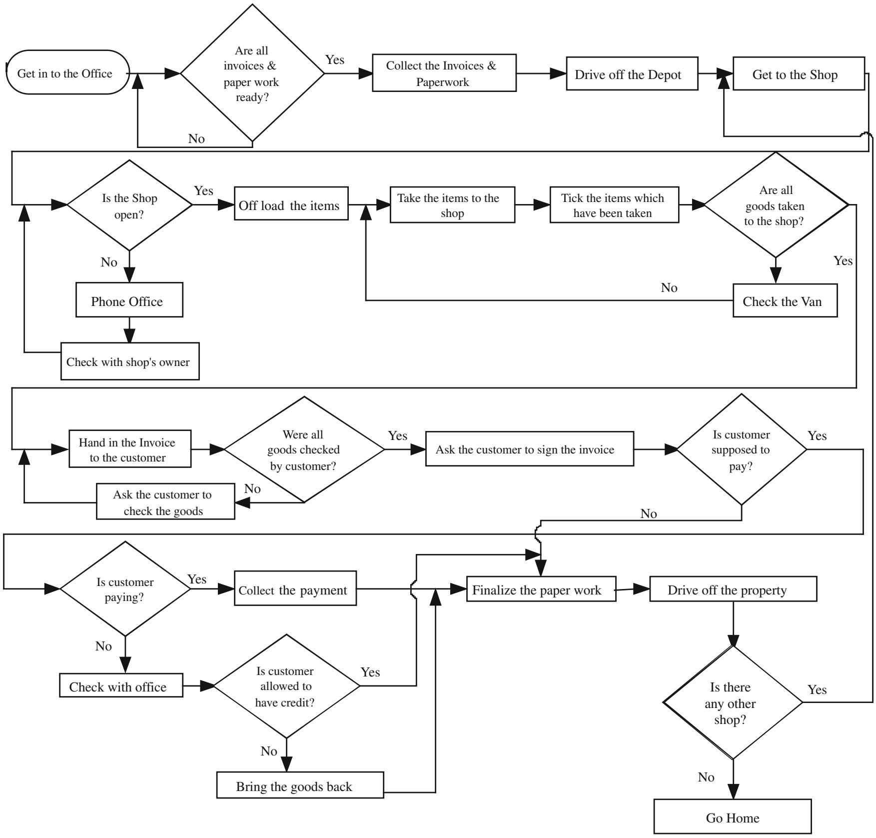

Fig. 16 Process map of a delivery process in a food SC

adopted in "Analyse" stage of the DMAIC to investigate the root causes of the variables and defect. This will enable the project team to identify the most important root causes of the defect in order to focus on them to generate more cost effective and strategic solutions. The possible root causes of three important variables in delivery lead time defect are presented in "root cause and effect XY matrix" (Table 5).

The possible sources of the three important variables were quantitatively analysed after generated by the relevant people and through brainstorming. This happened through scoring style to the effect of relationship between possible causes and three variables. Then, the most important causes with highest weighted score were selected. This was then discussed and analysed through brainstorming and cost/benefit analysis to decide about feasibility of the sources in order to be prepared for next steps. It is clear that the whole flow of methodology is going towards solving the problem, although the problem is yet to be resolved. The step-

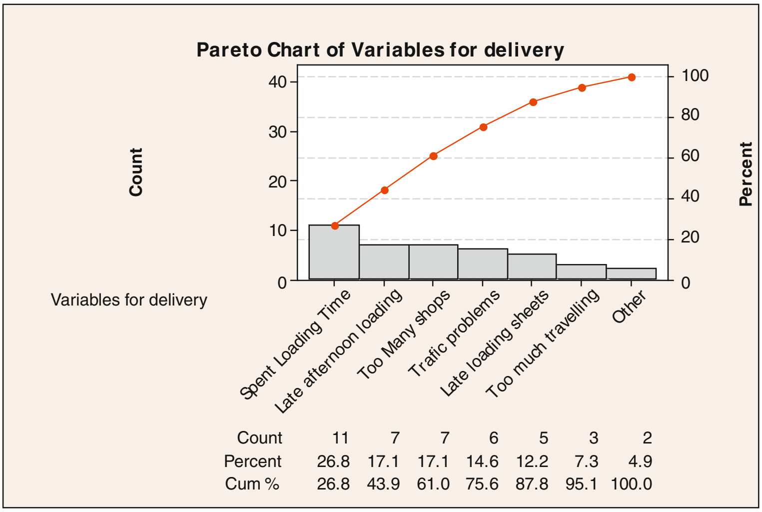

Fig. 17 The Pareto Analysis to select the most important sources of defect to be focused

by-step, deep drilled, data-driven and scientific approach of Six Sigma methodology towards solving the problem could be clearly observed by this point.

Having identified the root causes of the defect, the initialising of potential solutions is the next step in problem solving methodology of the Six Sigma. It is very important to make sure about the involvement of all relevant people in SC network and to buy their interest and willingness in order to participate in initialising any possible solution. Therefore, the SC collaboration, leadership and communication skills play an important role in this stage in order to envisage the chance of resistance to change, conflict of interest, political decisions and also fear of losing the job as the result of comments. It is clear that organisational values outweighed the technical intakes in here as one of the most important and critical stages of the Six Sigma problem solving methodology. Then these recommendations will be brainstormed through the whole individuals, departments and firms that are involved in the SC to select the most practical, sensitive and effective solutions.

The result of brainstorming will be possible bunch of recommendations and initials, which could be in the technical, organisational or even strategic nature. Then, these recommendations must be refined through the process of prioritisation in order to select the most optimum solution that not only solve the problem, but is practical and feasible for the organisation. There might be many recommendations in the SC issues which are inter-organisational and must be dealt with care and cautious. In contrast, there might be some basic internal recommendations that were always there but ignored and could have potential impact on the whole SC performance. It is important to make sure that all these recommendations are through prioritisation and selection channel to avoid any failure in the future.

Table 5 The root cause and effect XY matrix for delivery lead time

Output variables (Y's)	Late afternoon loading	Spent loading time	Too many shops at route	
Importance score (1–10)	6	9	3	
Input/process variables (X's)	Table of association scores (X's to Y's)			Weighted score
Bad loading planning	9	3	0	81
Bad route planning	3	3	9	72
Warehouse layout	9	9	1	138
Staff shortage	9	9	3	144
Late morning start	9	0	3	63
Number of shops at each run	1	9	9	114
Loading method	9	9	3	144
Van discrepancy	3	3	9	72
Late depot leaving	0	0	3	9
Lack of internal communication	9	9	3	144
Warehouse space	3	9	0	99
Goods In delivery distraction	9	9	0	135
Tonnage of orders	3	9	3	108
Failure in specific days	9	9	9	162

"Affinity diagram" is a tool in which different potential solutions could be categorised to make the decision making easier. The categorisation of different solutions for the previous case, which was "Delivery Lead Time", is presented in Fig. 18 and Table 6. The affinity diagram in Fig. 18 categorises potential solutions under 5 different headings and then these categories were brainstormed with all stakeholders in that food SC to select the most effective practical and strategic category based on various factors (see Table 6). However, there could be some occasions that one single recommendation from one category could be selected to be compared with other categories.

Then, each category or any individual solution from any category could be selected for the next step, which is final prioritisation. This prioritisation process deals with reviewing the effect of each solution or category of solutions to the causes of the defect in a comparative approach. It means that the number of potential solutions will be assessed in pairs through a prioritisation analysis in order to indicate the level of effectiveness and importance of that specific solution or strategy on the causes of the defect. This will enable the project team to be more focused and select the most optimum solution which will results in high significance in outcome and more competitiveness in implementation. In the case of reducing the delivery lead time case study, the category prioritisation could be helpful in terms of giving more transparency in decision making process and brainstorming. This was happened between different firms in SC network to ensure cross-functionality of solutions and also holistic approach towards all SC members.

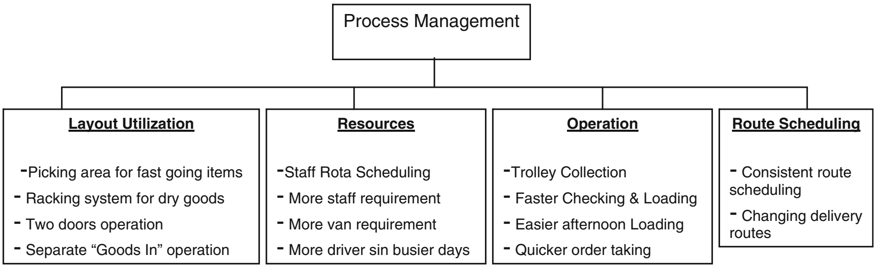

Fig. 18 Affinity diagram for the potential solutions in delivery lead time

Table 6 Prioritising the categories as the result of brainstorming

Header	Status	Priority
Layout utilisation	Consistent, practical, highly beneficial, costly, timely, low risk, Asset	1
Resources	Available, highly beneficial, complicated, expensive, high risk, overhead	3
Operation	Practical, low cost, complicated, high risk, high dependency, value adding	2
Route scheduling	Low cost, high risk, low practicality, complicated, high dependency	4

Analytical hierarchy process (AHP) is one of the most common tools to be used in the process of prioritisation through comparative approach. The few most effective solutions will be selected to be analysed by AHP through comparing their level of effectiveness on the cause of the defect in pairs. In the case of delivery lead time, the following solutions from category of "layout utilisation" were selected:

– Picking area for fast going items (A1)
– Racking system for dry goods (A2)
– Quicker Order Taking (A3)
– Separate "Goods In" operation with two doors in the warehouse (A4)

Each solution was tagged with a letter and number prior to be analysed in AHP. The analysis is based on a matrix comparison in which the level of importance of each individual solution will be scored in comparison with other individual solutions as the result of intensive and cross functional brainstorming within the SC. This will end up with selecting the most optimum solution to target the cause of the defect. Figure 19 represents the AHP for the delivery lead time in which the solution from another process of SC (loading process) was selected as the most optimum solution to reduce the number of defects. It means that "designing a picking area for fast going items" (A1) can be selected as the most optimum solution (with highest score) to reduce the spent loading time which was selected as the key cause of the defect (delivery lead time). The instruction over the calculation and analysis in AHP could be found in the internet or any statistical specific book.

$$\begin{array}{c} \\ A1j \\ A2j \\ A3j \\ A4j \end{array}\begin{array}{cccc} Ai1 & Ai2 & Ai3 & Ai4 \\ \end{array}\begin{pmatrix} 1 & 5 & 5 & 7 \\ 1/5 & 1 & 1/3 & 1/5 \\ 1/5 & 3 & 1 & 7 \\ 1/7 & 5 & 1/7 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 5 & 5 & 7 \\ 0.2 & 1 & 0.333 & 0.2 \\ 0.2 & 3 & 1 & 7 \\ 0.143 & 5 & 0.143 & 1 \end{pmatrix}$$

$$\begin{array}{c} \\ A1j \\ A2j \\ A3j \\ A4j \end{array}\begin{array}{cccc} Ai1 & Ai2 & Ai3 & Ai4 \\ \end{array}\begin{pmatrix} 1 & 5 & 5 & 7 \\ 1/5 & 1 & 1/3 & 1/5 \\ 1/5 & 3 & 1 & 7 \\ 1/7 & 5 & 1/7 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 5 & 5 & 7 \\ 0.2 & 1 & 0.333 & 0.2 \\ 0.2 & 3 & 1 & 7 \\ 0.143 & 5 & 0.143 & 1 \end{pmatrix}$$

$$W = \begin{bmatrix} 0.559 & 0.066 & 0.24 & 0.184 \end{bmatrix}$$

Fig. 19 AHP for selecting the most optimum solution to reduce the cause of the defect

Then, implementation plan could be adopted in the purpose of cost and benefit analysis. The level of risk, sensitivity, effectiveness, cost and actual benefit of this optimum solution can be presented in implementation plan to be discussed with different members of the SC. This solution was implemented in the case study resulted in £50,000 actual profit for the food distribution company and also other potential financial benefits for other SC stakeholders. The Six Sigma project could be more difficult to be carried out in inter-organisational level of food SC network. This is due to difficulty and complexity in information exchange, secrecy and also conflict of interest. But, it is important that the project team and especially the project manager focus on the bottom line which is customer and SC strategy rather than benefit for any individual firm within SC.

5.3 Six Sigma as a Quality Improvement Programme in SC

Six Sigma programme can be promoted as a quality improvement programme following an effective and continuous application of the Six Sigma projects in any organisation. Six Sigma programme embeds Six Sigma principles, success factors, training, methodology and tools and techniques. It means that if any SC sector considers Six Sigma projects in a complete version with some tangible results, Six Sigma can be labelled as the quality improvement programme for this SC. Therefore, application of some problem solving Six Sigma projects reactively in regular bases and through systematic and rigorous approach within SC possibly provides the platform for the whole SC entities to claim that they have successfully established Six Sigma quality improvement programme in their organisation. This would also cover some proactive approaches in the SC network to improve the performance. Six Sigma programme was the result of everlasting evolution in quality management and quality improvement initiatives. The requirement for more rigorous and systematic quality improvement programme to solve more complicated problems in complicated SC processes is the key motivation behind Six Sigma development in SC.

Six Sigma programme could improve the SC competence by focusing on quality, efficiency, effectiveness, reliability, and value-adding. It can reduce the variability in quality of delivered goods, delivery time, forecasting and scheduling. This will increase the chance of JIT application or service quality improvement. It means that Six Sigma can be used as a driving factor to improve the quality of service and achieve JIT in any SC activity through identifying and reducing the variability. There are number of time-related defects or variability in any SC process or sub-process, which can be targeted by Six Sigma. The systematic, rigorous and data-driven approach of Six Sigma can ensure the effectiveness, reliability and efficiency in any quality improvement project that is under taken in SC networks. Previous research case studies have indicated the role Six Sigma methodology in removing causes of the defect and therefore improving the equality of SC performance in delivery, supplier development and also order processing.

There are many hidden costs involved in SC activities that could be targeted by the Six Sigma as the cost of poor quality. For instance, reworking in relation to returned goods, poor transport and logistics in previous research case studies could be considered by Six Sigma project in reverse logistics. There are some waste measures related to the SC activities and processes that could be reduced through Six Sigma project to improve the quality and add value. Delivery lead time in one of the research case studies is a time-related measure, which is considered as a waste in any SC network. Six Sigma programme can be adopted, as it was indicated before to reduce the delivery lead time and add more value to the SC and logistics. Defect-free orders and deliveries in those case studies added more value to the SC by reducing the chance of inspection and rework. Six Sigma can also be used to reduce the process cycle time (refer to previous case studies) and also improve the agility of the SC. Lean SC can also be developed through identifying the lean-related measures to be improved through Lean Six Sigma (LSS) projects.

There are various quality-related SC measures that any improvement in their performance can result in SC quality improvement. Some of these measures have been adopted in these research case studies for a food distribution and wholesale company in a food SC. These measures, which are related and generalised to different SC processes, can be targeted by the Six Sigma project as the process of quality improvement. It means that if the Six Sigma programme is established in any organisation within any SC as quality improvement programme, these measures could be immediate targets by the project teams that need to be measured and improved. These measures could also be expanded to other entities in the SC to improve the inter-organisational measures in the SC. It means that cross-functionality and cross-integration in the SC to select these measures is a key success factor. Some of these SC measures were cited in Shepherd and Gunter (2006) and are listed in Table 7.

Table 7 Quality related supply chain measures (Shepherd and Gunter 2006)

Stages in supply chain	Measure	Quantitative (QN) or Qualitative (QL)
Plan	Fill rate	QN
	Order entry method	QN
	Accuracy of forecasting techniques	QN
	Autonomy of planning	QL
	Perceived effectiveness of departmental relations	QL
	Order flexibility	QN
	Perfect order fulfilment	QN
	Deviation from schedule	QN
Source	Buyer–supplier partnership level	QL
	Supplier defect-free deliveries	QN
	Supplier rejection rate	QN
	Mutual trust	QL
	Satisfaction with knowledge transfer	QL
	Satisfaction with supplier relationship	QL
	Supplier assistance in solving technical problems	QL
	Extend of mutual planning cooperation leading to improved quality	QL
	Extend of mutual assistance leading in problem-solving efforts	QL
Make	Distribution of decision competences between supplier and customer	QL
	Quality and frequency of exchange of logistics information between supplier and customer	QL
	Quality of perspective taking in supply network	QL
	Information accuracy	QL
	Information timeliness	QL
	Information availability	QL
	Inventory accuracy	QN
	Percentage of wrong products	QN
	Defect-free product	QN
Delivery	Delivery performance	QL
	Delivery reliability	QN
	Number of on-time deliveries	QN
	Effectiveness of distribution planning schedule	QL
	Effectiveness of delivery invoice method	QN
	Driver reliability for performance	QN
	Quality of delivered goods	QL
	Achievement of defect-free deliveries	QN
	Quality of delivery documentation	QL
Return (customer satisfaction)	Customer satisfaction	QL
	Level of customer perceived value of product	QL
	Customer complaint	QN
	Rate of complaint	QN

5.4 Six Sigma as a Business Strategy in SC

Six Sigma programme can be established as the part of business improvement strategy within and between all organisations and departments of the SC. It is required to practice Six Sigma in smaller projects and lower profile and gradually make the implication wider within organisation to inject it as a part of any strategy or policy setting in every single decision making within SC.

Collaboration, integration and inter and intra-team building is necessary to be adopted alongside other key success factors of Six Sigma to make the Six Sigma as a business improvement strategy. Its application originally needed top management and some commitment and support from relevant people to the process. However, wider spread commitment and involvement, deeper cultural transformation and broader view are required in order to establish the Six Sigma programme as a part of business strategy. It means that Six Sigma must be developed as the "mind-set" within SC in order to make it more effective in longer term as a business strategy. This is challenging in SC and needs more collaborative network of SC firms in order to communicate their strategic decisions, data and finally conduct a multi level and integrated Six Sigma team to be able to have a cross-functional and broad view in every single process involved in the SC.

This indicates the necessity of a partnership approach between firms in SC in order to facilitate to develop the Six Sigma programme as the business strategy for all relevant firms within SC and looks at the problems as the whole SC problem and work together to remove it. This also needs a valuable and distinctive cultural transformation equally and with the similar aspiration in spite of different power level within SC.

Figure 20 depicts that Six Sigma must be established as a mindset to keep all organisation within SC together and work with each other. This can set up a collaborative strategy within SC, which could be adopted to make the SC network stronger. It means that four elements of partnership, integration, collaboration and cultural transformation across any SC are required as pre-requisites to successfully

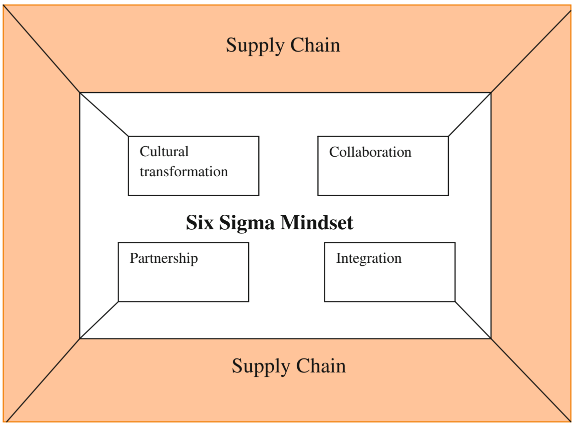

Fig. 20 The Six Sigma strategy within supply chain

implement Six Sigma programme as business strategy. However, this is as a matter of full implemention which results in establishing Six Sigma culture within any organisation and any SC.

6 Conclusion

This research article addressed the gap between practical aspects of Six Sigma programme and SC practices and measures. It was found that Six Sigma programme would be beneficial to any quantitative SC measure in terms of measurement, improvement and monitoring in a systematic and rigorous fashion. The result of research methodology and case studies highlighted the role of Six Sigma programme into practical aspects of SC such as supplier development, order processing and logistics. It is concluded that application of Six Sigma methodology in any SC process would not necessarily need the comprehensive model and it may be applied for targeting specific process or defect. The key finding of this research programme is that Six Sigma can be used as a single reliable and systematic package to measure and improve the SC processes by focusing on key measures with financial and strategic impact in whole SC. The biggest limitation of this research was focusing of the methodology on one specific SC as food SC and also focusing on just handful of SC measures in case studies, but the result can be generalised for any other SC and there is opportunity for further research programmes to review the role of four different aspects of Six Sigma on their measures. This research programme also highlighted more opportunity of Six Sigma and SC integration.

The managerial implication of this chapter relates to the integration of a systematic business improvement methodology into practical elements of SC and logistics to improve the efficiency and profitability in any organisation. The financial benefit of application Six Sigma methodology of DAMIC in SC and logistics is substantial, which will result in more competitiveness in market. Six Sigma applications in SC generate more opportunity for collaboration and reduce the chance of market failure. It is critically important to transform the culture, involve management team and to sustain the improvement via a cross-functional view in SC in order to establish any Six Sigma benefit in internal or external SCs.

Future studies are required to develop the effectiveness of Six Sigma methodology in SC and logistics through more practical approaches such as case studies and also research outputs. It is a great necessity to investigate the effect of Six Sigma implementation in SC for different sectors. This could be established through series of inter-related research studies and activities that can fill the gap in studies related to Six Sigma integration with SC. Further research studies can also focus more on specific logistics and SC measures in different types of industries and SCs as the process of problem solving methodologies.

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A Case Study on E-Kanban Implementation: A Framework for Successful Implementation

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Abstract This paper provides generic guidelines to ensure an electronic supplier Kanban can be successfully implemented across an organization. This approach is based on case study work conducted within a European manufacturing SME. A framework in the form of an eight-step approach for implementing an electronic supplier Kanban, that has been tested, proven, and realized, provides a clear process to follow. These steps provide a clear process from mapping and analyzing the current situation, an analysis of potential suppliers with corresponding criteria, and an analysis of purchased items and bottlenecks in their use within the organization. The stepped approach further reviews the Kanban loop, which needs fully dimensioned, together with relevant information, supplier preparation for using the system, and then the integration of processes to ensure success in its use. Operational issues are comprehensively covered, together with strategic aims and the underlying problems that may impact upon success. The above approach can be used to both introduce new suppliers to the system as well as giving assistance to other companies wishing to implement e-supplier Kanban. This will need to be adapted and contextualized to individual organizational requirements.

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1 Introduction

With the effects of globalization, competition and market pressure growing, organizations are being forced to work more efficiently, using Lean tools and techniques such as Just-In-Time or Kanban as important parts of their supply chain (SC) system (Kumar and Panneerselvam 2007). Synchronized manufacturing using Lean tools such as Kanban will minimize inventory and waste, leading to higher efficiency (Giard and Mendy 2008). According to Henderson (Henderson 1986), Kanban should not be seen as the end point of improvement, but as a milestone. Kanban in the form of a target condition reveals the unexpected potential of optimization, and thus leads to recurrent problem solving and improvement (Lage Junior and GodinhoFilho 2010).

The focus of this paper is the development of guidelines on how JIT purchasing in the form of a supplier e-Kanban can be implemented in a medium-sized organization. These guidelines are based on primary data collected within an organization where a supplier e-Kanban has been realized, including the identification of critical success factors (CSFs) for successful implementation. The research also explores the importance of the buyer–supplier relationship in e-Kanban implementation, challenges faced during implementation, and steps taken to prepare supplier to use such system.

2 Background Research

In the era of globalization, it is imperative to have internal and external integration of SC partners to improve the efficiency and effectiveness of SC operations (Harrison and van Hoek 2011; Christopher 2011). The SC integration ensures boundary-less collaboration to ease the flow of material, information, cash, and other resources (Singh et al. 1990; Naylor et al. 1999). The external integration is achieved through strategic collaboration with SC partners and effective use of IT based systems such as electronic data interchange (EDI) for real-time information exchange with SC partners (Cagliano et al. 2006). The internal integration is achieved through the use of planning systems such as material requirement planning (MRP), enterprise requirement planning (ERP), just-in time (JIT) using Kanban, resulting in reduced uncertainty of material flows, improved efficiency, and reduced process times (Cagliano et al. 2006; Mukhopadhyay and Shanker 2005; Slack et al. 2010).

Manufacturing companies in the past have used several policies to manage the flow of operations (task flows or order flows or material flows) as their effective management has a direct link to the company's bottom-line (González-R and Framinan 2009). The pull policies from the Toyota Kanban Production system have been one of the popular control policies in the last two decades (Monden 1998). Since then, several forms of Kanban system have been proposed in the literature to compare its performance with other production control systems (Framinan et al. 2003). Lage Junior and GodinhoFilho (Lage Junior and GodinhoFilho 2010) defined Kanban as a "material flow control mechanism which controls inventory levels, the supply of material and production". Kanban is a visual tool that forms an important part of the communication process which drives lean factories (Womack and Jones 1996). Kanban signals are used to communicate effectively with the internal and external operations on issues such as production schedules, lead time of delivery, stock information, to name a few (Singh et al. 1990; Parry and Turner 2006). According to Henderson (Henderson 1986), Kanban should not be seen as the end point of improvement, but as a milestone. Kanban in the form of a target condition reveals the unexpected potential of optimization, and thus leads to recurrent problem solving and improvement. The physical Kanban card serves as an order attached to the bin. It provides information about the supplier (supplier name, the vendor code, and the stocking location), the part (identification number, description, and quantity), and the customer (user group, storage location, and Kanban number) (Cimorelli 2005). The popular types of Kanban used in SC operations are move/withdrawal Kanban, production Kanban, and supplier Kanban (Kumar and Panneerselvam 2007; Cimorelli 2005; Ramnath et al. 2009; Dickmann 2007). To successfully run a Kanban system, some basic rules of operations need to be followed such as Kanban boxes need to be checked regularly and processed by following the first in-first out principle (FIFO), and production starts only when customer triggers an order and succeeding process withdraw semi-finished products from proceeding workstation (Ramnath et al. 2009).

A successful application of Kanban depends to a great extent on the supplier (Waters-Fuller 1995). This is underpinned by the fact that a zero or a small amount of safety stock exists: timing, quality, and quantity of deliveries are vital to meet end-customer expectations (Waters-Fuller 1995). For good collaboration between the buyer and the supplier, a close and a fair relationship is fundamental (Liker and Choi 2004). A relationship based on trust, commitment, and loyalty between SC partners creates profit increase for both sides, through the understanding of their counterpart's interests and needs (Hadaya and Cassivi 2007). An externally integrated SC toward the supplier builds the fundamentals of a close relationship. With better information flow and greater visibility, the supplier is able to forecast customer-specific needs and therefore is capable of responding better to manufacturer's requirements, benefiting the buyer as well (Hadaya and Cassivi 2007; Drickhammer 2005; Barkmeyer 2007). A close relationship also provides access to the customer's expertise and increased assistance from the buyer, receiving a long-term contract and favorable payment terms, allowing a better focus on R&D effort (Henderson 1986; Waters-Fuller 1995; Martel 1993).

The selection and evaluation of Kanban suppliers is a CSF for successful implementation. According to Waters-Fuller (Waters-Fuller 1995), selection and evaluation must be based on quality, speed, and delivery performance, rather than solely on the price. General criteria for selection include: Quality, co-operation, delivery performance and reliability, geographical location of the supplier, price structure, workforce, professionalism, management attitudes, and technical capabilities (Christopher 2011; Slack et al. 2010; Waters-Fuller 1995). However, a dependent relationship with a Kanban supplier does bring risks. If a supplier does not adopt the same procedures it may not be able to react quickly to demand changes over the short term, therefore not meeting contractual requirements (Henderson 1986). Unexpected interruptions can appear, such as bad weather conditions or a vehicle breakdown (Waters-Fuller 1995). To secure production stability a backup strategy should be developed to cover those risks.

This article proposes the use of supplier e-Kanban system to continue the efficiency of the procurement process which should lead to inventory reduction through frequent delivery, tied capital reduction through less stock volume, reduced cycle times due to faster processing, increased dependability and availability through enhanced stability, and increased transparency through simplicity of handling closer cooperation with supplier (Lage Junior and GodinhoFilho 2010; Waters-Fuller 1995; Barkmeyer 2007). e-Kanban is mostly an internet-based application that automates the transfer of the Kanban signal via a barcode scan to an upstream supplier (Barkmeyer 2007). No large investment is necessary to set up an electronic Kanban system (Wildemann 2003). According to Lage Junior and GodinhoFilho (Lage Junior and GodinhoFilho 2010), "e-Kanban is a variation of Kanban with modifications". This is why the essential characteristics of Kanban and supplier Kanban can be applied to e-Kanban as well, although the implementation can prove difficult. With e-Kanban, manual card handling and order-entry activities are reduced to a minimum, with no chance of lost cards. This simplifies the purchase process and releases the administrative workforce. Hence, the replenishment signal cannot get lost which almost eliminates the risk of starving (Drickhammer 2005). Additionally, e-Kanban formalizes the communication process and eliminates many of the manual errors which arise from faxing Kanban orders or emailing spread-sheets to suppliers. This also overcomes primary limitations such as physical distance, where the use of original Kanban is hindered (Hadaya and Cassivi 2007; Barkmeyer 2007). With e-Kanban as a mutual base, communication with suppliers is clarified. Electronic Kanban acts like a "control panel", enabling real-time visibility of demand signals and provides an overview of the status of every Kanban in the system. Evenmore value is added through an improved flow coordination of the purchased materials, reduction in the WIP, automatic record keeping, increased flexibility in supply. and an increased and faster responsiveness to fluctuations in demand using e-Kanban (Lage Junior and GodinhoFilho 2010). This offers the opportunity to ease, and speed, the analysis of supplier performance. Reporting on system performance is also both faster and more accurate.

Having carried out a review of the related literature, it was apparent that there was a research gap relating to guidelines to enable the successful implementation of e-Kanban systems in organizations, based on proven, practical application. The research aim, using this research case organization, was to generate a step-based process to enable the successful implementation of a e-Kanban system which would provide real-time replenishment benefits. The objectives in doing this were to; produce a step-based framework; identify critical success factors for implementation, and to outline the benefits and the risks involved. By doing this, the original contribution of this paper is in the generation of a generic, step-based framework based on a real case study where actual implementation, including problems encountered could be observed and a fact-based approach generated.

3 Research Methodology

This research used a case study based approach (Yin 2009) in a mid-sized company to evaluate the current situation and potential for improvement in the organization through the use of e-Kanban system. Such evaluation allowed the identification of critical success factors (CSFs) of a supplier e-Kanban and also provided a base (Rother 2010) from which to foresee possible benefits and risks. Secondary data collection through the literature review provided general descriptions of Kanban and surrounding topics. The primary data collection method used in the case study firm was participant observation to evaluate what employees think about the implementation of the system, what they expect, and what risks might occur in generating the expected added-value. Triangulation of data collection methods, in the form of documentation and archival records, facilitated in verifying the evidence of the identified CSFs for supplier e-Kanban implementation. The data gathered within the company offered internal information and identified special topics and relevant criteria points which need to be analyzed.

Through the above, the construction of guidelines on how to implement supplier e-Kanban in a mid-sized firm was possible. The case firm is a worldwide market leader in the manufacture of premium priced, high quality products, following a differentiation strategy, based on their product, quality, service, and lifecycle, but also including their operating systems and "lean"-thinking. The project was performed within the SC management team, which has been using manual Kanban systems for some years and are aware of the complexities and trials involved in adopting new systems including the risks involved, while being aware of their limitations. The organization has clear objectives for their work which would be generic; inventory reduction; reduced capital tie-up; reduced cycle times; and simplicity of operation. Their consideration and use of e-Kanban were seen as a further means of delivering greater value to customers. Their task was to spot and analyze improvement potential along the whole SC; to improve production processes through application of lean techniques (the organization recently started Lean application in their SC), thereby improving efficiency and reducing waste. The analysis of the current supply situation, the supplier structure, including integration and the analysis of purchased parts was intended to clarify the need for and the design of an action plan. In this organization, an internal Kanban exists in the final assembly and the supplier e-Kanban was built between the supplier and the stock of semi-finished parts.

Using a case organization that already used and knew the limitations of conventional Kanban systems, which operate in a changing marketplace where the customer expects enhanced added-value to the product, ensured that the case was relevant, and would provide knowledgeable input through engagement with experienced staff. Being medium-sized and operating in a field requiring numerous suppliers of varying complexity and mix, all contributed to a case providing a framework that was required to meet varying and changing demands.

4 Process Analysis and Data Evaluation

Based on a review of the literature and observations of alternative approaches to implementation, the findings generated a framework, as shown in Fig. 1, to follow for the implementation of a successful supplier e-Kanban.

The framework incorporates eight steps which should be followed for successful implementation of e-Kanban. CSFs and difficulties are analyzed and discussed below to provide issues to be considered when implementing e-Kanban, based on the analysis of all the methods used to collect primary data. This section briefly discusses each step of the framework, the challenge, and success factors involved in implementation of each stage of the framework.

Stage 1: Value stream mapping
To improve a process, it is important to first of all get an overview of the initial situation otherwise an action plan cannot be formulated. Value stream mapping (VSM) allows material and information flow within each process to be analyzed to find muda (waste). VSM is applicable to nearly every process and provides important knowledge about weaknesses and optimization potential (Leyendecker 2008). By means of Rother and Shook's guidelines (2003) for value stream mapping and Wee and Wu's explanations (Wee and Wu 2009) and by following Toyota's rules of "gembagembutsu", the current state map (CSM) was drawn, as shown in Fig. 2, on the basis of process observation at the place (gemba) to see the actual thing (gembutsu) in order to be able to eliminate waste (Liker 2004). Eight types of waste were identified as shown in Fig. 2. Based on the CSM, the target condition and the future state map (FSM) were designed by developing ways to eliminate waste and create a smoother flow.

The CSM shows the large administration effort required for production planning. Without this planning, workstations are not able to produce. Production planning is executed by the company's PPS system, and leveled on a minimum stock level. This contains and manages all information about products (construction plans, bills of material, production steps), and every workstation (lead times, workflow) schedules the production. Material is pushed through the SC and creates stock between every work station. This leads to high inventory, high WIP, complexity, and less space between and within the cells, with a resulting long lead time.

The FSM, Fig. 3, provides a realistic production design after implementation of a supplier e-Kanban. Material will still be pushed between the stations. Because lot sizes

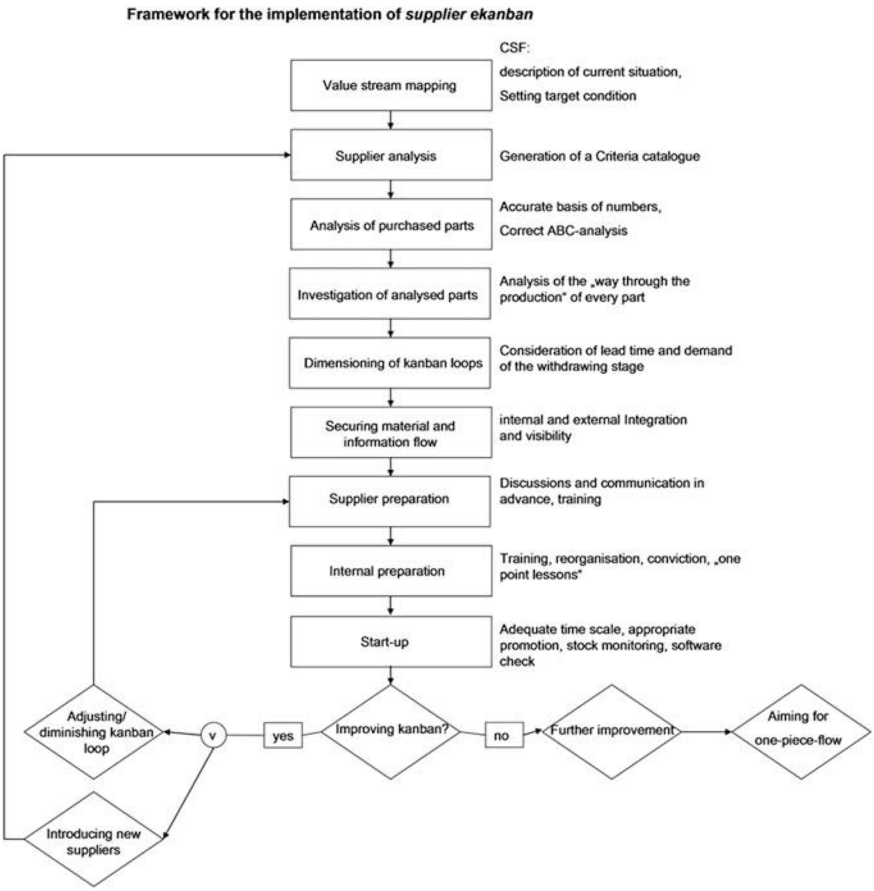

Fig. 1 Eight step framework for implementation of supplier e-Kanban. *Source*: Willert, 2010

are smaller than the batch in the CSM, and usually only one container at a time arrives at the work station, quick processing is possible and a vast buffer does not occur.

As shown in Fig. 3, electroplating and shop floor are both bottlenecks within the SC. Here, physical restrictions are created via the machinery which only works efficiently if a particular amount of parts is manufactured at once. This bottleneck was kept in mind for the later dimensioning of the Kanban loop. Comparing the two maps, a reduced administrational burden, a reduced WIP, and shorter lead times can be found.

Stage 2: Supplier analysis

To select possible e-Kanban suppliers, an ABC-analysis of archival data from the firms's production planning system (PPS) was conducted to categorize the suppliers with relation to the purchasing value (Ramnath et al. 2009). Analysis showed that 80 % of the total purchasing value was reached with the 36 most

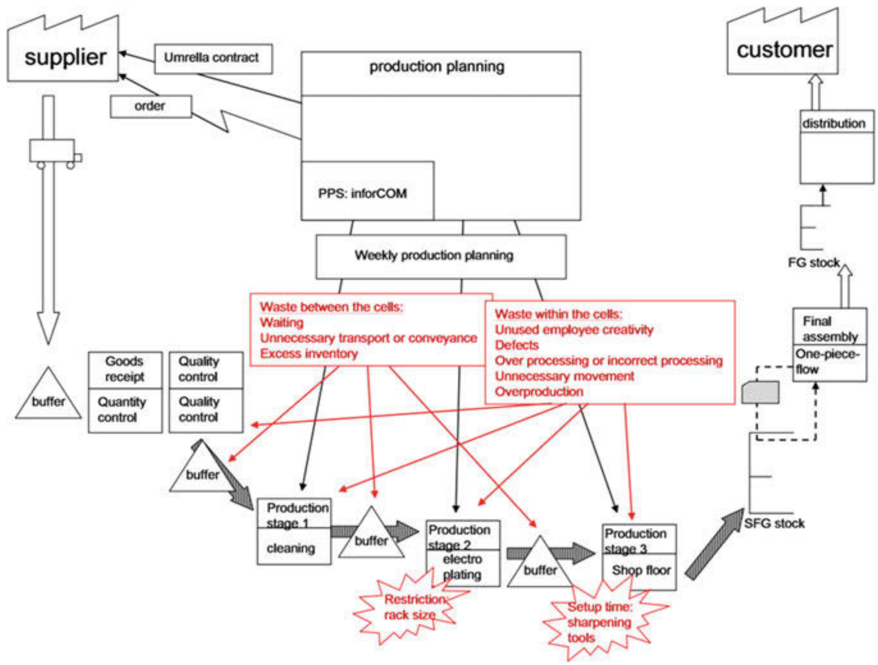

Fig. 2 Current state map of the firms' supply chain. *Source*: Willert, 2010

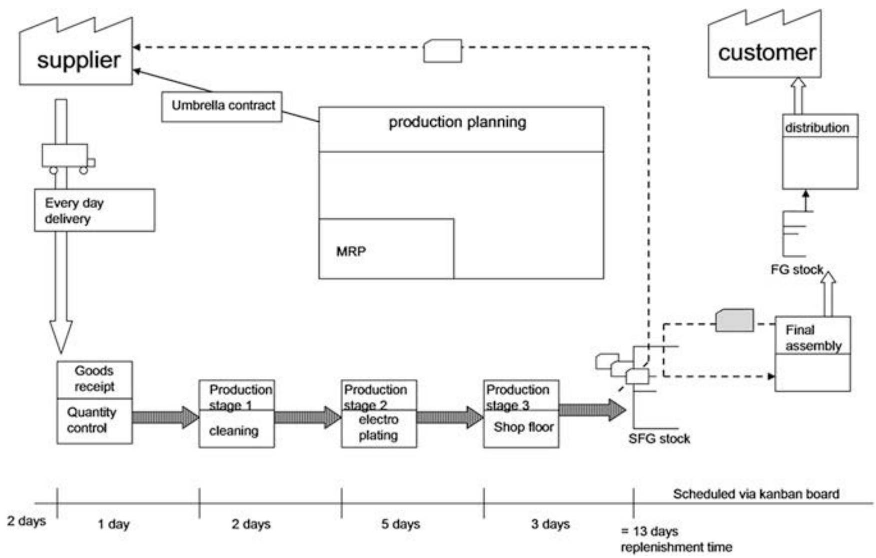

Fig. 3 Future state map of the organizations' supply chain. *Source*: Willert, 2010

important suppliers (classed within 'A' type) and that 54 % of all orders were accomplished by 6 % of the suppliers. This set of 36 suppliers is the target group to introduce to a supplier e-Kanban. It was not worth introducing a supplier e-Kanban to "B" and "C" vendors, owing to infrequent order patterns and small batch sizes. The fact that there was no investment required from the supplier in the project, was rewarded by the supplier making no price changes or other changes even if their field of tasks got extended.

Stage 3: Analysis of selected parts
By looking at the division of purchased parts according to their prices per unit (PPU), a supplier e-Kanban seemed the more feasible option. Over 50 % of all purchased parts have a value of less than one Euro. Therefore to introduce e-Kanban, the firm followed the rule of simplifying procurement procedures with low value products. Taking into consideration the structure of the purchased parts, it was decided to introduce only "A" materials first. Of 195 different parts, 75 are "A" parts and therefore suitable for supplier e-Kanban.

Stage 4: Investigation of analyzed parts
According to Ramnath et al. (2009), tabulating the component list with information on lead time, transportation, average demand, and the "way through the assembly" are needed for dimensioning the Kanban loop. The data for the aforementioned items were collated using the VSM conducted in Stage 1 and also using the firm's PPS. The two bottlenecks spotted in Stage 1 were considered as additional lead time. By observing the process, lead times within the work stations were calculated (shown in Fig. 3). In addition, actual batch sizes and inventories at all stages as well as final utilization and the final product which contain the purchased part, have all been investigated with the help of the PPS to create a base to dimension the Kanban loop.

Stage 5: Dimensioning of Kanban loops/sizes
Through process observation and analysis of archival data, a base was created to dimension the Kanban loop. The dimensioning was geared to the exact demand of the one-piece-flow at the final assembly which withdraws the material from the Kanban loop. The data collection for dimensioning was done in previous stages using criteria such as replenishment lead time (from SFG stock to SFG stock), daily consumption including a safety factor and scrap rate, total Kanban volume in the loop, total number of cards, container capacity, and volume per container. With the help of Toyota's Kanban formula (for more information, refer to (Kumar and Panneerselvam 2007)), the Kanban loop was dimensioned. Internal rules for dimensioning Kanban loops are laid down. The daily demand contains twice the standard deviation and a safety factor of 1.1. Multiplying the daily demand with the replenishment time equals the volume of the Kanban loop. The container capacity conforms to the bottleneck at the electroplating work station (size of the rack). Dividing the volume of the loop by the container capacity equals the number of necessary containers.

Stage 6: Securing material and information flow
After dimensioning the loops, a smooth information and material flow must be secured. Observing production processes provided an insight into the information flow before the supplier e-Kanban was started. After the implementation of the e-Kanban, information relating to routing of materials and its processing was transferred to the Kanban card. The software itself does not provide additional information to a conventional card, other than the status of every Kanban within the loop. Cells have information about the handling of the Kanban, such as maximum throughput time within the cell, or basic rules on material flow. The delivery of goods is carried out by rail via the “daily milk-run” (Waters-Fuller 1995). This is feasible because most of the “A” vendors are located in close proximity to the company. To coordinate the pick-up of goods the purchasing department monitors the system in order to inform the rail service when deliveries at the supplier’s plant are shown as “ready”. Later in the run, information flow goes directly to the rail service via direct access to the system.

Before the implementation of the supplier e-Kanban, the purchasing department monitored and edited the raw material account of the supplier by debiting and adding raw material by means of orders. This was replaced by the Kanban system and only delivery receipts and invoices pass the purchasing department for checking. Material needs a set number of days from entering the organization to the final SFG stock through various process steps. After that, the status of the Kanban changes to “full”. Not until then can the invoice be authorized and after that the payment to the supplier is made.

