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A REVIEW OF COORDINATION STUDIES IN THE CONTEXT OF SUPPLY CHAIN DYNAMICS

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ABSTRACT

Supply chain management is a popular research topic in recent years. Among the reported studies, coordination is an important ingredient to improve the performance of supply chains subject to the presence of system dynamics. This paper sets out to review some recent supply chain studies in the last decades that are related to coordination among supply chain members regarding supply chain dynamics. Focus is put on inventory management problems. More than a hundred research papers are reviewed and they are broadly categorised into analytical approaches and simulations approaches. They are further divided into sub-categorises. Observations of each category are summarised in this paper so that characteristics of each of which could be comprehended. In addition, the concluding section reveals some insights that could be considered for future research regarding coordination in supply chains and supply chain systems dynamics.

Keywords: Supply chain management; coordination, analytical approach, simulation approach, system dynamics.

1. INTRODUCTION

Supply chain management (SCM) is not a new topic in production and operations management, despite the fact that its origin is not quite well documented (Chen and Paulraj, 2004). This implies that there is no single origin for the study of SCM. Nevertheless, SCM is a popular topic that has still been researching extensively over the last two decades. Although the definition of supply chain or SCM is not unique, a supply chain can be viewed as a network of organisations that are connected from the ultimate suppliers(s) to the ultimate customer(s). In this connection, coordination, which is the management of dependencies between activities (Malone and Crowston, 1994), among supply chain members plays an imperative role in SCM. It is a means to optimise supply chain activities due to improvements in information flow with the recent advance in information technology in the last decade (Yu *et al.*, 2001; Boyacı and Gallego, 2002; Lewis and Talalayevsky, 2004; Sirias and Mehra, 2005; Li and Liu, 2006). Poor coordination, however, could be easily found in the industry (e.g. De Souza *et al.*, 2000).

On the other hand, system dynamics of industrial systems had also been studied long time ago (e.g. Forrester, 1961), and it has been revisited by some researchers in recent years (e.g. Sterman, 1989; Towill, 1991; Lee *et al.*, 1997; Holweg and Bicheno, 2002, etc.). Among them, Lee *et al.* (1997) conducted a seminal work that analysed, statistically, the effects of demand amplification along a supply chain, which is also the increasing trend in variability in the ordering patterns along the chain towards the suppliers (Dejonckheere *et al.*, 2004). This phenomenon is called the "Bullwhip Effect" (Lee *et al.*, 1997). In an attempt to counteract this phenomenon, many companies, however, increase their buffer inventory, which is known as safety stock. If this is not done in a coordinated manner, the whole supply chain could end up with excessive inventories and holding expensive levels of stock (Riddalls *et al.*, 2000).

System dynamics is in fact an approach for "studying and understanding the evolution and behaviour of real-world systems" (Rabelo *et al.*, 2005). Otto and Kotzab (2003) defined supply chain, from the systems dynamics perspective, as "a chain of consecutive, sequentially interdependent local transaction systems". From this definition, the purpose of SCM is thus to manage trade-offs among supply chain members (Min and Zhou, 2002; Sahin and Robinson, 2002; Otto and Kotzab, 2003; Li and Liu, 2006). If trade-offs exist, coordination may be a means to improve supply chain performance in the sense that in some situations all parties who get involved could gain benefits as a consequent of the compromise through coordination (Sirias and Mehra, 2005). The major objective of supply chain coordination is thus to "devise a mechanism that will induce the retailer to order the right quantity of product and set the right retail price so that the total profit of the supply chain is maximised" (Qi *et al.*, 2004).

In this connection, this paper aims at reviewing related literature with respect to coordination in supply chains and supply chain systems dynamics. The rest of the paper is organised as follows: Section 2 provides a discussion on previous review studies regarding supply chains, and to contrast them with the scope of this study. Criteria for selecting papers for review will be discussed in Section 2 as well. The papers under review were divided into two categories: analytical approaches and simulation approaches, which will be reviewed in Section 3 and Section 4 respectively. At the end of these two sections, a brief summary regarding the observations of the respective category will be presented. Finally, Section 5 provides a concluding remark on the review so that some insights could be gained for future research regarding coordination in supply chains and supply chain systems dynamics.