Stage 7: Supplier preparation
Before the supplier e-Kanban became operational, meetings and workshops were arranged to explain the aim of the Kanban, to describe the process, present the software, and to train the supplier in the use of software and equipment. Open orders were checked to be sure that they did not overlap with the Kanbans which would accumulate when hidden in the assembly line. To further avoid this problem, existing stocks were monitored at the supplier’s side as well as on the company’s side to create a fluent transfer to the system. Furthermore, the supplier must be equipped with necessary instrumentation—a Kanban card printer, as well as enough containers were provided. It was found that at least twice as many containers as the number in the loop were needed at supplier’s side, arising from the rapidity of the e-Kanban signal. The supplier also needs to be apprised of quality inspection which is outsourced together with corresponding policy and procedures. Installing supplier e-Kanban leads to new tasks and responsibilities on both sides which call for some regulatory fundamentals. A Kanban agreement, including Kanban rules, agreements about the quality of delivery, minimum purchased quantity by the manufacturer over a specified time period as well as penalties when a rule is not followed, is obligatory and must be signed by both sides.

Stage 8: Internal preparation

To start a supplier e-Kanban, stocks at all stages need to be taken into account. Therefore the current inventory must be calculated with the help of the PPS, thereafter reduced by the total WIP which will be in the loop when the supplier e-Kanban is started. The amount left over must be used before the system is started. The new WIP must be repacked in the newly-designed format (container size and quantity) and Kanbans must be attached to the containers. This should happen at the earliest point the stock arrives in the company to follow the pull principle and to avoid hidden stock within the company.

Internal Kanban rules must be established. The most important rule is that only the Kanban cards represent an order and no other route sheet should occur within the production concerning the Kanban material. Clear procedures need stated, and training provided as necessary. Questions and concerns need to be clarified and the action plan should be explained. A responsible person for the supplier e-Kanban should be appointed for addressing the queries between firm and suppliers. Resistance found during observation can be countered by broader involvement of the employees to ensure positive thinking about the change. After the implementation phase, an audit is necessary (Lee-Mortimer 2008) to ensure that inappropriate handling and mistakes do not occur, countering the success of the supplier e-Kanban. This audit should take place after a full introduction of the first supplier to the system.

The main factors to ensure success in the eight stages for implementation are summarized in Table 1.

Table 1 Critical success factors for successful implementation of e-Kanban

Stage	Critical success factors	How to achieve CSFs
1	A description of the current situation; Setting target condition	Analyzing production processes; Setting realistic targets to know where to go
2	Criteria catalogue for supplier selection	Organization-specific requirements which must be fulfilled by suitable suppliers
3	An accurate basis of numbers; correct ABC-analysis	Actual annual numbers which are reliable; accurately separating parts into A, B, & C related to PPU and amount
4	Analysing the way through the production of every part	In form of: Considering work station lead times, transportation times, bottlenecks & physical restrictions
5	Consideration of overall lead time and demand of the withdrawing stage	Calculating broad lot sizes at the beginning, then diminishing
6	Internal and external integration	Fast and precise information flow and access, communication and visibility provided by the system
7	Close co-operation and information exchange	Discussions and communication in advance, training
8	Promoting the system; starting rules; reorganization	Training, conviction, clarifying questions, explaining the aim; Explicit lessons, auditing; repacking inventory

To estimate the value of the implementation of a supplier e-Kanban, process costs need further analysis to show potential savings. Comparing the average of the old batch size with the new averaged lot size, a significant reduction of 93.8 % was found. Secondly, working effort has been reduced significantly. The gray-colored arrows, Fig. 3, show the diminished work-effort through implementing a supplier e-Kanban. Administration effort in the remaining steps has been reduced through collective invoices, digitalized invoices, delivery receipts, and their archival storage. As a result, wasted working time is reduced by simplified processes with the help of the software of the supplier e-Kanban. This is highlighted, for example, where 54 % of all orders are compiled by all "A" vendors. If these suppliers become e-Kanban suppliers, a reduction in the above described non-value adding steps in the region of 50 % will be achieved. The application of this system resulted in the elimination of eight steps (from initial 10 steps) from the purchasing department process, resulting in savings of approximately €82,000 per year. This saving shows the high potential and value of supplier e-Kanban and underpins the need to calculate process costs frequently.

5 Managerial Implications

Monetary and efficiency savings during the process of implementation highlighted the potential and value of supplier e-Kanban. There is a need to constantly re-evaluate the process costs as any factors or inputs change to ensure this complex process is continually improving, especially in times when changes within the production process are taking place to keep an oversight of the production and process costs. An evaluation of the detailed costs of the other departments is essential as well, as changes to one part of the process are likely to follow through to other areas of an organization.

The implementation of a supplier e-Kanban at the case organization related to one supplier as a pilot project. Due to complexities of introducing such systems with suppliers, this would appear as the better approach, rather than approaching and carrying out the exercise with a number of suppliers at one time; relationships and trust need built and may require different approaches due to the current relationship, culture, and capabilities of suppliers. Through the detailed work with a pilot supplier, the eight–step framework guidelines were formed to introduce the other suppliers to the system, together with success factors in their application.

With the implementation of a supplier e-Kanban, not only the operational task of providing material and guaranteeing a smooth run are covered, but also strategic aims in adding value to the customer can be achieved through the reduction of time, money, risk, and mistakes. Underlying problems that may impact success do come to the surface and need to be solved during the implementation; these are likely to differ depending on the organizations current state and what is involved in moving from that to a system of e-Kanban.

e-Kanban will never be the only system in a company for the supply of parts, as confirmed by Dickmann (2007) and Rother (2010). Supplier e-Kanban is only one step on the ladder of improvement. The overall vision should be to reach a one-piece-flow over the whole SC.

6 Conclusion

For the implementation of a supplier e-Kanban, the operational task of providing material and guaranteeing a smooth run are covered, as well as the strategic aims being followed. Underlying problems that may impact success come to the surface and need to be solved. With developing the Kanban further by reducing WIP and improving processes, the long-term vision is the elimination of the Kanban in order to produce in a one-piece-flow (Rother 2010; Gross and McInnis 2003). Kanban is certainly not the only system in a company and does not cover all requirements of a company (i.e., purchasing of “B” and “C” parts from “B” and “C” vendors) and therefore an efficient purchasing and production process require a mix of methods and techniques, as confirmed by Dickmann (2007) and Rother (2010). At the moment, clarity of production scheduling is not available at every stage within production, and the planning of the processing of Kanban parts is impossible within cells. This results from a lack of connection to the software. By installing one scanning station per work station and as a result giving more status to a part within the flow, visibility is given for the whole SC and internal cell planning is possible. While this research has reviewed the practical application of e-Kanban, it is recommended that further research should also be undertaken in applying an e-Kanban to new market requirements and conditions in volatile markets and where strong competition exists, including investigation of the SC in relation to dimensioning the Kanban loop.

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A Comparative Study of Periodic-Review Order-Up-To (*T, S*) Policy and Continuous-Review (*s, S*) Policy in a Serial Supply Chain over a Finite Planning Horizon

P. V. Rajendra Sethupathi, Chandrasekharan Rajendran and Hans Ziegler

Abstract In this paper, we consider a serial supply chain (SC) operating with deterministic and known customer demands and costs of review or orders, holding, and backlog at every installation over a finite planning horizon. We present an evaluation of two order policies: Periodic-review order-up-to *S* policy (i.e., (*T, S*) policy), and (*s, S*) policy. We first present a mathematical programming model to determine optimal re-order point and base-stock for every member in the SC. By virtue of the computational complexity associated with the mathematical model, we present genetic algorithms (GAs) to determine the order policy parameters, *s* and *S* for every stage. We compare the performances of GAs (for obtaining installation *s* and *S*) with the mathematical model for the periodic-review order-up-to (*T, S*) policy that obtains in its class optimal review periods and order-up-to levels. It is observed that the (*s, S*) policy emerges to be mostly better than the (*T, S*) policy.

Keywords Serial supply chain · Inventory management · Periodic-review order-up-to *S* (*T, S*) policy · (*s, S*) policy · Mathematical programming models · Genetic algorithms

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1 Introduction

Supply chain (SC) decisions are broadly classified into strategic, tactical, and operational decisions, and the operational perspective can be addressed in terms of four problem areas, namely, inventory management and control; production, planning, and scheduling; information sharing and coordination monitoring; and operation tools (Ganeshan et al. 1999). Inventory is held by installations or members in a SC in different forms so as to provide continuous service to the respective downstream customer and finally to customers/consumers. Love (1979) defined inventory as goods or materials in the control of an enterprise, and held for a time in a relatively idle or unproductive state, awaiting its intended use or sale. Efficient and effective management of inventory throughout the SC significantly improves the service provided to the customer (Lee and Billington 1992). Nahmias (2008) listed out the motivation for holding inventories in view of economies of scale, uncertainties, smoothing, transportation, control cost, and logistics. Some issues that are critical in the SC inventory management include the inventory order policy such as the periodic-review order-up-to policy (T, S) and continuous-review (s, S) policy. These order policies help answer basically two questions: When to order and how much to order? The objective is to minimize the sum of costs, mostly consisting of costs of review or order, holding, and shortage at different members in the SC. In this paper, a serial SC that manufactures a single product with discrete customer demands known a priori over the finite planning horizon is considered, and a relative evaluation of two inventory order polices, namely, periodic-review order-up-to policy (i.e., (T, S) policy) and the (s, S) policy, is presented by considering many SC settings. It is possibly for the first time in the literature that such a relative evaluation of such order policies is undertaken in a serial SC over a finite time horizon.

2 Literature Review

Clark and Scarf (1960) addressed the problem of determining optimal purchasing quantities in a serial multi-echelon system so as to minimize the long-run average cost, and showed that an echelon base-stock policy is optimal for the finite horizon problem. Federgruen and Zipkin (1984) extended Clark and Scarf's work to infinite horizon problem, and proved that a stationary order-up-to-level policy is optimal. Lee and Billington (1993) developed a decision support system for Hewlett-Packard company to aid inventory and service benchmarking, operational planning and control, and what-if analyses. Axsäter and Rosling (1993) compared the installation and echelon stock policy, and proved that when every stock-point in a multi-echelon inventory system is controlled by an order-up-to policy, an installation stock policy can always be replaced by an equivalent echelon stock policy, and vice versa. Glasserman and Tayur (1995) developed simulation-based methods to estimate sensitivities of inventory costs with respect to policy parameters. Gallego and Zipkin (1999) discussed the issue of stock positioning, and constructed heuristics to minimize the system average cost. Zipkin (2000) presented discussions on base-stock levels for series systems, assembly systems, and distributed systems with local control and central control.

Min and Zhou (2002) classified SC models into inventory theoretic and simulation hybrids, and stressed the need of mathematical programming models to explore multi-echelon and multi period issues in the SC. Shang and Song (2003) developed an easily implementable heuristic to determine the echelon base-stock levels for an N-stage serial system by solving 2 N single stage news vendor-type problems. Daniel and Rajendran (2005a) developed a simulation-based heuristic that attempts to optimize (in the class of base-stock policy) the base-stocks in a serial SC with the objective of minimizing the total SC cost consisting of holding costs and shortage costs at all installations in the SC. They proposed a genetic algorithm (GA) to determine the best installation base-stocks for a serial SC. Daniel and Rajendran (2005b) developed a problem-specific heuristic and a simulated annealing (SA) heuristic for finding the best installation base-stocks in a serial SC. Daniel and Rajendran (2006) developed different variants of GA to obtain the best installation base-stocks for a serial SC, and compared these variants with the complete enumeration and the best-move local search technique. However, they did not consider the presence of order costs in the SC.

Another application of GAs to SC inventory optimization was reported by Haq and Kannan (2006) by considering a two-echelon distribution-inventory SC for the bread industry. Cheng et al. (2006) proposed using a fuzzy inventory controller to determine the ordering quantity for the members in a SC. Axsäter (2006) provided discussions on multi-echelon inventory ordering policies including the determination of optimal lot sizing and re-order points. van Houtum et al. (2007) considered a single-item, periodic-review, serial inventory/production system, with linear inventory-holding and penalty costs, and proved the optimality of base-stock policies by deriving newsboy equations for the optimal base-stock levels, and described an efficient exact solution procedure for the case with mixed Erlang demands. Shang and Song (2007) considered two models of stochastic serial inventory systems and showed that the optimal policy parameters can be bounded and approximated by a series of independent, single-stage optimal policy parameters. Cheung and Zhang (2008) considered a SC with one supplier and multiple retailers in which base-stock policies are practiced, specifically two replenishment strategies: Synchronized ordering and balanced ordering. Johansen and Thorstenson (2008) extended the problem of determination of optimal base-stock of the inventory system with continuous review and constant lead time to the case with periodic review and stochastic and sequential lead times. For a detailed review of literature, see Sethupathi and Rajendran (2010).

Most studies considered only holding and shortage costs, and they did not consider the order costs to be significant which may not be true in all SCs; in that case, the total costs consist of holding, shortage, and order costs at various echelons in the SC. Sethupathi and Rajendran (2010) modeled a serial SC with periodic-review order-up-to policy (i.e., (*T, S*) policy), and determined the optimal and heuristic review periods and base-stocks at installations in the SC (with deterministic customer demands over a fine planning horizon) respectively using a mathematical programming model and two GAs. It is evident that the determination of order-up-to levels in SCs and the minimization of the total SC cost are quite complex and computationally quite tedious (e.g., see Lee and Billington 1993; Petrovic et al. 1998; Shang and Song 2003; Daniel and Rajendran 2006; Sethupathi and Rajendran 2010); it is also evident from the literature review that the determination of optimal order quantity and re-order level or re-order point is computationally difficult with the consideration of the exact total costs in SC, and that no attempt has been made to determine such optimal order policy parameters in a SC in a deterministic demand environment over a finite planning horizon (also see the related observations of researchers in the case of determination of inventory order policy parameters with respect to periodic-review base-stock policy in a serial SC).

The present study aims to model a serial SC operating with dynamic, known, and deterministic customer demands over a finite planning horizon: First with the consideration of (*s, S*) policy with re-order point to determine the installation base-stock and re-order point for every member in the SC; and compare its performance with that of periodic review order-up-to *S* policy (i.e., (*T, S*) policy) that operates with base-stock and review period for every installation. We make use of mathematical programming models to determine the optimal parameter values in the respective class of inventory order policies, and subsequently three GAs to determine the heuristic parameter values (via deterministic simulation) in view of the computational complexity associated with the mathematical programming models. We consider the installation inventory order policy and its parameters in view of the ease of implementation in the proposed mathematical programming model and the GAs. Our model consists of a serial SC with a supplier, a manufacturer, a distributor, and a retailer, and a time unit is assumed to be discrete and it corresponds to a day, though not restrictive. The present work employs the SC model similar to the one by Sethupathi and Rajendran (2010); however differs in terms of the order policy i.e., (*s, S*) policy considered in this study.

3 Mathematical Programming Model for the (*s, S*) Policy

The SC framework considered in this study comprises four members, namely, retailer, distributor, manufacturer, and supplier, and the material flow is shown in Fig. 1. This study primarily focuses on the determination of the optimal or heuristic best installation base-stocks and re-order points, i.e., *S* and *s* respectively at every installation, and hence we do not treat the customer as a member in the context of the current problem, except that a customer demand triggers the information flow and hence the material flow in the SC. All four members add value to the product as it passes through the SC before it is delivered to the

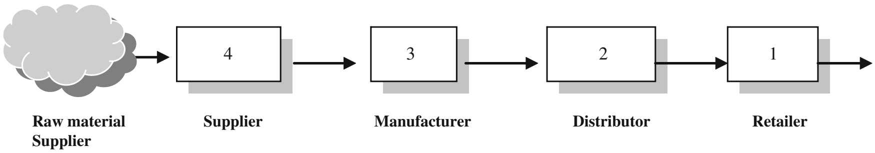

Fig. 1 Material flow in the serial supply chain

customer. The members are linked through information flow in both directions and products flow from the most upstream member to the lowest downstream member. The whole SC works with a pull strategy and the customer demand arising at member 1 (i.e., retailer) pulls the product from the subsequent upstream member. Inventory is controlled by the SC members by using the (s, S) policy with a re-order point. This review mechanism triggers replenishment orders at every member depending upon the inventory on hand, pre-specified installation base-stock, re-order point, outstanding orders, and backorders at that member. Every member continuously monitors its installation inventory position; when it equals or falls below the re-order point s, an order is triggered to the immediate upstream member. Different holding and shortage cost-rates and ordering costs exist at different SC members. Every member has a deterministic replenishment lead time equal to the sum of production lead time and transportation lead time with respect to the upstream member.

3.1 Model Assumptions

1. A single product flows through the SC.
2. Time is assumed to be discrete, and the unit of discrete time is assumed to be a day.
3. We consider a serial SC model comprising N installations with a finite time horizon and with known discrete customer demands varying over time.
4. All the N installations or stages or members in the SC operate under an installation (s, S) policy with the respective re-order points and base-stocks for every member in the SC.
5. Inventory order policy parameters such as the base-stock (S) and re-order point (s) for a given member remain the same across the entire finite time horizon.
6. Base-stock and re-order point for a given member or installation in the SC take integer values as the customer demands are assumed to be integers.
7. The retailer faces a customer demand, which is assumed to be stationary and uniformly distributed in the interval [20, 60] in the computational experiments considered in this study (though this demand distribution is not restrictive). Customer demands are sampled from the given distribution, and they are assumed to be discrete and known over the finite planning horizon in this study.

8. Lead time for information or order processing is zero.
9. Processing (procurement/production/packing) lead time and transportation lead time are combined accordingly at each stage and considered together as one component, called replenishment lead time for that installation or member in the SC, and is assumed to be deterministic.
10. There is no lot-size or discount policy for members in the SC.
11. Every member in the SC has its own installation or local holding and shortage cost rates, and an order cost per order.
12. Re-order point of a member is assumed to be less than or equal to the base-stock of that member.
13. If the demand exceeds on-hand inventory at a member, then the excess demand is backlogged.
14. Availability of raw material for installation N, i.e., the supplier, is unlimited.
15. All installations have infinite capacity.
16. The entire customer demand on day t is assumed to occur during the time epoch Δt within day t itself; the demand from installation j gets transmitted to upstream member $(j + 1)$ immediately at the end of time epoch Δt, if the installation inventory position equals or falls below the re-order point s_j at installation j. Hence, relevant inventory information gets updated at the beginning of and at the end of t at every installation.

3.2 Supply Chain Model Description with (s, S) Policy

The sequence of events taking place at installation or member j, for $j = 1$ to N in the same order, in time (or during day) t, where N is the number of installations in the SC, is as follows.

(1) The receipt of material at member j (shipped from member $(j + 1)$ to member j) takes place if the material is due to arrive at the beginning of current time instant t. The installation's inventory information, namely, on-hand inventory, is updated.
(2) Member 1 receives the customer demand; for member j, $j > 1$, the order from the immediate downstream member is received, when the inventory position of installation $(j - 1)$ has reached or has fallen below its re-order level.
(3) The possible order fulfillment (combining both installation's backorder as of the previous day and the current day's demand received from downstream member $(j - 1)$) takes place, depending upon the available on-hand inventory at stage j. If sufficient on-hand inventory is not there with member j to meet this combined demand, then the unsatisfied demand is backlogged. The downstream member $(j - 1)$ receives a partially or fully fulfilled order quantity after a delay corresponding to replenishment lead time of member $(j - 1)$. If the downstream member is the customer, then the customer receives it in the current day t itself. Installation inventory at stage j is updated.

(4) With the available local inventory information, member j triggers an order to the upstream member $(j + 1)$ only if the inventory position of j has reached or fallen below the re-order level of j; otherwise no order placement takes place. The order placement depends upon the inventory on hand, pre-specified base-stock S_j, re-order point s_j, outstanding order, and backorder at that member j. If order placement takes place, member $(j + 1)$ realizes the order placed by member j immediately, since the information/order processing lead time is assumed to be zero.
(5) Installation inventory such as on-hand inventory, on-order inventory, and backorder are updated, and the sum of local holding cost, shortage cost, and order cost, if an order takes place, are computed with respect to member j.

Since it is assumed in this study that a day corresponds to a unit time, t is incremented and the same sequence of events gets repeated on the following day; the same sequence of events takes place at all members in the SC, for $j = 1, 2,.., N$. The total supply chain cost (TSCC) is computed over the given finite-time horizon of T days.

3.3 Formulation of the Mathematical Model for the (s, S) Policy

The notations used in the mathematical model are as follows:

TSCC	total supply chain cost
j	installation/stage index
N	number of installations in the SC
T	total number of days (planning horizon) over which TSCC is computed
t	current time or current day
S_j	installation base-stock at installation j
s_j	installation re-order point for installation j
h_j	installation holding cost-rate for installation j
b_j	installation shortage cost-rate for installation j
O_j	installation ordering cost for installation j
LT_j	installation replenishment lead time with respect to installation j /* note that the member j receives on t, the possible shipment from $(j + 1)$ that has taken place at the end of $(t - \mathrm{LT}_j)$; hence in this study, when we assume $\mathrm{LT}_j = 1$, it means that member j receives on day t the shipment that has been shipped from member $(j + 1)$ on day $(t - 1)$, though theoretically LT_j equals 0; however, we set $\mathrm{LT}_j = 1$ and we carry on with this setting of LT_j for the sake of correctness of mathematical formulation in this study; also see Daniel and Rajendran (2005a, b, 2006) */
$I_{j,t}$	end installation on-hand inventory at installation j at t

$I^*_{j,t}$	installation on-hand inventory at installation j at the beginning of t, after the possible replenishment from installation (j +1) arrives at installation j
$\mathrm{OI}_{j,t}$	end on-order inventory at installation j at t
$\mathrm{OI}^*_{j,t}$	on-order inventory at installation j at the beginning of t
$\mathrm{SUMDEM}_{j,t}$	sum of demand at (i.e., received by) installation j up to t
$\mathrm{SUMORD}_{j,t}$	sum of orders placed by installation j up to t
$B_{j,t}$	backorder at installation j at the end of t
$D_{j,j+1,t}$	demand placed by installation j to upstream installation $(j + 1)$ at t /* this demand is assumed to be immediately realized by installation $(j + 1)$ at t itself; $D_{0,1,t}$ corresponds to customer demand at installation 1 on day t; as for other installations, $D_{j,j+1,t}$ equals zero if $(I_{j,t} + \mathrm{OI}^*_{j,t} - B_{j,t} > s_j)$; otherwise it equals $(S_j - (I_{j,t} + \mathrm{OI}^*_{j,t} - B_{j,t}))$ that is same as the sum of demands received by the installation up to t minus the sum its order quantities up to $(t - 1)$. */
$\delta^*_{j,t}$	a binary variable that assumes the value of 1, whenever there is an order placement at installation j at t; else it is 0
$\mathrm{QS}_{j,j-1,t}$	quantity shipped from installation j to $(j - 1)$ at the end of t
$\mathrm{QS}_{N+1,N,t}$	raw material shipped to installation N at the end of t /* installation $N + 1$ is assumed to have raw material supply of infinite capacity */

The objective is to minimize the total system-wide cost given as follows:

$$\text{Minimize TSCC} = \sum_{t=1}^{T}\sum_{j=1}^{N}\left(h_j I_{j,t} + b_j B_{j,t} + O_j\delta^*_{j,t}\right) \tag{1}$$

subject to the following:

{

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$$\mathrm{OI}^*_{j,t} = \mathrm{OI}_{j,t-1} - \mathrm{QS}_{j+1,j,t-LT_j} \tag{2}$$

$$I^*_{j,t} = I_{j,t-1} + \mathrm{QS}_{j+1,j,t-LT_j} \tag{3}$$

$$I_{j,t} - B_{j,t} = I^*_{j,t} - B_{j,t-1} - D_{j-1,j,t} \tag{4}$$

$$\mathrm{SUMDEM}_{j,t} = \mathrm{SUMDEM}_{j,t-1} + D_{j-1,j,t} \tag{5}$$

$$\mathrm{OI}^*_{j,t} + I_{j,t} - B_{j,t} \le s_j + M(1 - \delta^*_{j,t}) \tag{6}$$

$$\mathrm{OI}^*_{j,t} + I_{j,t} - B_{j,t} \ge s_j + 1 - M\delta^*_{j,t} \tag{7}$$

$$D_{j,j+1,t} \le \mathrm{SUMDEM}_{j,t} - \mathrm{SUMORD}_{j,t-1} + M\left(1 - \delta^*_{j,t}\right) \tag{8}$$

$$D_{j,j+1,t} \geq \text{SUMDEM}_{j,t} - \text{SUMORD}_{j,t-1} - M\left(1 - \delta^{*}_{j,t}\right) \tag{9}$$

$$D_{j,j+1,t} \leq M\delta^{*}_{j,t} \tag{10}$$

$$\text{QS}_{j,j-1,t} = I^{*}_{j,t} - I_{j,t} \tag{11}$$

$$\text{SUMORD}_{j,t} = \text{SUMORD}_{j,t-1} + D_{j,j+1,t} \tag{12}$$

$$\text{OI}_{j,t} = \text{OI}^{*}_{j,t} + D_{j,j+1,t} \tag{13}$$

}, for $j = 1, 2, \ldots, N$

$$\text{QS}_{N+1,N,t} = D_{N,N+1,t} \tag{14}$$

}, for $t = 1, 2, \ldots, T$
with initial conditions as

$$I_{j,0} = S_j, \quad \forall j \leq N \tag{15}$$

$$s_j \leq S_j, \quad \text{for } \forall j \leq N \tag{16}$$

$$\text{OI}_{j,0} = 0, \quad \forall j \leq N \tag{17}$$

$$B_{j,0} = 0, \quad \forall j \leq N \tag{18}$$

$$\text{SUMDEM}_{j,0} = 0, \quad \forall j \leq N \tag{19}$$

$$\text{SUMORD}_{j,0} = 0, \quad \forall j \leq N \tag{20}$$

$$\text{QS}_{j+1,j,t-LT_j} = 0, \quad \forall t \leq LT_j \text{ and } \forall j \leq N \tag{21}$$

$$\delta^{*}_{j,t} \in \{0,1\} \, \forall j \leq N \text{ and} \, \forall t \leq T \text{ and all other variables} \geq 0, \; \forall j \leq N \text{ and} \, \forall t \leq T. \tag{22}$$

Equation 1 shows the objective function to minimize the TSCC comprising the holding, shortage, and ordering costs for all installation over T days. Equation 2 updates the on-order inventory at j at the beginning of t. Equation 3 updates the on-hand inventory at j at the beginning of t. Equation 4 updates the on-hand inventory/backorder at j after the demand realization. This equation holds, in view of our assumption that $b_j \geq h_{j+1}$. However, if this assumption does not hold, both terms may co-exist in Eq. 4, and hence we need to have the following expressions introduced to avoid the co-existence of $I_{j,t}$ and $B_{j,t}$:

$$I_{j,t} \leq M\delta^{**}_{j,t} \text{ and } B_{j,t} \leq M(1 - \delta^{**}_{j,t}), \text{with } \delta^{*}_{j,t} \in \{0,1\}, \text{for } \forall j \leq N \text{ and } \forall t \leq T \tag{23}$$

where M denotes a large positive integer value.

Equation 5 updates the sum of demand up to t. Expressions 6 and 7 monitor inventory position at stage j (i.e., $\text{OI}^{*}_{j,t} + I_{j,t} - B_{j,t}$) and trigger the order if the end-inventory position equals or falls below the re-order level at j (and in this case $\delta^*_{j,t}$ becomes equal to one and hence $D_{j,j+1,t} = \text{SUMDEM}_{j,t} - \text{SUMORD}_{j,t-1}$, i.e., $(S_j - (I_{j,t} + \text{OI}^*_{j,t} - B_{j,t}))$; else $\delta^*_{j,t}$ becomes zero and hence $D_{j,j+1,t} = 0$, indicating no order placement. Expressions 8, 9, and 10 set the order to the upstream member accordingly (note that the order quantity equals zero if no order placement is there). Note that since we assume demands to be integers, we have '1' in Expression 7, and all variables in an optimal solution are also integers. Equation 11 shows the shipment quantity from member j to the downstream member. Equation 12 updates the sum of orders placed (or on-order inventory) at stage j up to t. Equation 13 computes the end on-order inventory at j at t. Equation 14 shows the immediate shipment of quantity from the raw material supplier (who has infinite raw material availability) to the supplier, namely, installation N. Equations 15–21 are constraints which are used for initial conditions. Equation 22 refers to the binary variable used to represent the order placement and non-negativity constraints.

3.4 Supply Chain Settings

Tables 1 and 2 show the experimental settings of the SC test problems with lead time settings and cost settings considered in this study.

We sample daily integer customer demands that are uniformly distributed between [20, 60], and treat them as known and deterministic over the finite planning horizon. We establish two different demand streams or patterns. One long stream of demands spanning over 1200 days (called FD in this study) is directly generated from a seed value through a uniform random number generator for sampling customer demands. Another long stream spanning over 1200 days (called AD in this study) of customer demands is generated by the antithetic uniform random number from the same seed value. For example, if one demand in the first run is 30, and then in the antithetic run demand equals 50 (in view of the demand distribution being U [20, 60]). The method of antithetic sampling is a commonly used procedure for negatively correlated pair of samples (Deo 1999). These demand streams are long and sufficient for substantive experiments. We assume three different deterministic lead time settings as given in Table 1. The different cost settings are assumed as follows:

Table 1 Lead time settings

Lead time setting	Lead time (in days)			
	Supplier (LT_4)	Manufacturer (LT_3)	Distributor (LT_2)	Retailer (LT_1)
LT1	1	1	1	1
LT2	2	2	2	2
LT3	3	3	3	3

Installation shortage cost rate, $b_j = C \times h_j$, where $C = 2, 4, 8, 16$; and installation ordering cost $O_j = K \times E(D) \times h_j$,

where $E(D)$ is the expected customer demand with respect to the customer demand distribution and $K = 2, 4, 8, 16$.

The rationale for this setting of O_j is that we relate the ordering cost to the setting of holding cost at stage j, and that we take the holding cost as the basis for the ordering cost because normally we deal with a SC with a very high service level (see Silver et al. 1998). See Table 2 for details of different cost settings where S, M, D, and R represent supplier, manufacturer, distributor, and retailer, respectively.

In all, we create 96 SC test problem instances in the present study (16 cost settings $\times$ 3 lead time settings $\times$ 2 demand patterns). It is to be noted that we increase the ratio of b_j/h_j with the installation order costs remaining the same (e.g., see CS1–CS4), and that we increase installation order costs with the ratio of b_j/h_j remaining the same (e.g., see CS1, CS5, CS9, and CS13). This is done in order to discover a possible pattern in the behavior of order policies (in terms of their base-stocks and re-order points) as a function of order costs and ratios of b_j/h_j.

Table 2 Supply chain settings with respect to supply chain members

Supply chain setting	Holding cost rate (h_j)				Shortage cost rate (b_j)				Ordering cost (O_j)				(C, K)
	S	M	D	R	S	M	D	R	S	M	D	R	
CS1	1	2	4	8	2	4	8	16	80	160	320	640	(2,2)
CS2	1	2	4	8	4	8	16	32	80	160	320	640	(4,2)
CS3	1	2	4	8	8	16	32	64	80	160	320	640	(8,2)
CS4	1	2	4	8	16	32	64	128	80	160	320	640	(16,2)
CS5	1	2	4	8	2	4	8	16	160	320	640	1280	(2,4)
CS6	1	2	4	8	4	8	16	32	160	320	640	1280	(4,4)
CS7	1	2	4	8	8	16	32	64	160	320	640	1280	(8,4)
CS8	1	2	4	8	16	32	64	128	160	320	640	1280	(16,4)
CS9	1	2	4	8	2	4	8	16	320	640	1280	2560	(2,8)
CS10	1	2	4	8	4	8	16	32	320	640	1280	2560	(4,8)
CS11	1	2	4	8	8	16	32	64	320	640	1280	2560	(8,8)
CS12	1	2	4	8	16	32	64	128	320	640	1280	2560	(16,8)
CS13	1	2	4	8	2	4	8	16	640	1280	2560	5120	(2,16)
CS14	1	2	4	8	4	8	16	32	640	1280	2560	5120	(4,16)
CS15	1	2	4	8	8	16	32	64	640	1280	2560	5120	(8,16)
CS16	1	2	4	8	16	32	64	128	640	1280	2560	5120	(16,16)

3.5 Results of Execution of Mathematical Model Through an Optimization Solver and the Need for Heuristic Algorithm

The proposed model considering problem instances with $T = 10$, $T = 15$, $T = 20$, $T = 25$, and $T = 30$ and with the consideration of CS1 and LT1 has been executed with CPLEX, an optimization solver, using a computer with an Intel Pentium IV processor of 3.0 GHz speed and 1 GB RAM. The solver is able to solve the problems with $T = 10$, $T = 15$, $T = 20$, and $T = 25$. When we set $T = 30$, the solver could obtain only an upper bound and not the optimal solution, and the solver could not solve this test problem even after 6 h of execution, and its execution got terminated due to its memory limitations. The base-stocks and re-order points, which lead to minimum SC costs, and the CPU times for the five test problems, are reported in Table 3, where S, M, D, and R represent supplier, manufacturer, distributor, and retailer, respectively. We have also obtained the LP-relaxed solution, i.e., a lower bound on TSCC, by relaxing the binary constraints in the mathematical programming model (i.e., by treating $\delta^*_{j,t}$'s as continuous variables in the interval (0,1)). The lower bounds thus obtained for the test problems are also reported in Table 3. As the lower bounds obtained in these problems appear to be weak, we do not consider the lower bound through the LP-relaxation in our further analyses.

Figure 2 shows the computational effort of the solver for test problems with $T = 10$, 15, 20, and 25. From Fig. 2, it can be noted that the computational time taken for obtaining solutions appears to increase exponentially. This is not unexpected due to the presence of binary variables in the mathematical programming model. Wang (2011) also presented a similar observation that when time is discrete, the large dimension of the inventory state for the exact formulation usually precludes an exact solution and hence the focus is shifted to approximate solutions. Hence, we resort to the use of a heuristic algorithm in the present study to obtain the best inventory parameters in the SC.

Table 3 Results obtained for the test problems using the solver

T	Base-stock levels				Re-order levels				TSCC	Solution status	CPU time (in s)	LP-relaxation-based lower bound
	S	M	D	R	S	M	D	R				
10	195	108	86	85	0	0	0	0	9454	Optimal	22.86	473.84
15	78	29	78	83	0	0	0	6	14148	Optimal	384.03	687.44
20	63	44	57	93	0	0	0	8	19199	Optimal	14406.41	873.44
25	49	50	57	93	0	0	0	8	23564	Optimal	50173.22	1100.24
30	799	61	320	98	0	0	0	13	49864	Upper bound	19642.69	1392.80

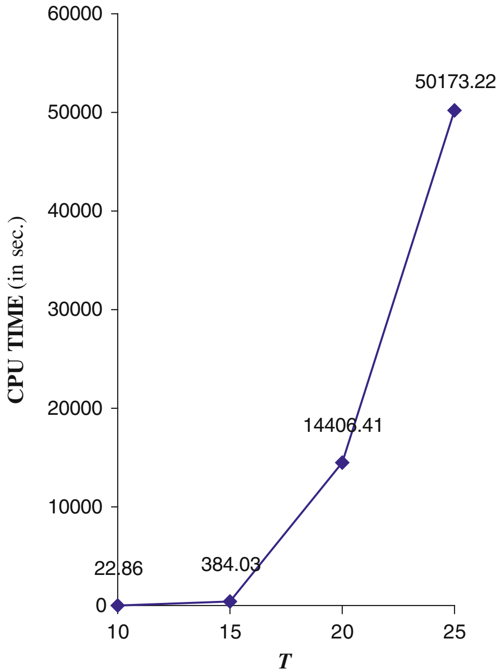

Fig. 2 Computational experience with test problems (setting CS1 + LT1)

4 Proposed Genetic Algorithms for the (*s*, *S*) Policy

GAs are search algorithms based on the mechanism of natural selection and natural genetics. Simplicity of operation and power of effect are two of the main attractions of the GA approach (Goldberg 1989). GA is applied as an optimization tool to a variety of SC problems. Attempts had been made to develop meta-heuristics such as GA for SC inventory optimization. Daniel and Rajendran (2006) developed simulation-based heuristics to obtain inventory levels (base-stock levels) in a serial SC with the objective of minimizing the total SC cost in the class of base-stock policy. They proposed GAs to determine the best base-stock levels for a serial SC, and their findings indicated the performance of GAs based on gene-wise crossover operators superior to the SA algorithm by Daniel and Rajendran (2005b). They found their GGA (gene-wise GA) to perform very well. Haq and Kannan (2006) and Kumanan et al. (2007) employed GAs for minimizing the total cost consisting of production, inventory, and distribution costs. Some applications of GAs in SCs/multi-echelon inventory systems were discussed by Berry et al. (1998), Zhou et al. (2002), Lee et al.(2002), Hong and Kim (2009), and Rom and Slotnick (2009); and Sethupathi and Rajendran (2010) considering (*T*, *S*) policy. For all these reasons, we have gone for GAs to obtain the best heuristic order policy parameters in our study in view of the well-established performance of GAs in supply-chain operations optimization. In this study, we present the modified gene-wise GA (called MGGA), and two hybrid GAs, called HGA1 and HGA2 (GAs with the hybridization of gene-wise crossover operator and arithmetic crossover operator), to determine the best installation base-stocks and re-order points in the present case of (s, S) policy. It is to be noted that our present study is different from earlier works such as those by Daniel and Rajendran (2005a, 2006) in that earlier researchers did not consider the presence of order costs and hence they did not investigate the performance of policies such as (s, S) policy.

4.1 Notations and Terminologies for the Proposed GAs

The notations and terminologies used in the proposed GAs are as follows:

no_gen	number of generations
l	length of a chromosome (or the number of genes)
pop_size	population size
n	number of chromosomes (equal to *pop_size*)
par_pop	parent population, consisting of n parent chromosomes
S_j	installation base-stock at member j, where $j = 1$ to N
s_j	installation re-order point at installation j /* it is ensured in the implementation of all GAs that $s_j \leq S_j$*/
S_j^{UL}	upper limit on the base-stock at installation j /*(set rather loose to 1,000 in this study)*/
S_j^{LL}	lower limit on the base-stock at installation j /*(set to 20 in view of demand distribution assumed in the computational experiments in this study)*/
s_j^{UL}	upper limit on the re-order point /*(set to S_j in this study)*/
s_j^{LL}	lower limit on re-order point/*(set to 0 in this study)*/
f_k	fitness value for the kth chromosome
P_k	probability of selecting chromosome k into the mating pool (relative fitness of the kth chromosome)
u	a uniform random number between 0 and 1
CR	probability of crossover or Crossover Rate (CR) /*(set to 1 in our study)*/
MR	probability of mutation or Mutation Rate (MR)
R_m	merging rate used in HGA2
P_m	merging probability used in HGA2
int_pop	intermediate population consisting of child chromosomes or offspring that are obtained from the crossover of parent chromosomes in *par_pop*
res_pop	resultant population consisting of offspring after mutation
S_j^{old}	base-stock at installation j before mutation

S_j^{new} base-stock at installation j after mutation
s_j^{old} re-order point at installation j before mutation
s_j^{new} re-order point at installation j after mutation

4.2 Mechanism of the Proposed GAs

The mechanism of MGGA, HGA1, and HGA2 is same except they vary in their respective crossover operators. All other steps are common for these three GAs.

4.2.1 Representation of a Chromosome

GA is a population-based search technique that works on a population represented by several individual chromosomes (solutions). Figure 3 shows the representation of a chromosome in our study as an example. It has eight genes of which the first four genes represent base-stocks, and the next four genes represent the corresponding re-order points of the supplier, manufacturer, distributor, and retailer, respectively. Genes 1 and 5 correspond to the supplier (representing respectively its base-stock and re-order point); genes 2 and 6 correspond to the manufacturer (representing respectively base-stock and re-order point), and so on.

4.2.2 Initialization of Population

The initial population *par_pop* is created by generating solutions randomly within limits with respect to base-stock and re-order point of the corresponding member. The lower limit on base-stock S_j^{LL} for every member j is set as their minimum

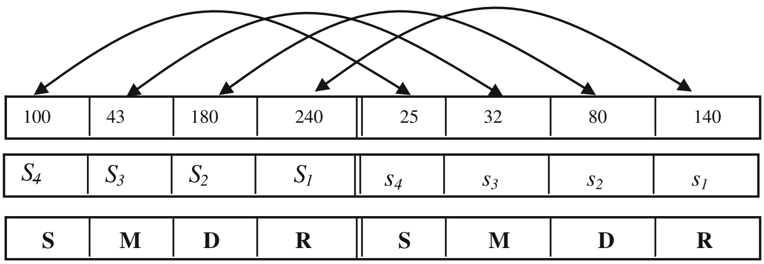

Fig. 3 Representation of the chromosome

S_4	S_3	S_2	S_1	s_4	s_3	s_2	s_1
200	95	120	245	120	40	80	125
:	:	:	:	:	:	:	:
142	66	180	125	25	15	100	65
:	:	:	:	:	:	:	:
28	48	140	320	10	22	75	180
:	:	:	:	:	:	:	:
190	85	108	127	85	24	66	19

Fig. 4 Initialization of population

customer demand which is equal to 20 in our computational experiments. The upper limit on base-stock S_j^{UL} for every member j is set as 1,000. We have fixed such a loose upper limit for base-stocks in order to test the robust performance of GAs in the large search space across all settings. The upper limit on the re-order point s_j^{UL} is set to S_j and the lower limit on re-order point s_j^{LL} is set to 0 in this study. The number of chromosomes (n) generated in the initial population, *pop_size,* is fixed as 40 (five times the length of the chromosome). For all n chromosomes, base-stocks and re-order points are generated randomly between their respective lower and upper limits. Figure 4 shows one such generated initial population.

4.2.3 Evaluation and Selection of Chromosomes for Crossover

Chromosomes in *par_pop* are evaluated through the deterministic simulation of SC using the demands sampled from the uniform distribution [20, 60] and known apriori over T days and their respective objective function values in terms of TSCC are obtained. For the sake of generality, let us use $TSCC_k$ corresponding to chromosome k. Fitness value f_k is computed for the kth chromosome by making use of the objective function value, i.e., set $f_k = 1/(1 + TSCC_k)$. Based on f_k values, the chromosomes are selected probabilistically for placement in the mating pool for crossover operation. The selection of chromosomes for the mating pool is done by using the roulette-wheel procedure (Goldberg 1989). The probability of selecting the kth chromosome from *par_pop* to the mating pool, P_k (i.e., relative fitness), is obtained by computing $\left(f_k / \sum_{k'=1}^{n} f_{k'}\right)$. Similarly, P_k's are calculated for all n chromosomes in *par_pop* and their respective cumulative probabilities are obtained.

4.2.4 Crossover Operators

We present three crossover operators in our GAs that employ arithmetic and gene-wise crossover operators either separately or in combination. The crossover rate *CR* is set to one in this study because the crossover operators are population-based crossover operators and we generate as many offspring as the number of parent chromosomes.

Modified Gene-wise Genetic Algorithm (MGGA)

The MGGA makes use of the crossover operator, called gene-wise crossover operator (see Daniel and Rajendran (2006)) that makes use of the information of genes of all the chromosomes that are present in *par_pop*, and builds an offspring out of those chromosomes. In their study, Daniel and Rajendran presented the superiority of the GGA to other crossover operators. We have chosen to adapt their GGA in our work (called the MGGA in our study) and the modified gene-wise crossover operator is explained with the example in Fig. 5. Assume that five chromosomes C1 to C5 are present in *par_pop* for the sake of illustration.

The gene-wise crossover operator constructs a child chromosome or offspring by considering the genes of all the chromosomes on the basis of its respective fitness function values. Assume that the probabilities of selection (or relative fitness values) of chromosomes (P_k) are 0.30, 0.25, 0.20, 0.15, and 0.10, respectively. Four uniform random numbers are generated because we need to construct one offspring with the first four genes representing the base-stocks and the next four corresponding genes

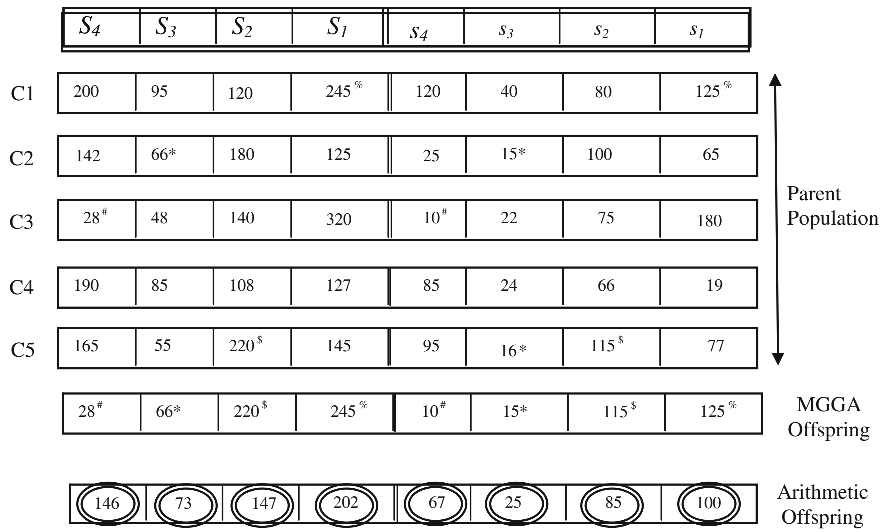

Fig. 5 An example of MGGA crossover operator and arithmetic operator with their parent population and the resultant offspring

representing re-order points. Let the random numbers be 0.61, 0.42, 0.93, and 0.14. Four parent chromosomes corresponding to these random numbers are selected as follows. The chromosome corresponding to $u = 0.61$ is chromosome C3 as seen from the cumulative probabilities of choosing chromosomes. Similarly, the chromosomes selected corresponding to the other three random numbers are chromosomes C2, C5, and C1, respectively. The offspring is now constructed gene-by-gene, by using the selected above four chromosomes in the same order. The first and fifth genes for the offspring are picked from the first selected chromosome C3, namely, {28, 10}. To construct the offspring's second and sixth genes, the second and sixth gene positions of the second selected chromosome C2 are chosen, i.e., {66, 15}. In this way we have the resultant offspring {28, 66, 220, 245, 10, 15, 115, 125}. Thus the generated offspring inherits eight genes from the four selected chromosomes in *par_pop* based on their fitness values. As the base-stock and re-order point of each member have inter-relationship ($s_j \leq S_j$), we inherit both base-stock and re-order point of a given member from the same parent into the offspring. In this way, the GGA proposed by Daniel and Rajendran (2006) is modified in our study taking into account both base-stocks and re-order points of members. The proposed gene-wise crossover operator may produce a good-quality offspring as the gene-wise crossover operator builds an offspring gene-by-gene, by making use of the fitness function values of all chromosomes in the parent population. This feature of the crossover operator leads to the generation of an offspring with proper and logical inheritance of both base-stock and re-order point from a given parent chromosome. This process is repeated until n offspring are generated.

Hybrid Genetic Algorithm 1 (HGA1)

Hybrid Genetic Algorithm 1 (HGA1) is an adapted version of the HGA proposed by Sethupathi and Rajendran (2010). In their work, Sethupathi and Rajendran employed a crossover operator using a combination of the arithmetic crossover operator and the gene-wise crossover operator to obtain the best heuristic order-up-to levels and review periods at installations. In the present work, we adapt their HGA to determine the best base-stocks and re-order points at installations. A chromosome is first obtained from the entire population by using the arithmetic crossover operator as follows. Assume that five chromosomes C1 to C5 are present in *par_pop* as shown in Fig. 5. Let the relative fitness values of these chromosomes be 0.30, 0.25, 0.20, 0.15, and 0.10. We make use of these values to construct the arithmetic offspring. The first gene in the offspring is constructed by an arithmetic operation (i.e., the first gene value of the first chromosome multiplied by its relative fitness plus the first gene value of the second chromosome multiplied by its relative fitness, and so on to obtain the first gene value of the offspring). For example, the value of first gene in the offspring is as follows:

$$((200 \times 0.3) + (142 \times 0.25) + (28 \times 0.2) + (190 \times 0.15) + (165 \times 0.1)) = 146$$

Likewise, every gene in the offspring is obtained by using this arithmetic operation on respective gene values of the respective chromosomes in *par_pop*. This offspring is placed first in the intermediate population *int_pop,* and this arithmetic chromosome is shown in Fig. 5. All the other offspring are constructed by the combination of gene-wise crossover operator and arithmetic crossover operator, as shown with examples in Fig. 6. For this, we proceed as follows: First, as per the procedure of the crossover operator in the MGGA, a chromosome is constructed by using the gene-wise crossover operator; then by selecting a set of positions, the respective arithmetic gene value gets superimposed on the gene value obtained by gene-wise crossover operator. By this procedure, we can obtain different offspring by filling up a set of genes with arithmetic crossover operator and the remaining genes by gene-wise crossover operator. For example, we can fill up one couple of positions by the arithmetic crossover operator and the remaining by the gene-wise crossover operator, and we can thus construct a total of 15 offspring in *int_pop* by the combination of both crossover operators. The remaining 25 offspring are built by using the gene-wise crossover operator presented in the MGGA. Figure 6 shows examples of thus constructed offspring by using the crossover operations in HGA1.

Hybrid Genetic Algorithm 2 (HGA2)

Hybrid Genetic Algorithm 2 (HGA2) employs a crossover operator which uses a combination of the arithmetic crossover operator and the gene-wise crossover operator. As in HGA1, a unique chromosome is first obtained from the entire population by using the arithmetic crossover operator (see Fig. 5). After the construction of a chromosome using the arithmetic crossover operator, the remaining chromosomes in *int_pop* are constructed as follows: First, a chromosome is constructed by using the gene-wise crossover operator as done in MGGA; then, every gene in this constructed chromosome is subjected to a probability of merging P_m and merging rate R_m (set as 0.25 and 0.3 respectively after a pilot study). Considering the first four genes corresponding to order quantities, one by one, a uniform random number u is generated; if u is $\leq P_m$, then the corresponding gene value will be altered as follows:

$$\text{value of new gene} = \begin{pmatrix} (R_m \times \text{ value of the gene obtained by arithmetic crossover operator}) \\ + (1 - R_m) \times (\text{value of the gene obtained by gene-wise crossover operator}) \end{pmatrix}$$

otherwise, the old gene value constructed by the gene-wise crossover operator remains. Note that the value of the re-order point is also altered if the corresponding installation's base-stock is altered. For example, let the chromosomes 3, 2, 5, and 1 be randomly selected in the gene-wise crossover operation, and four uniform random

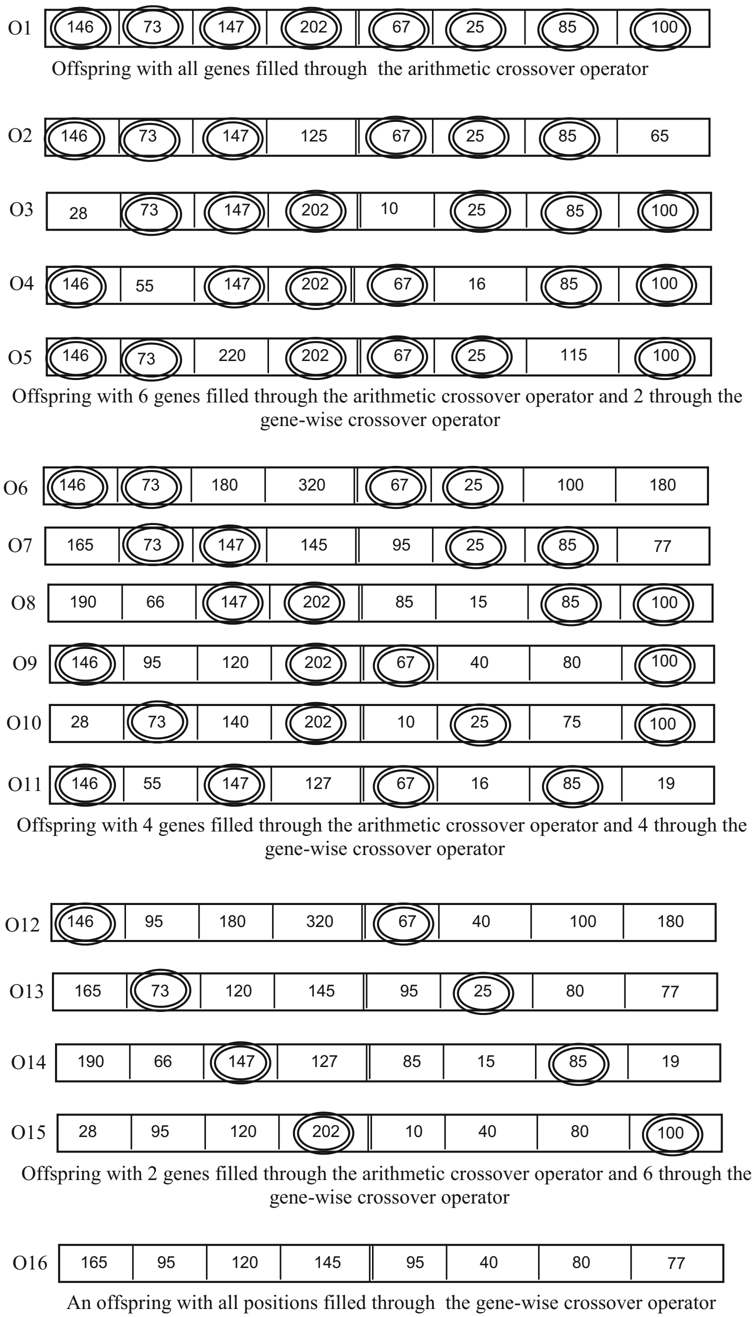

Fig. 6 Examples of the constructed offspring by the hybrid genetic algorithm 1 (HGA1)

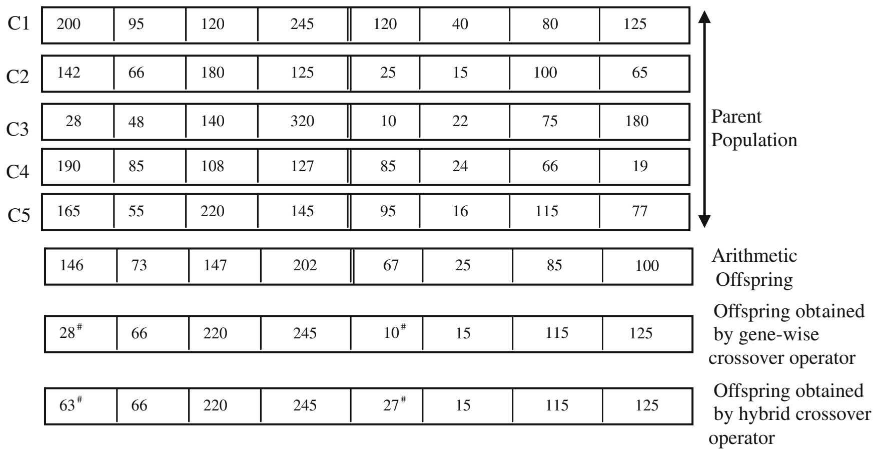

Fig. 7 An example of constructed offspring by the proposed hybrid genetic algorithm 2 (HGA2)

numbers sampled be 0.21, 0.38, 0.62, and 0.53. Gene positions 1 and 5 are altered, because the corresponding random number generated is less than or equal to P_{m} (i.e., 0.25). So the value of the first gene becomes $((0.3 \times 146) + (0.7 \times 28) = 63)$ and 5th gene becomes $((0.3 \times 67) + (0.7 \times 10) = 27)$, and the remaining genes are retained as constructed by the gene-wise crossover operator. The rationale of this approach of constructing offspring is to exploit the goodness of both arithmetic and gene-wise crossover operators. Figure 7 shows an example of the mechanism of the proposed hybrid crossover operator in HGA2. This process is repeated until all the offspring are built for *int_pop*.

4.2.5 Mutation Operation

The mutation operator used in this study is a gene-wise mutation. As the chromosomes are represented in a phenotypic manner, the first four genes are subjected to mutation with a probability of MR. When a gene is subjected to mutation, the value of the gene is altered as follows:

$$S_j^{\mathrm{new}} = \left(\min\left\{\max\left\{(S_j^{\mathrm{old}} \times (1-x)) + (S_j^{\mathrm{old}} \times 2 \times x \times u); S_j^{\mathrm{LL}}\right\}; S_j^{\mathrm{UL}}\right\}\right) \quad (24)$$

where u is a sampled uniform random number and $0 < x < 1$. We set $x = 0.2$ (after a pilot study). At the same time, we also mutate the corresponding gene containing the re-order point for that member which is altered as follows using the same u:

$$s_j^{\mathrm{new}} = \left(\min\left\{\max\left\{(s_j^{\mathrm{old}} \times (1-x)) + (s_j^{\mathrm{old}} \times 2 \times x \times u); s_j^{\mathrm{LL}}\right\}; S_j^{\mathrm{new}}\right\}\right) \quad (25)$$

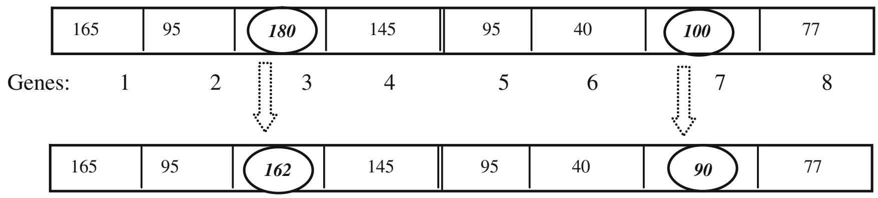

Fig. 8 Mutation operation

For example, consider the offspring shown in Fig. 8; let four random numbers be generated corresponding to the first four genes, and let them be 0.55, 0.46, 0.12, and 0.79, respectively. When the mutation rate (MR) is 0.2, the genes selected for mutation are the third gene and the seventh gene corresponding to this offspring. Again, a random number u is generated; let the value be 0.25. By using Equations 24 and 25, the values of third and seventh gene become 162 and 90, respectively. Here we use the same u that is sampled for mutating both base-stock and re-order point of the chosen installation so as to maintain proportionate perturbations in the base-stock and the corresponding re-order point. Figure 8 shows an example of how mutation is being carried out. As a result of mutation operation on the offspring in *int_pop,* we obtain the resultant pool called *res_pop.*

4.2.6 Survival of Chromosomes into the Next Generation

Now that there are n chromosomes in *par_pop* and n chromosomes in *res_pop*, we choose the best n distinct chromosomes out of these $2n$ chromosomes (present in *par_pop* and *res_pop*), on the basis of their TSCC values. The selected n distinct chromosomes become the parent chromosomes for the next generation. At the end of every generation, the best chromosome with the best TSCC value is subjected to a local search technique and updated.

4.2.7 Local Search Technique

We propose a local search on the best chromosome to enhance the convergence process. The best chromosome obtained at the end of Sect. 4.2.6 is removed from the population set and subjected to the following local search technique. We alter only one position randomly and with that generated neighborhood solution evaluate this setting of base-stocks and re-order points in the SC over the finite time horizon to find whether this neighborhood solution is better or worse than or same as that the seed solution. If the solution is better, the neighborhood solution replaces the seed solution; otherwise the seed chromosome is retained. For this purpose, a uniform random number u is generated between 0 and 1, and the couple of genes to be altered is decided as follows:

if $0 \leq u \leq 0.25$, then the gene-couple to be altered is 1 and 5;
if $0.25 < u \leq 0.50$, then the gene-couple to be altered is 2 and 6;
if $0.50 < u \leq 0.75$, then the gene-couple to be altered is 3 and 7; and
if $0.75 < u \leq 1$, then the gene-couple to be altered is 4 and 8.

Again, a uniform random number u is generated between 0 and 1, and by using Equations 24 and 25 (similar to the mutation process), the selected gene positions are altered. Then the resultant chromosome is evaluated. If its TSCC value has a better value than seed chromosome's TSCC, then the seed chromosome is replaced by the generated chromosome; otherwise the same chromosome is retained. This procedure is repeated eight times (corresponding to the length of chromosome). The final chromosome thus obtained is placed in *par_pop* for the next generation.

4.2.8 Termination

The termination criterion is fixed in terms of number of generations. After 500 generations, the algorithm is terminated and the best chromosome at the end of termination provides the best base-stocks and re-order points for respective members in the SC which lead to the minimum TSCC of the solutions generated.

4.3 Step-By-Step Procedure of the GAs for the (s, S) Policy

Step 1 Initialize *no_gen* = 0.

Step 2 Generate the initial population with the number of chromosomes (n) equal to *pop_size* ($5 \times l$), and each chromosome representing base-stocks and re-order points at N installations in the SC.

Step 3 Evaluate every chromosome in *par_pop* by evaluating them over the given finite time horizon in the SC, and hence obtain the objective function TSCC.

Step 4 Obtain the fitness value f_k for every chromosome k, selection probabilities P_k's and cumulative probabilities.

Step 5 Do crossover operator as follows to obtain *int_pop*:

(a) In the MGGA, generate n offspring, by constructing each offspring directly from the chromosomes in *par_pop* by using the modified gene-wise crossover operator.
(b) In HGA1, construct one chromosome by the arithmetic crossover operator; generate $(n - 1)$ offspring by constructing each offspring directly from the chromosomes in *par_pop* by using the combination of both gene-wise crossover operator and arithmetic crossover operator or using gene-wise crossover, as appropriate.

(c) In HGA2, construct one chromosome by the arithmetic operator; generate ($n - 1$) offspring, by constructing each offspring directly from the chromosomes in *par_pop*, with the possible combination of both gene-wise crossover operator and arithmetic crossover operator and by using the probability of merging P_{m} and merging rate R_{m}.

Step 6 Subject *n* chromosomes in *int_pop* to gene-wise mutation, with a probability of MR.

Step 7 Call the resultant *n* chromosomes as *res_pop*; Evaluate them with respect to TSCC, corresponding to every chromosome in *res_pop*.

Step 8 From both *par_pop* and *res_pop*, select the best *n* distinct chromosomes (equal to *pop_size*), based on the value of TSCC, to form *par_pop* for the next generation.

Step 9 Remove the best chromosome among *par_pop*.

Step 10 Do the proposed local search eight times on the best chromosome, and update the best chromosome, if it improves through local search, place the same chromosome in *par_pop* for the next generation.

Step 11 Increment $no\_gen = no\_gen + 1$;
If no_gen is $\leq$ 500, then return to Step 4; else proceed to Step 12.

Step 12 Stop. The best solution (i.e., the best chromosome) among the chromosomes in the final *par_pop* and its TSCC constitute the solution to the problem.

5 Performance Analysis of (*s, S*) Policy Under Consideration

As mentioned earlier, this paper attempts to determine best base-stocks and re-order points with (*s, S*) policy in a serial SC operating with deterministic demands over a finite planning horizon and make a comparative evaluation between policies, namely, periodic-review order-up-to *S* policy (i.e., (*T, S*) policy), and (*s, S*) policy. As for the determination of the optimal order-up-to *S* policy, Sethupathi and Rajendran (2010) proposed a mathematical programming model that can be executed with $T = 1200$ days, a substantive long time horizon. In view of the limitation in executing the proposed mathematical programming models for (*s, S*) policy over such a long time horizon, we present three GAs that are not constrained by such limitations even though GAs cannot guarantee optimal solutions in the respective class of inventory order policies. We can therefore compare the optimal solution from the mathematical model for order-up-to S policy and heuristic solutions from GAs in order to have an idea about the relative evaluation of the respective order policies in a serial SC.

As for SC settings, we consider the same settings presented in Sect. 3.4, with T set to 1200 days. Before embarking on this relative evaluation of control polices, we first present the details of a pilot study involving parameter settings for the MGGA in respect of (s, S) policy. We wish to state that similar observations with respect to GA parameters in HGA1 and HGA2 have been made in the case of (s, S) policy and all these details of the pilot study are not presented here for saving space.

5.1 Parameter Settings for GAs

The crossover rate CR is set to one in this study because the crossover operators are population-based crossover operators and we generate as many offspring as the number of parent chromosomes. For fixing the MR and parameter x which are used in the mutation operator, we conduct a pilot study with the consideration of the MGGA and with lead time setting LT1. As for (MR, x), we have experimented respectively with the values of (0.1, 0.1), (0.2, 0.1), (0.1, 0.2), and (0.2, 0.2); we have chosen these values as in most experiments involving GAs, MR is usually small and we have set x not to exceed 0.2 in order to search in a limited neighborhood. The TSCC values corresponding to these parameter settings with their relative percentage deviations from the best solution among them are evaluated in a pilot study. After evaluating the four settings, we have found that the setting (MR $= 0.2$, $x = 0.2$) performs the best.

As for fixing the probability of merging P_m and merging rate R_m for the case of HGA2, we have conducted a pilot study with the values of (0.2, 0.25), (0.2, 0.3), (0.25, 0.25), and (0.25, 0.3). The reasoning of these settings are as follows: since there are four genes corresponding to the base-stocks/re-order points at four installations, the probability of altering a gene's value (obtained by gene-wise crossover operator) is not to exceed 0.25; and the relative importance given to the gene values obtained by arithmetic crossover operator is set not to exceed one-third in relation to the gene-wise crossover operator as otherwise we may not have a diversity in the generated offspring. The TSCC values corresponding to the lead time setting LT1 with their relative percentage deviations from the best solution among them are evaluated. After evaluating the four settings, we have found that the setting ($P_m = 0.25$, and $R_m = 0.3$) performs the best.

5.2 *Performance of Local Search Technique in the Search Process*

We have employed a local search technique to search in the neighborhood of the best solution at the end of every generation in our GAs. The introduction of local search into the GA mechanism is seen to hasten the convergence and hence the local search technique appears effective.

5.3 *Run Length Concerning the Execution of GAs*

Almost all the three GAs converge within 50 generations which is the common phenomenon observed over all SC settings. However, we executed the GAs over 500 generations because the CPU time is in the order of few seconds only.

5.4 *Results of Execution of GAs for (s, S) Policy*

The GAs for the (*s, S*) policy have been executed with the consideration of various SC and lead time settings with $T = 1200$ days, and with two customer demand streams, namely, first demand stream (FD) and antithetic demand stream (AD). Tables 4, 5, 6, 7, 8, and 9 show the consolidated results obtained with the respective TSCC values with best base-stocks and re-order points for all members by the three GA variants, and their performance comparison. Tables 4 and 5 show the performance of the proposed GA variants with respective TSCC values, and base-stocks and re-order points in respect of lead time setting 1 (LT1) with FD and AD, respectively. Tables 6 and 7 show the performance of the GA variants with respective TSCC values, and base-stocks and re-order points in respect of lead time setting 2 (LT2) with the FD and AD demand stream, respectively. Tables 8 and 9 show the performance of the proposed GA variants with respective TSCC values, and base-stocks and re-order points in respect of lead time setting 3 (LT3) with the FD and AD demand stream, respectively.

The relative percentage deviation for a given GA variant's solution from the best GA solution is calculated as follows:

$$\text{Relative percentage deviation} = (\{(\text{TSCC}_{\text{GA}} - \text{TSCC}_{\text{best}})/(\text{TSCC}_{\text{best}})\} \times 100) \tag{26}$$

where TSCC_{GA} is the TSCC value obtained by the respective GA variant and $\text{TSCC}_{\text{best}}$ is the best TSCC obtained from the three GA variants for the particular cost and lead time settings. The computational time taken by GA variants are also reported in the tables. For every SC setting and lead time setting, the number of

Table 4 Performance of the different approaches, in respect of TSCC values, base-stocks and re-order points at different members with the lead time setting 1 (LT1) with the first demand stream (FD) using the (*s*, *S*) policy

Supply chain setting	Solution technique	Base-stocks {S, M, D, R}	Re-order points {S, M, D, R}	TSCC	Rel. % dev.	CPU time(in seconds)	SOL En.	Supply chain setting	Solution technique	Base-stocks {S, M, D, R}	Re-order points {S, M, D, R}	TSCC	Rel. % dev.	CPU time(in seconds)	SOL En.
CS1	MGGA	{56, 125, 65, 84}	{53, 10, 32, 21}	1262474	2.42	14.13	10272	CS9	MGGA	{23, 102, 66, 164}	{12, 96, 5, 0}	2420490	0	2.45	1488
(LT1)	HGA1	{55, 52, 62, 89}	{53, 40, 27, 15}	1232615	0	5.93	4128	(LT1)	HGA1	{23, 102, 66, 164}	{10, 81, 61, 0}	2420490	0	5.38	3648
	HGA2	{56, 125, 65, 84}	{32, 10, 14, 21}	1262474	2.42	15.00	10992		HGA2	{27, 108, 64, 179}	{14, 85, 5, 0}	2420700	0.01	1.45	768
CS2	MGGA	{78, 78, 79, 86}	{76, 61, 73, 23}	1449759	0	2.12	1248	CS10	MGGA	{76, 117, 82, 164}	{74, 110, 3, 0}	2918794	0.33	11.31	7968
(LT1)	HGA1	{78, 78, 79, 86}	{68, 66, 41, 23}	1449759	0	2.57	1440	(LT1)	HGA1	{70, 113, 77, 159}	{36, 88, 5, 9}	2909248	0	4.56	2880
	HGA2	{78, 64, 79, 88}	{48, 1, 41, 25}	1455079	0.37	4.64	2256		HGA2	{71, 112, 78, 158}	{49, 61, 6, 8}	2909319	0	17.01	12384
CS3	MGGA	{92, 92, 92, 95}	{90, 85, 83, 34}	1579650	0	6.99	4896	CS11	MGGA	{155, 155, 155, 140}	{78, 147, 16, 0}	3349598	4.64	6.66	4512
(LT1)	HGA1	{92, 92, 92, 95}	{43, 86, 75, 34}	1579650	0	3.96	2256	(LT1)	HGA1	{135, 135, 135, 138}	{125, 107, 44, 25}	3201355	0.01	4.41	2880
	HGA2	{92, 92, 92, 90}	{56, 51, 84, 27}	1594189	0.92	2.24	1344		HGA2	{135, 135, 135, 139}	{105, 61, 46, 26}	3201091	0	14.44	10320
CS4	MGGA	{100, 100, 100, 102}	{98, 79, 92, 41}	1668764	0	3.83	2496	CS12	MGGA	{145, 145, 145, 148}	{74, 144, 129, 35}	3312095	0	6.77	4608
(LT1)	HGA1	{100, 100, 100, 100}	{94, 78, 88, 39}	1670508	0.10	3.48	2208	(LT1)	HGA1	{145, 145, 145, 148}	{139, 111, 48, 35}	3312095	0	5.13	3264
	HGA2	{175, 100, 100, 102}	{75, 99, 51, 41}	1698479	1.78	2.65	1392		HGA2	{270, 146, 145, 148}	{111, 88, 54, 35}	3330771	0.56	20.73	10992
CS5	MGGA	{29, 73, 72, 127}	{14, 67, 36, 0}	1731981	0.05	2.71	1680	CS13	MGGA	{128, 73, 56, 257}	{127, 56, 27, 0}	3384284	0	3.19	2064
(LT1)	HGA1	{29, 69, 65, 121}	{16, 65, 4, 8}	1731087	0	10.47	7008	(LT1)	HGA1	{47, 314, 63, 239}	{22, 20, 28, 0}	3395575	0.33	10.26	7200
	HGA2	{31, 75, 68, 131}	{30, 48, 30, 4}	1731175	0.01	11.71	8400		HGA2	{128, 73, 56, 257}	{124, 39, 6, 0}	3384284	0	3.77	2496
CS6	MGGA	{84, 84, 85, 94}	{79, 65, 42, 18}	2085400	0	6.32	4368	CS14	MGGA	{60, 188, 73, 231}	{56, 147, 36, 0}	3970360	0	2.43	1440
(LT1)	HGA1	{84, 84, 85, 94}	{78, 65, 37, 18}	2085400	0	5.71	3888	(LT1)	HGA1	{61, 187, 74, 231}	{43, 103, 34, 0}	3970370	0	4.38	2880
	HGA2	{84, 84, 85, 94}	{82, 46, 35, 18}	2085400	0	2.43	1488		HGA2	{61, 187, 74, 231}	{58, 100, 5, 0}	3970370	0	4.06	2688
CS7	MGGA	{92, 92, 92, 96}	{86, 86, 85, 34}	2250332	0.52	7.50	4368	CS15	MGGA	{198, 198, 198, 190}	{121, 121, 67, 0}	4624960	1.31	5.65	3744
(LT1)	HGA1	{92, 92, 92, 96}	{85, 73, 75, 33}	2250277	0.52	3.05	1920	(LT1)	HGA1	{177, 177, 177, 181}	{112, 114, 45, 17}	4566792	0.04	3.81	2448
	HGA2	{98, 98, 98, 102}	{72, 58, 34, 28}	2238603	0	5.89	2976		HGA2	{190, 190, 190, 197}	{100, 173, 32, 18}	4565050	0	6.29	4320
CS8	MGGA	{102, 102, 102, 103}	{99, 79, 90, 40}	2341597	0	6.79	4656	CS16	MGGA	{411, 214, 214, 190}	{60, 41, 74, 0}	5056339	7.15	3.68	2304
(LT1)	HGA1	{102, 102, 102, 103}	{100, 78, 91, 40}	2341597	0	4.74	3168	(LT1)	HGA1	{362, 362, 192, 193}	{175, 130, 62, 29}	4872679	3.26	2.83	1728
	HGA2	{103, 103, 103, 101}	{58, 90, 41, 36}	2350979	0.40	7.13	4896		HGA2	{204, 204, 205, 206}	{103, 108, 55, 27}	4719010	0	4.20	2352

{*S*, *M*, *D*, *R*} {Supplier, Manufacturer, Distributor, Retailer}, *MGGA* Modified Gene-wise Genetic Algorithm, *HGA1* Hybrid Genetic Algorithm-1, *HGA2* Hybrid Genetic Algorithm-2, *SOL En.* Number of solutions enumerated to find the best solution, *Rel. % Dev.* Relative percentage deviation within the different approaches, *CPU time (in seconds)* CPU time required to obtain the best solution

Table 5 Performance of the different approaches, in respect of TSCC values, base-stocks and re-order points at different members with the lead time setting 1 (LT1) with the antithetic demand stream (AD) using the (*s*, *S*) policy

Supply chain setting	Solution technique	Base-stocks {S, M, D, R}	Re-order points {S, M, D, R}	TSCC	Rel. % dev.	CPU time (in seconds)	SOL En.	Supply chain setting	Solution technique	Base-stocks {S, M, D, R}	Re-order points {S, M, D, R}	TSCC	Rel. % dev.	CPU time (in seconds)	SOL En.
CS1	MGGA	{56, 47, 62, 83}	{28, 44, 29, 19}	1240754	0	5.80	3744	CS9	MGGA	{26, 105, 64, 167}	{13, 99, 32, 0}	2416464	0	2.40	1440
(LT1)	HGA1	{58, 46, 66, 81}	{43, 43, 25, 14}	1242656	0.15	5.02	3408	(LT1)	HGA1	{26, 105, 64, 167}	{15, 81, 31, 0}	2416464	0	2.82	1728
	HGA2	{57, 116, 66, 82}	{35, 13, 27, 18}	1269382	2.31	8.66	8448		HGA2	{26, 104, 65, 167}	{15, 62, 8, 0}	2416464	0	1.83	1392
CS2	MGGA	{76, 76, 78, 88}	{74, 60, 69, 24}	1458483	0	3.13	1872	CS10	MGGA	{75, 113, 83, 159}	{69, 104, 5, 0}	2914694	0.30	4.93	3312
(LT1)	HGA1	{76, 76, 78, 87}	{73, 45, 22, 23}	1459043	0.04	2.95	1872	(LT1)	HGA1	{67, 119, 75, 165}	{60, 92, 37, 7}	2905845	0	3.19	2016
	HGA2	{76, 76, 78, 88}	{65, 39, 27, 24}	1458483	0	2.01	1440		HGA2	{67, 119, 75, 165}	{63, 83, 18, 7}	2905845	0	4.53	4080
CS3	MGGA	{86, 86, 86, 89}	{80, 67, 77, 34}	1586585	0	5.51	3696	CS11	MGGA	{155, 155, 154, 139}	{143, 146, 15, 0}	3341346	4.50	16.90	12048
(LT1)	HGA1	{86, 86, 86, 89}	{84, 66, 75, 34}	1586585	0	3.28	2112	(LT1)	HGA1	{142, 142, 142, 144}	{105, 38, 75, 21}	3197606	0	2.69	1584
	HGA2	{86, 86, 86, 88}	{45, 47, 40, 33}	1586921	0.02	4.72	2400		HGA2	{142, 142, 142, 140}	{82, 108, 26, 15}	3210656	0.41	7.11	6720
CS4	MGGA	{94, 94, 94, 94}	{92, 72, 85, 39}	1671642	0	3.48	2208	CS12	MGGA	{145, 145, 145, 147}	{63, 113, 129, 33}	3321356	0	11.68	7056
(LT1)	HGA1	{94, 94, 94, 94}	{51, 74, 86, 39}	1671642	0	2.45	1488	(LT1)	HGA1	{145, 145, 145, 147}	{50, 111, 44, 33}	3321356	0	6.51	4416
	HGA2	{102, 102, 102, 103}	{67, 56, 42, 39}	1699639	1.67	1.95	1536		HGA2	{269, 145, 145, 147}	{107, 79, 58, 33}	3342001	0.62	22.66	22128
CS5	MGGA	{26, 183, 77, 114}	{10, 10, 37, 0}	1767358	2.19	13.25	9120	CS13	MGGA	{60, 80, 56, 272}	{31, 76, 27, 0}	3379794	0	2.81	1728
(LT1)	HGA1	{27, 73, 69, 123}	{15, 57, 32, 2}	1729407	0	3.82	2496	(LT1)	HGA1	{47, 306, 62, 234}	{21, 24, 19, 0}	3393434	0.40	10.58	7200
	HGA2	{29, 72, 70, 121}	{27, 67, 4, 0}	1731265	0.11	1.97	1440		HGA2	{60, 80, 56, 272}	{55, 63, 12, 0}	3379794	0	1.89	1392
CS6	MGGA	{86, 86, 87, 98}	{81, 52, 43, 18}	2087041	0.08	8.19	4368	CS14	MGGA	{60, 190, 72, 234}	{58, 150, 36, 0}	3964442	0	3.32	2112
(LT1)	HGA1	{86, 86, 87, 98}	{82, 67, 38, 18}	2087041	0.08	3.04	1824	(LT1)	HGA1	{61, 189, 72, 234}	{47, 118, 25, 0}	3964430	0	5.18	3456
	HGA2	{91, 118, 92, 99}	{80, 8, 42, 19}	2085283	0	3.05	2688		HGA2	{61, 189, 72, 234}	{28, 114, 4, 0}	3964430	0	8.82	8448
CS7	MGGA	{94, 94, 94, 97}	{92, 72, 84, 30}	2252113	0.02	8.95	6288	CS15	MGGA	{190, 190, 190, 180}	{186, 116, 55, 0}	4620248	1.27	3.21	2016
(LT1)	HGA1	{108, 108,108, 112}	{105, 85, 59, 30}	2255693	0.18	2.69	1632	(LT1)	HGA1	{190, 190, 190, 195}	{134, 10, 25, 15}	4562360	0	16.38	11616
	HGA2	{101, 101, 101, 105}	{58, 62, 56, 29}	2251563	0	4.18	2064		HGA2	{190, 190, 190, 195}	{114, 102, 45, 15}	4562360	0	3.28	2784
CS8	MGGA	{103, 103, 103, 104}	{102, 81, 92, 37}	2360495	0	9.47	6576	CS16	MGGA	{219, 219, 218, 194}	{80, 218, 138, 0}	5000461	6.0	3.15	1968
(LT1)	HGA1	{183, 102, 102, 104}	{63, 55, 90, 39}	2371349	0.46	5.09	3408	(LT1)	HGA1	{362, 191, 191, 193}	{135, 189, 30, 30}	4738642	0.41	9.13	6288
	HGA2	{117, 117, 117, 114}	{80, 87, 56, 32}	2376583	0.68	5.90	5472		HGA2	{206, 206, 206, 205}	{115, 107, 68, 25}	4719524	0	7.79	7296

{*S*, *M*, *D*, *R*} {Supplier, Manufacturer, Distributor, Retailer}, *MGGA* Modified Gene-wise Genetic Algorithm, *HGA1* Hybrid Genetic Algorithm-1, *HGA2* Hybrid Genetic Algorithm-2, *SOL En*. Number of solutions enumerated to find the best solution, *Rel. % Dev*. Relative percentage deviation within the different approaches, *CPU time (in seconds)* CPU time required to obtain the best solution

Table 6 Performance of the different approaches, in respect of TSCC values, base-stocks and re-order points at different members with the lead time setting 2 (LT2) with the first demand stream (FD) using the (*s*, *S*) policy

Supply chain setting	Solution technique	Base-stocks {S, M, D, R}	Re-order points {S, M, D, R}	TSCC	Rel. % dev.	CPU time (in seconds)	SOL En.	Supply chain setting	Solution technique	Base-stocks {S, M, D, R}	Re-order points {S, M, D, R}	TSCC	Rel. % dev.	CPU time (in seconds)	SOL En.
CS1	MGGA	{95, 97, 95, 121}	{93, 76, 85, 55}	1160293	0	4.25	2736	CS9	MGGA	{132, 81, 148, 186}	{121, 64, 16, 0}	2490912	2.71	13.88	8976
(LT2)	HGA1	{95, 97, 95, 121}	{85, 75, 48, 55}	1160293	0	5.44	3744	(LT2)	HGA1	{116, 80, 122, 195}	{77, 63, 65, 31}	2425106	0	19.66	14208
	HGA2	{94, 98, 96, 120}	{74, 48, 84, 52}	1161689	0.12	2.68	2208		HGA2	{115, 81, 122, 195}	{74, 42, 52, 31}	2425116	0	19.61	19584
CS2	MGGA	{104, 107, 105, 135}	{97, 86, 93, 61}	1292146	2.25	3.45	2160	CS10	MGGA	{143, 146, 140, 174}	{139, 115, 47, 51}	2805508	0	7.05	4464
(LT2)	HGA1	{189, 105, 106, 130}	{68, 83, 86, 59}	1324509	4.81	3.84	2400	(LT2)	HGA1	{143, 146, 140, 174}	{71, 113, 38, 51}	2805508	0	5.16	3456
	HGA2	{98, 100, 99, 130}	{47, 50, 73, 69}	1263679	0	19.12	19392		HGA2	{143, 146, 140, 170}	{105, 78, 47, 47}	2809068	0.13	2.89	2400
CS3	MGGA	{109, 110, 109, 142}	{107, 66, 101, 71}	1392565	2.53	3.05	1632	CS11	MGGA	{213, 213, 214, 152}	{77, 119, 73, 68}	3235280	9.48	12.11	6720
(LT2)	HGA1	{103, 103, 103, 141}	{62, 97, 80, 80}	1358145	0	2.66	1584	(LT2)	HGA1	{150, 151, 150, 183}	{148, 114, 74, 64}	2955200	0	4.27	2784
	HGA2	{103, 103, 103, 141}	{54, 93, 54, 80}	1358145	0	3.55	3168		HGA2	{275, 148, 144, 181}	{111, 82, 82, 68}	2985629	1.03	3.56	2784
CS4	MGGA	{116, 115, 116, 148}	{113, 89, 104, 74}	1505806	5.38	15.90	9216	CS12	MGGA	{351, 186, 186, 216}	{154, 183, 83, 67}	3224856	0	18.71	10080
(LT2)	HGA1	{107, 107, 107, 148}	{105, 99, 94, 87}	1428967	0	2.73	1680	(LT2)	HGA1	{252, 253, 253, 175}	{122, 169, 103, 79}	3391258	5.16	4.44	2928
	HGA2	{280, 107, 107, 148}	{73, 82, 67, 87}	1509804	5.66	9.12	4416		HGA2	{228, 228, 229, 162}	{108, 120, 75, 78}	3386104	5.00	5.92	3072
CS5	MGGA	{78, 124, 170, 127}	{40, 117, 17, 56}	1843996	5.58	7.25	4512	CS13	MGGA	{29, 135, 139, 257}	{16, 104, 124, 0}	3420768	0.13	2.66	1584
(LT2)	HGA1	{110, 112, 115, 141}	{69, 78, 48, 44}	1748986	0.14	3.51	2256	(LT2)	HGA1	{29, 135, 139, 257}	{16, 104, 23, 0}	3420768	0.13	2.89	1632
	HGA2	{109, 112, 112, 145}	{67, 100, 97, 49}	1746523	0	4.53	4080		HGA2	{29, 143, 130, 265}	{28, 85, 34, 8}	3416216	0	3.94	3408
CS6	MGGA	{113, 114, 113, 144}	{111, 89, 101, 60}	1900822	0	15.57	9360	CS14	MGGA	{201, 77, 203, 223}	{55, 45, 31, 0}	4291938	3.94	8.45	5616
(LT2)	HGA1	{170, 187, 105, 135}	{116, 75, 94, 61}	1986028	4.48	6.97	4800	(LT2)	HGA1	{192, 192, 192, 224}	{108, 165, 24, 36}	4129102	0	3.16	1968
	HGA2	{113, 114, 113, 144}	{56, 88, 85, 60}	1900822	0	19.21	19104		HGA2	{192, 192, 192, 223}	{135, 112, 65, 35}	4129422	0.01	3.02	2352
CS7	MGGA	{121, 122, 120, 154}	{117, 95, 110, 70}	2028180	0	3.74	2016	CS15	MGGA	{192, 192, 192, 225}	{118, 34, 28, 58}	4328618	0	26.94	18816
(LT2)	HGA1	{121, 122, 120, 153}	{53, 114, 100, 69}	2028228	0	2.99	1872	(LT2)	HGA1	{192, 192, 192, 225}	{85, 108, 81, 58}	4328618	0	12.40	8736
	HGA2	{197, 111, 111, 142}	{79, 64, 43, 68}	2032496	0.21	15.19	7968		HGA2	{214, 214, 214, 236}	{140, 45, 70, 48}	4356324	0.64	4.31	1824
CS8	MGGA	{222, 129, 126, 161}	{51, 93, 79, 78}	2175005	0	6.94	3120	CS16	MGGA	{402, 207, 213, 249}	{180, 30, 152, 72}	4524178	1.61	13.18	9120
(LT2)	HGA1	{197, 197, 199, 151}	{121, 137, 88, 78}	2357094	8.37	28.62	20784	(LT2)	HGA1	{377, 198, 198, 235}	{167, 196, 84, 71}	4481540	0.66	16.31	11616
	HGA2	{181, 182, 110, 150}	{112, 90, 48, 84}	2204878	1.37	9.30	8784		HGA2	{198, 198, 198, 235}	{105, 185, 63, 71}	4452336	0	5.49	4944

{*S*, *M*, *D*, *R*} {Supplier, Manufacturer, Distributor, Retailer}, *MGGA* Modified Gene-wise Genetic Algorithm, *HGA1* Hybrid Genetic Algorithm-1, *HGA2* Hybrid Genetic Algorithm-2, *SOL En*. Number of solutions enumerated to find the best solution, *Rel. % Dev*. Relative percentage deviation within the different approaches, *CPU time (in seconds)* CPU time required to obtain the best solution

Table 7 Performance of the different approaches, in respect of TSCC values, base-stocks and re-order points at different members with the lead time setting 2 (LT2) with the antithetic demand stream (AD) using the (*s*, *S*) policy