2. SCOPE OF THIS REVIEW STUDY

2.1 General Review on Supply Chain Studies

Many researchers tried to review supply chain studies and attempted to develop some generic frameworks or research directions for further research (e.g. Harland, 1996; Thomas and Griffin, 1996; Beamon, 1998; Min and Zhou, 2002; Chen and Paulraj, 2004). Thomas and Griffin (1996) conducted a review on traditional mathematical programming for coordinated supply chain. They broadly classified supply chain models to support two planning decisions, namely operational planning and strategic planning. Operational planning model can be further broken down into buyer-vendor coordination, production-distribution coordination, and inventory-distribution coordination. They found that most of the principles behind strategic planning models had been discussed in business related journals (e.g. Simatupang *et al.*, 2002). Finally, they concluded that "independently managing facility can result in poor overall behaviour". They also claimed that there is a deficient in the literature addressing supply chain coordination at an operational level, which is the main area for review in this paper.

With respect to multi-stage supply chain studies, Beamon (1998) reviewed and classified four types of models in the literature, namely, deterministic analytical (all variables are known), stochastic analytical (at least one of the variables is unknown and is assumed to follow a known probability distribution), economic, and simulation. The categorisation in this study is similar to Beamon's study (1998). However, our focus is on those studies concerning supply chains with coordination or system dynamics. Similar to Beamon's approach (1998), Min and Zhou (2002) reviewed integrated supply chains models and classified four types of supply chains, namely, deterministic models, stochastic models, hybrid models (e.g. simulation models that are capable to handle both deterministic and stochastic variables), and IT-driven models (e.g. real-time collaborative planning and forecasting replenishment which aims to integrate and coordinate different phases of supply chain planning so that visibility can be enhanced throughout the supply chain). However, IT-driven models are usually limited to those with specific application software. In addition, Chen and Paulraj (2004) reviewed a wide range of supply chain studies and analysed those studies from two perspectives, namely, critical elements of SCM and supply chain performance. According to their classification, there are four critical elements of SCM, which are strategic purchasing, supply management, logistics management, and supply network coordination. They also reviewed supply chain performance measures in terms of financial and operational perspectives.

Research that analysing decision models for integrated production or distribution planning in supply chains has been done by a number of researchers. One good review were conducted by Erengüç *et al.* (1999) who emphasised the operational aspects of supply chains and noted that most network design models in the literature do not consider operational issues such as lead times in making decisions. They suggested that applying hybrid analytical and simulation models to integrate all the procurement, production and distribution stages of supply chains could be utilised in future research. Riddalls *et al.* (2000) also reviewed various mathematical methods that used to model and analyse supply chains. They concluded that theses models failed to cope with dynamic behaviour of supply chains as a whole because their approaches provide no insight into how system parameters affect the solution. They claimed that "the impact of these solutions on the global behaviour of the whole supply chain can only be assessed using dynamic simulation".

With the advanced development of information technology, information sharing becomes possible in order to make some valuable information become visible among supply chain members so that better decisions (e.g. on ordering, capacity allocation and production planning, etc.) could be made to alleviate the effects of supply chain dynamics (e.g. bullwhip effect). In fact, information sharing is generally regarded as one of the solutions to reduce the bullwhip effect (Lee *et al.*, 1997, Cachon and Fisher, 2000). From another point of view, Sahin and Robinson (2002) reviewed those literature with two dimensions which are information sharing and physical flow coordination at the operational level, with focus on the interfaces between them. They concluded that although both dimensions could be viewed as pre-requisites for integrating supply chain effectively, this may require substantial investment in information technology infrastructure. Huang *et al.* (2003) conducted a review on sharing production information with respect to supply chain dynamics. Based on the review findings, they proposed a reference framework to reflect major elements that commonly involved in this direction of research.