Supply chain setting	Solution technique	Base-stocks {S, M, D, R}	Re-order points {S, M, D, R}	TSCC	Rel. % dev.	CPU time (in seconds)	SOL En.	Supply chain setting	Solution technique	Base-stocks {S, M, D, R}	Re-order points {S, M, D, R}	TSCC	Rel. % dev.	CPU time (in seconds)	SOL En.
CS1	MGGA	{94, 98, 95, 118}	{92, 77, 87, 53}	1159704	0	3.04	1920	CS9	MGGA	{132, 80, 148, 187}	{123, 75, 15, 0}	2483804	2.51	2.40	1392
(LT2)	HGA1	{94, 98, 96, 117}	{87, 76, 86, 52}	1160244	0.05	2.63	1584	(LT2)	HGA1	{111, 86, 117, 195}	{104, 65, 98, 31}	2423126	0.01	12.56	8880
	HGA2	{94, 98, 95, 118}	{93, 91, 32, 53}	1159704	0	2.47	1920		HGA2	{112, 85, 118, 194}	{80, 50, 45, 30}	2422974	0	12.97	12576
CS2	MGGA	{103, 105, 103, 131}	{101, 84, 94, 59}	1291230	1.56	3.23	1920	CS10	MGGA	{179, 239, 126, 161}	{176, 65, 115, 59}	2940405	4.87	15.14	10368
(LT2)	HGA1	{100, 101, 100, 128}	{96, 80, 87, 64}	1271446	0	3.21	2016	(LT2)	HGA1	{143, 145, 141, 174}	{90, 113, 87, 49}	2803990	0	4.52	2976
	HGA2	{103, 102, 102, 125}	{53, 65, 90, 58}	1284596	1.03	4.56	4128		HGA2	{143, 145, 141, 174}	{93, 84, 54, 49}	2803990	0	13.82	13584
CS3	MGGA	{106, 106, 106, 134}	{100, 70, 95, 67}	1397560	2.18	6.39	4272	CS11	MGGA	{210, 210, 215, 149}	{131, 142, 74, 68}	3206676	7.99	3.55	2064
(LT2)	HGA1	{171, 179, 104, 139}	{97, 80, 81, 78}	1495958	9.38	2.63	1584	(LT2)	HGA1	{251, 139, 135, 170}	{91, 104, 122, 68}	3009665	1.36	16.74	11232
	HGA2	{105, 105, 104, 140}	{97, 104, 64, 76}	1367716	0	2.49	2064		HGA2	{146, 147, 144, 181}	{92, 82, 124, 67}	2969288	0	2.92	2208
CS4	MGGA	{114, 114, 115, 143}	{111, 80, 101, 71}	1532334	5.38	3.45	2064	CS12	MGGA	{415, 224, 225, 161}	{185, 150, 92, 79}	3434724	9.84	31.25	22512
(LT2)	HGA1	{109, 108, 109, 147}	{107, 101, 96, 83}	1454086	0	11.70	8352	(LT2)	HGA1	{250, 250, 251, 173}	{183, 134, 87, 78}	3401776	8.79	3.18	2256
	HGA2	{109, 109, 109, 147}	{66, 69, 63, 83}	1454086	0	2.92	2064		HGA2	{258, 144, 143, 179}	{115, 96, 90, 77}	3126982	0	7.13	5760
CS5	MGGA	{109, 113, 110, 143}	{100, 103, 102, 48}	1747675	0	20.15	14064	CS13	MGGA	{32, 137, 138, 259}	{18, 109, 126, 0}	3427836	0.15	3.20	2016
(LT2)	HGA1	{109, 113, 111, 142}	{91, 85, 48, 47}	1747723	0	2.36	1392	(LT2)	HGA1	{40, 142, 125, 262}	{28, 106, 26, 12}	3422756	0	2.97	1824
	HGA2	{108, 114, 110, 143}	{67, 93, 79, 48}	1747672	0	7.99	7728		HGA2	{101, 138, 121, 255}	{94, 78, 59, 16}	3427866	0.15	12.31	12000
CS6	MGGA	{113, 114, 113, 144}	{111, 90, 101, 62}	1898080	0	5.56	3696	CS14	MGGA	{76, 358, 196, 191}	{73, 119, 21, 0}	4323456	4.89	35.00	23376
(LT2)	HGA1	{118, 117, 116, 143}	{105, 104, 89, 55}	1906080	0.42	2.88	1776	(LT2)	HGA1	{192, 191, 191, 223}	{152, 150, 27, 36}	4121822	0	2.63	1584
	HGA2	{113, 114, 113, 144}	{88, 60, 76, 62}	1898080	0	2.17	1728		HGA2	{191, 191, 191, 222}	{134, 103, 45, 35}	4122182	0.01	2.21	1728
CS7	MGGA	{118, 118, 118, 149}	{115, 117, 108, 68}	2017472	0	5.79	3744	CS15	MGGA	{188, 188, 188, 224}	{140, 82, 26, 60}	4336532	0.06	17.97	11280
(LT2)	HGA1	{217, 120, 118, 150}	{80, 92, 50, 69}	2039543	1.09	10.05	7056	(LT2)	HGA1	{194, 194, 194, 227}	{69, 34, 87, 60}	4333738	0	7.70	5280
	HGA2	{181, 105, 104, 139}	{78, 104, 85, 75}	2045619	1.40	13.53	13392		HGA2	{211, 211, 211, 235}	{141, 120, 70, 48}	4338776	0.12	4.93	4512
CS8	MGGA	{196, 196, 193, 150}	{192, 152, 79, 80}	2386342	11.11	28.80	20784	CS16	MGGA	{216, 216, 212, 252}	{134, 145, 32, 72}	4496444	0.58	21.28	13824
(LT2)	HGA1	{196, 196, 197, 150}	{117, 172, 83, 80}	2380510	10.84	7.97	7632	(LT2)	HGA1	{372, 199, 199, 234}	{167, 192, 72, 70}	4496856	0.59	9.29	6240
	HGA2	{130, 130, 130, 161}	{127, 123, 118, 73}	2147752	0	3.23	1824		HGA2	{202, 202, 202, 238}	{93, 119, 108, 71}	4470316	0	8.00	7488

{*S*, *M*, *D*, *R*} {Supplier, Manufacturer, Distributor, Retailer}, *MGGA* Modified Gene-wise Genetic Algorithm, *HGA1* Hybrid Genetic Algorithm-1, *HGA2* Hybrid Genetic Algorithm-2, *SOL En*. Number of solutions enumerated to find the best solution, *Rel. % Dev*. Relative percentage deviation within the different approaches, *CPU time (in seconds)* CPU time required to obtain the best solution

Table 8 Performance of the different approaches, in respect of TSCC values, base-stocks and re-order points at different members with the lead time setting 3 (LT3) with the first demand stream (FD) using the (*s*, *S*) policy

Supply chain setting	Solution technique	Base-stocks {S, M, D, R}	Re-order points {S, M, D, R}	TSCC	Rel. % dev.	CPU time (in seconds)	SOL En.	Supply chain setting	Solution technique	Base-stocks {S, M, D, R}	Re-order points {S, M, D, R}	TSCC	Rel. % dev.	CPU time (in seconds)	SOL En.
CS1	MGGA	{141, 143, 141, 193}	{130, 113, 122, 80}	1131416	0	13.05	9408	CS9	MGGA	{158, 158, 160, 201}	{146, 96, 101, 64}	2398797	0.30	6.82	4512
(LT3)	HGA1	{141, 144, 143, 175}	{84, 110, 30, 62}	1164298	2.91	14.10	7488	(LT3)	HGA1	{157, 159, 157, 210}	{138, 134, 72, 73}	2391652	0	3.79	2016
	HGA2	{141, 143, 141, 193}	{81, 89, 100, 80}	1131416	0	10.53	10464		HGA2	{157, 159, 157, 210}	{99, 89, 86, 73}	2391652	0	7.01	6576
CS2	MGGA	{148, 147, 147, 207}	{138, 98, 94, 94}	1282426	0	7.94	4368	CS10	MGGA	{151, 152, 150, 210}	{140, 122, 95, 91}	2549510	0	13.33	7632
(LT3)	HGA1	{148, 147, 147, 207}	{136, 138, 55, 94}	1282426	0	4.10	2160	(LT3)	HGA1	{178, 179, 177, 226}	{70, 109, 87, 76}	2622960	2.88	7.21	4944
	HGA2	{148, 147, 147, 207}	{111, 84, 63, 94}	1282426	0	12.76	12480		HGA2	{166, 166, 164, 223}	{61, 95, 93, 88}	2578870	1.15	2.76	2304
CS3	MGGA	{288, 156, 155, 217}	{130, 148, 99, 101}	1511206	6.76	3.42	1920	CS11	MGGA	{156, 157, 157, 221}	{97, 124, 144, 102}	2683438	0.06	2.76	1488
(LT3)	HGA1	{285, 152, 153, 211}	{119, 92, 139, 98}	1509697	6.65	12.98	9120	(LT3)	HGA1	{156, 157, 156, 222}	{90, 113, 96, 103}	2681954	0	3.76	2256
	HGA2	{152, 152, 152, 219}	{81, 89, 80, 106}	1415521	0	2.31	1584		HGA2	{293, 158, 156, 226}	{126, 103, 95, 107}	2709617	1.03	4.44	3984
CS4	MGGA	{297, 159, 158, 231}	{134, 151, 99, 115}	1610888	6.02	3.52	2016	CS12	MGGA	{177, 178, 177, 251}	{108, 107, 126, 116}	2847567	1.26	3.36	2112
(LT3)	HGA1	{161, 161, 160, 234}	{99, 95, 70, 115}	1545372	1.71	11.51	7968	(LT3)	HGA1	{203, 203, 202, 279}	{114, 122, 149, 115}	2935495	4.39	3.78	2448
	HGA2	{155, 155, 155, 233}	{89, 93, 101, 120}	1519424	0	12.44	12336		HGA2	{298, 161, 160, 236}	{129, 141, 76, 117}	2812082	0	3.22	2784
CS5	MGGA	{141, 143, 141, 193}	{138, 112, 129, 80}	1559816	0	16.89	10272	CS13	MGGA	{189, 101, 196, 285}	{112, 79, 21, 28}	3400310	0.49	2.31	1392
(LT3)	HGA1	{141, 143, 142, 191}	{123, 110, 82, 78}	1560348	0.03	2.60	1584	(LT3)	HGA1	{172, 118, 178, 303}	{154, 50, 111, 46}	3383694	0	42.17	23664
	HGA2	{141, 143, 141, 193}	{104, 71, 81, 80}	1559816	0	7.71	7488		HGA2	{169, 121, 176, 305}	{106, 81, 43, 48}	3384230	0.02	23.55	23568
CS6	MGGA	{148, 147, 147, 207}	{136, 116, 92, 94}	1710826	0	5.09	3168	CS14	MGGA	{201, 203, 199, 261}	{124, 124, 59, 82}	3878515	0	4.78	3168
(LT3)	HGA1	{152, 154, 153, 190}	{80, 153, 32, 69}	1825025	6.68	41.50	23184	(LT3)	HGA1	{201, 203, 199, 259}	{103, 56, 64, 80}	3878835	0.01	9.72	6720
	HGA2	{148, 147, 147, 207}	{69, 83, 95, 94}	1710826	0	12.60	12480		HGA2	{201, 203, 199, 261}	{129, 104, 53, 82}	3878515	0	6.43	6000
CS7	MGGA	{152, 152, 152, 223}	{94, 85, 96, 110}	1841857	0	5.31	3168	CS15	MGGA	{230, 230, 229, 293}	{144, 217, 79, 94}	4095436	1.07	6.74	4608
(LT3)	HGA1	{155, 155, 155, 217}	{96, 102, 105, 101}	1856621	0.80	10.56	7488	(LT3)	HGA1	{212, 212, 211, 272}	{139, 168, 52, 93}	4061339	0.23	7.84	5328
	HGA2	{152, 152, 152, 223}	{91, 96, 93, 110}	1841857	0	8.04	7776		HGA2	{212, 212, 211, 279}	{96, 119, 106, 100}	4052147	0	4.90	4320
CS8	MGGA	{159, 159, 158, 232}	{101, 125, 100, 116}	1953151	0.27	9.28	5520	CS16	MGGA	{255, 255, 255, 319}	{159, 153, 184, 101}	4288635	1.61	10.72	7488
(LT3)	HGA1	{161, 161, 161, 223}	{81, 96, 134, 104}	2024148	3.92	11.11	7584	(LT3)	HGA1	{418, 219, 218, 290}	{186, 148, 162, 111}	4220558	0	16.81	12000
	HGA2	{155, 155, 155, 233}	{85, 81, 97, 120}	1947824	0	6.90	6000		HGA2	{472, 245, 245, 311}	{216, 153, 86, 105}	4334670	2.70	18.14	17712

{*S*, *M*, *D*, *R*} {Supplier, Manufacturer, Distributor, Retailer}, *MGGA* Modified Gene-wise Genetic Algorithm, *HGA1* Hybrid Genetic Algorithm-1, *HGA2* Hybrid Genetic Algorithm-2, *SOL En*. Number of solutions enumerated to find the best solution, *Rel. % Dev*. Relative percentage deviation within the different approaches, *CPU time (in seconds)* CPU time required to obtain the best solution

Table 9 Performance of the different approaches, in respect of TSCC values, base-stocks and re-order points at different members with the lead time setting 3 (LT3) with the antithetic demand stream (AD) using the (*s*, *S*) policy

Supply chain setting	Solution technique	Base-stocks {S, M, D, R}	Re-order points {S, M, D, R}	TSCC	Rel. % dev.	CPU time (in seconds)	SOL En.	Supply chain setting	Solution technique	Base-stocks {S, M, D, R}	Re-order points {S, M, D, R}	TSCC	Rel. % dev.	CPU time (in seconds)	SOL En.
CS1	MGGA	{141, 143, 143, 191}	{130, 111, 131, 79}	1156468	0.88	14.18	10272	CS9	MGGA	{156, 159, 157, 201}	{146, 96, 45, 64}	2387865	0.19	2.46	1488
(LT3)	HGA1	{141, 143, 143, 191}	{127, 91, 127, 79}	1156468	0.88	6.87	4800	(LT3)	HGA1	{156, 159, 158, 199}	{104, 119, 23, 62}	2390349	0.30	6.59	4512
	HGA2	{142, 143, 143, 181}	{119, 105, 46, 68}	1146424	0	6.99	3216		HGA2	{156, 159, 155, 209}	{91, 88, 47, 72}	2383241	0	5.57	4944
CS2	MGGA	{147, 148, 147, 207}	{91, 82, 92, 95}	1327737	2.96	3.25	1968	CS10	MGGA	{260, 280, 150, 212}	{162, 123, 93, 95}	2727575	6.55	7.51	4992
(LT3)	HGA1	{147, 148, 147, 204}	{78, 115, 92, 92}	1329817	3.12	5.91	4032	(LT3)	HGA1	{288, 156, 152, 215}	{116, 119, 95, 93}	2593838	1.33	10.07	7056
	HGA2	{147, 147,148, 201}	{106, 115, 82, 88}	1289576	0	3.42	3648		HGA2	{157, 157, 153, 216}	{110, 92, 56, 91}	2559789	0	8.84	7920
CS3	MGGA	{154, 154, 154, 224}	{141, 145, 127, 111}	1487303	3.36	3.04	1872	CS11	MGGA	{215, 216, 215, 265}	{134, 205, 179, 83}	2964752	9.71	5.72	3840
(LT3)	HGA1	{161, 161, 161, 227}	{85, 151, 80, 106}	1501187	4.32	2.49	1488	(LT3)	HGA1	{163, 163, 162, 228}	{118, 127, 102, 103}	2702244	0	4.11	2688
	HGA2	{155, 155, 155, 217}	{76, 91, 125, 101}	1439021	0	3.94	3312		HGA2	{174, 174, 172, 228}	{103, 119, 86, 91}	2744701	1.57	12.50	6144
CS4	MGGA	{166, 166, 165, 240}	{102, 157, 104, 119}	1618965	5.11	3.21	2016	CS12	MGGA	{329, 177, 176, 249}	{141, 133, 111, 115}	2881811	1.64	29.12	20976
(LT3)	HGA1	{166, 166, 166, 237}	{87, 158, 99, 116}	1621473	5.27	10.76	6960	(LT3)	HGA1	{177, 177, 177, 249}	{79, 101, 147, 115}	2835294	0	3.21	2016
	HGA2	{159, 159, 158, 230}	{94, 80, 109, 114}	1540287	0	5.04	13536		HGA2	{303, 167, 165, 240}	{135, 97, 105, 119}	2865521	1.07	3.31	2832
CS5	MGGA	{141, 143, 143, 191}	{139, 113, 39, 79}	1588468	0	12.53	8880	CS13	MGGA	{147, 131, 151, 314}	{35, 76, 36, 84}	3480987	2.35	33.08	23856
(LT3)	HGA1	{145, 148, 146, 197}	{127, 116, 96, 76}	1595345	0.43	3.54	2160	(LT3)	HGA1	{165, 125, 172, 308}	{103, 118, 48, 49}	3401291	0.01	31.81	22944
	HGA2	{141, 143, 143, 191}	{83, 77, 94, 79}	1588468	0	5.05	4656		HGA2	{167, 123, 173, 307}	{103, 57, 38, 48}	3401117	0	5.30	4800
CS6	MGGA	{151, 152, 149, 213}	{149, 102, 50, 96}	1759692	0.08	6.08	4176	CS14	MGGA	{208, 211, 205, 262}	{76, 200, 71, 75}	3867092	0	11.32	7728
(LT3)	HGA1	{157, 157, 155, 207}	{96, 105, 98, 82}	1777353	1.08	2.68	1680	(LT3)	HGA1	{208, 211, 205, 262}	{120, 47, 60, 75}	3867092	0	6.43	4368
	HGA2	{147, 148, 147, 209}	{116, 95, 87, 96}	1758359	0	3.13	2736		HGA2	{208, 211, 205, 262}	{119, 105, 71, 75}	3867092	0	3.82	3360
CS7	MGGA	{161, 161, 161, 226}	{100, 90, 103, 105}	1906283	0	3.77	1920	CS15	MGGA	{219, 219, 217, 275}	{80, 124, 73, 88}	4064763	0	6.40	4272
(LT3)	HGA1	{293, 162, 161, 226}	{120, 105, 132, 105}	1964041	3.03	4.37	2784	(LT3)	HGA1	{421, 221, 217, 279}	184, 39, 142, 92	4106849	1.04	23.23	12624
	HGA2	{294, 159, 157, 225}	{116, 86, 79, 108}	1964332	3.05	3.96	1632		HGA2	{219, 219, 217, 275}	{92, 83, 72, 88}	4064763	0	3.96	3504
CS8	MGGA	{232, 169, 169, 168}	{105, 159, 76, 107}	2055043	0.26	3.33	2112	CS16	MGGA	{249, 249, 249, 307}	{154, 167, 209, 97}	4305884	1.32	6.42	4320
(LT3)	HGA1	{169, 169, 168, 233}	{163, 102, 104, 108}	2049683	0	4.17	2736	(LT3)	HGA1	{244, 244, 244, 311}	{142, 162, 174, 106}	4249953	0	8.73	5904
	HGA2	{303, 167, 166, 238}	{135, 100, 106, 117}	2084053	1.68	9.09	8784		HGA2	{468, 244, 244, 303}	{217, 168, 76, 98}	4347356	2.29	22.11	21696

{*S*, *M*, *D*, *R*} {Supplier, Manufacturer, Distributor, Retailer}, *MGGA* Modified Gene-wise Genetic Algorithm, *HGA1* Hybrid Genetic Algorithm-1, *HGA2* Hybrid Genetic Algorithm-2, *SOL En*. Number of solutions enumerated to find the best solution, *Rel. % Dev*. Relative percentage deviation within the different approaches, *CPU time (in seconds)* CPU time required to obtain the best solution

solutions enumerated by the respective GA variant to obtain the best solution is also given in the tables. The average relative percentage deviation with respect to every GA variant across all the SC setting and lead time setting are found, and reported in Table 10. From the results, we find that HGA2 performs very well with an average relative percentage of only 0.455 %, when compared with HGA1 with an average relative percentage of 1.18 %, and MGGA with an average relative percentage of 1.747 %.

We find that as the ratio of (b_j/h_j) increases for the given order costs at installations (e.g., CS1–CS4; CS5–CS8; CS9–CS12; CS13–CS16), re-order points mostly increase so as to increase the order frequency in order to replenish faster and hence reduce shortage costs across members in the SC. We also find that as the order costs increase across the SC for the given ratio of (b_j/h_j) (e.g., see CS1, CS5, CS9, and CS13; CS2, CS6, CS10, and CS14; and so on), base stock also increases at every installation to bring down the costs of orders at installations in the SC over the finite-time horizon.

5.5 *Relative Performance Evaluation of* (*s, S*) *Policy with the Order-Up-To* S *Policy with Periodic Review*

As for the determination of the optimal base-stock policy, Sethupathi and Rajendran (2010) proposed a mathematical programming model that can be executed with time horizon $T = 1200$ days. We compare these optimal TSCC values in the class of order-up-to *S* policy (i.e., (*T, S*) policy) with periodic review obtained through the execution of the above model in CPlex Solver with the best TSCC values obtained through the execution of GAs for the (*s, S*) policy. Tables 11, 12, 13, 14, 15, and 16 show the comparison of optimal TSCC values obtained for order-up-to *S* policy with periodic review (Policy I) with best TSCC values obtained by GAs for (*s, S*) policy (Policy II) for all SC settings and their relative percentage deviations.

Table 10 Performance of the different GA approaches in terms of their average relative percentage deviations

Supply chain setting	Average relative percentage deviation		
	MGGA	HGA1	HGA2
CS1 to C16 (LT1-FD)	1.03	0.27	0.40
CS1 to C16 (LT1-AD)	0.90	0.11	0.36
CS1 to C16 (LT2-FD)	2.10	1.49	0.89
CS1 to C16 (LT2-AD)	3.20	2.03	0.17
CS1 to C16 (LT3-FD)	1.12	1.89	0.31
CS1 to C16 (LT3-AD)	2.15	1.30	0.60
Overall average	1.747	1.180	0.455

Table 11 Performance of inventory order policies, in respect of TSCC values, with lead time setting 1 (LT1) and with the first demand stream (FD)

Supply chain setting	TSCC			Relative percentage deviation	
	Policy-1	Policy-2	Best TSCC	Policy-1	Policy-2
CS1	1269796	1232615	1232615	3.02	0.00
CS2	1477956	1449759	1449759	1.94	0.00
CS3	1626552	1579650	1579650	2.97	0.00
CS4	1728088	1668764	1668764	3.55	0.00
CS5	1785700	1731087	1731087	3.15	0.00
CS6	2128808	2085400	2085400	2.08	0.00
CS7	2340970	2238603	2238603	4.57	0.00
CS8	2448088	2341597	2341597	4.55	0.00
CS9	2473186	2420490	2420490	2.18	0.00
CS10	2943948	2909248	2909248	1.19	0.00
CS11	3285595	3201091	3201091	2.64	0.00
CS12	3464999	3312095	3312095	4.62	0.00
CS13	3375814	3384284	3375814	0.00	0.25
CS14	3986046	3970360	3970360	0.40	0.00
CS15	4475403	4565050	4475403	0.00	2.00
CS16	4886498	4719010	4719010	3.55	0.00
Average relative percentage deviation				2.526	0.141

Policy-1 Order-up-to *S* policy with periodic review; the results from the solver for the mathematical model are reported here, *Policy-2* (*s*, *S*) policy; the best results from the three GAs are reported here

TSCC values obtained for Policy-1 are optimal in the class of order-up-to *S* policy with periodic review and TSCC values obtained for Policy-2 are the best heuristic values obtained across three genetic algorithms. The relative percentage deviation for a given policy is computed with respect to the best solution obtained across two policies

The relative percentage deviation of a given TSCC value for an order policy is computed with respect to the best TSCC value among two order policies for given SC and LT settings.

$$\text{Relative percentage deviation} = \left(\left\{\left(\text{TSCC}_{\substack{\text{given}\\\text{policy}}} - \text{TSCC}_{\substack{\text{best}\\\text{across}\\\text{two}\\\text{policies}}}\right) \Big/ \left(\text{TSCC}_{\substack{\text{best}\\\text{across}\\\text{two}\\\text{policies}}}\right)\right\} \times 100\right) \tag{27}$$

where $\text{TSCC}_{\substack{\text{given}\\\text{policy}}}$ is the TSCC value obtained by the respective model, and $\text{TSCC}_{\substack{\text{best}\\\text{across}\\\text{two}\\\text{policies}}}$ is the best TSCC value obtained among the three models for the given cost and lead time settings. The average relative percentage deviation with respect to two policies across all SC settings and lead time settings are found, and reported in Table 17.

Table 12 Performance of inventory order policies, in respect of TSCC values, with lead time setting 1 (LT1) and with the antithetic demand stream (AD)

Supply chain setting	TSCC			Relative percentage deviation	
	Policy-1	Policy-2	Best TSCC	Policy-1	Policy-2
CS1	1276128	1240754	1240754	2.85	0.00
CS2	1482414	1458483	1458483	1.64	0.00
CS3	1639252	1586585	1586585	3.32	0.00
CS4	1746782	1671642	1671642	4.49	0.00
CS5	1786562	1729407	1729407	3.30	0.00
CS6	2121121	2085283	2085283	1.72	0.00
CS7	2353012	2251563	2251563	4.51	0.00
CS8	2465827	2360495	2360495	4.46	0.00
CS9	2470582	2416464	2416464	2.24	0.00
CS10	2950900	2905845	2905845	1.55	0.00
CS11	3288207	3197606	3197606	2.83	0.00
CS12	3477966	3321356	3321356	4.72	0.00
CS13	3364038	3379794	3364038	0.00	0.47
CS14	3991674	3964430	3964430	0.69	0.00
CS15	4509889	4562360	4509889	0.00	1.16
CS16	4881722	4719524	4719524	3.44	0.00
Average relative percentage deviation				2.61	0.102

Table 13 Performance of inventory order policies, in respect of TSCC values, with lead time setting 2 (LT2) and with the first demand stream (FD)

Supply chain setting	TSCC			Relative percentage deviation	
	Policy-1	Policy-2	Best TSCC	Policy-1	Policy-2
CS1	1189399	1160293	1160293	2.51	0.00
CS2	1296907	1263679	1263679	2.63	0.00
CS3	1390537	1358145	1358145	2.39	0.00
CS4	1468331	1428967	1428967	2.75	0.00
CS5	1770090	1746523	1746523	1.35	0.00
CS6	1994638	1900822	1900822	4.94	0.00
CS7	2110537	2028180	2028180	4.06	0.00
CS8	2188331	2175005	2175005	0.61	0.00
CS9	2490090	2425106	2425106	2.68	0.00
CS10	2878023	2805508	2805508	2.58	0.00
CS11	3114440	2955200	2955200	5.39	0.00
CS12	3235882	3224856	3224856	0.34	0.00
CS13	3503646	3416216	3416216	2.56	0.00
CS14	4104041	4129102	4104041	0.00	0.61
CS15	4423184	4328618	4328618	2.18	0.00
CS16	4671965	4452336	4452336	4.93	0.00
Average relative percentage deviation				2.619	0.038

Table 14 Performance of inventory order policies, in respect of TSCC values, with lead time setting 2 (LT2) and with the antithetic demand stream (AD)

Supply chain setting	TSCC			Relative percentage deviation	
	Policy-1	Policy-2	Best TSCC	Policy-1	Policy-2
CS1	1185175	1159704	1159704	2.20	0.00
CS2	1300597	1271446	1271446	2.29	0.00
CS3	1407285	1367716	1367716	2.89	0.00
CS4	1497425	1454086	1454086	2.98	0.00
CS5	1770945	1747672	1747672	1.33	0.00
CS6	1996948	1898080	1898080	5.21	0.00
CS7	2127285	2017472	2017472	5.44	0.00
CS8	2217425	2147752	2147752	3.24	0.00
CS9	2490945	2422974	2422974	2.81	0.00
CS10	2875325	2803990	2803990	2.54	0.00
CS11	3113750	2969288	2969288	4.87	0.00
CS12	3255496	3126982	3126982	4.11	0.00
CS13	3504536	3422756	3422756	2.39	0.00
CS14	4106109	4121822	4106109	0.00	0.38
CS15	4414134	4333738	4333738	1.86	0.00
CS16	4678101	4470316	4470316	4.65	0.00
Average relative percentage deviation				3.050	0.024

Table 15 Performance of inventory order policies, in respect of TSCC values, with lead time setting 3 (LT3) and with the first demand stream (FD)

Supply chain setting	TSCC			Relative percentage deviation	
	Policy-1	Policy-2	Best TSCC	Policy-1	Policy-2
CS1	1118691	1131416	1118691	0.00	1.14
CS2	1272799	1282426	1272799	0.00	0.76
CS3	1411866	1415521	1411866	0.00	0.26
CS4	1529193	1519424	1519424	0.64	0.00
CS5	1598691	1559816	1559816	2.49	0.00
CS6	1752799	1710826	1710826	2.45	0.00
CS7	1891866	1841857	1841857	2.72	0.00
CS8	2009193	1947824	1947824	3.15	0.00
CS9	2476469	2391652	2391652	3.55	0.00
CS10	2687585	2549510	2549510	5.42	0.00
CS11	2851866	2681954	2681954	6.34	0.00
CS12	2969193	2812082	2812082	5.59	0.00
CS13	3470301	3383694	3383694	2.56	0.00
CS14	4007610	3878515	3878515	3.33	0.00
CS15	4254890	4052147	4052147	5.00	0.00
CS16	4447580	4220558	4220558	5.38	0.00
Average relative percentage deviation				3.038	0.135

Table 16 Performance of inventory order policies, in respect of TSCC values, with lead time setting 3 (LT3) and with the antithetic demand stream (AD)

Supply chain setting	TSCC			Relative percentage deviation	
	Policy-1	Policy-2	Best TSCC	Policy-1	Policy-2
CS1	1121140	1146424	1121140	0.00	2.26
CS2	1274896	1289576	1274896	0.00	1.15
CS3	1416888	1439021	1416888	0.00	1.56
CS4	1537614	1540287	1537614	0.00	0.17
CS5	1601140	1588468	1588468	0.80	0.00
CS6	1754896	1758359	1754896	0.00	0.20
CS7	1896888	1906283	1896888	0.00	0.50
CS8	2017614	2049683	2017614	0.00	1.59
CS9	2472191	2383241	2383241	3.73	0.00
CS10	2686637	2559789	2559789	4.96	0.00
CS11	2856888	2702244	2702244	5.72	0.00
CS12	2977614	2835294	2835294	5.02	0.00
CS13	3467880	3401117	3401117	1.96	0.00
CS14	4008291	3867092	3867092	3.65	0.00
CS15	4259830	4064763	4064763	4.80	0.00
CS16	4462191	4249953	4249953	4.99	0.00
Average relative percentage deviation				2.227	0.464

Table 17 Overall performance comparison of inventory order policies in respect of average relative percentage deviations of their TSCC from the best TSCC

Supply chain setting	Average relative percentage deviation	
	Policy-1	Policy-2
CS1 to C16 (LT1-FD)	2.526	0.141
CS1 to C16 (LT1-AD)	2.610	0.102
CS1 to C16 (LT2-FD)	2.619	0.038
CS1 to C16 (LT2-AD)	3.050	0.024
CS1 to C16 (LT3-FD)	3.038	0.135
CS1 to C16 (LT3-AD)	2.227	0.464
Overall average	2.678	0.151

6 Managerial Implications and Further Work of this Study

It is evident that on the whole, Policy-II, namely, the (*s, S*) policy emerges to be better with an average relative percentage deviation of 0.151 %, when compared with Policy-I namely, order-up-to *S* policy with periodic review with an average relative percentage deviation of 2.678 % over the SC settings. This finding is interesting in the sense that the (*s, S*) policy that capitalizes on the tight control by using the re-order point at every installation yields the least TSCC in most cases, as opposed to the periodic review system operating with order-up-to *S* policy. We observe that the (*s, S*) policy performs better than the (*T, S*) policy on the whole over a number of SC settings. However, at relatively larger lead times with low cost settings, we find that the (*T, S*) policy becomes competitive. This is because of demand aggregation over large lead times coupled with low costs lead to less sensitivity with order policy. Hence, we can resort to the (*T, S*) policy under these circumstances. Further work can look at comparative study involving more inventory order policies such as (*R, Q*) policy, which the authors are investigating using approaches and algorithms similar to the ones presented here.

7 Summary

In this paper, we have considered the (*s, S*) policy and developed a mathematical model to determine the optimal base-stocks and re-order points in the class of (*s, S*) policy in a SC operating with deterministic demands over a finite time horizon in order to minimize the sum of holding costs, shortage costs, and order costs. In view of the computational complexity associated with this policy, we have presented three GAs to obtain the best heuristic base-stocks and re-order points across members in a SC. We have carried out a relative evaluation of the periodic review order-up-to *S* policy ((*T, S*) policy) and (*s, S*) policy by considering many SC costs and lead time settings. We have found that the (*s, S*) policy performs mostly better, in comparison to the periodic review order-up-to *S* policy.

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Modeling of Scheduling Batch Processor in Discrete Parts Manufacturing

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Abstract Processing using batch processors (BPs) is common in many manufacturing environments. Generally in a manufacturing environment, BPs are bottleneck operations due to their longer processing time. Batch processing also involves many complexities like compatibility of jobs that can be processed, sizes of different jobs, capacity constraint of the processor, and so on. Considering all these factors, proper scheduling of BPs is important. This chapter focuses on scheduling of BPs in three real life applications, namely, automobile gear manufacturing, semiconductor manufacturing, and steel casting industries. Integer programming models are formulated for the problems under consideration. These models will help the decision makers to understand the problems better and hence work toward appropriate solutions for the problems.

1 Introduction

In the late 1970s and the early 1980s, market pressure for greater product variety forced a gradual shift from continuous manufacturing to batch manufacturing (Roberts et al. 1999). As a sequel to this, in the past 15 years, deterministic manufacturing batch scheduling problems have attracted the attention of researchers.

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Batch scheduling in a manufacturing system is very common policy in most industries. The main reasons for batching are avoidance of set ups and/or facilitation of material handling. Batching occurs in two versions: serial-batching and parallel-batching. In serial-batching, jobs may be batched if they share the same setup on a machine and one job is processed at a time. In parallel-batching, several jobs can be processed as a batch (that can possibly be grouped up to the capacity of the machine) simultaneously on a machine at one time and once the process begins, the machine cannot be interrupted. In literature, scheduling of the parallel-batching is known as scheduling of batch processor (BP) or scheduling of batch processing machine (BPM). In this chapter, we discuss the scheduling problem related to BP, which is involved in discrete parts manufacturing.

Scheduling of BP research is encountered in many discrete parts manufacturing. Table 1 provides the types of industry along with the specific operation carried out in BP and the research references. Though different discrete parts manufacturing industries involves batch processing operations, the problem dimensions or parameters or characteristics considered on these different applications vary. Based on the analysis of the problem characteristics of these discrete parts manufacturing industries, the general problem dimensions/parameters and their attributes of scheduling BP research are presented in Table 2. Using Table 2, one can generate different scheduling BP problems theoretically if not related to specific industries.

Every researcher (e.g., Azizoglu and Wester 2000) has highlighted that the scheduling of BP is very important due to one or more of the following reasons:

(a) Generally, BP is bottleneck machine in every discrete parts manufacturing industry, addressed in the literature, because the processing time at BP is often long compared to other operations in the system.
(b) Scheduling BP is critical for work in process (WIP) balancing as well as throughput since it determines the capacity of the production line.
(c) Effective use of BP resource is especially important because of the very high cost of equipment.
(d) BP model is important because it signifies a source of tension present in many practical scheduling problems—efficiency (related to maximizing the utilization of the BP) versus timely completion of individual jobs (related to higher priority jobs should be processed before lower priority jobs). Insights into how to deal with various signs of this conflict may eventually lead to practical solution methods more complex.

The above reasons and the increase in real life applications in the area of scheduling BP motivated us to discuss the mathematical model and its complexity in scheduling BP related to three different discrete parts manufacturing in which the authors have direct research experiences. With this, the main objective of this chapter is to present, demonstrate the workability, and understand the computational complexity of the mathematical model for scheduling BP problems involved in three different discrete parts manufacturing: (a) automobile gear manufacturing, (b) semiconductor manufacturing (SM), and (c) steel casting Industries and these are discussed in the following sections.

Table 1 Application of scheduling BP in discrete parts manufacturing

Industry/ manufacturer	Operations/batch processor	Sample references
Aircraft Industry	Hardening of synthetic parts/ oven	Zee et al. (2001)
Automobile Gear Manufacturing	Hardening and soaking/heat-treatment furnace	Gokhale and Mathirajan (2011)
Electronics Manufacturing industry	Testing PCBs in environmental stress screening (ESS) chambers	Damodaran and Srihari (2004)
Furniture Manufacturing Industry	Dry kiln	Yaghubiana et al. (2001)
Glass Container Industry	Annealing/lehr or annealing kiln	Almada-Loba et al. (2008)
Hospital (Hospital sterilization services)	Washing of Reusable medical devices (RMD)	Ozturk et al. (2010)
Ion Plating (IP) Industry	IP machine (has been widely used in Watch and Clock Industry)	Chan et al. (2006)
Iron and Steel Industry	Multi-head hole-punching machine	Oulamara (2007)
Multi-Layer-Ceramic Capacitor Manufacturing	Bake-out/box-oven	Koh et al. (2004)
Semiconductor Manufacturing	Oxidation or diffusion furnace, burn-in oven	Uzsoy et al. (1992), Potts and Kovalyov (2000), Mathirajan and Sivakumar (2006b), Ponsignon and Monch (2011)
Shoe Manufacturing Factory	Carousel rotation/carousel	Fanti et al. (1996)
Steel Casting Industry	Heat-treatment furnace	Mathirajan and Sivakumar (2006a), Ramasubramanian et al. (2010)
Steel Ingot Production	Preheating/soaking bit	Li et al. (2011)

2 Scheduling BP in GEAR Manufacturing

Automobile gears need a high amount of precision. They require an elaborate manufacturing process, which involves many types of machines. We first give a brief description of automobile gears and an overview of the automobile gear manufacturing process.

Table 2 General parameters and their attributes in scheduling batch processors

Problem dimensions/parameters	Characteristics/SINGLE valued attribute
Batch processing machine (BPM)	Single BPM
	Multiple and homogeneous type of BPM
	Multiple and heterogeneous type BPM
Job-type	Single family of jobs
	Multiple and compatible job-families
	Multiple and in-compatible job-families
Job-size	Identical job size
	Non-identical job size
Job dimension/volume	Identical job dimension/volume
	Non-identical job dimension/volume
Job splitting between the batches	Allowed
	Not allowed
Processing time of a batch	Dependent on the jobs in the batch
	Independent on the jobs in the batch
Set-up time	Included in the processing time
	Not-included in the processing time
Number of scheduling objectives	Single
	Multiple
Scheduling objective	Completion time based
	Due-date based
Availability of the data	Deterministic and known
	Stochastic
Nature of the scheduling problem	Static
	Dynamic

2.1 Automobile Gears

The 'gear train' as referred to in automobile terminology is an important constituent of the transmission system of an automobile. The other constituents of the transmission system (housed in steel casting mostly referred to as the *transmission case*) are axles, clutch system, oil seals, various other housings (castings), etc. The gear train comprises of number of different types of gears, couplings, shifter rails and shifter forks. There are different ways of classifying the automobile gears. For example, it is classified based on the type of teeth (spur, helical, hypoid, etc.); based on geometry (module, diametric pitch, etc.); and based on shape (solid, hollow, simple, cluster, shoulder, etc.) The gears are manufactured from steel forgings. They require very high precision (measured in terms of microns) for the smooth operation of the transmission system. Thus, they form an important component in the automobile in terms of quality.

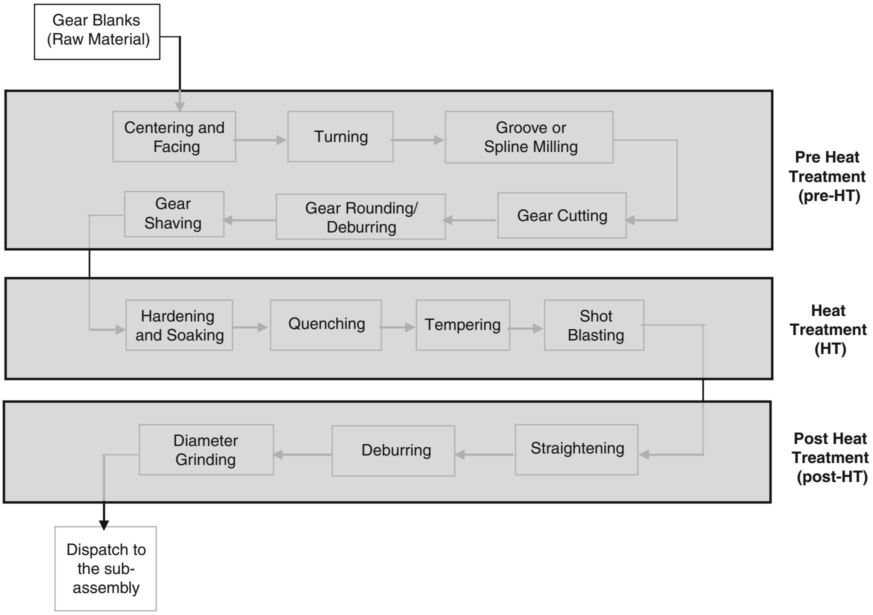

Fig. 1 A flow diagram of the automobile gear manufacturing process

2.2 Automobile Gear Manufacturing Process

The automobile gear manufacturing process is, in general, grouped into three distinct stages: pre heat treatment (pre-HT), heat treatment (HT), and post heat treatment (post-HT). A flow diagram of the automobile gear manufacturing process is shown in Fig. 1 and a brief description of the same is as follows:

> On the steel forgings (known as 'gear blanks') which are the raw materials for gears, different machining operations are carried out: centering and facing, turning, groove/spline milling, gear cutting, gear rounding, and gear shaving. The machined gears obtained from this pre-HT stage are still in the soft (or so-called 'green') state. These gears are subjected to heat treatment by grouping into batches appropriately depending on the type of gear and loading them in the furnaces for the process-controlled operations: hardening and soaking, quenching, tempering; and finally cleaned using shot blasting. The output of the heat treatment stage is 'hardened gears.' These hardened gears are subsequently processed through the post-HT stage: straightening, deburring, and gear grinding; and finally dispatched to the sub-assembly

For all the operations of the pre-HT stage and the post-HT stage of gear manufacturing, a single gear is processed on a machine at a time. These types of machines that process a single part at a time are termed as *discrete processors* or *unit processors* in the scheduling terminology, but generally referred to as simply *machines*. On the contrary, for the operations of the heat treatment stage of gear manufacturing, the equipments used are the *furnaces*. Multiple gears can be processed simultaneously in a furnace. These types of equipments that process more than one part simultaneously are termed as *batch processors* in the scheduling terminology.

A common practice observed among automobile manufacturing organizations is outsourcing a part of gear manufacturing process to the sub-contractors. Accordingly, the pre-HT and the HT stages of gear manufacturing are outsourced. For a particular type of gear, the same sub-contractor performs these two stages. The post-HT stage, being the finishing stage and important from the quality aspect, is carried out in-house. Thus, a major portion of gear manufacturing operations is carried out by sub-contractors (known as gear manufacturers). This part of the study focuses on the scheduling issues related to these gear manufacturers, particularly related to HT-stage of gear manufacturing.

2.3 Scheduling Issues for Gear Manufacturers

A gear manufacturer receives orders (known as *jobs* in the scheduling terminology) from different automobile manufacturing organizations. A job consists of certain number of identical gear blanks. These jobs are to be processed at the pre-HT stage and HT-stage of gear manufacturing. The real research problem lies in identifying bottleneck operations in both pre-HT and HT stages. By addressing the bottleneck operations, one can expect to have a competitive advantage among the gear manufacturers and in turn among the automobile manufacturing organizations.

There are two bottleneck operations in gear manufacturing process. The first bottleneck operation is identified in the pre-HT stage of the gear manufacturing, particularly the operation: *gear shaving*, since this operation takes a relatively longer duration of time and hence is the bottleneck operation. The machine involved for this operation is called discrete processor. The second bottleneck operation is identified in the HT stage of the gear manufacturing, particularly the operation: *hardening and soaking*. The machine involved for the operation: hardening and soaking is a batch processor. Furthermore, all the other machines involved in the HT stage are also batch processors.

The operation hardening and soaking typically takes 6–18 h depending on the physical characteristics required (e.g., case-depth, microstructure, etc.) and the geometry of the jobs in a furnace (here after this furnace is called hardening and soaking furnace (HSF)). Other operations take roughly 30, 90, and 15 min, respectively. Also, being the first operation of the HT stage, once the hardening and soaking operation is completed, the other operations can be streamlined. Hence, among all the BPs of the HT stage, the HSF is the bottleneck, as it takes very long processing time in comparison with other BPs in the HT-stage and this being the first BP.

The HSF used in this operation has a fixed and finite capacity called as *net capacity*. This capacity is expressed in terms of mass (in kilogram). Although a HSF can process multiple jobs simultaneously, different jobs will have different processing requirements such as processing time, temperature, etc., depending on the metallurgical properties desirable for the job. Thus, for example, a particular job say *job A*, cannot be processed with another job, say *job B*. But the same *job A* may be processed with a third job, say *job C* due to similar processing requirements. The jobs that can be processed together are grouped in *job families*. All *jobs of the same family have the same processing time* and jobs of different families cannot be processed together. This gives rise to the problem situation of *incompatible job families*.

Different jobs will have different masses due to the number of gears (lot-size) and type of gears constituting the job. This is termed as *non-identical job sizes*. Although a HSF can process multiple jobs at a time, the capacity of the HSF cannot be violated. Also, since a job is composed of individual gears, it may be split into different sub-lots. Practically, *splitting of a job is not preferred, but is allowed* in case if the available capacity of the HSF exceeds that of the job.

Since this stage is a downstream stage, the jobs will arrive as and when they are completed on the pre-HT stage. Hence, the arrival time (called as *release time* in the scheduling literature) of different jobs will be different; and this gives rise to the situation of *unequal release times* (or *dynamic job arrivals*). Also, since this stage is the final stage before dispatching to the respective automobile manufacturing organizations, the job will have a pre-specified due dates and *the due dates may be independent of the release times*. This situation is known as *non-agreeable release times* (r_i) *and due dates* (d_j) in the scheduling literature (i.e. $r_i < r_j$ *need not imply* $d_i <= d_j$); and hence *represents a generalized situation*.

Another job characteristic related to the HT stage of gear manufacturing is job weight. Different jobs will have different weights depending upon the nature of the automobile manufacturing organization, monetary value of the job, and urgency for the next operation.

As the HT stage is the second important stage, and the final stage (which is the post-heat treatment stage) being a non-critical stage in the gear manufacturing, the focus will be delivery of the job to the automobile manufacturing organizations. Out of the various due date-based scheduling objectives, the objective of minimizing the total weighted tardiness (TWT) is considered in this research problem. The tardiness of the job j (T_j) is defined as $T_j = \max(0, C_j - d_j)$, where C_j and d_j are completion time and due date of job j, respectively. The weighted tardiness of the job j (WT_j) is defines as $WT_j = (w_j \times T_j)$, where w_j is priority and/or size of the job j. In general, TWT is a difficult objective function, even in the most straightforward scheduling environments (Perez et al. 2005).

With the problem features explained so far is defined as: "The scheduling of single HSF in presence of unequal release times, incompatible job families and non-identical job sizes, with allowance for job splitting to minimize the total weighted tardiness." The problem considered here can be written in the standard three-field notation as of Graham et al. (1979) as: 1/B, r_j, incompatible job families, non-identical job sizes, split/$\Sigma w_j T_j$. A pictorial representation of the problem under consideration is as shown in Fig. 2.

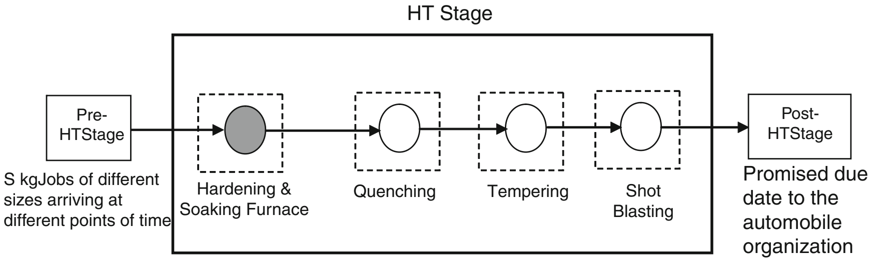

Fig. 2 A pictorial representation of the operations in the heat treatment stage of the gear manufacturing with single BP and the position of HSF

Furthermore, the following assumptions are made for this problem:

- Jobs are released in the system at fixed and discrete time epochs.
- The processing times of the jobs are inclusive of setup times. This assumption is justified since; practically setting up the batch for the HSF takes around 15–30 min which is much less compared to the processing time (6–18 h) of the job in the HSF.
- All processing times are deterministic and known apriori.
- Processing of a job cannot be discontinued in between (non pre-emptive).
- Mass of a job cannot exceed the capacity of the HSF.
- Work In Process inventory in front of the HSF is unlimited.
- Breakdowns of the HSF are not considered.
- Splitting of a job is allowed only once (i.e., only when the capacity of the HSF exceeds during the batch formation).

2.4 A Mathematical Model for Scheduling HSF

Different researches have given mathematical models based on the problem characteristics considered by them on a specific application for scheduling of BP. In all the applications related to scheduling BP, the practical job splitting aspect is not discussed and probably the job splitting is not permitted in their approach. In this section, a mathematical formulation is presented, which simultaneously deals with a variety of practical situations like unequal release times, incompatible job families, non-identical job sizes, and job-splitting, as observed in the HT stage of gear manufacturing. The nomenclature used for the mathematical model is presented followed with the presentation of the mathematical model.

Sets:

J Jobs

F Families

Derived Sets—Batches on the batch processor

Parameters:

- r_j Release time of a job j
- d_j Due date of a job j
- w_j Weight (priority) of a job j
- v_j Mass of a job j
- S Capacity of the HSF
- A First time availability of the HSF
- p_f Processing time of family f
- a_{jf} Family association for a job, equals 1 if job j belongs to family f; 0 otherwise

Decision Variables:

- X_{jb} 1 if job j is processed in batch b of the HSF; 0 otherwise
- Y_{fb} 1 if family f is processed in batch b of the HSF; 0 otherwise

Dependent Variables:

- C_b^B Completion time of a batch b on the HSF—This is the time at which the processing of the batch is completed. The next batch can be started only after the current batch is completed
- r_b^B Release time of a batch b on the HSF—The time at which a batch can be released into the BP for processing,
- p_b^B Processing time of a batch b on the HSF—The time for which the batch has to remain in the BP for processing
- C_j Completion time of a job j—*The completion time of a job is the completion time of the batch in which it was processed*
- Q_{jb} Fraction of job j processed in batch b of the HSF
- T_{j} Tardiness of a job j
- C_{jb}^{Frac} Completion time of fraction of job j processed in batch b of the HSF

Assume that in the scheduling window there are ***n*** number of available jobs, distributed among ***g*** number of job families. Thus, the *maximum* number of batches that can be formed on the HSF will be ***n***. Note that it is *quite unlikely that all **n** batches are physically formed*. That is, toward the end, many batches will be empty. But since the number of physical batches on the HSF cannot be determined apriori, a provision has to be made for the maximum number of batches.

Integer Linear Programming (ILP) model for scheduling HSF

$$\text{Minimize} \sum_{j=1}^{n} w_j T_j \tag{1}$$

Subject to:

$$\sum_{f=1}^{g} Y_{fb} \leq 1 \qquad b = 1, 2, \ldots, n \tag{2}$$

$$\sum_{f=1}^{g} Y_{fz} \geq \sum_{f=1}^{g} Y_{fb} \qquad b = 2, \ldots, n; \quad z = b - 1 \tag{3}$$

$$r_b^B \geq C_z^B \qquad b = 2, \ldots, n; \quad z = b - 1 \tag{4}$$

$$p_b^B \geq \sum_{f=1}^{g} (p_f \ * \ Y_{fb}) \qquad b = 2, \ldots, n \tag{5}$$

$$C_b^B \geq r_b^B + p_b^B \qquad b = 2, \ldots, n \tag{6}$$

$$(X_{jb} \ * \ a_{jf}) \leq Y_{fb} \qquad \forall j \in J; \ \forall f \in F; \ b = 1, 2, \ldots, n \tag{7}$$

$$\sum_{j=1}^{n} (X_{jb} \ * \ a_{jf}) \geq Y_{fb} \qquad \forall f \in F; \ b = 1, 2, \ldots, n \tag{8}$$

$$r_b^B \geq (r_j \ * \ X_{jb}) \qquad \forall j \in J; \ \ b = 1, 2, \ldots, n \tag{9}$$

$$\sum_{b=1}^{n} X_{jb} \leq 2 \qquad \forall j \in J \tag{10}$$

$$\sum_{b=1}^{n} X_{jb} \geq 1 \qquad \forall j \in J \tag{11}$$

$$Q_{jb} \leq 1 \qquad \forall j \in J; \ b = 1, 2, \ldots, n \tag{12}$$

$$Q_{jb} \geq 0 \qquad \forall j \in J; \ b = 1, 2, \ldots, n \tag{13}$$

$$\sum_{b=1}^{n} Q_{jb} = 1 \qquad \forall j \in J \tag{14}$$

$$X_{jb} \geq Q_{jb} \qquad \forall j \in J; \ \ b = 1, 2, \ldots, n \tag{15}$$

$$Q_{jb} > (\text{Big } M) \times (X_{jb} - 1) \qquad \forall j \in J; \ \ b = 1, 2, \ldots, n \tag{16}$$

$$\sum_{j=1}^{n} (Q_{jb} \ * \ v_j) \leq S \qquad b = 1, 2, \ldots, n \tag{17}$$

$$C_{jb}^{\text{Frac}} \geq C_b^B - (\text{Big } M) \times (1 - X_{jb}) \qquad \forall j \in J; \quad b = 1, 2, \ldots, n \tag{18}$$

$$C_j \geq C_{jb}^{\text{Frac}} \qquad \forall j \in J; \ \ b = 1, 2, \ldots, n \tag{19}$$

$$r_b^B \geq A \qquad b = 1 \tag{20}$$

$$\text{T}_j \geq C_j - d_j \qquad \forall j \in J \tag{21}$$

$$T_j \geq 0 \qquad \forall j \in J \tag{22}$$

$$X_{jb} \in \{0,\ 1\} \qquad \forall\, j \in J; \quad b = 1, 2, \ldots, n \tag{23}$$

$$Y_{fb} \in \{0,\ 1\} \qquad \forall f \in F; \quad b = 1, 2, \ldots, n \tag{24}$$

Objective (1) minimizes the TWT over all the jobs. Constraint (2) states that the jobs of at most one family can be processed in a batch. Constraint (3) ensures that a batch can be formed only if the previous batch has been formed.

Constraints (4), (5), and (6) are used to define the release time, processing time, and completion time respectively of a batch. Constraint (4) states that the release time of a batch should be at least as large as the completion time of the previous batch. Constraint (5) ensures that the processing time of a batch is not be less than the processing time of the jobs of the family that constitutes that batch. Constraint (6) states that the completion time of a batch should be at least as large as the sum of release time and processing time of the batch.

Constraint (7) ensures that a job can be processed in a batch only if the family to which it belongs to is processed in that batch. On the other hand, Constraint (8) states that a batch must contain at least one job of a family that is assigned to that batch. Constraint (9) states that release time of a batch must not be less than the release time of any of jobs constituting that batch.

Constraints (10)–(16) are concerned with the fractional allocations of the jobs to batches. Constraints (10) and (11) ensure that a job is processed in *at most two* (*some part of the job in one batch and remaining part of the job in another batch*) *but at least one* batch among all the batches. Constraints (12) and (13) assign bounds on the fraction of a job processed in a batch between 0 and 1. Constraint (14) ensures that the sum of the fractions of a job processed in batches add up to 1 (meaning the complete job). Constraints (15) and (16) together ensure that whenever a job is assigned to a batch, then at least some fraction of the job is processed in that batch. Also when the job is not allocated, then no fraction of the job gets processed.

Constraint (17) ensures that the quantity (mass) of the jobs processed in any batch should not exceed the capacity of the HSF. Constraint (18) states that the completion time of a job (or fraction of a job) should not be less than the completion time of the batch in which it is processed. Constraint (19) ensures that the completion time of a job (i.e., the whole job) is not less than the completion times of any of its fractions. Constraint (20) takes care of the dynamic starting conditions. It states that the release time of the first batch is not less than the first time availability of the HSF. Constraints (21) and (22) are used to form the definition of tardiness of a job. Thus, as per Constraint (21), the tardiness of a job cannot be less than the difference between completion time of the job and its due date and as per Constraint (22) the tardiness of a job cannot be negative. Finally, Constraints (23) and (24) assign binary values to the decision variable.

Table 3 A numerical example for scheduling HSF

Job (j)	Release time (r_j)	Due date (d_j)	Weight (w_j)	Mass (v_j)	Job-family association		
					Family 1 (a_{j1})	Family 2 (a_{j2})	Family 3 (a_{j3})
1	6	36	6	20	1	0	0
2	1	15	4	18	0	1	0
3	10	52	6	13	0	1	0
4	10	22	5	19	0	0	1
5	4	14	3	3	1	0	0
6	0	20	3	11	1	0	0
7	0	10	5	11	1	0	0
8	2	32	6	2	1	0	0
9	7	27	3	12	1	0	0
10	6	24	2	6	0	0	1

2.5 Validation of the ILP Model for Scheduling HSF

In order to validate the proposed ILP model, a numerical problem is developed. In the numerical problem there is a HSF with the capacity of 750 kg. There are ten jobs to be processed on a single BP. Among themselves, the jobs constitute three incompatible job families. Thus, $n = 10$ and $g = 3$. The data on job release time, due date, weight, mass, and job-family association are given in Table 3. Note that the mass of job is given as a multiple of 25 kg to avoid unnecessary large numbers. Thus a mass of 20 means 500 kg.

All time units are assumed in terms of hours. Also, dynamic condition that the BP will be free at time = 1 h (i.e., the first time availability) is assumed. The processing times for the families 1, 2, and 3 are assumed to be 10, 14, and 6 h respectively.

A LINGO set code is developed for generating the proposed ILP model for any given numerical data and the same is given in Annexure 1. Using the LINGO set code, the numerical example is solved and the optimal solution is obtained. The optimal TWT is 223. The jobs included in different batches and the optimum sequencing of batches on the BP is obtained from the optimal solution and the same is presented in Table 4.

Although the given numerical example can be solved in a relatively small amount of time, it is required to test the computational capability for different types of problems. Following this, the computational complexity of the proposed ILP model is empirically demonstrated using planned computational experiments.

Computational intractability of the ILP model for scheduling HSF. In order to understand the computational complexity of the ILP model presented for scheduling HSF, two things are required: experimental design and computational analysis. These are discussed next.

Experimental design. Using the experimental design, a suitable test data for the research problem is generated. For generating suitable test data, one has to

Table 4 Details of the optimal decisions for the numerical example for scheduling HSF

Batch sequence	Jobs (j) in the batch	r_j	d_j	w_j	v_j	Fraction of job processed in the batch	Mass of the job processed in the batch	Total mass processed in the batch	Start time of the batch	End time of the batch	C_j	T_j	WT_j
1	1	6	36	6	20	25 %	5	30	6	16	–	–	–
	5	4	14	3	3	100 %	3				16	2	6
	6	0	20	3	11	100 %	11				16	0	0
	7	0	10	5	11	100 %	11				16	6	30
2	4	10	22	5	19	100 %	19	25	16	22	22	0	0
	10	6	24	2	6	100 %	6				22	0	0
3	1	6	36	6	20	75 %	15	29	22	32	32	0	0
	8	2	32	6	2	100 %	2				32	0	0
	9	7	27	3	12	100 %	12				32	5	15
4	2	1	15	4	18	100 %	18	18	32	46	46	31	124
5	3	10	52	6	13	100 %	13	13	46	60	60	8	48

r_j release time; d_j due date; w_j weight; v_j mass; C_j Completion time; T_j Tardiness; WT_j Weighted Tardiness

understand the factors that can affect the scheduling of HSF. Practically, these factors can assume different values, depending on the operating conditions and various other scenarios. To capture these different values, one also needs to define different levels of each factor. These levels are based on the observations in a couple of gear manufacturers in the Western part of India and related literature. Accordingly, the experimental design is developed and summarized in Table 5. Furthermore, the $C_{\max\_bound}$ is computed as follows:

$$C_{\max\_bound} = \frac{\sum_{j=1}^{n} p_j}{m\bar{Z}}$$

where, n is the number of jobs

p_j is the processing time of a job j

$\bar{Z}$ is the average capacity of the HSF in terms of number of jobs

Note that $\bar{Z} = \frac{c}{\bar{v}}$

where, c is the capacity of the BP in terms of mass

$$\bar{v} = \frac{\sum_{j=1}^{n} v_j}{n} = \text{average mass of a job}$$

A program is written in MATLAB 7.0 to generate suitable number of problem instances as per the experimental design summarized in Table 5. For each of the problem configuration, a problem instance is generated using the MATLAB code. Accordingly, 192 problem instances are generated.

Table 5 Summary of the proposed experimental design—scheduling HSF

Problem factors	Number of levels	Level wise values
No. of jobs (n)	3	8; 10; 12
No. of families (g)	2	No. of families = 2 (F1, F2); No. of families = 3 (F1, F2, F3)
Job-family association (a)	2	Equal; Unequal (i.e. F1 = 70 % and F2 = 30 % in case of two families and F1 = 60 %, F2 = 25 % and F3 = 15 % in case of three families)
Family processing time (p)	1	F1—10 h, F2—14 h and F3—6 h
HSF capacity (c)	1	750 kg (i.e. 30 mass units)
Job mass (v)	2	U[2,20]; U[2,3] and U[19,20] with probability 5 % each, U[4,7] and U[15,18] with probability 20 % each, U[8,14] with probability 50 %
Job weight (w)	2	U[1,8]; U[1,2] or U[7,8] with probability 30 % and U[3,6] with probability 70 %
Job release time (r)	2	U[0,α] $\times$ $C_{\max\_bound}$ where $\alpha = 0.25; 0.75$
Job due date (d)	2	$d_j = r_j +$ U[1,β] $\times$ (processing time) where $\beta = 3; 5$
Number of configurations	192 (i.e. 3 × 2 × 2 × 1 × 1 × 2 × 2 × 2 × 2)	

Using the LINGO set code given in Annexure 1, the proposed ILP model is generated for each of the 192 problem instances and solved using the LINGO solver. The optimal results obtained and the computational time required is observed for each of the 192 problem instances, and the same is presented in Annexure 2. For each combination of (n, g, a), the average, minimum, maximum, and standard deviation of the computational time required with Pentium 4 is computed using the results shown in Annexure 2, and the same is given in Table 6. Table 6 clearly indicates that the time required for solving the problems using the ILP model is non-deterministic and non-polynomial.

3 Scheduling BP in Semiconductor Manufacturing (SM)

The SM industry is one of the fastest growing industries in the world having annual sales of approximately $25 billion worldwide at the end of Sept. 2012 (SIA 2012). This is because of the diverse market focusing on integrated circuits (ICs) for networking, storage components, telecommunications, and/or wireless, consumer, computer, and storage systems that have become necessary tools of today.

Table 6 A summary of the computational time required by the ILP model for each combination of (n, g, a)—scheduling HSF

Problem factors			Number of instances	Computational time statistics			
Number of jobs (n)	Number of families (g)	Distribution of job-family association (a)		Average solution time (h–min)	Minimum solution time (h–min)	Maximum solution time (h–min)	Standard deviation of solution time (h–min)
8	2	Equal	16	<00–00	<00–00	00–03	00–01
8	2	Unequal	16	00–01	<00–00	00–10	00–02
8	3	Equal	16	<00–00	<00–00	00–02	00–01
8	3	Unequal	16	<00–00	<00–00	00–01	<00–00
10	2	Equal	16	00–07	<00–00	00–27	00–08
10	2	Unequal	16	00–01	<00–00	00–04	00–01
10	3	Equal	16	00–09	<00–00	01–11	00–18
10	3	Unequal	16	00–07	<00–00	00–25	00–08
12	2	Equal	16	01–38	00–01	12–29	03–07
12	2	Unequal	16	00–24	<00–00	02–27	00–43
12	3	Equal	16	01–05	00–01	03–26	01–15
12	3	Unequal	16	00–31	<00–00	01–25	00–26

SM is a highly competitive business. In the past, competition has been primarily in the product design arena, but in the last several years the cost of manufacturing ICs has become an important competitive factor. Furthermore, the time to manufacture a product is becoming increasingly important. Planning and scheduling research addresses these needs.

The manufacturing of semiconductor products consists of four distinct stages: wafer fabrication, wafer probe, assembly, and final testing (Fig. 3). These four stages can be divided into two categories. Wafer fabrication and wafer probe are referred to as the *front-end manufacturing* operations; assembly and final testing are referred to as the *back-end manufacturing* operations. In brief, wafer

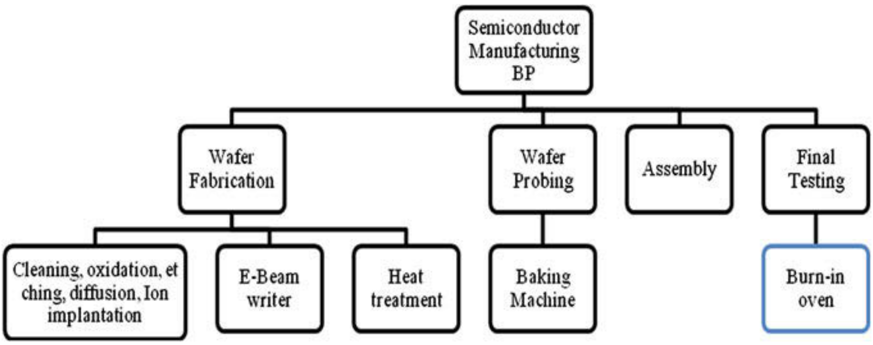

Fig. 3 Batch processes/processors in semiconductor manufacturing

fabrication is the stage where hundreds of circuits are layered through successive operations onto a smooth, typically silicon, and wafer. In wafer probe stage, the individual circuits are tested electrically, using thin probes. The wafers are cut up into individual circuits, and the circuits which fail to meet specifications are discarded. The third stage, assembly, consists of placing the circuits in packages designed to protect them from the environment. Finally, in the last stage, a final test is conducted before the ICs are shipped.

The SM industries today represent one of the most complex industrial processes. In SM, we have to deal with parallel machines, different types of processes like batch processes and single wafer processes, sequence dependent setup times, prescribed customer due dates for the lots, very expensive equipment and reentrant process flows. As a part of the complex production line that exists in a SM facility, operations involved in BPs are considered to be bottleneck. This is due to the reason that the processing times of the lots on the BP are usually very long compared to other processes and batching decisions may affect the performance of the entire SM process. SM involves numerous batch processing operations like oxidation, diffusion, deposition, etching, e-beam writing and heat treatment of wafer fabrication, baking of wafer probing and burn-in operation of device testing (Fig. 3).

Out of various batch processing operations in SM process, the diffusion operation in wafer fabrication area and burn-in operation in final testing area are considered to be very important based on the long processing time required in each of the respective stages of the SM. Accordingly, in this section, the integer programming models for deterministic scheduling related to the diffusion process and the burn-in process are discussed.

3.1 Scheduling a Diffusion Furnace in Wafer Fabrication

Wafer fabrication is the most technologically complex and capital intensive phase, where circuits are fabricated on wafers of silicon or gallium arsenide using chemical and mechanical processes. In diffusion operation, wafers are placed in a cylindrical reactor (called as furnace), which is then sealed, heated, and filled with carrier gas to allow dopant atoms present in the gas to diffuse into the exposed layer of the wafers (Malve and Uzsoy 2007). Wafers are processed in standard lots of 25 and these are placed in a Proof of Delivery (POD), a container. The Diffusion Furnace (DF) can usually accommodate between 6 and 12 standard lots (PODs) that are processed simultaneously as a batch. Hence this DF is referred to as BP. Due to chemical nature of the process, it is impossible to process lots with different receipts together in the same batch. Thus, all lots (jobs) requiring same recipe can be viewed as a job-family, where all jobs of the same family require the same processing time. Furthermore, we shall call these job families incompatible since jobs of different families cannot be processed together.

The effective scheduling of these DFs is particularly important because of their long processing time (that is, days as opposed to hours) requirements in comparison with any other processors in the wafer fabrication. Particularly, we address the problem of scheduling DF with incompatible job families along-with jobs having (i) non-agreeable release times and due dates, (ii) different lot sizes, and (iii) compatibility only with a few available diffusion furnaces for diffusion operations (i.e., DF eligibility requirement). The objective of scheduling DF is the maximum completion time (i.e., makespan) which can directly represent the throughput measure attracting practical interest from wafer fabrication, which accounts roughly 70 % of the SM time.

3.2 An Integer Nonlinear Programming Model for Scheduling a DF

The integer nonlinear programming (INLP) model for scheduling a single diffusion furnace with multiple incompatible job families, non-identical job sizes, and non-agreeable release times and due dates in minimizing the completion time of last job (minimizing makespan) is presented along with the assumptions and notations used in formulating the model:

Assumptions:

- Each lot has different number of wafers ranging from 1 to 25 and all lots are independent.
- BPM has a capacity B (= number of lots = number of PODs). POD is a container, which holds a number of wafers between 1 and 25. The sum of the wafers in a batch must be less than or equal to number of PODs × Maximum number of wafers possible to place in a POD (= 25 wafers).
- Splitting of lots between different batches is not allowed.
- Once processing of a batch is initiated it cannot be interrupted and other lots cannot be introduced into the machine until processing is completed.

Notations

Sets:

J $\{1, 2, - - - n\}$ jobs and j indicates *jth* job
B $\{1, 2, - - - m\ (= n)\}$ batches and b indicates *bth* batch
F $\{1, 2, - - -k\}$ families and k indicates *kth* family

Parameters:

S The total capacity of the machine on number of wafers
p_j The processing time of job j (= Processing time of family)
s_j The size (= the number of wafers) of job 'j'
r_j Release time of job 'j'
d_j The due date of job 'j'

w Capacity on number of lots (number of PODs) that can be processed in a furnace

Decision Variables:

X_{jfb} 1 if job j of family f is assigned to batch 'b'; 0 otherwise

Y_{fb} 1 if family f is assigned to batch 'b'; 0 otherwise

Dependent Variables:

C_n Completion Time of batch 'n'

p_b Processing time of batch 'b'

S_b Starting time of batch 'b'

An Integer Non Linear Programming Model for scheduling a DF

min C_n

Subject to:

$$\sum_{f=1}^{k}\sum_{b=1}^{m} X_{jfb} = 1 \qquad \forall j \in J \tag{25}$$

$$\sum_{j=1}^{n} s_j X_{jfb} \leq S \qquad \forall f \in F,\ \forall b \in B \tag{26}$$

$$\sum_{j=1}^{n} X_{jfb} \leq w \qquad \forall f \in F,\ \forall b \in B \tag{27}$$

$$\sum_{f=1}^{k} Y_{fb} \leq 1 \qquad \forall b \in B \tag{28}$$

$$X_{jfb} \leq Y_{fb} \qquad \forall j \in J, \forall b \in B, \forall f \in F \tag{29}$$

$$r_j X_{jfb} \leq S_b \qquad \forall j \in J, \forall b \in B, \forall f \in F \tag{30}$$

$$p_b \geq X_{jfb} p_j \qquad \forall j \in J, \forall b \in B, \forall f \in F \tag{31}$$

$$S_b X_{jfb} + p_b \leq d_j \qquad \forall j \in J, \forall b \in B, \forall f \in F \tag{32}$$

$$S_b + p_b \leq S_{b+1} \qquad \forall b \in B \tag{33}$$

$$C_n = S_n + p_n \qquad \forall f \in F \tag{34}$$

$$X_{jfb}, Y_{fb} \in 0 \text{ or } 1 \tag{35}$$

The objective is to minimize the completion time of the last job. The constraint (25) ensures that job j of family f is assigned to only one batch. The constraint (26) makes sure that machine capacity is not exceeded in terms of wafer assigned to a batch. Constraint (27) restricts the number of lots (number of PODs) that can be processed in a furnace. Constraint (28) ensures that at most one family is assigned to a batch. Constraint (29) ensures that a job (a lot) of a particular family is assigned to a particular batch if and only if the corresponding family is assigned to the particular batch. Constraint (30) assures that the ready time of a job must at most be equal to the starting time of the batch to which it belongs.

Constraint (31) calculates the processing time of batch b as the maximum processing time of all jobs which go into the batch. Constraint (32) restricts a deadline on job j. This means that if job j is processed in batch b then processing of batch b must be completed before the due date of job j. A schedule is feasible only if all jobs are completed before their due date. Constraint (33) ensures that the completion time of batch b is at most equal to the start time of the next batch. Constraint (34) calculates completion time of the last batch. Constraint (35) enforces binary restrictions on decision variables X_{jfb} and Y_{fb}.

3.3 Validation of the INLP Model for Scheduling a DF

To validate the formulation proposed in this section, we give a test problem with data as follows: processing time of families 1 and 2 are 7 h and 10 h, respectively, capacity on number of wafers = 75, and capacity on number of lots (= PODs) that can be processed in DF = 3. Lot size, processing time required for lot, release time, the due date for the lot and family id of each job are given in Table 7.

The optimal solution for the numerical example was obtained using LINGO 8.0. The batch wise job details, starting of time each batch, processing time of each batch, and the completion time of each batch are given in Table 8. Finally, needless to say, there are five empty batches that have no jobs assigned in optimal solution of LINGO, and we eliminate these empty batches when interpreting the solution.

Computational intractability of the INLP model for scheduling a DF. Furthermore, a computational experiment was conducted for scheduling diffusion furnace with multiple incompatible job families, non-identical job size, and non-agreeable release times and due dates to understand the computational difficulties, when number of lots keeps on increasing, while using the proposed INLP model to obtain optimal $C_{\max}$. The optimal $C_{\max}$ obtained for various problem sizes in terms of number of lots is reported in Table 9 along with the required computational time with Pentium 4. From Table 4, it is observed that the computational time required to solve various problem sizes (in terms of number of lots) is non-deterministic and non-polynomial.

From the empirical evidence (Table 9) on the computational difficulties in getting optimal schedule for a single job-independent diffusion furnace with incompatible job families, non-identical job sizes, and non-agreeable release times and due dates, it is obvious that the real life problem of scheduling parallel and

Table 7 Numerical example for validating the INLP model in scheduling a DF

Job code	Family	No. of wafers in a lot (= POD)	Process time	Due date	Release time
J1	1	17	7	35	13
J2	1	23	7	37	22
J3	1	22	7	30	11
J4	2	23	10	33	3
J5	2	17	10	93	34
J6	2	25	10	88	33
J7	1	16	7	45	22
J8	2	23	10	71	13
J9	2	18	10	23	8
J10	1	20	7	10	3

Table 8 The optimum schedule for the numerical example—scheduling a DF

Batch	Optimal solution				
	Jobs in the batch	Family	Start time of the batch	Processing time of the batch	Completion time of the batch
1	J10	1	3	7	10
2	J4, J9	2	10	10	20
3	J1, J3	1	20	7	27
4	J2, J7	1	27	7	34
5	J8, J6, J5	2	37	10	44

$C_{\max} = 44$:
Computational Time = 00:14:01 (hr:min:sec) with Pentium 4 with 2.40 GHz, 512 MB of RAM

Table 9 Computational time required for the INLP model in scheduling a DF

Number of lots	Optimal $C_{\max}$	Time required to get optimal $C_{\max}$ (hr:min:sec)
10	44	0:12:11
12	50	0:17:24
14	70	0:46:20
16	–	1:30:00 (Terminated)

heterogeneous diffusion furnaces will be of computationally intractable one, as this subsumes the single diffusion furnace case.

3.4 Scheduling a Burn-in Oven in Testing

The purpose of burn-in operation is to test the IC chips such as DRAMs, microprocessors, etc. Due to various processes employed in the manufacturing process, some chips may be "fragile" and may fail after only a short period of time. It is essential that these devices are identified and scrapped as "infant mortality".

The process of identifying and scrapping these "fragile" devices is known as the burn-in operation. It involves subjecting the chips to electrical and thermal stress to force the failure of weak or fragile devices. The devices are placed in an oven at temperatures up to 150 °C and voltages as high as 1.5 times the normal operating voltage is applied for a duration ranging between a few hours to as long as 48 h. Some space and military applications require two burn-in cycles with total time of more than 240 h at specified temperatures.

IC chips arrive at the burn-in area in lots consisting of a number of IC chips of the same product type. Each lot is referred to as a job. In a burn-in operation, IC chips of each job are loaded onto the boards; each job has different lot sizes so that the number of boards demanded (job sizes) is not identical. The boards are often product-specific, and the job cannot be processed without the necessary boards. Once IC chips have been loaded onto the boards, the boards are placed into an oven (a BP). Typically, the oven capacity is larger than the job size, so the number of boards an oven can hold defines the oven capacity, and the size of a job is defined by the number of boards it requires.

Each IC chip has a pre-specified minimum burn-in time, which may depend on its type and/or the customer's requirements. Since IC chips may stay in the oven for a period longer than their minimum required burn-in time, it is possible to place different products (jobs) in the oven simultaneously. The processing time of each batch equals the longest minimum-exposure time among all the products (jobs) in the batch. Effective burn-in operation scheduling is a key because it is frequently a bottleneck due to long processing times relative to other testing operations (e.g., days as opposed to hours) and because it occurs at the end of the manufacturing process and thus has a strong influence on the shipping dates (Azizoglu and Webster 2000).

The problem discussed in this section involves scheduling the single burn-in oven of SM with non-identical size jobs having non-identical processing times and non-agreeable release times and due dates with the objective of minimizing the TWT.

To concisely describe the problem discussed in this section, we shall use the three-field notation of Graham et al. (1979) to denote the scheduling of single burn-in oven problem as "*1/batch, non-identical job-sizes, non-identical processing times, non-agreeable release times and due dates/TWT*" problem. We make the following assumptions:

- All data related to scheduling of burn-in oven problem considered in this study are assumed to be deterministic and known a priori. In practice, estimates of the required parameters for this problem can be obtained from the shop-floor information system that tracks WIP in real time.
- We are given a set of n jobs. Each job, j, is associated with a size $s_j \geq 1$, the number of boards required to place all the IC chips of a lot (job); a release time $r_j \geq 0$, before which it cannot be scheduled; a due-date $d_j \geq 0$, which is the latest date that processing of job i can be completed; a processing time $p_j > 0$,

which specifies the minimum time needed to process job; and the release time and due dates are non-agreeable (i.e., $r_i < r_j$ not-implied $d_i \le d_j$).

- Each job requires one operation and all jobs are independent.
- Batch processing machine has a capacity B. The sum of the sizes of jobs in a batch must be less than or equal to B and the size of a job cannot be greater than B.
- Splitting of jobs between different batches is not allowed.
- Once processing of a batch is initiated, it cannot be interrupted and other jobs cannot be introduced into the machine until processing is completed. The processing time of a batch is given by the longest processing time of the jobs in the batch.
- The objective is to minimize the TWT.

3.5 An ILP Model for Scheduling Burn-In Oven

We present an ILP model in this section for scheduling a single burn-in oven with job characteristics: non-agreeable release times and due dates, non-identical processing time, and non-identical job-size in minimizing the TWT of the jobs. The notation used along with the definition of sets, parameters, and decision variables related to the model presented are as follows:

Notations

Sets:

Jobs—{1, 2, 3,.., j,.., J}; j indicates jth job.
Batches—{1, 2, 3,.., b,.., B} b indicates bth batch.

Parameters:

N Capacity of the oven (in terms of number of boards)
r_j Release time of job j—The time at which the job to be processed arrives at the oven
d_j Due date of job j—The time before which the job has to be processed without facing any penalty
p_j Burn-in processing time of job j—The minimum time for which the job has to be processed in the burn-in oven
s_j Job size: Number of boards required for the job j

Decision variables:

$$X_j^b \begin{cases} 0 & \text{if Job } j \text{ is not processed in batch } b \\ 1 & \text{if Job } j \text{ is processed in batch } b \end{cases}$$

Dependent variables:

R^b Release time of a batch b
P^b Processing time of a batch b. This is the maximum processing time of all jobs in the batch

C^b Completion time of a batch b
c_j Completion time of a job j

The Mathematical Formulation

Minimize

$$\sum_{j=1}^{n} W_j \times t_j \tag{36}$$

Subject to

$$\sum_{b=1}^{B} X_j^b = 1 \, \forall j = 1 \text{ to } J \tag{37}$$

$$\sum_{j=1}^{J} s_j \times X_j^b \leq N \, \forall b = 1 \text{ to } B \tag{38}$$

$$R^b \geq r_j \times X_j^b \quad \forall j = 1 \, to \, J; b = 1 \text{ to } B \tag{39}$$

$$P^b \geq p_j \times X_j^b \quad \forall j = 1 \, to \, J; b = 1 \text{ to } B \tag{40}$$

$$C^b \geq R^b + P^b \;\; \forall b = 1 \text{ to } B \tag{41}$$

$$R^{b+1} > C^b \;\; \forall b = 1 \text{ to } B - 1 \tag{42}$$

$$C_j \geq C^b - M\left(1 - X_j^b\right) \forall j = 1 \text{ to } J \text{ and } b = 1 \text{ to } B; M \text{ is a very large positive number} \tag{43}$$

$$t_j \geq c_j - d_j \, \forall j = 1 \text{ to } J \tag{44}$$

Objective (36) is to minimize the TWT of the jobs. Constraint (37) specifies that each job can be processed in exactly one batch. Constraint (38) restricts the total number of boards of different jobs in each batch to utmost the capacity of oven N. Constraint (39) ensures that the release time of a batch is at least equal to the latest arrival time of all jobs in the batch. Constraint (40) states that the processing time of a batch as the maximum processing times of all jobs in the batch. Constraint (41) indicates that the completion time of a batch is at least equal to sum of the release time of the batch and the processing time of the batch. Constraint (42) ensures that each batch can be released only after the previous batch has been completed. Constraint (43) defines the completion time of each job as the completion time of the batch that it is processed. Constraint (44) defines the tardiness of a job. The tardiness of a job is defined as the minimum of the difference between the due date of a job and its completion time or 0.

3.6 Validation the ILP Model for Scheduling Burn-in Oven

To validate the (0–1) ILP model presented, we provide a numerical problem whose data are: Batch size = 20; and Number of jobs = 10; Number of batches = 4. Also, the processing time, release time, due-date, and job-sizes of these 10 jobs are given in Table 10.

As we can see from the data, there are jobs (Example: J5 and J6) for which the release times and due dates are non-agreeable. An appropriate LINGO set code is written for generating the ILP model as proposed above for the given data. The given numerical problem is used as input to the LINGO set code. The LINGO set code then generates the required ILP Model. The generated model is then solved using LINGO. The optimal TWT (= TWT = 169) is obtained from LINGO for the given numerical example. Using the optimal solution obtained, we find batch wise the job details, processing time, release time, completion time, and utilization and presented in Table 11.

Although the model has provided an optimal solution for the numerical example, there is no guarantee that the model will solve any problem size with reasonable computational effort. So, the computational complexity of the proposed ILP model is studied as follows.

Computational Intractability of the ILP Model for Scheduling Burn-in Oven. A computational experiment was conducted for scheduling burn-in oven with non-agreeable release times and due dates to understand the computational difficulties, when number of jobs increases, while using the proposed ILP model to obtain optimal TWT. The computational time required to obtain optimal TWT for various problem sizes is observed and shown in Fig. 4.

From Fig. 4, it is observed that the computational time required to solve various problem sizes (in terms of number of jobs) might be non-deterministic and non-polynomial. From the empirical evidence on the computational difficulties in getting optimal schedule for a single burn-in oven with non-agreeable release times and due dates, it is obvious that the problem of scheduling jobs in real-time will be computationally intractable.

Table 10 A numerical example to validate the ILP model for scheduling burn-in Oven

Job	J1	J2	J3	J4	J5	J6	J7	J8	J9	J10
Processing time	5	10	12	8	4	10	12	6	7	10
Release time	10	10	15	28	30	31	33	35	40	43
Due date	21	25	30	40	51	44	47	45	55	60
Job size	4	10	6	7	8	5	7	9	8	10

Table 11 Batch wise the optimal solution for the numerical example—scheduling burn-in oven

Batch Id.	Job			Processing time of		Release time of		Completion time of batch	Utilization of batch in terms of No. of Boards	Tardiness of job	Weighted tardiness of job = tardiness of job × Job-size
	Id.	Size	Due-date	Job	Batch	Job	Batch				
B1	J1	4	21	5	12	10	15	27	20	6	24 (= 6 × 4)
	J2	10	25	10		10				2	20 (= 2 × 10)
	J3	6	30	12		15				0	0
B2	J4	7	40	8	10	28	31	41	20	1	7 (= 1 × 7)
	J5	8	51	4		30				0	0
	J6	5	44	10		31				0	0
B3	J8	9	45	6	7	35	41	48	17	3	27 (= 3 ×9)
	J9	8	55	7		40				0	0
B4	J7	7	47	12	12	33	48	60	17	13	91 (= 13 × 7)
	J10	10	60	10		43				0	0
Total weighted tardiness											169

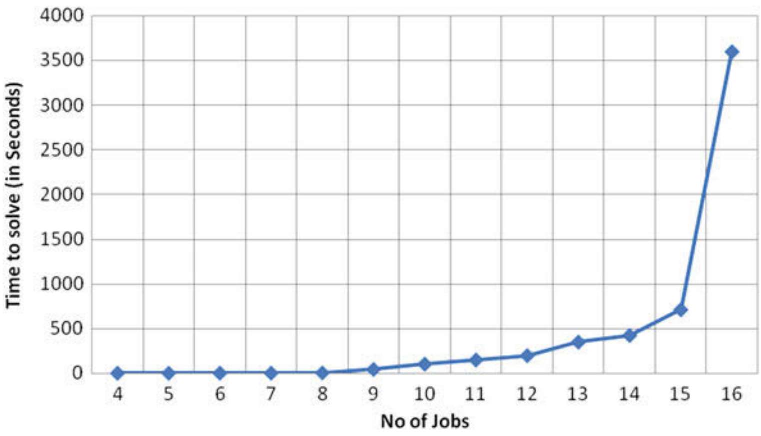

Fig. 4 Computational intractability of the ILP model for scheduling burn-in oven

4 Scheduling BP in Steel Casting Manufacturing

In this section, we consider the problem of scheduling jobs on heat-treatment furnaces (HTFs), a BP, in the post-casting stage of steel casting manufacturing. A fundamental feature of steel casting manufacturing is its extreme flexibility, enabling castings to be produced with almost unlimited freedom in design over an extremely wide range of sizes, quantities, and materials suited to practically every environment and application. In addition, the steel casting manufacturing industry is capital intensive and highly competitive. The latter forces a greater emphasis on customer service. Planning and scheduling research address these needs.

Like all foundries, a steel casting foundry is a flow line production system in which the sequence of operations is fixed and the workflow is in a single direction. The manufacturing process of steel castings is often composed of three stages including pre-casting stage, casting stage, and post casting stage (Fig. 5). The working mechanism of the steel casting foundry studied is briefly described here.

> Based on planned orders, moulds (and cores) are prepared using patterns. These moulds are moved to the pouring area where molten metal from melting furnaces are poured and allowed to cool. In the next operation, castings are knocked out of the mould cavity either manually or mechanically. The knocked out rough castings are then shot blasted and cut to the finished castings, which are generally moved to storage prior to the next process; heat-treatment. The stored castings are grouped into batches depending on the type and family of castings, and loaded on the furnaces for the process-controlled heat treatment operation. Subsequently, the heat-treated castings are fettled, finished, and inspected prior to dispatch to the customers.

The heat-treatment operation is critical because it determines the final metallurgical properties that enable the components to perform under demanding service conditions such as large mechanical load, high temperature, and corrosive environment. Generally, different types of castings have to undergo more than one type

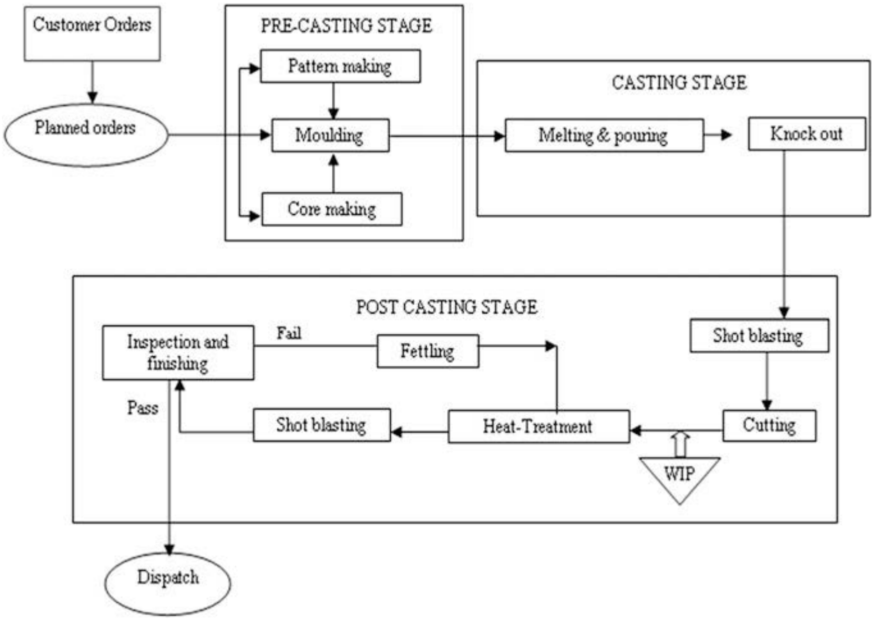

Fig. 5 An overview of steel casting process

of heat-treatment operation, where the total heat-treatment processing times change. For control purposes, castings are primarily classified into a number of job-families based on the alloy type such as low-alloy castings and high alloy castings. These families are further classified into various sub-families based on the type of heat-treatment operations required by them. For technical reasons, such as type of alloy, temperature level, and the expected combination of heat-treatment operations, the castings (jobs) from different families *cannot* be processed together in the same batch. These job families are therefore mutually incompatible for processing.

It is important to note that the heat-treatment operation is the only lengthiest processes in the entire steel casting industries, taking up a longest processing time (taking maximum of few days versus other processes that typically take an hour or less). With such large processing times required in heat-treatment operations, the scheduling HTF can have profound effect on the overall production rate. Furthermore, since the post-casting stage is the last stage in casting manufacturing, its scheduling is critical in productivity and on-time delivery management. Thus, better scheduling of HTF can improve the throughput and can significantly reduce the overall production time. Accordingly, the objective of the study considered here is to minimize the maximum completion time.

Particularly in this section, we consider the research problem of scheduling a single HTF with single job family (SJF), non-identical job sizes (NIJS), and non-identical job dimensions (NIJD) to minimize makespan. This research problem is

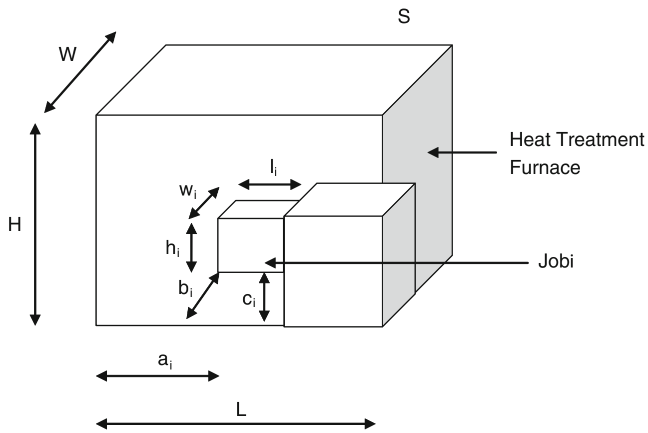

Fig. 6 Pictorial representation of scheduling heat treatment furnace in steel casting

applicable for a situation where the small-scale steel casting industry performs only one type of special heat-treatment operation such as surface hardening. Generally, there would be few steel casting industries which undertake such type of special heat-treatment operation and thus the customer is willing to accept delay in the completion of his orders. A pictorial representation of the problem statement is shown in Fig. 6.