From above summary, simulation seems to be a better technique in analysing the behaviour of dynamic supply chain. Nevertheless, analytical approaches in relation to coordination in supply chains are also invaluable in supply chain studies. Therefore, they will be reviewed as well so that a more complete picture with respect to coordination in supply chains could be delivered in this paper.

2.2 Scope of This Study and Criteria for Review

As reflected from the above review studies in supply chains, the scope of supply chains is really broad (e.g. inventory management, product design, information system, etc.). Although some researchers attempted to formulate a framework for supply chains, it is not surprising that no universally accepted framework for supply chains can be found. One of the reasons is that there are too many articles under review in the above review studies (e.g. over 400 articles in Chen and Paulraj (2004)). Therefore, it may be too ambitious to generalise a unique framework for supply chains. In this connection, this study takes another approach as compared with the above reviews.

First of all, supply chains studies under review in this paper are those highly related to coordination studies with regard to inventory management or materials flow, and the studies may probably subject to supply chain dynamics. Within this scope, uncertainties are usually the main issue to be tackled in the reported research. Secondly, the papers under review in this study are limited to those being published in the last decade, and focus would be put on those being published in the most recent five years, so that a recent trend of related studies, if any, could be observed. As a matter of fact, the scope of this paper usually belongs to one of the sub-topics in the above review studies. However, as mentioned above, their focus had been put on a general supply chain studies, rather than on the topic of this study.

It is a convenient point to define what coordination is. In this study, the definition from Malone (1987), who defined coordination as "the pattern of decision making and communication among a set of actors who perform tasks to achieve goals", is adopted. Obvious, when decision makers have incomplete information, coordination is easily to be failed. Based on these criteria, over 150 research papers had been selected at the early stage, and some of them were then screened out due to their diverse scope of study. The remaining papers (about 100) form the basis in the following review. They are first classified under two broad categories, namely analytical approaches and simulation approaches, according to the methodology being applied to solve the supply chain problem of each study. Then, they are further divided into different groups with respect to the similarities of the studies, as summarised in Section 3 and Section 4.

3. ANALYTICAL APPROACHES

3.1 Introduction

Although traditional analytical models usually deal with deterministic parameters only, there are still some modified versions of them to cope with supply chain dynamics. Taking the study of Escudero *et al.* (1999) as an example, they took uncertainties into consideration in a manufacturing, assembly and distribution supply chain such that they were modelled via a set of scenarios so that optimal solution could be obtained under different scenarios. In other word, non-deterministic parameters became deterministic in a particular scenario. In reality, however, it is not easy to obtain a set of such possible scenarios because uncertainty is something that you cannot predict, and the set of scenarios may be too large. Even if a problem could be modelled through analytical techniques, solution may not be obtained easily and sometimes heuristic is employed to obtain the solution. For example, Lakhal *et al.* (2001) developed a mixed-integer model for optimising supply chain networking decisions with regard to allocate different internal and external resources in a supply chain. However, they still needed to apply a heuristic to obtain a solution of the said problem. They said "mixed integer programming is difficult to solve optimally for realistic problems".

It could be concluded from the above examples that analytical or mathematical modelling approaches, such as linear and integer programming or mixed integer programming, etc., are certainly excellent in understanding well-defined supply chains, which involve few decision variables and restrictive assumptions (Chen and Paulraj, 2004). When more complex settings are involved, like supply chain dynamics with demand and supply uncertainties, this approach may not be satisfactory in providing good results (Riddalls *et al.*, 2000; Van Der Vorst *et al.*, 2000). Therefore, the strength of traditional mathematical modelling techniques, which is to obtain robust optimal solution, may not be easily achieved in solving supply chain problems. However, there is still a rich body of literature that attempted to apply such techniques in coordinated supply chain problems. They will be reviewed in the following sub-sections.