To describe the problem concisely, we shall use the three-field notation of Graham et al. (1979) to denote the scheduling problem addressed in this papers as "*1/batch, SJF, NIJS, NIJD/*$C_{\max}$". We make the assumptions as follows:

- There are n jobs (n single castings) to be processed and these jobs are from a single job-family. Each job has a size s_i (in terms of weight) with dimensions l_i length, w_i width and h_i height
- All jobs must pass through the HTF
- There is a single HTF, which has capacity limit in terms of size S (in terms of weight) and dimensions L Length, W Width, and H Height
- Orientation of jobs is not allowed
- All data of $S, L, W, H, s_i, l_i, w_i$, and h_i are deterministic, known a priori and $s_i \leq S; l_i \leq L; w_i \leq W;$ and $h_i \leq H$ for all jobs i
- Processing time of job family is constant and independent of number of jobs in the batch
- Preparation time, if any, is included in the processing time and there is no setup time in switching from one batch to another
- Once processing of a batch is initiated, the HTF cannot be interrupted and other jobs cannot be introduced into the HTF until the current processing is completed
- Machine breakdowns are not considered.

4.1 A Mixed Integer Linear Programming Model for Scheduling a HTF

The problem of scheduling a HTF with a SJF, NIJD, and NIJS can be viewed as an extension of the three dimensional bin packing problem. Mathematical models proposed by various researchers (Fasano 2008; Padberg 2000) for bin packing problem consider NIJD characteristics explicitly and there is no restriction on capacity of the bins in terms of job sizes considered in these studies. But in scheduling a HTF, job (casting) sizes vary widely (from 10 g to 1,000 kg) which puts a serious restriction on the number of jobs that can be accommodated in a batch to satisfy the capacity restrictions of HTF in terms of size in addition to dimensions of job. Accordingly, based on the mathematical models available in the literature for bin packing problem, the problem of scheduling a HTF with capacity restrictions on both job dimensions and sizes has been formulated as Mixed Integer Linear Programming (MILP). The MILP model for scheduling a HTF with a SJF, NIJD and NIJS is as follows:

Notations

Indices:

i and k	*1, 2, 3, …,* N Jobs
j	*1, 2, 3, …,* m Batches

Parameters:

M	A large arbitrary number
(l_i, w_i, h_i)	Parameters indicating length, width and height of job i
s_i	Size of job i
(L, W, H)	Length, Width and Height of BP
S	Size capacity of BP
p	Processing time of job family

Continuous Decision Variables:

(a_i, b_i, c_i)	Coordinates of the front left bottom corner of job i. It is assumed that the origin is fixed at Front Left Bottom corner of the BP
(a_k, b_k, c_k)	Coordinates of the front left bottom corner of job k. It is assumed that the origin is fixed at Front Left Bottom corner of the BP

Binary Decision Variables:

x_{ij}	1 if job i is assigned to batch j; 0 otherwise
n_j	1 if job i is assigned to batch j; 0 otherwise
$left_{ik}$	1 if job i is on left side of job k $\forall\ i < k$; 0 otherwise
$right_{ik}$	1 if job i is on right side of job k $\forall\ i < k$; 0 otherwise
$behind_{ik}$	1 if job i is behind job k $\forall\ i < k$; 0 otherwise
$front_{ik}$	1 if job i is in front of job k $\forall\ i < k$; 0 otherwise

$below_{ik}$ 1 if job i is below job k $\forall$ $i < k$; 0 otherwise
$above_{ik}$ 1 if job i is above job k $\forall$ $i < k$; 0 otherwise

Dependent Variables:
p_j Processing time of batch j
$C_{\max}$ Completion time of last batch

A MILP Model for Scheduling a HTF
Min $C_{\max}$
Subject to

$$\sum_{j=1}^{m} x_{ij} = 1 \qquad \forall i \tag{45}$$

$$a_i + l_i \le L \qquad \forall i \tag{46}$$

$$b_i + w_i \le W \qquad \forall i \tag{47}$$

$$c_i + h_i \le H \qquad \forall i \tag{48}$$

$$\sum_{i=1}^{N} s_i x_{ij} \le S * n_j \qquad \forall i \tag{49}$$

$$a_i + l_i \le a_k + (1 - left_{ik})M \qquad \forall i, k, i < k \tag{50}$$

$$a_k + l_k \le a_i + (1 - right_{ik})M \qquad \forall i, k, i < k \tag{51}$$

$$b_i + w_i \le b_k + (1 - behind_{ik})M \qquad \forall i, k, i < k \tag{52}$$

$$b_k + w_k \le b_i + (1 - front_{ik})M \qquad \forall i, k, i < k \tag{53}$$

$$c_i + h_i \le c_k + (1 - below_{ik})M \qquad \forall i, k, i < k \tag{54}$$

$$c_k + h_k \le c_i + (1 - above_{ik})M \qquad \forall i, k, i < k \tag{55}$$

$$left_{ik} + right_{ik} + behind_{ik} + front_{ik} + below_{ik} + above_{ik} \ge x_{ij} + x_{kj} - 1 \qquad \forall i, k, j,\ i < k \tag{56}$$

$$left_{ik} + right_{ik} + behind_{ik} + front_{ik} + below_{ik} + above_{ik} \le 1 + x_{ij} - x_{kj} \qquad \forall i, k, j,\ i < k \tag{57}$$

$$p_j \ge p * n_j \qquad \forall j \tag{58}$$

$$C_{max} = \sum_{j=1}^{m} p_j \tag{59}$$

Binary Restrictions:
$left_{ik}$, $right_{ik}$, $behind_{ik}$, $front_{ik}$, $below_{ik}$, $above_{ik}$, x_{ij}, $n_j = 0$ *or* 1
Non-negativity constraints: a_i, b_i, c_i, a_k, b_k, c_k, p_j, $C_{\max} \geq 0$

The objective of the proposed MILP model is to minimize the completion time of the last batch. Constraint (45) guarantees that each job will be assigned to only one HTF. Constraints (46)–(48) ensure that all the jobs assigned to a batch fit within the physical dimensions of the HTF. Constraint (49) ensures that weight capacity of HTF is not exceeded. The constraints (50)–(55) ensure that jobs do not overlap with one another. Checking for overlap is necessary only if a pair of jobs is placed in the same HTF. This is taken care of by Constraints (56) and (57). Constraint (58) accounts for minimum processing time of a batch. Constraint (59) computes makespan as the sum of processing time of all batches.

4.2 Validation of the MILP Model for Scheduling a HTF

To validate the MILP model presented here, we develop a numerical example assuming one HTF with one job family having $n = 10$ jobs with the processing time of the job family as 15 h. The capacity of the HTF is in terms of size of the HTF = 1,000 kg; and in terms of dimensions: $L = 1{,}500$ mm; $W = 950$ mm; H = 900 mm. The size, dimensions, and processing time of the 10 jobs are given in Table 12.

A LINGO set code is developed to generate the MILP model presented here for any given data. Using the LINGO set, the MILP model is generated for the numerical example presented in Table 12. The generated MILP model is solved using LINGO. The optimal solution obtained for the numerical example is presented in Table 13, which gives the batch wise job details, starting time, processing time (with Pentium 4) and the completion time of each batch.

Computational intractability of the MILP model for scheduling a HTF. Although we are able to solve the numerical example optimally for $n = 10$ jobs, we attempt to empirically understand the computational difficulty of solving the MILP model for various values of n. That is, we attempt to solve six instances for various values of n ($n = 10$, 20, 30, 40, 50, and 60) using the MILP model (using

Table 12 A numerical example—scheduling HTF

Parameter	Job = j =									
	1	2	3	4	5	6	7	8	9	10
s_j (kg^a)	275	115	189	250	133	160	157	222	298	291
l_j (mm^b)	466	223	321	164	165	251	359	474	253	155
w_j (mm)	105	188	142	258	292	149	301	190	202	197
h_j (mm)	245	256	204	213	103	213	281	150	236	290
p_j	15	15	15	15	15	15	15	15	15	15

[a] Kilogram, [b] Millimetre

Table 13 Optimal solution obtained using the MILP model—scheduling HTF

Batch	Optimal solution			
	Jobs in the batch	Start time of the batch (*h*)	Processing time of the batch (*h*)	Completion time of the batch (*h*)
1	3,6,8,10	0	15	15
2	1	15	15	30
3	2,4,5,7,9	30	15	45

$C_{\max} = 45$ h;
Computational time = 00:00:02 (hr:min:sec) with Pentium 4 with 2.40 GHz, 1 GB of RAM;
Number of iterations = 4520

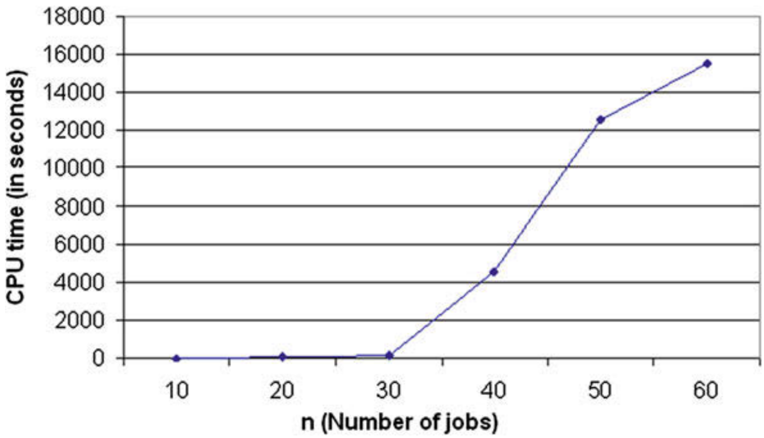

Fig. 7 CPU time (in seconds) required for different **n** to obtain optimal solution—scheduling a HTF

LINGO set code) and observe the optimal makespan value and the computational time taken. The CPU time (in seconds) taken for each of the problem instances with varying sizes is shown in Fig. 7.

It is evident from Fig. 7 that the growth in computational time as a function of problem size, is non-deterministic and non-polynomial and empirically highlights the computational intractability of the MILP model in scheduling a HTF. Furthermore, as the research problem defined in this section considers only one job family with processing time remaining the same for all job, the minimizing makespan problem is equivalent to well-known bin packing problem. According to Garey and Johnson (1979) the bin packing problem is strongly NP-hard, and then the problem of scheduling a single HTF with NIJS and NIJS is strongly NP hard, too.

Though the MILP model presented here may not be useful for solving the real life sizes scheduling problem on HTF, the learning process and the insights gaining in observing the solutions by solving various small size problems would provide a good background and creativity while developing an alternative method(s): heuristic method for scheduling HTF.

5 Conclusion

Based on the authors' own experience in addressing research problems related to scheduling BP, in this chapter, they define scheduling BP problems, very close to the reality, from three discrete parts manufacturing: (i) automobile gear manufacturing, (ii) semiconductor manufacturing, and (iii) steel casting industries. For each of the scheduling BP problems defined, a mathematical model is presented.

A LINGO set code, which would provide solution to the proposed mathematical model for the given data, is developed for each of the respective mathematical models. The workability of each mathematical model is demonstrated by developing suitable numerical example and solving it using the LINGO set code. Finally, each one of these mathematical models has been empirically proved for their computational intractability for solving larger size problems.

The formulation presented for each of the classes of problems discussed in this chapter can be used to prescribe exact solutions for reasonable size of the problems. Though these formulations cannot be used for real life sized problems, the experience in attempting to obtain optimal solution gives tremendous insights in terms of problem data and the solution based on the respective formulation. These insights are very useful input for developing alternative procedures such as heuristic algorithms for real life large sized problems.

For each of the classes of the problems considered in this study, it is assumed that the real life practice will have only one BP. But, in reality the real life problem situation will be having more than one BPs and that too with different capacity. Incorporating this real life characteristic increases the computational intractability of the mathematical model presented here. However, the academic exercises in including this problem characteristics and obtaining optimal solution on various small size problems provide many insights on the problem data and the solution obtained for the same. This will be of immediate research direction in addition to propose efficient alternative methods: heuristic algorithms for scheduling BPs related to each of these three discrete parts manufacturing for the readers.

Annexure 1

A LINGO set code and sample data input for the ILP model for research problem with Hardening and Soaking Furnace (HSF)

```
SETS:
JOBS:RELEASE_TIME,DUE_DATE,WEIGHT,MASS,TARDINESS,
CT_JOB;
FAMILIES:PROCESSING_TIME;
BATCHES:CT_BATCH,RELEASE_BATCH,PROCESSING_BATCH;
```

```
JTOF(JOBS,FAMILIES):FAM_CLASS;
FTOB(FAMILIES,BATCHES):Y;
JTOB(JOBS,BATCHES):X,FRACTION,CT_FRAC;
ENDSETS

DATA:
JOBS = @FILE('job_index.ldt');
FAMILIES = @FILE('family_index.ldt');
BATCHES = @FILE('batch_index.ldt');
RELEASE_TIME = @FILE('release.ldt');
DUE_DATE = @FILE('duedate.ldt');
WEIGHT = @FILE('weight.ldt');
MASS = @FILE('mass.ldt');
CAPACITY = @FILE('capacity.ldt');
AVAILABILITY = @FILE('availability.ldt');
PROCESSING_TIME = @FILE('proc.ldt');
FAM_CLASS = @FILE('fam_assoc.ldt');
ENDDATA

! OBJECTIVE FUNCTION (EQUATION 1)
MIN = @SUM(JOBS(J): WEIGHT(J)* TARDINESS(J));

! ATMOST ONE FAMILY CAN BE PROCESSED IN A GIVEN BATCH
(EQUATION 2);
@FOR(BATCHES(B):
@SUM(FAMILIES(F): Y(F,B)) <= 1);

! A BATCH CAN BE FORMED ONLY IF ITS PREVIOUS BATCH HAS BEEN
FORMED (EQUATION 3);
@FOR(BATCHES(B)|B #GT# 1:
@SUM(FAMILIES(F): Y(F,B-1)) >= @SUM(FAMILIES(F):
Y(F,B)));

! RELEASE TIME, PROCESSING TIME, AND COMPLETION TIME OF
BATCHES RESPECTIVELY (EQUATIONS 4, 5 AND 6);

@FOR(BATCHES(B)|B #GT# 1:
RELEASE_BATCH(B) >= CT_BATCH(B-1));

@FOR(BATCHES(B):
PROCESSING_BATCH(B) >= @SUM(FAMILIES(F):PROCESSING_
TIME(F)*Y(F,B)));

@FOR(BATCHES(B):
CT_BATCH(B) >= RELEASE_BATCH(B) + PROCESSING_
BATCH(B));
```

```
! A JOB CAN BE PROCESSED IN A BATCH ONLY IF THE FAMILY TO
WHICH IT BELONGS TO IS PROCESSED IN THAT BATCH
(EQUATION 7);
@FOR(JOBS(J):
@FOR(FAMILIES(F):
@FOR(BATCHES(B):
X(J,B) * FAM_CLASS(J,F) <= Y(F,B))));

! IF SOME FAMILY IS ASSIGNED TO A BATCH, THEN THAT BATCH
MUST CONTAIN ATLEAST ONE JOB OF THAT FAMILY (EQUATION 8);
@FOR(FAMILIES(F):
@FOR(BATCHES(B):
@SUM(JOBS(J): X(J,B) * FAM_CLASS(J,F)) >= Y(F,B)));

! RELEASE TIME OF A BATCH MUST NOT BE LESS THAN THE RELEASE
TIME OF ANY OF JOBS CONSTITUTING THE BATCH (EQUATION 9);
@FOR(BATCHES(B):
@FOR(JOBS(J):
RELEASE_BATCH(B) >= RELEASE_TIME(J) * X(J,B)));

! A JOB CAN BE PROCESSED MAXIMUM IN TWO BATCHES
(EQUATION 10);
@FOR(JOBS(J):
@SUM(BATCHES(B):X(J,B)) <= 2);

! A JOB MUST BE PROCESSED ATLEAST IN ONE BATCH
(EQUATION 11);
@FOR(JOBS(J):
@SUM(BATCHES(B):X(J,B)) >= 1);

! THE FRACTION OF A JOB MUST BE LESS THAN OR EQUAL TO 1
(EQUATION 12);
@FOR(JOBS(J):
@FOR(BATCHES(B):FRACTION(J,B) <= 1));

! THE FRACTION OF A JOB MUST BE GREATER THAN OR EQUAL TO 0
(EQUATION 13);
@FOR(JOBS(J):
@FOR(BATCHES(B):FRACTION(J,B) >= 0));

! SUM OF ALL FRACTIONS FOR A JOB MUST BE 1 (EQUATION 14);
@FOR(JOBS(J):
@SUM(BATCHES(B):FRACTION(J,B)) = 1);

! IF A JOB IS ASSIGNED TO A BATCH THEN SOME FRACTION OF THAT
JOB MUST BE PROCESSED IN THAT BATCH. ALSO WHEN A JOB IS NOT
ASSIGNED TO A BATCH, NO FRACTION CAN BE PROCESSED (EQUA
TIONS 15 AND 16);
```

```
@FOR(JOBS(J):
@FOR(BATCHES(B):X(J,B) >= FRACTION(J,B)));

@FOR(JOBS(J):
@FOR(BATCHES(B):FRACTION(J,B) > 10000 * (X(J,B) - 1)));

! THE QUANTITY PROCESSED IN ANY BATCH SHOULD NOT EXCEED THE
BATCH PROCESSOR CAPACITY (EQUATION 17);
@FOR(BATCHES(B):
@SUM(JOBS(J): FRACTION(J,B) * MASS(J)) <= CAPACITY);
! FRACTIONAL COMPLETION TIME OF A JOB SHOULD NOT BE LESS
THAN THE COMPLETION TIME OF THE BATCH IN WHICH IT IS PRO
CESSED (EQUATION 18);
@FOR(JOBS(J):
@FOR(BATCHES(B):
CT_FRAC(J,B) >= CT_BATCH(B) - 10000 * (1 - X(J,B))));

! COMPLETION TIME OF THE JOB MUST NOT BE LESS THAN ANY OF ITS
FRACTIONS (EQUATION 19);
@FOR(JOBS(J):
@FOR(BATCHES(B):CT_JOB(J) >= CT_FRAC(J,B)));

! RELEASE TIME OF THE FIRST BATCH ON A BP IS THE FIRST TIME
AVAILABILITY OF THE BP (EQUATION 20);
@FOR(BATCHES(B)|B #EQ#
1:RELEASE_BATCH(B) >= AVAILABILITY);

! DEFINE TARDINESS (EQUATIONS 21 AND 22);
@FOR(JOBS(J): TARDINESS(J) >= CT_JOB(J) - DUE_DATE(J));
@FOR(JOBS(J): TARDINESS(J) >= 0);

! ASSIGNS BINARY RESTRICTION ON THE DECISION VARIABLES
(EQUATION 23 AND 24)
@FOR(JTOB:@BIN(X));
@FOR(FTOB:@BIN(Y));
```

The sample input files for LINGO implementation, for the numerical example described in Sect. 2.4 (Table 3) are given below

Input file 'job_index.ldt': A B C D E F G H I J

Input file 'family_index.ldt': P Q R

Input file 'batch_index.ldt': a b c d e f g h i j

Input file 'release.ldt':	Input file 'duedate.ldt':	Input file 'weight.ldt':	Input file 'mass.ldt':	Input file 'fam_assoc.ldt':
6	36	6	20	1 0 0
1	15	4	18	0 1 0
10	52	6	13	0 1 0
10	22	5	19	0 0 1
4	14	3	3	1 0 0
0	20	3	11	1 0 0
0	10	5	11	1 0 0
2	32	6	2	1 0 0
7	27	3	12	1 0 0
6	24	2	6	0 0 1

Input file 'capacity.ldt': 30 Input file 'availability.ldt': 1
Input file 'proc.ldt':
10
14
6

Annexure 2

Problem instance wise optimal total weighted tardiness (TWT) and required computational time for research problem with hardening and soaking furnace (HSF)

Problem instance	Optimal TWT	Time required to obtain optimal TWT (hr-min-sec)	Problem instance	Optimal TWT	Time required to obtain optimal TWT (hr-min-sec)	Problem instance	Optimal TWT	Time required to obtain optimal TWT (hr-min-sec)
1	250	00-00-32	33	83	00-01-12	65	432	00-26-57
2	0	00-00-01	34	0	00-00-02	66	30	00-00-16
3	93	00-00-05	35	112	00-00-10	67	200	00-03-55
4	230	00-00-37	36	1	00-00-01	68	205	00-01-44
5	190	00-00-11	37	97	00-00-03	69	122	00-00-21
6	30	00-00-01	38	96	00-00-05	70	324	00-18-00
7	40	00-00-11	39	51	00-00-02	71	254	00-11-25
8	36	00-00-04	40	32	00-00-03	72	111	00-00-27
9	208	00-00-32	41	307	00-02-01	73	347	00-17-33
10	133	00-00-07	42	146	00-00-38	74	27	00-00-08
11	106	00-00-10	43	0	00-00-01	75	389	00-08-50
12	24	00-00-06	44	64	00-00-12	76	74	00-03-41
13	268	00-02-53	45	28	00-00-10	77	212	00-02-40
14	95	00-00-03	46	6	00-00-06	78	66	00-00-32

(continued)

(continued)

Problem instance	Optimal TWT	Time required to obtain optimal TWT (hr-min-sec)	Problem instance	Optimal TWT	Time required to obtain optimal TWT (hr-min-sec)	Problem instance	Optimal TWT	Time required to obtain optimal TWT (hr-min-sec)
15	187	00-00-24	47	69	00-00-14	79	347	00-09-39
16	48	00-00-12	48	3	00-00-02	80	0	00-00-01
17	369	00-01-51	49	73	00-00-04	81	67	00-01-04
18	0	00-00-01	50	14	00-00-14	82	131	00-00-19
19	81	00-00-07	51	64	00-00-08	83	152	00-01-48
20	4	00-00-04	52	43	00-00-11	84	29	00-00-51
21	121	00-00-27	53	220	00-00-23	85	54	00-00-18
22	34	00-10-03	54	210	00-00-21	86	280	00-02-17
23	20	00-00-01	55	60	00-00-01	87	106	00-01-12
24	68	00-00-02	56	0	00-00-01	88	85	00-00-29
25	250	00-00-27	57	61	00-00-11	89	151	00-00-50
26	41	00-00-01	58	44	00-00-07	90	68	00-00-32
27	156	00-00-07	59	220	00-01-06	91	111	00-03-47
28	14	00-00-02	60	48	00-00-02	92	0	00-00-01
29	185	00-00-20	61	205	00-00-21	93	257	00-03-57
30	76	00-00-02	62	24	00-00-11	94	90	00-00-11
31	141	00-00-20	63	137	00-00-19	95	167	00-00-52
32	0	00-00-03	64	48	00-00-05	96	0	00-00-14
97	277	00-25-40	129	667	02-22-04	161	373	02-32-33
98	62	00-02-10	130	35	00-01-39	162	147	00-12-46
99	217	00-08-49	131	275	00-56-47	163	426	03-26-48
100	0	00-00-01	132	124	00-07-35	164	109	00-16-37
101	147	00-04-19	133	495	12-29-19	165	574	02-50-40
102	101	00-04-30	134	178	00-30-27	166	12	00-01-02
103	184	00-08-28	135	196	01-02-27	167	215	01-20-32
104	117	00-01-42	136	35	00-03-26	168	78	00-04-00
105	84	00-00-01	137	452	03-51-31	169	528	02-38-17
106	164	00-03-40	138	164	00-04-53	170	99	00-07-12
107	98	00-02-36	139	301	01-04-06	171	277	02-29-49
108	0	00-00-03	140	13	00-00-43	172	56	00-09-33
109	434	01-11-33	141	302	02-53-37	173	179	00-36-19
110	33	00-00-09	142	284	00-07-00	174	17	00-02-30
111	149	00-06-06	143	124	00-05-23	175	220	00-29-22
112	226	00-05-33	144	176	00-27-51	176	48	00-07-27
113	339	00-24-55	145	204	00-11-32	177	169	00-14-08
114	115	00-01-55	146	86	00-04-10	178	76	00-10-41
115	201	00-08-43	147	150	00-14-40	179	200	00-27-29
116	3	00-00-45	148	58	00-01-41	180	119	00-38-35
117	223	00-11-16	149	487	01-59-33	181	310	01-03-00
118	257	00-03-16	150	82	00-00-35	182	208	00-35-32

(continued)

(continued)

Problem instance	Optimal TWT	Time required to obtain optimal TWT (hr-min-sec)	Problem instance	Optimal TWT	Time required to obtain optimal TWT (hr-min-sec)	Problem instance	Optimal TWT	Time required to obtain optimal TWT (hr-min-sec)
119	312	00-18-05	151	61	00-01-02	183	198	01-25-14
120	24	00-00-17	152	91	00-05-11	184	102	00-12-48
121	401	00-08-52	153	263	02-26-40	185	279	00-45-40
122	60	00-00-18	154	288	00-15-02	186	288	00-32-20
123	18	00-00-07	155	297	00-23-08	187	149	00-11-18
124	208	00-02-30	156	0	00-00-29	188	161	00-33-31
125	229	00-03-59	157	199	00-06-16	189	279	01-16-51
126	325	00-18-28	158	0	00-00-16	190	20	00-03-04
127	122	00-01-50	159	201	00-27-07	191	93	00-08-38
128	101	00-00-50	160	54	00-14-03	192	0	00-00-30

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Cooperative Purchasing in Small and Medium-sized Enterprises

Wantao Yu

Abstract Despite the increasing research interests in the purchasing group, cooperative purchasing in small and medium-sized enterprises (SMEs) has not received significant attention from the operations and supply chain management researcher. This study investigates the typical advantages of cooperative purchasing for SME retailers, and critical success factors for managing a purchasing group, using a case study of a purchasing group established by Chinese SME retailers. The study suggests that a successful purchasing group can help SME retailers to survive in today's competitive marketplace. The main advantages of cooperative purchasing for SME retailers are lower purchasing prices, mutual learning and support, dealing with illegal bribes, and quality improvement. The success factors for SME retailers to manage a purchasing group are good guanxi (personal and business relationships) among group members, similar characteristics of group members, similar personality traits of top executives, and the role of a "big brother" (group leader) in the group. This study also provides practical insights for retail managers to consider when developing a purchasing group in dynamic environments, in order to achieve the benefits of cooperative purchasing.

1 Introduction

During the past two decades, there has been a paradigm shift in the role of purchasing in many firms (Carra and Pearson 1999). The present competitive environment requires that purchasing become part of the firm's strategic planning process (Carr and Smeltzer 1997). Cooperative purchasing has been considered as

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a vital strategic issue in many world-class supply chains (Choi and Han 2007). Despite its long history, cooperative purchasing has not received significant attention from the operations and supply chain management researcher (Essig 2000; Laing and Cotton 1997; Schotanus and Telgen 2007; Tella and Virolainen 2005). The lack of research attention seems unjustified, with cooperative purchasing being increasingly well established in practice (Doucette 1997; Nollet and Beaulieu 2003; Schotanus and Telgen 2007). In particular, cooperative purchasing among small and medium-sized enterprises (SMEs) does not seem to be either widely practised or, even when practised, well understood (Mudambi et al. 2004).

The small company attracts increasing attention from academia (Ellegaard 2006). Some previous studies (e.g., Gadde and Hakansson 2001; Pressey et al. 2009) have agreed that SMEs would particularly benefit from effective purchasing. Compared to large firms, SMEs operate under circumstances that pose different purchasing challenges (Ellegaard 2006). Due to the limited resources, SMEs are likely to need external resources to complement them in their purchasing activities (Pressey et al. 2009). Although there is a growing body of research on purchasing practices, research on purchasing in SMEs is still limited (Ellegaard 2006; Pressey et al. 2009; Quayle 2002). In addition, Tella and Virolainen (2005) suggested that there are a number of research opportunities in cooperative purchasing, such as "how can cooperative purchasing benefit SMEs?", while considerable efforts have been directed to investigating the critical success factors for managing cooperative purchasing among SMEs in developed countries (e.g., Hoffmann and Schlosser 2001; Schotanus et al. 2010), only few studies have considered the purchasing practices in emerging economies such as the Chinese retail sector.

2 Literature Review

2.1 Theoretical Reasoning for Cooperative Purchasing

Resource dependence theory (RDT) (Pfeffer and Nowak 1976; Pfeffer and Salancik 1978) has a high level of value in the cooperative purchasing context. RDT has been commonly used in previous studies (e.g., Schotanus et al. 2010; Tella and Virolainen 2005; Bakker et al. 2008) to assess the main advantages of cooperative purchasing and critical success factors for managing a purchasing group. RDT is based largely on the concept of interdependence and the assumption that organizations use their relationships in order to gain access to the resources, which are vital to their continuing existence (Handfield 1993; Fynes et al. 2004). It views interfirm governance as a strategic response to conditions of uncertainty and dependence (Thibaut and Kelley 1959; Emerson 1962). Handfield (1993) suggested that RDT provides a rich predictive framework for explaining how organizations can operate in dynamic environments to make them more stable or munificent. RDT asserts that companies facing substantial environmental uncertainty will attempt to stabilize it by imposing

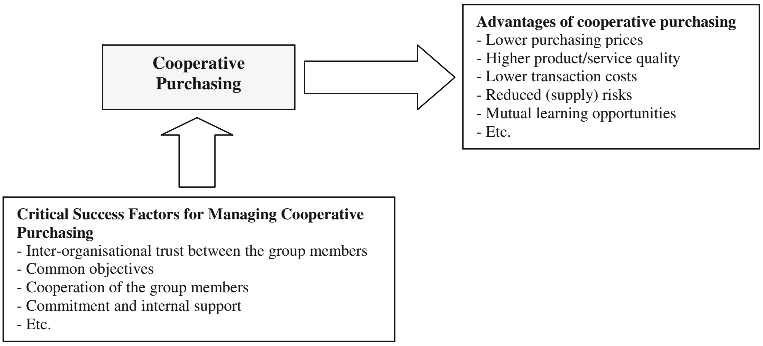

Fig. 1 Conceptual framework

interorganizational ties (Pfeffer and Nowak 1976; Pfeffer and Salancik 1978). The formation of close long-term strategic relationships is one means of creating governance mechanisms to reduce uncertainty and manage dependence, can help firms gain access to or acquire unique and valuable resources that they lack (Eisenhardt and Schoonhoven 1996; Fynes et al. 2004). By focusing on interorganizational coordination and relationships in hostile and dynamic environments, stronger cooperative purchasing allows SMEs to draw the necessary resources from partners in order to sustain performance (Paulraj and Chen 2007; Fynes et al. 2004).

Drawing upon RDT (Pfeffer and Nowak 1976; Pfeffer and Salancik 1978) and previous studies on cooperative purchasing (Schotanus and Telgen 2007; Tella and Virolainen 2005), we develop a theoretical framework that explores two issues that have attracted considerable scholarly interest, which have nevertheless not yet received sufficient attention in academic research in the SMEs context, namely: (1) the advantages of cooperative purchasing for SMEs and (2) the critical success factors for managing cooperative purchasing in SMEs. The framework is presented in Fig. 1 and its main constructs are discussed in more detail below.

2.2 Cooperative Purchasing

In today's competitive environment, companies need to find ways to create more value in supply chains. Purchasing has been an integral and important part of supply chain formation. Building a strategic relationship with similar companies in the field of purchasing practices is one way of achieving this (Katusiime 2008). Purchasing has assumed an increasingly fundamental strategic role, evolving from an obscure buying function into strategic business partnerships (Ellram and Carr 1994), and firms that emphasize cooperation are more likely to achieve greater economic benefits (Dyer 2000). RDT suggests that the establishment of interfirm relationships is viewed as dealing with problems of uncertainty and dependence by increasing the extent of coordination with exchange partners (Cyert and March 1963). Cooperative actions enable members to achieve goals none can realize alone (Chisholm 1998). Although purchasing cooperation between independent companies has been practiced for a long time, the phenomenon is not extensively researched. Tella and Virolainen (2005) further stated that cooperative purchasing in particular formed by industrial companies has received relatively little attention in the literature of the discipline.

In the purchasing literature, many terms are used when referring to cooperative purchasing (Schotanus and Telgen 2007; Tella and Virolainen 2005). A review of the literature shows that "group purchasing" and "cooperative purchasing" are the most popular terms (Schotanus and Telgen 2007). Thus, the two terms are used interchangeably in this chapter. Schotanus and Telgen (2007) defined cooperative purchasing as "the cooperation between two or more organisations in a purchasing group in one or more steps of the purchasing process by sharing and/or bundling their purchasing volumes, information, and/or resources". Cooperative purchasing generally consists of two or more independent buyers. They join together, or utilize an independent third party, for the purpose of combining their individual needs for purchasing materials and capital goods/services to leverage more value-added pricing, services, and technology from sellers that could not be obtained if each firm purchased goods/services individually (Choi and Han 2007). Tella and Virolainen (2005) also stated that cooperative purchasing is "horizontal cooperation" between independent organizations that pool their purchases in order to achieve various benefits. Drawing upon both the theory of partnerships and centralizing, Tella and Virolainen developed a theoretical framework (see Fig. 2) of cooperative purchasing.

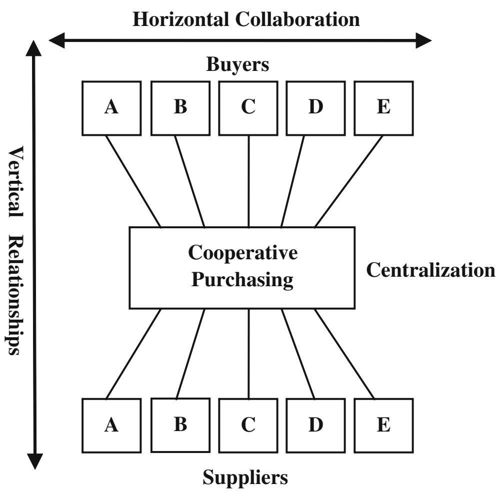

Fig. 2 Cooperative purchasing (*Source* Tella and Virolainen (2005))

2.3 Advantages of Cooperative Purchasing

According to RDT, by fostering the relationship–specific capabilities that are far superior to what the companies may possess on their own (Dyer and Singh 1998), resource dependence can ultimately lead to sustainable competitive advantage (Paulraj and Chen 2007). Collaborative relationships can help firms share risks (Kogut 1988), access complementary resources (Park et al. 2004), reduce transaction costs and enhance productivity (Kalwani and Narayandas 1995), and strengthen learning and innovation capability (Luo et al. 2006). Whatever the duration and objectives of business alliances, being a good partner has become a key corporate asset. Some previous studies (e.g., Anderson and Katz 1998; Johnson 1999; Nollet and Beaulieu 2005; Tella and Virolainen 2005; Choi and Han 2007; Schotanus and Telgen 2007) have examined the advantages of cooperative purchasing. In many manufacturing or retail companies, purchasing managers have long pursued a policy of reducing costs, and cooperative purchasing has been considered as one of the most competitive strategies for cutting costs in dynamic and competitive business environments (Choi and Han 2007). In particular, Anderson and Katz (1998) identified three types of cost reductions that cooperative purchasing can generate: Price, administrative costs, and utilization costs. The companies involved in cooperative purchasing usually expect to achieve lower costs, in addition to price reduction, lower management costs, increased flexibility of inventories, and lower logistics costs are benefits that the members of a purchasing group may achieve (Tella and Virolainen 2005). Moreover, Rozemeijer (2000) stated that cooperative purchasing brings about pooled negotiation power (purchasing together); by combining their purchases, different companies can obtain greater leverage over suppliers, reducing the cost or even improving the quality of the goods/services they purchase. Cooperative purchasing leads to better quality and value for customers and stronger partnerships with suppliers through commitment to contracts (SCEP 2005).

In sum, typical advantages of cooperative purchasing are lower purchasing prices, higher quality, lower transaction costs, reduced workloads, reduced (supply) risks, and mutual learning opportunities (Schotanus and Telgen 2007). On the other hand, some anticipated and actual disadvantages of cooperative purchasing have been anecdotally reported in the literature, such as set-up costs, coordination costs, loosing flexibility, supplier resistance, and possible interference by anti-trust legislation and the disclosure of sensitive information (Schotanus and Telgen 2007). However, in a large number of cases, the advantages of cooperative purchasing outweigh the disadvantages for many situations in the public and private sectors (Schotanus et al. 2010; Schotanus and Telgen 2007). Thus, at least in theory, cooperative purchasing can be a beneficial concept for organizations (Schotanus et al. 2010). A review of the literature suggests that the advantages of purchasing group have rarely been identified in the Chinese context, especially for Chinese SME retailers. Therefore, one of the aims of this study is to investigate the main advantages of cooperative purchasing for SME retailers in China.

2.4 Critical Success Factors for Managing Cooperative Purchasing

As noted above, some previous studies have investigated the advantages of cooperative purchasing. However, in practice, purchasing groups do not always flourish, and often end prematurely (Schotanus et al. 2010). A better understanding of factors affecting cooperative purchasing could help such groups to flourish, and could prevent premature endings (Schotanus et al. 2010). Potential success factors for cooperative purchasing can be related to several theories (Schotanus et al. 2010). Drawing upon RDT and previous empirical findings, we examine important success factors for managing a purchasing group.

Over recent years, some authors (e.g., Bakker et al. 2008; Johnson 1999; Laing and Cotton 1997; Nollet and Beaulieu 2005; Quayle 2002; Schotanus et al. 2010) have identified a set of potential success factors for managing cooperative purchasing. RDT suggests that interorganizational trust plays an important role for group members in improving their interorganizational cooperation. Several empirical studies (e.g., Nollet and Beaulieu 2005; Quayle 2002) have examined the importance of roles of competence and trust in organizing cooperative relationships. The importance of formality of a purchasing group has also been discussed by several authors (e.g., Johnson 1999). Moreover, Laing and Cotton (1997) stated that the existence of common objectives and interests of the group members has an important effect on managing a successful purchasing group. In addition, from the point of view of RDT, interorganizational cooperation among group members is important for them to strengthen the relationship–specific capabilities. Some previous studies (e.g., Hoegl and Wagner 2005; Laing and Cotton 1997; Jost et al. 2005; Schotanus et al. 2010) have suggested that efficient and effective communication among group members has a significant impact on cooperative purchasing. More specifically, drawing upon transaction cost economics, social exchange theory, and equity theory, Schotanus et al. (2010) identified critical success factors for managing small and intensive purchasing groups by comparing successful and unsuccessful purchasing groups in a large-scale survey. They concluded that the main success factors include enforcement of cooperation; cooperation of the group members and communication; commitment and internal support; common objectives and influence of the group members; and allocation of gains and costs. However, the critical success factors for managing cooperative purchasing have rarely been identified in the Chinese context, especially in China's retail sector. Few studies to date have investigated how SME retailers in China organize their purchasing practices to survive in an increasingly dynamic and complex environments.

3 Cooperative Purchasing in Chinese SME Retailers

3.1 Chinese SME Retailers and Culture

Since the 1980s, a number of major structural changes have been witnessed in China's retail market. As one of the main service industries in China, the retail market has experienced exponential growth in the last 20 years. However, the high levels of economic development have generated pressures from a wide variety of factors, including rising logistics costs, intense competition, and buyer–suppliers relationships (Hingley et al. 2009; Yu 2011). China's retail market is highly fragmented and composed of many small and medium-sized retailers (Lu 2010). SME retailers in China have been experiencing unprecedented development during the transformation process from a centrally planned to a market economy, which has increasingly contributed to China's economic growth (CCFA 2010; Mofcom 2010; Supermarket Weekly 2010). In 2008, more than 98 % of retail companies in China were SME retailers, accounting for about 96 % of the total sales volume of China's retail industry. SME retailers generated about 80 % of the total employment in the retail sector (CCFA 2010; Mofcom 2010). China's retail sector is becoming increasingly dynamic and competitive (Yu and Ramanathan 2012). SME retailers face keen competition not only from local giant retailers also from other multinational retailers in China. Building upon the analysis of the implementation of cooperative purchasing among a number of SME retailers, CCFA (2010) suggested that establishing purchasing groups is an innovative way for SME retailers in China to survive in a dynamic and competitive marketplace.

A typical characteristic of the small company is its limited resources, and one critical effect of this shortage is lack of attention to strategic purchasing. Small company owners perform operational acquisition of components, but do not develop their purchasing skills and procedures. Moreover, limited resources mean that vulnerability is high (Ellegaard 2006; Arend and Wisner 2005). In addition, the small company owner typically has limited supply market knowledge. Purchasing is a critical task in the small company, which is particularly dependent on external resources due to its limited size (Gadde and Hakansson 2001; Scully and Fawcett 1994; Ellegaard 2006). Based on Confucian values, Chinese culture emphasizes kin, community, or family relationships and quasi-relative relationships (Weber 1920/1995). Arising from the unique attributes of Chinese culture, guanxi (personal and business relationships), based on personal connections and trust has generally been considered to be one of the most important sources of competitive advantages for companies doing business in China (Tan et al. 2009; Yu 2011). Establishing long-term guanxi with business partners (such as suppliers and customers) is vital for a retailer's business development and survival in China (Yu 2011). Guanxi has widely been used by Chinese SMEs as a strategic weapon in managing environmental uncertainty and reducing transaction risks (Tan et al. 2009).

3.2 Cooperative Purchasing in China

Over the last decade, a few Chinese SME retailers with good guanxi have conducted cooperative purchasing (CCFA 2010; Mofcom 2010). For example, as a pioneer of launching cooperative purchasing in China, the four SME retailers that are located in the same province in China (AB Province) established a special purchasing group, named PGSME. All four retail firms have been involved in the food retail sector for about 10 years in China. According to CCFA (2010)'s report, PGSME was one of the few purchasing groups in the Chinese SME retail market that achieved great success. Currently, the purchasing group consists of more than 100 retail stores, with annual sales volume of about US$ 800 million. The average annual sales growth rate was more than 50 % (Supermarket Weekly 2010; CCFA 2010). In the fifth annual conference for chains of supermarket (CCS) 2010: Chinese SME Retailers Development, *PGSME* was chosen as an outstanding example of managing cooperative purchasing in China's retail sector (Supermarket Weekly 2010). The descriptions of PGSME members are summarized in Table 1.

We undertook in-depth interviews with senior executives (e.g., purchasing manager, operations manager, or store manager) of PGSME members. Our interviews were guided by the conceptual framework presented in Fig. 1. The in-depth interviews focused on the three topics about cooperation purchasing in SME retailers, namely: (1) the main characteristics of the purchasing group; (2) advantages of cooperative purchasing; and (3) critical success factors for managing a purchasing group. The interviewees were asked about details on how SME retailers manage a purchasing group to achieve the potential benefits. Field research that investigates the views and opinions of companies directly and indirectly involved in the decision-making process is becoming increasing prevalent within the literature (Palmer and Quinn 2003). Therefore, some interviews were also conducted with cashiers, stock persons, and salesmen. Further, shop visits were arranged after interviews, so that we could have a better understanding of case company purchasing practices. In addition, multiple and independent sources of evidence, including market research reports, government statistics, company profiles, financial statements, and other media were used to corroborate the interview data and develop convergent lines of inquiry (Yin 2003; Voss et al. 2002; Stuart et al. 2002). The use of multiple types of data increases the odds of capturing the organization's view of a construct (Yin 2003). In the present study,

Table 1 Profiles of PGSME members

Name used in this study	Retail type	Market areas in AB province	Established (year)	Number of stores
PGSME-1	Food	Northwest	1992	34
PGSME-2	Food	Southwest	1999	28
PGSME-3	Food	Central and Northeast	1995	23
PGSME-4	Food	Southeast	1995	25

interview data were triangulated based on information collected through interviews, observation, and document review. According to Yin (2003), the interview data were examined using both within- and cross-case analysis methods in the study. Once the within-case analysis was completed, a cross-case analysis was undertaken to compare the retail operations and purchasing practices of group members.

4 Findings and Discussion

The purchasing group (PGSME) established by the four independent SME retailers constitutes a type that has no correspondence in the purchasing literature. Schotanus and Telgen (2007) developed a typology for purchasing groups. Five main forms of cooperative purchasing were distinguished in their work, namely: piggy-backing groups, third-party groups, lead buying groups, project groups, and program groups. PGSME is not only a purchasing agreement, but also a strategic alliance (Hoffmann and Schlosser 2001). Within the PGSME, the four SME retailers have: (a) good guanxi; (b) rigorously divided the geographical market; (c) free access to individual companies' databases; (d) joint practices for human resources management; and (e) also provided a sort of internal financial support. In general, the results of case study analysis not only provide empirical evidence in support of our theoretical framework presented in Fig. 1, but also find some special advantages and success factors that have not been identified in previous studies of cooperative purchasing (e.g., Schotanus and Telgen 2007; Tella and Virolainen 2005). The typical advantages and critical success factors for managing a purchasing group in the Chinese context are discussed in more detail below.

4.1 Advantages of Cooperative Purchasing

Over the last few years, business costs (such as labor, rental, and transportation costs) have increased tremendously in China; profit margins are quite low, particularly in the food retail sector, where some daily products have zero profit margins (CCFA 2010). Price competition is becoming more and more intense in the Chinese retail market (Hingley et al. 2009). Cooperative purchasing can help SME retailers to reduce logistics costs and gain lower purchasing prices. As a consequence, the retailers can provide a lower price and add more value for their customers. Over the last few years, annual sales and profits of the purchasing group have increased significantly. Using cooperative purchasing, the group members can achieve a huge amount of purchasing volumes. Purchasing together, the group can obtain more capabilities to negotiate with supplier for the lower purchasing prices, consequently adding more value for final users. This finding is consistent with the principles of RDT, which suggests that SEMs can use their interorganizational relationships to gain competitive advantages (Handfield 1993; Fynes et al. 2004). In addition, the group members can support and learn from each other through the cooperative purchasing. For instance, PGSME-3s financial incentive scheme was introduced and successfully implemented by the other three group members. The incentive scheme significantly helps the group members to reduce high labor turnover and improve employee loyalty.

China's retail sector is a buyer's market and various varieties of products are on sale. There is keen and even vicious competition among suppliers, and retailers have the luxury of selecting from a number of suppliers that have a similar level of quality and price. The potential for "illegal bribe kickbacks" during the purchasing process exists. For example, employees in purchasing department routinely are given kickbacks by suppliers. In addition, Chinese retailers face ethics challenges with corruption, bribery, and kickback, due to the unique cultural characteristics of China's retail sector. Confucianism is a common characteristic of Chinese societies. Because of the influence of Confucianism, the gift giving is widely accepted as legal practice in business in Chinese cultural society. Tian (2008) stated that bribery or kickback is closely linked to "gift-giving" ethos in China. A cooperative purchasing team, which is placed under strict surveillance by the different group members, can help SME retailers to combat bribes and kickbacks, and consequently improve product quality. Over the last two decades, the standard of living in China has drastically increased. The rapid rise in household income has simultaneously increased the demand for consumer goods. Chinese consumers, especially in big cities, are becoming more discerning and demanding with respect to quality, variety, and taste (Hingley et al. 2009; CCFA 2010). In response to customer demand, PGSME considers quality as one of the most important criteria of choosing suppliers. Through cooperative purchasing, the group members establish strict quality control procedures, and require all suppliers to pass a formal certification of quality control system (e.g., QS and ISO9001).

To gain the benefits, it is very essential for the group members to recognize critical factors influencing cooperative purchasing, which are discussed in more detail below.

4.2 The Critical Success Factor for Managing Cooperative Purchasing in SMEs

There are a number of critical factors for managing cooperative purchasing in the context of China's retail sector, including good guanxi among group members, similar characteristics of group members, similar personality traits of top executives, and the role of a "big brother" in the group. Our results are generally consistent with the findings of previous studies (e.g., Schotanus et al. 2010) and the principles of RDT.

Good guanxi among group members is a critical success factor for SME retailers to manage cooperative purchasing in China. Guanxi and business networking are important mechanisms that enable Chinese SMEs to deal with the uncertainty and increased risks arising from ongoing institutional transitions (Tan et al. 2009). A purchasing group with good guanxi can achieve benefits not only in information sharing but also in problem solving. Cultivating close guanxi among purchasing group members is a critical task of business. RDT also recommends developing long-term guanxi (relationships) based on mutual dependence and trust (Yu 2011). Trust and honesty among the group members play a vital role in managing a successful purchasing group. PGSME considers trust as the "blood" of a purchasing group. All members of PGSME should be honest and loyal, and "like" each other personally. This finding is somewhat contrary to a previous study by Schotanus et al. (2010), who found that interorganizational trust is not identified as a success factors for managing purchasing groups. This is not surprising when we examine the unique aspects of Chinese culture. As mentioned earlier, guanxi is uniquely rooted in the context of Confucianism that dominates various aspects of Chinese people's life. Guanxi building is the process of producing trust among group members, and the accessibility of guanxi is determined by the level of personal trust existing among group members (Chen and Chen 2004). Without good guanxi based on mutual trust, successful cooperative purchasing would not be possible for the four SME retailers.

PGSME members use familiar analogies to describe friendships (guanxi) among top executives. Such analogies are appropriate, because business partnerships are not entirely "cold-blooded" (Kanter 1994). In a purchasing group, a good personal rapport among top executives creates an important opportunity for member employees to obtain an effective communication. Also, the personality traits of a president, especially in a SME retailer, significantly influence the direction of organizational growth. Miller and Toulouse (1986) suggested that CEO personality will be most closely related to strategy, performance, decision-making methods, and structures in organizations that are small. PGSME members prefer to establish guanxi and do business with people who have similar personality characteristics and traits. The similar personality traits of top executives (such as openness, agreeableness, conscientiousness, and stability) enable the group members to obtain an effective communication among different departmental functions and various levels of employees. Indeed, a successful purchasing group nearly always depends on the creation and maintenance of a comfortable personal relationship (guanxi) among the top executives. In addition, at least one member acts as a "big brother" (group leader) in a purchasing group. In PGSME, PGSME-3 plays a champion role; the other three SME retailers consider the president of PGSME-3 as their "big brother". Because of the influence of the ancient Confucianism, Chinese often extend kinship terms to close nonrelatives to show friendship, warmth and kindness, such as "big brother". Chinese families are very close-knit. Generally, older brothers/sisters in the traditional Chinese family have to take care of and protect their younger siblings. Like a "big brother" in the family, PGSME-3 provides support and help for other group members, for example, providing interest free loans and sharing company's databases and salary incentive system with other three SME retailers. PGSME members view the leading role of PGSME-3 as one of the important success factors for managing a purchasing group in China.

Similar characteristics of group members affect the success of cooperative purchasing. The PGSME members have similar retail characteristics, such as similar industry, similar characteristics of supply chain market, similar firm size and age, and similar physical location (see Table 1). The uniformity of the group members makes it possible for them to organize effective cooperative purchasing. Operating in the same industry (the food retail sector) enables the group members to achieve more effective communication. All four SME retailers established in the 1990s have the similar retail formats, such as supermarket and convenience store. At one extreme, in mutual service consortia, similar companies in similar industries pool their resources to gain a benefit too expensive to acquire alone—such as access to a large number of purchasing volumes (Kanter 1994). In addition, operating in the same province with different business locations enables the group members to deal with the psychic distance. There is, to some extent, fewer and lower psychic distance, such as cultural, regulatory, legal, and financial, among four SME retailers. The retailing literature (e.g., Johanson and Vahlne 1992) has implied that psychically close location is more similar and, because similarities are easier to manage than differences, it is expected that businesses will achieve greater success in similar markets. Further, since the group members operate chain stores in different cities in AB Province (see Table 1), they are not potential competitors, which facilitate easier cooperation.

Similar organizational culture is another critical success factor for managing a purchasing group. In practice, every company has its own unique organizational culture. Hence, it is very important for the members of a purchasing group to integrate their organizational cultures. After establishing PGSME, the group members began to develop and consider "add more values for both customers and employees" as their common organization culture. The group members place great emphasis on improving customer and employee loyalty. Learning and borrowing ideas from partners can also help group members to smooth over cultural and organizational differences. In a purchasing group, member employees, at all levels, must become teachers as well as learners (Kanter 1994). Uniformity of group members, such as all members having similar organizational cultures, is an important factor for members to achieve competitive advantages (Polychronakis and Syntetos 2007). In addition, PGSME considers effective and efficient communication among group members as a success factor for conducting cooperative purchasing. This finding is consistent with previous studies (e.g., Hoegl and Wagner 2005; Laing and Cotton 1997) demonstrating the important impacts of efficient communication on interorganizational cooperation.

5 Conclusions

This study investigates the typical advantages of cooperative purchasing for SME retailers, and the critical success factors for managing a purchasing group, using a case study of a purchasing group established by four independent SME retailers in China. This study makes a contribution to the understanding of cooperative purchasing on two fronts. On a theoretical front, this study fills a gap in the existing literature. Research on purchasing group in SMEs is still limited (Ellegaard 2006; Pressey et al. 2009), especially in the Chinese context. Generally, the results of case study analysis support the conceptual framework presented in Fig. 1. Furthermore, the study finds some special advantages and important success factors in the Chinese SMEs context that have not been identified in previous studies of purchasing, such as the advantage of dealing with illegal bribes, the factors of good guanxi among group members, the role of a "big brother" (group leader), and similar personality traits of top executives. On a practical front, the findings of this study also provide practical insights for retail managers to consider when developing a purchasing group in dynamic environments, in order to achieve the benefits of cooperative purchasing.

While this study makes contributions to research and practice, there are limitations that need to be considered when interpreting the study findings. Like all case studies, the external validity of our proposed model needs to be empirically tested in a much larger sample. The research reported here draws on a very small sample. As such, any analytical generalizations drawn from a limited number of case studies, no matter how carefully sampled and researched, clearly deserve healthy caution. CCFA (2010) reported that the purchasing group in China faces a number of challenges, such as anti-trust, different organizational culture, and a lack of communication. A few purchasing groups established by SME retailers in China have failed over the last few years. For example, as a pioneer purchasing group in China's retail sector, nine small and medium-sized electronic appliance retailers established a purchasing group in 2002. However, because two of the nine group members were purchased by the leading electrical retailers in China over the last few years, the purchasing group ceased to exist (CCFA 2010). In addition, four small food retailers in Zhejiang Province launched cooperative purchasing in 2004. During the last few years, some of the group members were purchased by retail giants. At the same time, the group accepted several new members. Burt et al. (2003) suggested that a better understanding of failure would be of benefit to academics and retailers alike and might help to close the gulf between theory and practice. Hence, future research should study failure in cooperative purchasing, and also test the results obtained in this research.

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Supply Chains with Service Level Agreements

U. Dinesh Kumar

Abstract Supply chain has emerged as an important differentiator between successful and not so successful companies across the world. The importance of supply chain has resulted in service level agreements between the supplier and customer with various types of guarantees such as on-time delivery, equipment availability, etc., that usually include a penalty if the agreed service level is not met. Dell, Fedex, and Mumbai Dabbawallas are a few examples, where success is mainly attributed to supply chain strategies. The main focus of this chapter is to study supply chain contracts with delivery guarantees and other service level agreements and how such supply chains can be managed effectively. We will look at an array of mathematical techniques, which can be used to model supply chains with service level agreements across industries.

Keywords Delivery guarantees · Performance-based logistics · Service level agreements

1 Introduction

The importance of efficient and effective supply chain strategy on profitability has been recognized by all industries. Although supply chain exists in all the industries, the complexity of the chain may vary significantly from industry to industry. Commercial aircraft can have as high as six million parts, manufactured by thousands of suppliers across the world and finally assembled at aircraft manufacturer's facilities. Any delay in aircraft manufacturing can result in significant financial impact, for example, delay in delivery of Airbus A380 aircraft resulted in

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26 % drop in the share price of the European Aeronautic Defense and Space (EADS). Similarly, several courier delivery service companies transport millions of parcels across the globe and attempt to deliver them on time. The cost of nonperformance of supply chains varies across different industries. Nonavailability of critical spares resulting in cancelation of a flight can be much more expensive compared to nondelivery of food by a delivery service.

Today's contracts between suppliers and customers usually have some element of supply-chain-related agreements or service level agreements along with penalty if the agreed service level is not achieved by the supplier. Companies such as FedEx (which uses a famous "the world on time" slogan) and UPS pioneered delivery guarantees that also benefitted several on-line companies such as Amazon. Companies such as Domino's Pizza Inc introduced 30-min delivery guarantees for their pizza delivery way back in 1973. Black Angus restaurants provide free lunch if the waiting time is more than 10 min (So and Song 1998; Hwang et al. 2010). Best box lunches, a deli service based in St. Louis guarantees no-mistake delivery of lunches or refund of 110 % of the order.[1] The list of companies that use delivery guarantees has been increasing. Ralph Wilson Plastics, Thomasville Furniture, and Citicorp have made use of delivery promises (Urban 2009). Delivery guarantees and other service level agreements are becoming a part of competitive strategy across industries. Sieke et al. (2012) reported an example of a service level contract implemented by *dm-drogeriemarkt*, one of the largest drugstores in Germany in which the service levels of its suppliers are continuously monitored; vendors who do not meet the target service level are penalized. Hindustan Aeronautics Limited (HAL) that supplies doors to Airbus and Boeing has a delivery guarantee agreement with its customers. Under this agreement, each door is assigned a customer window period of 7–8 days for delivery. Any delivery outside this window period (both early as well as late) is penalized. ''Just in time'' contracts are very common among automobile companies. Few organizations have mastered the art of supply chain, for example, Mumbai dabbawallas, who deliver more than 200,000 lunch boxes every day have a Sigma level of approximately 5.25. Their incorrect delivery rate is one in 16 million lunch boxes.

Fill rate, that measures the percentage of filled orders with on-hand inventory, is a popular service level agreement used by the defense industry especially for spare parts inventory. Defense services, especially, in the USA use a supply chain strategy called performance-based logistics (PBL) in which the defense suppliers guarantee several performance measures, such as operational availability, mission reliability, total cost of ownership, etc (Phillips 2005). An important component of PBL contract is a reward function using which the suppliers are rewarded for achieving higher performance. Defense services in the UK, use "availability contracts'' in which they guarantee a certain level of availability and readiness of the systems (such as fighter aircraft) to their customers. Table 1 lists examples of service level contracts that are practised by many companies.

[1] Source. http://www.bestboxlunches.com/.

Table 1 Sample performance level agreements

S. No	Company name	Core business activity	Type of delivery guarantees and service level agreements
1	Amazon.com	Electronic commerce	Amazon prime: 1–2 day delivery guarantees for selected products
2	Blockbuster video rental	DVD rental	Guarantee for availability of DVDs
3	Dell	Computers and peripherals	1–2 weeks
4	Domino's Pizza Inc	Pizza delivery	30 min or free pizza
5	FedEx Corporation	Logistics services	Overnight service
6	Hindustan Aeronautics Limited	Aircraft manufacturing	Delivery guarantees for doors to airbus and Boeing
7	Boeing	Aerospace	PBL contract for operational readiness
8	JeLuSS	Manufacturing	On-time shipment guarantee
9	BAe Systems	Aerospace	Availability contracting in which BAe Systems guarantees operational readiness of its systems to customers

It is evident from the examples listed in Table 1 that the supply chain contracts use a variety of performance metrics to enforce service guarantees. The real challenge for the suppliers as well as the customers would be to meet the service level agreements at the least cost. In this chapter, we analyze a few supply chain contracts and develop models that can be effectively used for managing such contracts.

The structure of this chapter is as follows: In Sect. 2, we provide the literature survey on supply chains with service level agreements. In Sects. 3–5, we discuss a few supply chain contracts. Conclusions and future research are presented in Sect. 6.

2 Literature on Supply Chains with Service Level Agreements

Hendry et al. (1993) discuss the case study of a company that produces engraved copper cylinders for manufacture of items such as wall papers. Each cylinder is made to customer-order specification, the company quotes delivery dates for its order that has to be maintained. Hendry et al. (1993) developed a decision support system to address the delivery issues in this case. So and Song (1998) studied the impact of using delivery time guarantees as a competitive strategy in service industries. A mathematical framework is proposed to understand the interrelationships among pricing, delivery time guarantees, and capacity expansion decisions. Rao et al. (2005) studied how a firm can optimize expected profits by quoting a uniform guaranteed maximum lead time to all customers. Urban (2009) developed analytical models for establishing optimal delivery time guarantees and pricing policies for firms offering blanket guarantees for their product and service.

Complex service level agreements, such as availability contracting and PBL have received limited attention from researchers (Nowicki et al. 2008; Kumar et al. 2007). Kumar et al. (2007) used a goal programming model to optimize service level agreements, such as reliability, maintainability, and cost agreements. Optimizing spares to support PBL contracts was studied by Nowicki et al. (2008). In the following sections, we discuss two types of supply chain contracts, namely: (1) supply chain with delivery guarantees and (2) supply chains with service level agreements, such as availability contracting and PBL.

3 Supply Chains with On-time Delivery Guarantees

The most common guarantees in the supply chains are on-time delivery guarantees such as the one practised by Domino's Pizza Inc. It can be assumed that there are two activities associated with the delivery guarantees in such systems, namely: (1) production of the product itself and (2) delivery of the product. This can be modeled as a sum of two random variables assuming that the time taken to produce the product is a random variable X with corresponding distribution function $F(.)$ and the time taken to deliver the product is another independent random variable Y with corresponding distribution function $G(.)$. If the supplier guarantees to deliver the product within "t" hours after it receives the order, then the probability that the product will be delivered within time t is given by:

$$P(X + Y \leq t) = \int_0^t f(u)G(t - u)du. \tag{1}$$

For example, if the production time follows a normal distribution, $N(\mu_1, \sigma_1^2)$, and the delivery duration follows normal distribution, $N(\mu_1, \sigma_1^2)$, then the probability that the delivery will be made within "t" hours is given by:

$$P(X + Y \leq t) = \Phi\left(\mu_1 + \mu_2, \sigma_1^2 + \sigma_2^2\right), \tag{2}$$

where $\Phi\left(\mu_1 + \mu_2, \sigma_1^2 + \sigma_2^2\right)$ is the normal distribution with mean $(\mu_1 + \mu_2)$ and variance $(\sigma_1^2 + \sigma_2^2)$. Associated with on-time delivery is the location problem. For example, if a restaurant promises delivery of orders placed by the customers to their home or office within a stipulated time, then the distance between the restaurant and the customer's delivery point will be a critical factor. In general, such problems are modeled using p-center problems (mini–max location problem). For example, if there are n customer nodes and the supplier has to decide their facility location, then the corresponding linear programming model, for p = 1, can be written as:

Min Z
Subject to constraints:
$D(\mathrm{FC}, i) \le Z$

D(FC, i) is the radial distance between the supplier's facility (FC) and the customer's node. FC is the location of the facility identified by the coordinates (x, y) and the customer i's locations is given by the coordinates (x_j, y_i). Thus,

$$D(\mathrm{FC}, j) = \sqrt{\left(x - x_j\right)^2 + \left(y - y_j\right)^2} \qquad j = 1, 2, \ldots, n \tag{3}$$

4 Service Level Guarantees with Availability

Many systems have availability guarantees, for example, fill rate, which measures the percentage of demand that can be met by the inventory on-hand, is regularly used in defense contracts. If the demand for the product follows a Poisson distribution with rate λ and the stock level is "n", then the fill rate for period T is given by (Kumar et al 2000):

$$\text{Fill Rate} = \sum_{k=0}^{n} \frac{\exp(-\lambda T) \times (\lambda T)^k}{k!}. \tag{4}$$

Probability of stock-out, PS, for n spares in stock is:

$$\mathrm{PS} = \sum_{k=n+1}^{\infty} \frac{\exp(-\lambda T) \times (\lambda T)^k}{k!} = 1 - \sum_{k=0}^{n} \frac{\exp(-\lambda T) \times (\lambda T)^k}{k!}. \tag{5}$$

The expected number of demands that will not be met is:

$$\text{Expected unmet demand} = \sum_{k=n+1}^{\infty} (k - n) \times \frac{\exp(-\lambda T) \times (\lambda T)^k}{k!}. \tag{6}$$

5 Performance-Based Logistics

In this section, we discuss one of the service level agreements that is becoming popular in the defense industry. Performance-based logistics is a strategy initiated by the Department of Defense (DoD), USA and currently used by many other global defense services and companies for procurement and sustenance of defense equipment. PBL strategy ensures that acquisition of the weapon system maximizes system readiness through long-term support arrangements with clear lines of authority and responsibility. PBL strategy focuses on buying performance rather than equipment. The DoD defines PBL as “the purchase of logistics support as an integrated, affordable, performance package designed to optimize system readiness and meet performance goals of a weapon system”. Over a period of time, several performance measures have been suggested by academics (Kumar 2007) and practitioners. Most frequently recommended performance measures are: (1) operational availability, (2) mission reliability, (3) total cost of ownership, (4) operation and maintenance cost, (5) logistic footprint, etc. During the design stage of a product development, the designers face the tough task of choosing different architectures and product alternatives that would result in maximum benefit to the user. The challenging task during the design stage is to optimize requirements set by reliability, maintainability, and supportability engineers. In this section, we develop a goal programming model that can be used for solving multiobjective problems faced by design engineers. The goal programming model developed in this section is based on an earlier work by the author (Kumar et al. 2007).

Goal programming is a mathematical programming model used to solve problems with multiple objectives or goals. The goals are classified into the following three categories:

1. A lower one-sided goal establishes a lower limit. Operational availability and reliability are two objectives where a lower limit is set.
2. An upper one-sided goal establishes an upper limit. An upper limit is set for mean time to repair (MTTR), mean logistic delay time (MLDT), and the total cost of ownership (TCO).
3. A two-sided goal sets a specific target on both the lower and higher sides. In this paper, no two-sided goals are specified.

For supply chain with service level agreements, each performance guarantee can be set as a goal and any deviation from the goal may be penalized based on the importance of the goal. In this section, we have developed a goal programming model for a system with N subsystems that are treated as series configuration for reliability purpose. The following notations are used in defining the goal programming model:

N Total number of subsystems in the system
n_i Number of design alternatives available for subsystem i
L Designed life of system measured in years
R Discount rate per annum
A_0 Target operational system availability
c_{ij} Unit cost of component type j in the subsystem i
o_{ij} Operating cost of component type j in the subsystem i
λ_{ij} Annual failure rate of component type j in the subsystem i
s_i Stock level (spare parts) for subsystem i
PNS Probability of no stock-out for subsystem
μ_{ij} Annual repair rate of component type j in the subsystem i
m_{ij} Average repair cost of component type j in the subsystem i
w_{ij} Weight of alternative j for subsystem i
d_{ij} Disposal value of component type j in the subsystem i

δ_{ij} Binary variable associated with component type j in the subsystem i
δs_i,s Binary variable associated with number of spares chosen for subsystem alternative i

In this case, we set four nonpreemptive goals, namely the TCO, probability of no stock-out, system MTTR, and logistic footprint. With nonpreemptive goals, all goals are treated equally important. Assume that the system under consideration has n subsystems connected in series for reliability purpose. All four goals of the system are stated below:

Goal 1: Minimize the total cost of ownership. For a series system with n subsystems, the TCO is given by:

$$\sum_{i=1}^{n}\sum_{j=1}^{n_i} c_{ij} \times \delta_{ij} + \sum_{i=1}^{n}\sum_{j=1}^{n_i} \left(\lambda_{ij}m_{ij} + o_{ij}\right)\delta_{ij} \times K_L, \tag{7}$$

where

$$K_L = \frac{1-(1+r)^{-L}}{r}.$$

In Eq. 7, we have included only procurement cost, corrective maintenance, and operating cost. However, calculation of TCO can be very complex for many systems. The objective here is not to discuss the complexities associated with any of the performance measures that may be used in supply chain contracts.

Goal 2: Maximize the spares availability of the system. Since the time to failure of the system follows exponential distribution, the demand for spares follows a Poisson distribution with mean $\lambda_{ij}T$, where T is the turn-around time for spares. In this formulation, we have used product probability of no stock-out for all subsystems as a surrogate measure for both the availability and supportability of the system:

$$\text{Maximize PNS} = \prod_{i=1}^{n}\left(\sum_{j=1}^{n_i}\left(\sum_{s=0}^{S}\left(\sum_{k=0}^{s_i}\frac{e^{-\lambda_{ij}T} \times \left(\lambda_{ij}T\right)^k \times \delta_{ij}}{k!}\right)\delta_{s_i.s}\right)\right). \tag{8}$$

Goal 3: Minimize the MTTR of the series system. The corresponding mathematical function is given by:

$$\text{Minimize MTTR}_s = \sum_{i=1}^{n}\sum_{j=1}^{n_1}\frac{\lambda_{ij}\mu_{ij}\delta_{ij}}{\lambda}, \tag{9}$$

where λ is the system failure rate and is given by:

$$\lambda = \sum_{i=1}^{n}\sum_{j=1}^{n_i}\lambda_{ij}\delta_{ij}. \tag{10}$$

Goal 4: Minimize the logistic footprint of the system. In this paper, logistics footprint is measured as the weight of the support infrastructure necessary to achieve the operational availability (Goal 2) and maintainability (Goal 3) goals. The corresponding objective function equation is given by:

$$\text{Minimize L } = \sum_{i=1}^{n}\left(\sum_{j=1}^{n_i}\left(\sum_{s=0}^{S}\left(\sum_{k=0}^{s_i} w_{ij}s_i\right)\delta_{s_i,s}\right)\delta_{ij}\right). \tag{11}$$

We have now defined four goals and the next step is to set targets for these four goals. We set upper one-sided targets for TCO, system MTTR, and logistic footprint. A lower one-sided target is set for the probability of no stock-out. Let:

T_{TCO} Target total cost of ownership
PNS_T Target probability of no stock-out
MTTR_S Target system mean time to recover
L_S Target logistic footprint
P_1 Penalty for crossing the target total cost of ownership
P_2 Penalty for falling below the target PNS
P_3 Penalty for crossing the target MTTR_S
P_4 Penalty for crossing the target logistics footprint

Next, we define four deviation variables; each variable represents the difference between the target value of a goal and the corresponding achieved value for each of the four goals. Let:

$$Y_1 = \sum_{i=1}^{n}\sum_{j=1}^{n_i} c_{ij} \times \delta_{ij} + \sum_{i=1}^{n}\sum_{j=1}^{n_i}\left(\lambda_{ij}m_{ij} + o_{ij}\right)\delta_{ij} \times K_L - T_{\text{TCO}} \tag{12}$$

$$Y_2 = \prod_{i=1}^{n}\left(\sum_{i=1}^{n}\sum_{j=1}^{n_i}\sum_{k=0}^{s_i}\frac{e^{-\lambda_{ij}T} \times (\lambda_{ij}T)^k \times \delta_{ij}}{k!}\right) - \text{PNS}_T \tag{13}$$

$$Y_3 = \sum_{i=1}^{n}\sum_{j=1}^{n_1}\frac{\lambda_{ij}\mu_{ij}\delta_{ij}}{\lambda} - \text{MTTR}_S \tag{14}$$

$$Y_4 = \sum_{i=1}^{n}\sum_{j=1}^{n_i} w_{ij}s_i - L_S \tag{15}$$

Y_1, Y_2, Y_3, and Y_4 are deviation variables corresponding to four goals. These variables can take either positive or negative values depending on the resulting values of $G1$, $G2$, $G3$, and $G4$. Positive values for Y_1, Y_3, and Y_4 mean that the design allocation has exceeded the target values and therefore, must be penalized. However negative value of Y_2 indicates that the probability of no stock-out target is not met. Since Y_1, Y_2, Y_3, and Y_4, are unrestricted variables, we can rewrite these variables as below:

$$Y_1 = Y_1^+ - Y_1^-;\ Y_2 = Y_2^+ - Y_2^-;\ Y_3 = Y_3^+ - Y_3^-;\ Y_4 = Y_4^+ - Y_4^-.$$

In the above definition, $Y_i > 0$ implies $Y_i^+ > 0$; similarly, if $Y_i < 0$ then $Y_i^- > 0$. Using this new representation, the objective of the goal programming problem is now formulated as:

$$\text{Minimize } Z = P_1 Y_1^+ + P_2 Y_2^- + P_3 Y_3^+ + P_4 Y_4^+. \tag{16}$$

The objective function defined in Eq. (16) minimizes the total penalties for undesirable deviations from the specified target values for all four goals. Equations (12–15) are the constraints of the goal optimization problem along with the nonnegativity constraints $(Y_i^+, Y_i^- > 0)$. In this formulation, we do not have any other system constraint. The formulation defined in Eqs. (12–16) is a zero–one goal programming formulation.

The example (reproduced from Kumar et al. 2007) considers a series system with four subsystems and for each subsystem there are three available design alternatives. Table 2 contains the annual component failure and repair rates along with the weight of the alternative design, while Table 3 shows each component's TCO. The system has an expected design life of 10 years for which an annual discount rate of 12 % has been assumed.

For an illustrative example, we set the goals and the corresponding penalty as defined below:

T_{TCO}	1,200,000
PNS_T	0.80
MTTR_S	5
L_S	20
P_1	100 for every 100,000 above the T_{TOC} target
P_2	10,000 for every 1 % less than the target availability of 0.80
P_3	100 for every one unit above the target MTTR_S
P_4	100 for every one unit above the target logistic footprint value

The zero–one goal programming problem was solved using the software Linear Interactive Discrete Optimizer (LINDO®) and the optimal solution as shown in Table 4. The corresponding optimal value of $Z = 0$, i.e., all the goals set in the objective are met by the solution given in Table 4. Table 5 shows the target values of goals and the corresponding values from the optimal solution.

Table 2 Component failure, repair rates, and weight

i	λ_{ij}			μ_{ij}			w_{ij}		
	1	2	3	1	2	3	1	2	3
1	0.04	0.042	0.039	4.0	3.5	4.2	2	2.1	2.3
2	0.016	0.018	0.0155	5.5	4.8	6.0	2.7	3.1	2.2
3	0.0106	0.0112	0.011	3.8	2.9	4.5	3.9	4.5	4.0
4	0.012	0.0119	0.0108	4.4	4.0	3.8	5.1	5.7	6.2

Table 3 Procurement, operation, maintenance, and disposal costs

i	d_{ij}			c_{ij}			m_{ij}			o_{ij}		
	1	2	3	1	2	3	1	2	3	1	2	3
1	150	300	200	12,000	20,000	25,000	340	435	342	20,000	25,000	18,000
2	255	300	180	46,000	70,000	68,500	255	260	280	70,000	68,500	71,000
3	120	120	120	34,000	40,000	41,500	400	415	372	40,000	41,500	45,000
4	100	50	80	52,000	56,000	55,000	380	410	380	56,000	55,000	45,000

Table 4 Optimal selection of components that minimizes the total penalty

I	δ_{ij}			Spares
	1	2	3	
1	0	0	1	1
2	0	0	1	2
3	0	1	0	0
4	0	0	1	1

Table 5 Target value of goal and the optimal solution value

Goal	Target	Optimal solution value
T_{TOC}	1,200,000	1,180,263
PNS_T	0.80	0.8363
MTTR_S	5	4.137
L_S	20	20

It is evident from Table 5 that all the target goal values have been met for the optimal solution shown in Table 4. The real challenge with this goal programming formulation is in solving the problem for complex systems with large number of subsystems. The number of goals is not likely to change much, however, as the number of subsystems within the system increases, the problem becomes computationally complex and thus an exact algorithm may not be able to solve the problem. In such cases, meta-heuristic algorithms such as genetic algorithms can be used to solve the problem.

6 Conclusions and Future Research

Supply chains across industries may decide the success or failure of organizations. The criticality of supply chain has forced organizations to develop several performance guarantees and service level agreements. Although service level agreements create competitive advantage, they can have a negative impact, if not carefully monitored. Many service providers had withdrawn the guarantees that they announced due to the risk associated with such guarantees. For example, in 1992, a woman in Indiana was killed by a Domino's delivery driver resulting in a lawsuit. The delivery guarantee was withdrawn the same year due to public perception of reckless driving by the drivers to meet the delivery guarantee.[2]

Service level agreements, without any doubt provide advantage to both suppliers and customers in the supply chain. These agreements can be as simple as on-time delivery guarantees or a complex performance guarantee such as PBL. Irrespective of the industry type, service level guarantees are likely to dominate the supply chain contracts in future. Such contracts, if not managed properly, can result in increased risk. It is necessary that such contracts are understood clearly and processes and systems are developed to ensure optimization of the contracts.

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[2] Source. http://en.wikipedia.org/wiki/Domino's_Pizza.

The Role of Logistics in E-commerce Transactions: An Exploratory Study of Customer Feedback and Risk

Ramakrishnan Ramanathan, Joseph George and Usha Ramanathan

Abstract Logistics plays an important role in e-commerce; while most part of the transactions happen electronically, physical products need to be shipped to customers using conventional transport means. We report in this paper an exploratory study to understand how customers view logistics performance in deciding performance of sellers in e-commerce. Since it has been observed that risk plays a stronger role in online transactions compared to offline transactions, we study how the importance of logistics performance is influenced by risk characteristics of products sold through e-commerce websites. Our data for analysis have been derived from customer feedback available in eBay. Based on Chi square tests and the Marascuilo procedure, we find that the importance of logistics services increases as risk characteristics of products decreases from high to low.

Keywords Logistics · E-commerce · Product risk

1 Introduction

E-commerce has shown impressive growth in the last few years. For example, according to the survey of the UK Office for National Statistics, Internet sales by UK businesses rose to £222.9 bn in 2008 which was 9.8 % of the total value of all

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sales by nonfinancial sector businesses and an increase of 36.6 % on the 2007 Internet sales figure.

The role of logistics services has evolved as e-commerce grew. When online shopping business started growing, many prophesied that it was the end of the road for many of the intermediaries, who were dominant in traditional supply chains, as more and more suppliers and manufacturers were likely to prefer selling direct to customers in order to reduce delivery time, costs, and compete in the online market (Lancioni et al. 2000; Yankelovich 2000). This meant that most of the business for logistics service providers would be mainly limited to the "last mile" of the online shopping order cycle. However, this has not been the case and the logistics service providers dealing with Internet shopping have witnessed tremendous growth in business (Rabinovich and Bailey 2004). The focus of this paper is to study the role of logistics service providers in e-commerce transactions.

Several studies have stressed the importance of various operational factors, including factors related to logistics performance, in determining overall performance of a seller or an e-tailer (Sum et al. 2001). The importance of quality of physical distribution in the "last-mile" of e-commerce has been stressed (Lee and Whang 2001; Rabinovich and Bailey 2004). E-commerce, especially the B2C segment, is typically characterized by large numbers of small order sizes demanding shipments with a different distribution system compared to the brick-and-mortar business and hence provides larger scope for the role of logistics (Cho et al. 2008). It is believed that e-commerce has provided new opportunities to third-party logistics (3PL) service providers (Kroll 1999) and that with continued growth of e-commerce, the importance of logistics is set to increase.

Risk plays an important role in businesses and is considered more important in online transactions than normal offline transactions (Massad and Tucker 2000). Though there is a huge literature studying risk (e.g., Hofacker 2000; Miyazaki and Fernandez 2001; Finch 2007), there are not many studies that looked at the role of risk on the importance of logistics service in the e-commerce context. We take up this important research issue in this paper. Specifically, we study how the importance of logistics performance is influenced by risk characteristics of products sold through e-commerce websites. We have used customer feedback information available in eBay for the purpose.

The rest of the paper is organized as follows: It starts with a brief description of e-commerce along with the other literature relevant to logistics and risk in e-commerce. Our research hypothesis is established with reference to the existing literature in this section. Research methodology and analysis are detailed in Sect. 3. Section 4 discusses the analyses. Section 5 summarizes our research findings and discusses managerial implications. Section 6 concludes the paper with limitations and future research.

2 Literature Survey and Research Hypothesis

The Role of Logistics Performance in E-commerce

While the role of logistics on firm performance has been well researched in a traditional context (e.g., Morash and Clinton 1997; Wisner 2003), this topic has received relatively less attention in e-commerce context (Gunasekaran et al. 2007). Traditionally, logistics services are built to facilitate efficient flow of goods, information, and cash. This linear relationship is said to have been broken in the e-commerce context, but Rabinovich and Knemeyer (2006) have highlighted that this is not the case with evidence from the events of the past decade. According to them, the importance of logistics service providers has increased in the electronic marketplace.

Logistics plays a very important role in ensuring customer satisfaction. The factors related to logistics are experienced by customers after making payments, and are often grouped as one of the postpurchase factors. Studies have found that customers generally consider physical delivery as a very important factor (Esper et al. 2003; Agatz et al. 2008) and that logistics capability is positively associated with firm performance over the Internet (Cho et al. 2008). Much has been written about this “last mile” of Internet supply chains (Esper et al. 2003; Kull et al. 2007; Lee and Whang 2001). Unlike brick-and-mortar stores where the customer has the option of bringing the product himself, most of the transactions over the Internet rely on the use of a logistics channel for delivery of the products. Significant sources of customer dissatisfaction arises either due to late arrival (or nonarrival) of the product, accuracy of the order, and/or due to damaged products.

Late arrival of the product would often make customers wait for the product with compounded anxiety levels. Logistics performance mainly deals with delivery speed and reliability but several studies have also included responsiveness, communication, order handling, and distribution (e.g., Cho et al. 2008) in the scope of logistics. In general, logistics performance can be improved by employing multichannel distribution, and most multichannel e-tailers offer online consumers the option to return product via online stores, which is greatly valued by customers (Agatz et al. 2008). The logistic platform for e-commerce fulfillment consists of logistics structure (e.g., direct distribution or via distribution centers), logistics processes (e.g. order handling, storing, packing, and transportation), and systems for information and reporting (Aldin and Stahre 2003).

In spite of the rich literature on the role of logistics in physical distribution, a detailed look at the studies on the role of logistics in e-commerce reveals that they have not considered how the importance of logistics varies depending on risk characteristics of products. However, there is evidence that risk plays a significant role in e-commerce and risk characteristics of products could affect the role of logistics in ensuring customer satisfaction. We review some important studies on risk in e-commerce in the next section.

2.1 Risk on Consumer Behavior in E-commerce

While it has been recognized that perceived risk plays a very significant role in influencing consumer behavior especially in e-commerce transactions, there does not seem to be many studies that analyzed the impacts of risk. Massad and Tucker (2000) have provided a comparative study of online and offline (or traditional) bidding behaviors. Following the classification of risk by Hofacker (2000), they have proposed that price comparison risk is higher in traditional auction, while four other types of risk (time risk, vendor risk, security risk, privacy risk, and performance risk) are higher in the online environment. Miyazaki and Fernandez (2001) have found that perceived risks of online transactions might reduce with higher levels of Internet experience. Doolin et al. (2005), using an Internet-based survey in New Zealand, have found significant association of perceived risk and perceived benefits of Internet shopping with the amount and frequency of online purchases made. Lim (2003) has identified four sources of risk in relation to online shopping: Technology, vendor, consumer, and product. Lacohee et al. (2006) have found that online users carried out a personal risk assessment prior to engaging with a service.

In this research, we use an interesting new framework suggested for deciding risk classification by Finch (2007). As per this perspective, the risk characteristic of a product is a function of its price and ambiguity. Finch (2007) has provided a detailed empirical testing on the behavior of online consumers of auction environment based on risk classifications of Massad and Tucker (2000). He has proposed that the risk exposure was determined both by the amount (price) paid and the degree to which a product could be accurately described (ambiguity). Collecting and analyzing 1,000 customer feedbacks for each category, he has found that service-oriented quality dimensions are likely to be given higher importance for low-risk categories and that product-oriented quality dimensions will get higher importance for high-risk categories.

However, a review of the available previous literature shows that there are no studies relating product risk specifically with logistics. It is generally accepted that logistics-related factors are essentially service-oriented. Hence, in the absence of other specific studies on the impact of risk on logistics-related factors, we extend the findings of Finch (2007) to the case of online ratings in terms of the following hypotheses.

Research Hypothesis: *The importance associated with logistics in e-commerce transactions will be more for lower risk products than for higher risk products.*

3 Research Methodology

3.1 Data Collection

In this research, we have used customers' feedback from eBay. The online auction site, eBay, was founded in 1995 and is well-known as the world's best auction engine or marketplace. It has operations in 37 countries with a total customer base of 233 million. The second author has collected data from eBay's UK website, which is the UK's largest online market with more than 14 million active users and more than 10 million items on sale at any given time. A significant number of users utilize eBay as their primary or secondary source of income (eBay Worldwide 2008).

3.1.1 Data Collection Strategy

We have collected our data from e-Bay during the summer of 2008. At the end of a transaction on eBay, the buyer rates the seller with a feedback, which could be positive, negative, or neutral. The feedback is not necessarily only based on the product characteristics; it frequently stresses the service attributes of the entire transaction. Such feedbacks have been collected to interpret the customer's/buyer's satisfaction level. Each feedback has been read and converted into a quantitative form by classifying it into one of the following six categories:

(1) Delivery speed/timeliness
(2) Delivery speed/timeliness and other service factors like sorting, picking, packaging, communication, order tracking etc.
(3) Other service factors (all excluding delivery speed/timeliness)
(4) Product-only
(5) Product and service related and
(6) Nonspecific

The first three categories together form the service-only category. Of these three, the first two are related to logistics (transport and delivery).

3.1.2 Risk Characterizations

As mentioned earlier, we are interested in understanding how the importance of logistics varies depending on the risk characteristics of the products involved in e-commerce transactions. Based on Finch (2007), we have characterized risk of a product in the form of price and ambiguity. High-price products with high ambiguity (HPHA) are classified as high-risk products, and low-price products with low ambiguity (LPLA) are classified as low-risk products. The other two products such as high price with low ambiguity (HPLA) and low price with high ambiguity (LPHA) are classified as medium-risk products. Thus, we have created three product classifications—high risk, medium risk, and low risk.

Low price products are defined in this study as products below £100 and high price products were those costing above £200. In the low-price low-ambiguity category, DVDs, comics, video games, and accessories and computing accessories were considered. In the high-price low-ambiguity category, laptops, digital cameras, and other electronics were considered. In the high-ambiguity category, products such as antiques (wooden and oriental), paintings, art, pottery ,and coins were considered. Based on the price range of the high-ambiguity products sold, sellers were classified into one of the two categories low-price high-ambiguity and high-price high-ambiguity. Our choices of these product categories to represent the risk groups are consistent with those of Finch (2007).We have collected 1000 positive feedback ratings for each of the four product categories (therefore, 4000 in all). Evaluation of positive feedback provides a sense of what customers view as important and is in line with previous studies (e.g., Finch 2007).

For each of the product categories, effort was made to ensure that the sellers selected were active with significant activity levels in the past few months. This could be confirmed by the number of customer feedbacks within the past 90 days (from June to August 2008). Only the latest 25–100 feedbacks were considered for each seller.

3.2 Interpretation of Feedback Data

The following strategy was adopted for interpreting customer feedback. Feedback such as "thank you" and "excellent eBayer" were considered as nonspecific. Feedback such as "excellent item," "product met expectations," and "excellent product price" were classified as product-only. "Fast and excellent condition" and "great transaction" were considered to be both product and service related. "Fast and well packed" was put into the service-only category under the subcategory of delivery speed and others, while comments such as "excellent service" and "great communication" were placed in the other services subcategory.

This data interpretation process can be more easily understood with the help of Table 1, which gives examples of a few customer feedback data being converted into quantitative data.

As mentioned earlier, we have collected 1000 positive feedback ratings for each of the four product categories (therefore, 4000 in all) and the ratings were classified into one of the earlier mentioned six categories. Details are included in Table 2.

After collecting the data, in line with the focus of this study, we have considered only the following feedbacks for further analysis:

Table 1 Examples of Feedback category description

Feedback examples	Service-only			Product-only	Service and product	Not specific
	Delivery speed	Speed & other service	Other service			
1) Super fast delivery, product as described.					1	
2) Brilliant service, highly recommended.			1			
3) Good eBayer!						1
4) Perfect transaction.			1			
5) Super fast delivery and excellent item.					1	
6) Great product and communication.					1	
7) Quick delivery, would recommend.	1					
8) Item as described and quick delivery.					1	
9) GREAT eBayer. Thank you!						1
10) Brilliant, wow very impressed. Very quickly received. Not a mark or scratch.					1	
11) Great item!				1		
12) Fast and good packing		1				
Total	1	1	2	1	5	2

Table 2 Frequencies of eBay feedback

	Low price—low ambiguity (Low-risk products)	High price—low ambiguity (Medium-risk products)	Low price—high ambiguity (Medium-risk products)	High price—high ambiguity (High-risk products)
1. Service related				
1.1 Speed of Delivery/Timeliness	202	256	45	63
1.2 Speed and other service factors	95	98	102	91
1.3 Others (excluding speed of delivery and timeliness)	45	70	94	80
Service-related total	342	424	241	234
2. Product related	91	142	245	244
3. Service and Product related	318	322	388	417
4. Not specific	249	112	126	105
Grand Total	1000	1000	1000	1000

a) pure logistics-related (combining frequencies corresponding to items 1.1 and 1.2 of Table 2)
b) other services-related (item 1.3 of Table 2) and
c) product-related (item 2).

We have excluded frequencies corresponding to items 1.3, 3, and 4 from further analysis. Since the above table lists 2000 feedbacks for medium-risk group, we have used the average for 1000 feedbacks in the remainder of this study. The data collected were tabulated and statistical tests were conducted to draw a conclusion regarding the research hypothesis. Details are discussed below.

4 Analysis and Results

We have conducted data analyses in two stages. In Stage 1, we have first verified whether there is a significant difference in the frequency of logistics-related, other service-related, and product-related feedbacks across the three risk categories. We have employed the Chi square test for this purpose of analysis. Stage 2 was based on the results of Stage 1 to check if the frequency of feedbacks is higher or lower for different categories.

Stage 1
In this stage, we have used a simple Chi square test (Anderson et al. 2002) to test whether the number of pure logistics-related, other service-related, and product-related feedbacks differ significantly across the risk groups.

Table 3 shows the results of the Chi square analysis. The Chi squared value is significant ($p = 0.000$) showing that frequencies of logistics-related, other service-related, and product-related feedbacks differ significantly among the low-risk, medium-risk, and high-risk products. This result partially supports our research hypothesis in that the importance of logistics varies across the risk categories. However, in order to verify the hypothesis further, we need to complete Stage 2.

Table 3 Results of Chi square analysis for risk categories

	Low risk	Medium risk	High risk
Pure logistics related feedback—actual value	297	251	154
Pure logistics related feedback—expected value	211.53	256.96	255.51
Other services related feedback—actual value	45	82	80
Other services related feedback—expected value	62.37	75.77	68.86
Product related feedback—actual value	91	193	244
Product related feedback—expected value	159.1	193.27	175.63
Chi square = 124.7			
Degree of freedom = 4			
$p = 0.000$			

Stage 2

The Chi square test shows that the frequencies are significantly different. We can intuitively conclude, by looking at the absolute values of frequencies, that logistics-oriented feedbacks have a higher frequency for low-risk products than for high-risk products (297 > 154). To confirm this statistically, we have used the Marascuilo procedure (Marascuilo 1966; Levine et al. 2007).

Application of the procedure requires three steps (Levine et al. 2007). Calculations for these steps are shown in Table 4.

Step 1 Let k be the number of groups to be compared. In our case, $k = 3$ as there are three groups (low risk, medium risk, and high risk). Further, let p_i be the proportion of logistics-related feedbacks over total feedbacks considered for group i. We compute absolute values of the differences $\left(p_i - p_j\right)$ (where i is not equal to j) among all $k(k-1)/2$ pairs of proportions. In our case, we have three pairs (low–medium, medium–high, and low–high) to be compared

Step 2 Calculate critical value using the formula $\left(\sqrt{\chi_U^2}\sqrt{\frac{p_i(1-p_i)}{n_i}+\frac{p_j(1-p_j)}{n_j}}\right)$ where χ_U^2 is obtained from Chi square statistical tables based on a prespecified significance level and $(k-1)$ degrees of freedom and n is the total number of observations for each group. For calculations in Table 4, χ_U^2 = 5.9915 for a 5 % significance level with two degrees of freedom

Step 3 The difference in proportions $\left(p_i - p_j\right)$ among a pair is compared with the critical value. A pair is considered to be significantly different if the absolute difference in proportions is greater than the corresponding critical value. Table 4 shows that the absolute values of differences in proportions are greater than the corresponding critical values for all the three pairs (low–medium, medium–high, and low–high). These findings support our research hypothesis

It can be seen from Table 4 that the absolute value of the proportion difference for medium and low risk (0.2087) is greater than the critical range (0.0763), and hence it can be concluded that the difference in logistics-related feedbacks for low- and medium-risk products is statistically significant (297 > 251). Thus, logistics-related factors are more important for low-risk products than for medium-risk

Table 4 Comparison of 'logistics only' feedbacks

Groups	Low risk	Medium risk	High risk
Pure logistics-related feedbacks	297	251	154
Other services-related feedbacks	45	82	80
Product related-feedbacks	91	193	244
Proportion of pure logistics-related feedbacks to total	0.6859	0.4772	0.3222
Pairs	Med–low	High–med	Low–high
Absolute value of difference in proportions	0.2087	0.1550	0.3637
Marascuilo critical value	0.0763	0.0747	0.0756

products. Similarly, we can observe that the difference in logistics-related feedbacks for medium- and high-risk products is statistically significant (251 > 151), and further that the difference in logistics-related feedback for low- and high-risk products is statistically significant (297 > 154). Thus, we can conclude in this study that logistics-related products are more important for medium-risk products than for high-risk products.

5 Discussion and Managerial Implications

While there are studies on the importance of logistics and on the influence of risk in e-commerce transactions, there seems to be no study that combines these two important research avenues. The present study has contributed to the literature by filling this gap by providing risk perspective on the importance of logistics in online transactions. Drawing on positive feedbacks of buyers in eBay transactions, this study has found that logistics-related feedbacks are more frequent for low-risk products (characterized by low price and low ambiguity) than for high-risk products (characterized by high price and high ambiguity). Our study agrees with the findings of Finch (2007) who found that service-oriented factors (that also included logistics service) would get higher importance for low-risk categories. Figure 1 summarizes these findings.

Our study has interesting practical implications to managers of online businesses. Logistics performance contributes to satisfaction of online customers more for low-risk products than for high-risk products. We interpret this result as support for customers being more attentive to logistics performance in the case of low-risk products. For low-risk products (low price and low ambiguity), customers do not usually spend much time on researching the product, order the product, and expect that the product is delivered as promised. Thus, delivery of the right product at the promised time seems more important to customers. On the other hand, for high-risk products (high price and high ambiguity), customers spend comparatively more time in reading product specifications more thoroughly and locating the most cost-effective supplier. Though they also expect that the product be delivered as per the original specification and at the promised time, customers

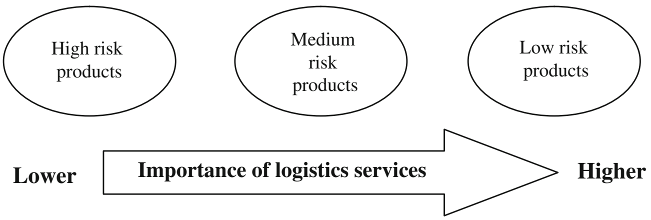

Fig. 1 Importance of logistics for different product types

buying high-risk products seem to provide lesser importance to logistics compared to other features of the product. This result agrees well with the literature. For example, Finch (2007) has found service-oriented attributes receive higher priority for low-risk products, while product-oriented attributes receive higher priority for high-risk products.

Managers of e-commerce websites can use our results to provide "optimal" level of logistics service for their products. Logistics performance attributes such as fast shipping and communication will be important for low-risk products, and will contribute to the favorable service perception of customers. However, for high-risk products, customers may not attach performance in terms of delivery time or communication at very high importance, and any special efforts and money spent on this may not necessarily be optimal.

6 Limitations and Future Research

In spite of the interesting finding on the importance of logistics for various product risk groups, our study has some limitations and future research could overcome them. We first wish to caution about the results discussed in the previous section. We have observed that logistics related feedbacks were more for low-risk products. However, this need not mean that those customers who posted logistics-related feedback do not care at all about other features of the transaction—such as product quality or other service categories. They do care about all features, but satisfied customers of low-risk products tend to emphasize logistics performance more.

Though online ratings and feedback data have been extensively used by previous research studies, our choice of data collection via eBay has the usual disadvantages of a secondary data source. For example, the researcher is not in control of data collection and raw data need to be converted to a form that is useful for the analysis. However, secondary data also have its own advantages, namely availability of large amounts of data and data collection without any bias on the part of the researcher.

We have used reasonable definitions of low and high prices in our study. Our maximum threshold for low price is £100, while the minimum threshold for high price is £200. However, given that these are subjective values, an interesting approach for future research would be to perform sensitivity analysis of the thresholds used for high and low prices.

We studied only positive feedback in this research. Thus, this study has examined how logistics supported e-commerce firms to improve their performance. In this sense, we studied logistics as a satisfier in the language of Ramanathan (2010). That is, we have studied how logistics performance contributed positively to customers who are happy with an e-commerce transaction. The fact that we have not included negative feedback in our analysis could be considered as a limitation of this study. We did not include negative feedback in our analysis, because (i) negative feedback is not so frequent in eBay compared to positive feedback; (ii) there are very few cases where logistics services are cited as the main reason for dissatisfaction. However, we wish to stress that negative feedback could provide another equally important component to understanding customer preferences. This can help to understand the role of logistics as a dis-satisfier—how logistics would contribute to the dissatisfaction of a customer who is not happy with a transaction. Study of negative feedback exclusively or in combination with positive feedback could also help to understand customer behavior further. This forms scope for future research.

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Supply Chain Strategies in Difficult Times

Yongmei Bentley

Abstract This chapter examines the strategic decisions taken by supply chain managers during the current (post-2008) economic recession. The objective was to identify and understand the changes that companies had made, or planned to make, in their company supply chain strategy in response to this changing economic environment. A longitudinal approach was adopted, and a series of questionnaire survey rounds were carried out. Over 300 responses from three countries were received. The findings from the first two survey rounds indicated that only a limited number of companies had made significant changes to their supply chain strategies, but this number increased as the recession continued. While a common company response was to downsize the organisation, there were also other strategic changes such as changes in the use of third party logistics, in warehousing choices and in a move to more local suppliers. In the broader context, the results can contribute to the understanding of how companies evolve their supply chain strategies when dealing with a significant change in the external environment.

Keywords Logistics · Supply chain · Strategy · Survey

1 Introduction

Many companies around the world have struggled with the consequences of the economic downturn that followed the financial crisis of 2008, where this is considered by some as 'the worst of such crises since the Great Depression of the 1930s' (Reuters 2009). It can be argued that the logistics industry was impacted to a greater degree by this crisis than many other industries because of the 'ripple

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effect', whereby the decline in economic activity led to a sharply lower demand for transportation of goods, and hence to a direct loss in volumes shipped (Blanchard 2009). For the same reason, the supply chain activities of non-logistics businesses were also seriously affected. As a result of these pressures, management of logistics and supply chain activities attracted significant attention from company boards to further improve processes, cut costs and reduce risks. Moreover, the changes resulting from the downturn should be set against the more general background that it was only over the last 2 decades or so that many companies around the world adopted formal logistics and supply chain management strategies with the aim of ensuring cost-effective operational processes and a quick response to market trends.

The development and implementation of logistics and supply chain strategies has been examined widely in the literature, for example, by Christopher (1992; 1998), and van Hoek (1998). However, the recent financial crisis posed additional challenges to conventional logistics and supply chain management strategies and there is a research need therefore to understand how these global financial difficulties impacted the decisions of logistics and supply chain management. This, in turn, relates to the more general question of how businesses formulate such strategies in reaction to significant changes in the external environment.

This chapter reports on an investigation into the perceptions of logistics and supply chain managers, and other related senior personnel, about how the economic recession impacted their organisations' logistics and supply chain strategies. The research covered a period of nearly two years, running from near the start of the financial crisis in 2008 until September 2010, and examined responses from the three countries—UK, Oman and Poland. This chapter opens with a brief literature review followed by a description of the research methodology adopted for four rounds of questionnaire survey. Analysis of the survey data and research findings are then presented. This chapter finishes with a discussion of the research limitations, a summary of key findings and conclusions.

2 Literature Review

According to Tan and Litschert (1994), strategy is about competing and winning, about making a difference in a firm's performance. A successful logistics strategy, if aligned with corporate strategy and the resource capabilities of the firm, will coherently unify activities, functions and objectives that otherwise would conflict (LaLonde and Masters 1994). In addition, the authors point out that the firm's external business environment will affect the development and implementation of their logistics strategy. Burgelman (1983) recognises that as the characteristics of the environment are constantly changing, new strategic activities will emerge and be adopted by firms to face these changes.

In economically difficult times, if organisations align their strategies with the changes of such an environment, their performance is likely to be optimised

(Zajac et al. 2000). The theory of strategic decision processes suggests that an organisation's strategy illustrates the extent of 'matching' or 'alignment' between its external environment and its internal structure and processes (Fredrickson and Mitchell 1984; Priem et al. 1995). The foundation of this alignment is based on the firm's intention of seeking superior performance, while at the same time avoiding market risks. Risk represents 'the chance of loss, danger, or other undesired consequences' (Harland et al. 2003), while in the logistics and supply chain industries in particular, risk can incorporate 'any event or action that presents an impediment to information, material, or product flows from original supplier to end-user' (Jüttner et al. 2003). Wagner and Bode (2008: 309) define supply chain risk as 'a negative deviation from the expected value of a certain performance measure, resulting in undesirable consequences'; while some researchers have made efforts to incorporate both positive and negative effects of risk, allowing also for potential opportunities when companies face unexpected events (Michell 1995; Borge 2001). According to Jüttner (2005), many organisations expect such risks to increase due to growth in supply chain globalisation, reductions in inventory, centralised distribution, supplier base reductions, growth in outsourcing and centralised production. This increase in risk, whether generated by outside environmental factors or as a result of internal issues, forces organisations to formulate strategic plans to deal with potential disruptions.

Miller and Friesen (1983) suggest that increases in environmental dynamism—as exemplified by the economic downturn—are accompanied in general by greater levels of rationality in the planning processes of high-performing firms. They imply that in order to achieve superior economic performance, firms have to be aware of the changes in market environment, and hence to make the necessary adjustments. Miller and Friesen (1983) further assert that the best strategic choice is the one aligned with the attributes of the business environment, and that this will be affected by a number of variables interacting with each other. Some of these variables, as identified by Hoffer (1975), relate to the current research including economic conditions, supplier variables, industry structure, competitors and consumer behaviour. In this chapter, it is argued that these variables have been affected by the magnitude and speed of the recent economic downturn, and have brought consequent changes to the operations and processes of logistics and supply chains.

Christopher and Holweg (2011) recently argued persuasively that the post-2008 downturn might not be just another normal business cycle, but the entry into a much longer period of business turbulence. They base their view on measured levels of volatility in key business parameters, and point to drivers that are likely to make such volatility the norm. These drivers include fluctuation in commodity prices caused by population demand pressures; technology advances; 'peak oil' concerns (Leggett 2005); exchange rate uncertainties as currencies come under pressure and no single currency becomes fully trusted; changes in customer demand and government regulation due to climate change issues and structural changes in comparative labour costs across the producing regions of the world. The authors argue that in the face of such turbulence, business needs to move away from supply chain models (see for example, Beamon 1998) that were designed over the last 30 years of relativity stability, and move instead to ‘structural flexibility’, where this, importantly, includes changes in accounting practices that currently favour ‘fixed parameter’ modelling.

As noted above, the decision-making processes of logistics and supply chain management are essential to the ability of companies to gain competitive advantage, and to survive market competition. This has been especially true in response to the recent economic downturn, which itself may be part of the ongoing turbulent business environment that Christopher and Holweg (2011) foresee. It was the purpose of this research, therefore, to find out how company management responded to these economic pressures in terms of their logistics and supply chain decisions.

3 Research Methodology

A notable feature of the recent economic situation was that it was poorly predicted. It would be expected therefore that there would be changing perceptions over time concerning the seriousness of the situation by logistics and supply chain managers, and that there would be corresponding changes in the way that organisations responded. As a result, a ‘quasi-longitudinal’ approach was adopted for this research, collecting data by a sequence of semi-structured questionnaire surveys in order to collect information that would reflect both the changing perceptions, and the evolving strategic decisions, of managers. A ‘convenience sampling’ technique was applied whereby participants were selected because of their accessibility and proximity to the researcher (Freeman et al. 1998). The investigation took place from November 2008 to September 2010 in order to track the changes in company logistics and supply chain strategies over this important initial part of the recession. The approach followed that of cohort study, where a cohort is ‘a group of people who share a certain characteristic’ (Bryman 2004: 46); where in this research participants in the 13 cohorts surveyed that all had commercial experience of logistics and supply chain management.

Four survey rounds were conducted collecting primary data on managers’ perceptions across the period from the three countries studied. Initial results of the data analysis from the first two survey rounds have been reported in Bentley and He (2009), while the present chapter extends this analysis to the full period of the research and presents the corresponding findings.

As mentioned above, the main instrument for data collection was a semi-structured questionnaire comprising a mixture of closed and open questions. The reason for this approach was to accommodate a wide range of responses from the target respondents. The use of semi-structured questionnaires, according to Hague et al. (2004), enables a mix of qualitative and quantitative information to be gathered; and it was considered important here to capture a wide range possible of managers’ perspectives. A ‘purposive sampling plan’ (Glaser et al. 1967) was therefore adopted to ensure that the sample included mangers in logistics and supply chain management with responsibilities for business continuity and risk management across a wide range of industrial, consumer and service industries.

The questionnaire was designed to be concise to encourage the high participation rate needed for valid conclusions to be drawn. Typically it took a respondent about 30 min to complete a survey. Most of the survey forms were handed directly to participants at convenient times and locations, including logistics and supply chain events, conferences, seminars and classroom teaching. In most cases, the survey forms were completed immediately on-site following hand-out, and returned directly to the researcher. This helped ensure a high response rate.

4 Data Analysis

4.1 Classification of Participants by Groups and Cohorts

Table 1 gives an overview of the research participants by groups and by cohorts. As indicated in the table, Group 1 respondents were members of the Chartered Institute of Logistics and Transport (CILT-UK), and consisted of two cohorts—the supply chain group in London and the logistics group in Milton Keynes. Virtually, all these respondents were senior or middle level managers or other senior operations personnel, working directly in logistics or supply chain activities.

Group 2 were delegates surveyed at three key UK logistics events—two Logistics Research Network (LRN) conferences held respectively in September 2009 in Cardiff and in September 2010 in Harrogate; and the Logistics Exhibition (2010), the UK's largest logistics and transport annual event held at the National Exhibition Centre in Birmingham. Delegates surveyed at these events were mostly

Table 1 Overview of the research participants by groups and cohorts

Research Groups	Research cohorts
1. Members of the chartered institute of logistics and transport (UK)	A. Supply Chain Group, London B. Logistics Group, Milton Keynes
2. Logistics practitioners	C. LRN conference 2009, UK D. LRN conference 2010, UK E. Logistics exhibition UK
3. M.Sc. logistics students (UK)	F. Academic year 2008–2009 G. Academic year 2009–2010
4. MBA students (UK)	H. Academic years 2007–2009 I. Academic years 2008–2010
5. MBA students (Oman)	J. Academic years 2007–2009 K. Academic years 2008–2010 L. Academic years 2009–2011
6. MBA students (Poland)	M. Academic years 2009–2011

executive managers and key practitioners from logistics and transport companies. Most of those surveyed were also members of CILT.

Group 3 consisted of two cohorts of students taking the M.Sc. Logistics Management course offered by a UK university. Many of these students were 'mature students' who had previous work experience before taking the M.Sc. course, and those who were invited to participant in the survey all had prior experience of working in logistics or supply chain management.

Groups 4, 5 and 6 consisted of six cohorts of respondents from three countries (UK, Oman and Poland) enrolled on the Executive MBA course provided by the same university. These cohorts were mainly people who had also been working for a number of years, and who were taking the MBA part time while still in full time employment. Most of these held senior or middle management roles in their organisations, and were directly involved in strategic decision-making in logistics and supply chain management.

4.2 Overview of the Questionnaire Survey

As mentioned earlier, four rounds of survey were carried out across the research period (November 2008 to September 2010). Table 2 gives the dates and number of returned questionnaires from each cohort as well as the percentage of data collected by group and by survey round. As indicated in the table, a total of 316 completed questionnaires were collected from the six broad groups of respondents in 13 cohorts. The table indicates that the split of responses versus survey round was roughly even, albeit with a falling trend across the research period.

Questionnaires were delivered to Group 1 participants at the regular logistics and supply chain network meetings, and to Group 2 delegates at the three logistics and supply chain events mentioned. These two groups represent 46 % of the total response rate (145 out of 316).

For Groups 3–6, questionnaires were given out in class. The 316 completed questionnaires returned represented an overall response rate of over 60 percent. This high return rate reflected both the questionnaire design—being concise and easy to complete, and its method of distribution where the researcher handed the questionnaire to the participants and collected after filling in.

The following sections discuss the data obtained from this study, and is structured in the sequence of the questions in the survey. The first three questions examined the profile of the participants.

4.3 Participants' Profile

Question 1 was '*What industry are you in*?' An analysis of the responses shows that the coverage by industry was relatively wide, in line with the intention of the study. As indicted in Fig. 1, the largest sector was logistics, supply chain and

Table 2 Overview of the questionnaire survey rounds

Groups & Cohorts (See Table 1)	1st survey (Nov 08–Jan 09)		2nd survey (Feb–Apr 09)		3rd survey (Aug–Nov 09)		4th survey (Apr–Sept 10)		Total No.	Total (%)
	Date	No. of returns	Date	No. of returns	Date	No. of returns	Date	No. of returns		
Group 1										
Cohort A	11/08	18	03–09	12	11–09	13	04–10	14		
	–	–	–	–	–	–	07–10	4		
Cohort B	12–08	17	02–09	14	–	–	06–10	9	101	32
Group 2										
Cohort C	–	–	–	–	09–09	16	–	–		
Cohort D	–	–	–	–	–	–	09–10	3		
Cohort E	–	–	–	–	–	–	04–10	25	44	14
Group 3										
Cohort F	11–08	10	04–09	14	–	–	–	–		
Cohort G	–	–	–	–	–	–	06–10	5	29	9
Group 4										
Cohort H	12–08	15	03–09	13	–	–	–	–		
Cohort I	01–09	13	03–09	13	–	–	–	–	54	17
Group 5										
Cohort J	01–09	12	02–09	12	–	–	–	–		
Cohort K	01–09	11	02–09	10	–	–	–	–		
Cohort L	–	–	–	–	08–09	20	–	–	65	21
Group 6										
Cohort M	–	–	–	–	10–09	23	–	–	23	7
Total responses		96		88		72		60	316	
Total (%)		30		28		23		19		100

transport (28 %), followed by manufacturing and retailing (26 % combined). The other sectors participating in the survey included: Education, health care and government bodies (11 %); finance and banking (6 %); energy (4 %); travel and hospitality (4 %) and construction (3 %). As noted above, all the participants in this research, no matter what industry or organisation they were from, had roles related to logistics or supply chain management within their organisation.

The sizes of the respondents' organisations were determined by Question 2: '*What is the total number of employees in your company?'* For simplicity, the classification of company sizes given here is based on the European Union definition (though a non-European country was also participated in this research) which distinguishes organisations as large (>250 employees), medium (<250), small (<50) and micro (<10) enterprises (European Union 2003).

The results presented in Fig. 2 indicate that large companies dominated the research—57 % in total with 36 % of the respondents from companies with over 1,000 employees and 21 % from companies between 251 and 1,000 employees. In

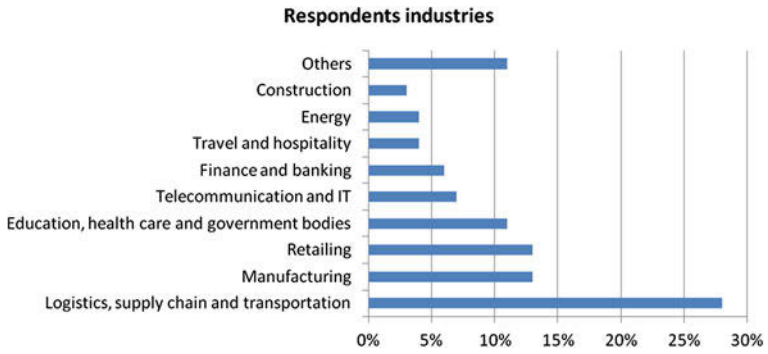

Fig. 1 Industries covered by respondents in the surveys

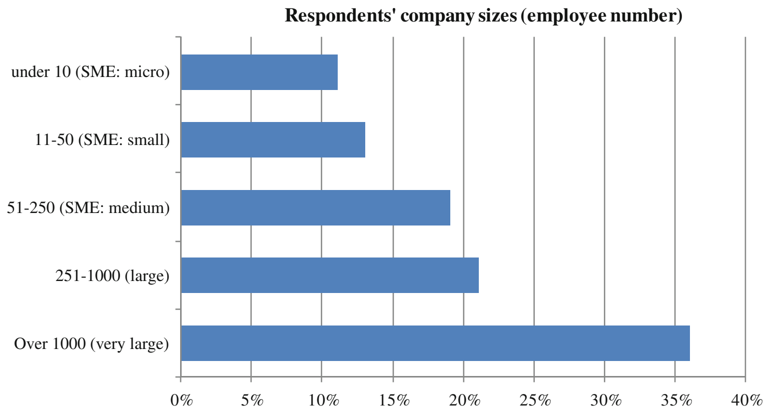

Fig. 2 Participants' company sizes

this research, small and medium-sized enterprises (SMEs) represented 43 % of the participants—19 % from medium enterprises, 13 % from small enterprises and 11 % from micro enterprises.

This skewed distribution of organisation sizes very probably reflects the better opportunities and funding for personnel in large organisations to attend seminars and conferences, and to take further degrees in business-related areas. This might represent a bias in the data gathering, but since a focus of the overall study was to look for *economically significant* changes in logistics and supply chain management practice, including in strategy setting, this degree of participation by larger organisations was appropriate.

The results from Question 3: '*What is your role in your company*' showed that over 60 % of respondents held senior positions (21 % CEO/Executive/Director positions; 41 % Country/Region/Division Head/Manager positions), and the rest of the respondents held other roles with all having active participation in logistics and supply chain activities. This was a useful result, as it indicated that the majority in the survey group respondents held positions which encompassed the strategic decision-making activities that were the primary focus of the research.

5 Main Findings

This section discusses the responses to the subsequent questions of the survey, which related to changes made by the organisations in response to the downturn. They are discussed here by category.

5.1 Changes Being Made or Planned

To Question 4 of the survey '*Are you making (or do you plan to make) changes in your logistics and supply chain activities because of the current economic downturn*?' the responses provided an indicator of management intentions across the whole survey period. The responses are set out in Table 3.

Table 3 Are changes being made or planned because of the downturn?

Survey Round	Date	Yes		No		Not yet decided		Total
		Count	Row N (%)	Count	Row N (%)	Count	Row N (%)	Count
1st	11-08	8	33	5	21	11	46	24
	12-08	12	40	9	30	9	30	30
	01-09	12	35	8	24	14	41	34
	Total/Av. (%)	32	36	22	25	34	39	88
2nd	02-09	12	34	13	37	10	29	35
	03-09	26	68	6	16	6	16	38
	04-09	11	79	1	7	2	14	14
	Total/Av. (%)	49	60	20	20	18	20	87
3rd	08-09	6	30	8	40	6	30	20
	09-09	6	46	7	54	0	0	13
	10-09	9	39	8	35	6	26	23
	11-09	9	82	1	9	1	9	11
	Total/Av. (%)	30	49	24	34	13	16	67
4th	04-10	19	51	13	35	5	14	37
	06-10	5	38	5	38	3	23	13
	0710	0	0	1	25	3	75	4
	09-10	1	50	1	50	0	0	2
	Total/Av. (%)	25	35	20	37	11	28	56
All rounds	Total/Av. (%)	136	46	86	29	76	26	298

Averaged across all cohorts across all four survey rounds, nearly half the respondents (46 %) answered ‘yes’ to this question that changes were being made or planned; the remainder—at the date surveyed—were either not making specific changes (29 %) or were still undecided (26 %).

However, when looked at on a survey-round basis, the reactions to the economic downturn were more instructive. Though variable across months, the reactions showed an increasing trend of ‘Yes’ to the question from the first survey to the second. By this date, the combined ‘No’ and ‘Not yet decided’ categories had fallen to 21 % at the end of the second survey period from 67 % at the beginning of the first survey period (see Table 2). However, by the third and fourth rounds of the survey the percentage of respondents who reported that actions were being taken or planned, decreased to an average of only 49 % and 35 %, respectively. Here, it is clear that the decision to take action increased markedly from the first to the second round, but had largely stabilised by the third and fourth rounds, although with the November 2009 response for ‘yes’ (82 %) appearing to be something of an outlier.

Figure 3 gives a clearer view of the changes of the survey results across the research period (note that the percentages shown are the average percentages of each survey round).

The probable explanation for this pattern is as follows. At the outset of the survey (November 2008) most organisations were well aware of the problem of the global banking and investment sectors, but it was not yet clear how much these severe problems in the ‘paper’ economy would affect the ‘real’ economy—the question sometimes being phrased as: ‘to what extent would the problems on Wall Street affect the High street?’ However, even at this early stage, about a third of the organisations surveyed were already taking action or anticipating this, either because real pressures on their organisations had already shown up or because of management anticipation of problems to come. However, a year later, towards the end of 2009 by the end of the third survey, the ‘real economy’ impacts of the downturn had indeed become clear and many organisations had already taken significant action. By the end of 2010 with considerable speculation that the

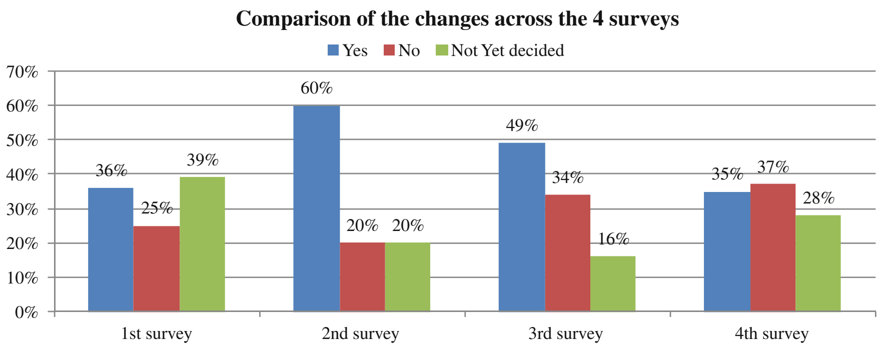

Fig. 3 Comparison of the changes across the four surveys

recession might be over, and not be a 'double-dip' recession, it seems that organisations also felt under reduced pressure to take or plan further action. It is worth noting, however, that at the time of writing, in autumn 2011, this assumption of avoiding a double-dip recession has turned out to be wrong in a number of countries.

5.2 Main Changes Made by Organisations

The next question of the survey was designed to obtain additional information about the nature of changes being made or planned. Question 5 asked: '*If changes are underway or planned, what are the main changes*?' In this case, options were provided and the respondents were asked to tick as many of the categories as applicable. The proportion of responses for each of the categories across all survey rounds is presented in Fig. 4.

Of the 286 respondents who replied to this question, approximately one-third made two or more choices. Perhaps unsurprisingly, the most frequent response to the downturn was 'reduction in employment'; while downsizing in general, including 'decrease in total stock levels', 'leaner work-in-process inventories' and 'reduction in product lines', covered nearly 60 % of all the responses. Changes were also identified in the use of third party logistics (3PL) and warehousing, but here the increase in the use of these services was roughly matched by a decrease reported by other respondents. There was a tendency to move to more local suppliers, reflecting a desire to shorten product lead time and reduce transportation costs. This latter change may also be due to the fact that the downturn came on the back of a period of increased fuel costs, particularly since summer 2008. Indeed, in considering the changes reported here, undoubtedly the main driver was the

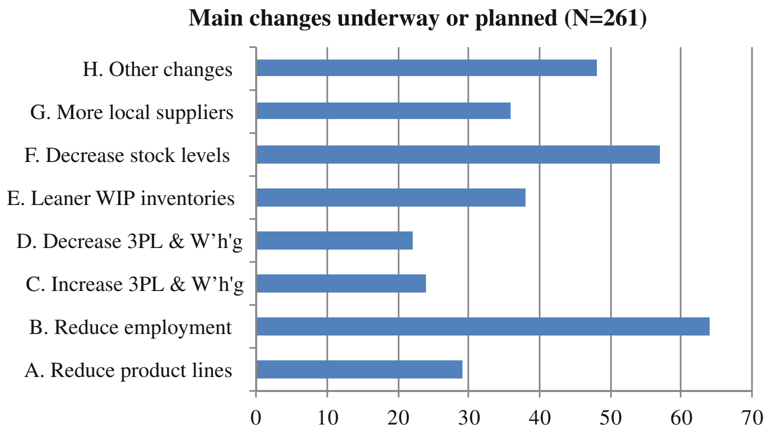

Fig. 4 Classification of the main changes underway or planned across all survey rounds

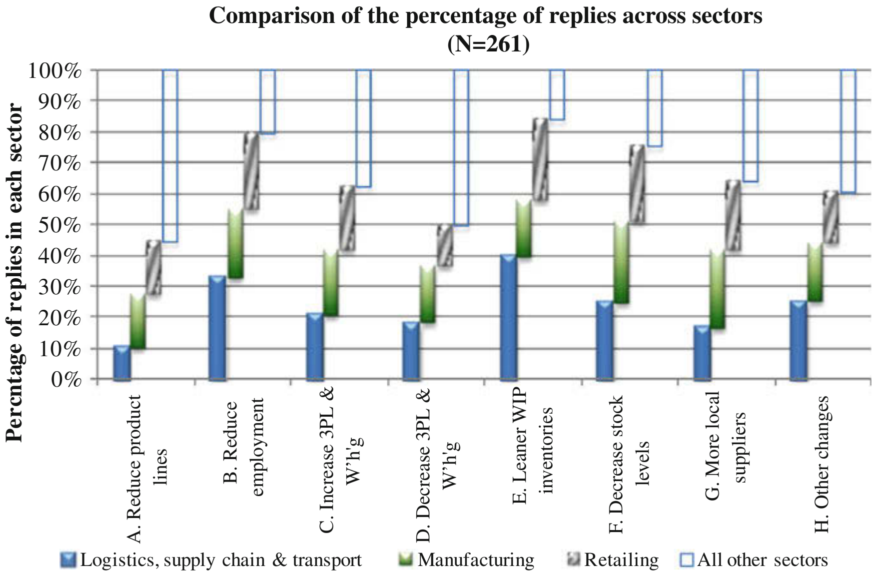

Fig. 5 Comparison of the changes in different sectors

significant reduction in economic activity over the period, but the driver of high fuel cost should not be overlooked in understanding the changes made.

A more detailed analysis was conducted of the responses to the question about '*main changes*' (see Fig. 5). This indicated that there was a difference between the three main industries covered (logistics and related, manufacturing and retailing) and the other business categories, particularly in terms of reacting to the downturn by changing the number of product lines, stock levels and changes in third party logistics and warehousing. The 'other industry' sectors, including education, health care and government, telecommunication, finance and banking, travel and hospitality and energy and construction, placed more emphasis on reducing product lines rather than on reducing stock levels and in decreasing third party logistics and warehousing. This difference probably reflects the preponderance of service industries in these other business categories in comparison with the three main sectors.

5.3 'Other Changes' Specified by the Respondents

The survey question on '*main changes*' allowed for 'other changes', and about 20 % of the respondents ticked this category. In many cases respondents amplified with specific comments. These covered four main areas as follows:

Cost reduction and waste elimination: Logistics represents a significant cost for many company operations, so senior management of many of the companies investigated had focussed on this area in order to reduce costs and increase revenues. The actions listed by respondents included: Streamlining needs and reducing waste as well as decreasing stock levels and reducing the use of third party logistics (3PL) and warehousing in line with volume reduction. One 3PL company reported that it had converted a number of its diesel lorries to liquid gas as a cost-reduction measure.

Improvement in processes: Some organisations had focussed on driving efficiency through improved processes as a means of additional cost reduction. Examples included: Process review, re-design and business re-organisation; decreasing production lead-time, and reducing costs while maintaining existing service levels; setting ‘travel bans’ unless the travel was absolutely necessary; making changes in 3PL for transport to reduce carriage costs; offering more ocean carrier options to clients; reviewing networks (globally where appropriate) and consolidating warehouses; implementing warehouse management systems; introducing a new consolidated super-distribution centre; (for a train company) improved productivity of locomotives and train drivers to improve turnover and profits; improved IT systems; and managing clients to increase efficiency and avoid costs.

Review of contracts: Some companies saw in the downturn both the pressure, and the opportunity, to review contracts, making comments such as: Review of contractual and procurement terms; reducing contract rates; renegotiating discount deals and supply contracts; making some existing suppliers redundant and seeking more efficient suppliers; and tightening up on credit control by reviewing credit policies.

Price changes: Some companies, mostly retailers, had cut prices of goods and services during the downturn, but others had increased their prices. A general manager of one manufacturer commented that “since our supplies have increased in cost by over 20 %, we have to pass these costs onto our clients”.

5.4 Cost Reduction in Logistics and Supply Chain Activities

Question 6 asked the strategic question about the views of senior management: ‘*Does the company’s senior management see logistics and supply chain activities as an important area for cost reduction in the current economic climate*?’ A total of 63 % of the respondents answered ‘yes’; the remainder answered either ‘no’ (15 %) or ‘not yet clear’ (22 %). It was apparent, therefore, that it was not just the logistics and supply chain managers who saw the need for action in their areas, but also the more senior management with these companies. However, in contrast to this trend, one of the respondents, a company executive manager, did not see logistics and supply chain activities as important for cost reduction in this economic climate, saying that “we are extremely lean in this area”, and stressed that it was better instead to “become more responsive, seek new opportunities and increase customer-centric focus”.

5.5 Impact of the Economic Recession

Question 7 broadened the issue from logistics and the supply chain to overall company activity. The question asked: *'(In your opinion) what are the likely impacts of the downturn on your company's overall level of activity?'* and the choices were: *Zero to Moderate; Fairly Severe; Very Severe; Not certain*'. The result shows that 'fairly severe' plus 'very severe' totalled over 40 % of the responses when averaged over the full survey period; 9 % of the respondents considered it 'very severe', and there was a higher percentage for those who answered either 'zero to moderate' (40 %), or 'not certain' (19 %). However, there might have been a degree of concern for the managers surveyed about acknowledging that their companies were severely affected by the recession.

Table 4 summarises additional comments made by participants in response to this question. It indicates that the impacts of the recession are inter-related.

5.6 Additional Remarks by the Respondents

The final question was deliberately open-ended. It asked respondents for "*Other comments on likely responses to the downturn in your area of responsibility*." About half of the respondents entered comments, giving insights into the respondents' perceptions of the situation. These comments were one of the most useful parts of the survey, providing a rich picture of the viewpoints, and types of actions that were adopted by the organisations surveyed. Table 5 is a summary of

Table 4 Additional comments on the impact of the economic recession

Impacts of the recession	Typical comments made by the participants
Contracts cancellation	Suppliers significantly reduced the levels of services in order to reduce costs, and clients cancelled contracts
Change in stocks	[Mobile phone supplier:] Less handset renewals and more SIMs only (a change to the stocks)
Payment delays	The payment delays from clients (not in the lack of clients or new business)
Reduced cash flow	Focus on divestment rather than investment; Rebalance of employee effort to maximize cash flow; Vast reduction in infrastructure investment
Higher saving targets	Tight budget challenges: Reduction of service provided; Longer haul times for distribution; The clients' focus on cost savings efficiency
Decrease in income	Subsidies from our parent company reduced by 30 %, and this will mean an up to 10 % less income in some departments
Other impacts	Consolidate warehouses, review networks; Reduction in headcount by 10 % globally; Pressure to work smarter to improve productivity

Table 5 A summary of typical comments from the respondents by category

Category	Typical comments
Cutting cost	• 'The downturn has created greater focus and opportunity to reduce cost' • [We will] 'try to reduce cost as much as possible, cut down capital expenditure, and not replace employees as they resign' • 'Streamlining needs, reducing waste. For example, using electronic documents rather than hard copies' • 'While decreasing the production lead-time, trying to be leaner and more agile in the supply chain, and having reduced stock holding' • 'Though not yet clear, I foresee the future reduction in overall resources available, e.g. [in] some IT systems; and no expansion' • 'Decrease the number of hours to work per week as orders from customers are reduced—bring down the costs and human resources' • 'Increase in use of third party logistics and warehousing, leaner work-in-process inventories and decrease in total stock levels' • 'Logistics and supply chain activities are the major cost drivers—80 % of [our] total costs. Currently major efforts made at identifying means of reducing costs, waste and increase efficiency. Review spending activities, e.g. more analysis into whether or not a project is necessary before the tendering process is started' • A regional warehousing manager from a major high street retailer reported that they had replaced 90-watt light bulbs with 75-watt ones in all its UK food stores. "This not only reduces the energy consumption for lighting by 17 % but also reduces refrigeration and air conditioning needs"
Logistics and business consolidation	• A large UK pharmacy and personal products chain reported that it had been through a major supply chain transformation, resulting in the closure of 18 regional sites and the creation of a state-of-the-art, automated National Distribution Centre near to its headquarters. As a result of the change, reduced capital tie-up had been achieved, as well stock reduction, higher productivity, improved inventory control and significant advances in service levels to the stores • 'We have many distribution centres across the country but due to this crisis, there is a plan to cut down on these centres and link distributors directly from the suppliers while the company manages the links' • 'Consolidate business; keep the business units which are in growth and sell or close the ones that are already affected in the downturn. The economic slowdown will affect severely the company business'

(continued)

Table 5 (continued)

Category	Typical comments
Adaptation and performance improvement	• 'Improve performance in all supply chains, addressing particularly procurement and stock issues' • 'Increase diversity of training, work harder to deepen relationships with suppliers and customers. Be more creative in developing projects' • 'Reviewing contractual and procurement terms' • 'For a service industry [like ours], it is more important to maintain quality instead of making cost-reduction plans' • 'Modify services typically 'sold' to clients. Reducing cost while maintaining existing service levels' • 'Tough times require better information and awareness. Adjust rates to accommodate market fluctuations, faster account clearing for payables, e.g. payment terms changed to 30 days from 45 days' • 'Cutting costs in the traditional manner does not work. Business is already lean. What you have to look at is the total value chain and their interfaces' • 'Leasing; leaner JIT deliveries; better interaction with customers, suppliers, and competitors; slimming product lines' • 'We store and distribute. The orders coming through that need processing have reduced. This means that more products are remaining in storage in our warehouse so we are making more money this way'
Taking business opportunities and the longer term view	• 'Reducing suppliers and carrying on business re-organisation' • 'More logistics facilities are now available in the market which is a good opportunity to negotiate cost cutting. For Euro zone supplies—take advantage of exchange rates' • [From a rail industry executive] 'Economic cycles occur periodically. The rail industry and government must remain strong and take a long term view. We should invest while money is cheap, with good availability of contractor's employees' • 'My company invests during a downturn! This can help put the company in a better position than the competitors during an upturn'

typical comments set out by category, including cutting cost, logistics and supply chain business consolidation, adaptation and improving performance, and taking business opportunities and the longer-term view. Taken together, the above replies illustrate well the wide range of responses taken by companies facing the difficult times, from simple cost-reduction to seeing the economic recession as an opportunity to be capitalised upon.

6 Limitations and Further Research

Like all research, this investigation faced limitations. The main ones include:

Missed survey periods: Due to limited access to respondents, data were not collected during two periods of time: May to July 2009, and December 2009 to March 2010. However, this is not seen as a significant loss.

Three countries: The surveys were limited to the three counties where the researchers had access to logistics and supply chain management personnels in significant numbers and on a face-to-face basis. This level of access was thought essential for the survey to be a realistic reflection of management views, but it is true that had respondents from more countries been surveyed a more valid 'international' view was likely to have been obtained. Thus, the results should be seen as indicative for the countries concerned but not necessarily fully valid across the wider scene.

Changes in cohorts and the people surveyed: This is an important point, and means that the surveys were not truly longitudinal, i.e. as having the same respondents across the survey periods. However, the groups surveyed were cohorts with similar experience and background with regard to the research topic, and so were judged to yield useful responses for comparison purposes.

Evening seminars: Because the logistics and supply chain seminars were held in the evening, some attendees were in a hurry to leave the venue afterwards. The results could might been more meaningful had more time for responses been available.

Numbers of replies: There were a limited number of replies from some cohorts in the final survey round.

Number of large companies: Finally, as noted above, there was an over representation of responses from large companies, though this is considered a plus rather than the opposite in terms of the aim of the survey because of the desire to capture changes of significant impact within the sector.

The limitations discussed above leaves a lot of potential for the researcher to conduct further research in the areas under discussion.

7 Summary and Conclusions

This research examined the decisions taken by logistics and supply chain managers during the recent economic recession with the objective of understanding strategic changes that companies made in response to the changing environment. The findings, not unexpectedly, indicated that the most common response was a reduction in employment. This was reported by over a fifth of companies, while more general 'downsizing' activities (which included reduction in product lines, leaner work-in-process inventories, and decreased stock levels, as well as reduction in employment) made up 60 % of the responses.

With regard to the difference between industries in terms of downsizing, the three main industry sectors covered (i.e. logistics/supply chain and transportation; manufacturing and retailing) reacted more by shedding labour in comparison to the other industries surveyed, whereas, by contrast, the latter grouping reacted more to the downturn by reducing the number of product lines and inventories. In addition, there was a wide range of responses by companies other than downsizing. In terms of adaptation these included tightening of credit terms, increased use of electronic documentation to save on costs, reduced company travel, and similar adaptation activities. Companies also responded to the changed situation by taking more strategic decisions. These included changes in the use of third-party logistics, in warehousing, in re-organisation of their distribution networks (sometimes quite extensively) and in a move to more local suppliers. Some companies used the impetus of the recession in a more positive light, seeing it as an opportunity to get ahead of the competition. As one manager reported: 'My company invests during a downturn! This can help to put the company in a better position than the competitors during an upturn.'

It is hoped that the findings from this study have practical implications and can offer suggestions to companies to help manage their logistics and supply chains more effectively in difficult times. In addition, the results should contribute to a better understanding of how companies' strategies evolve for dealing with significant changes in their external business environment.

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