3.2 Control Theoretic Approach

Control Theoretic Approach is a formal approach which views supply chain as an input-output systems, and tries to model supply chain from control theory (mainly with Laplace transform or z-transform). In this school of thought, the transfer function of a system represents the relationship describing the dynamics of the system under consideration (i.e. supply chains in our concerns) by relating its output to its input. Earlier research could be traced back to Towill (1991), or even earlier. Riddalls and Bennett (2002) replicated the MIT beer game from control theoretical perspective. In other words, they attempted to analyse the MIT beer game analytically. For a general review of applications of control theory to production inventory problem, please refer to Ortega and Lin (2004). By adopting control theoretical approach, Disney and Towill (2002) analysed the dynamic behaviour of Vendor Management Inventory (VMI) system. They derived closed form condition to ensure that the VMI system is stable and robust. Subject to different forecasting models for the mean and variance of Normal demand function, Dejonckheere *et al.* (2003) modelled order-up-to inventory replenishment policy from control theoretic approach. An insightful comment was drawn from their study: order-up-to policy will result in variance amplification, i.e. bullwhip effect, for every possible forecasting method.

Like most of the mathematical programming approaches, control theoretical approach could provide conditions for systems to operate stably and robustly. It can also transform some uncertain variables to manageable parameters in the z-domain. However, the reported research from control theoretical perspective does not allow flexibility due to the fact that it is still a sort of analytical approach. Therefore, if the system configuration is changing from time to time, the transfer functions have to be updated accordingly. On one hand this is certainly a drawback of this approach; on the other hand it could be a new direction for future research regarding control theoretical approach if this shortcoming could be managed well.

3.3 Channel Coordination Approach

3.3.1 Discount Policy

In supply chain studies, the relationship between product demand and product price are usually assumed to be linear, i.e. price is not a function of demand or vice versa. However, under the discount policy approach, demand and price are related to each other such that either price is a variable for discount subject to different order quantity, or order quantity is a variable for discount. For example, a supplier may be able to reduce its ordering costs by providing an incentive in the form of price discounts to buyers, provided that the order quantity exceeds a certain amount. In other words, discount policy is in fact a kind of incentive system (Sirias and Mehra, 2005). In this research direction, the optimal solution is found subject to a variety of supply chain settings.

Some reported studies (Viswanathan and Piplani, 2001, Chen *et al.* 2001, Boyacı and Gallego 2002, Klastorin *et al.*, 2002, Mishra, 2004) support the argument that there is little research regarding quantity discount that takes either the demand or the lead-time as a random variable, i.e. stochastic parameters as advocated by Sirias and Mehra (2005). Nevertheless, there are still some researchers who took stochastic variables into consideration. For example, Weng (1999) showed that when a manufacturer and a distributor coordinate together, the order quantity and joint profits would increase and the selling price would decrease. Li and Liu (2006) showed that quantity discount policy is a possible way to achieve coordination so that all parties in the supply chain could be better off by sharing of profit. In another study, Cachon (1999) investigated the effect of demand variability in a supply chain with one supplier, many retailers that face non-deterministic demand. The author advocated that a flexibility in quantity strategy that is able to compensate this problem: to lengthen the ordering interval and to increase the ordering batch size, which forms a flexible quantity strategy, is the most effective way to reduce the supplier's demand variability. Although demand variability is the most commonly considered uncertainty, there are still other types of uncertainties which could be considered. Since most of the coordination schemes as discussed above are static in nature, they are not able to face disruptions. By making use of wholesale quantity discount policy, Qi *et al.* (2004) studied a single-supplier, single-retailer supply chain that is experiencing demand disruptions.

It could be observed that most of the models of the abovementioned studies are two-stage supply chains. On the other hand, Munson and Rosenblatt (2001) considered the quantity discount in a three-tier supply chain with supplier, manufacturer and retailer. Their work provides further evidence for the value of supply chain coordination by extending two-stage study to three-stage study.

3.3.2 Return Policy

A return policy (sometimes known as buyback policy) is a commitment made by a manufacturer, or any upstream supply chain members in general, who accept products from a downstream partner to be returned for some reasons and credit will be given to the downstream partner subject to the agreement. Return policy could encourage a buyer to order more. This could be done because the supplier will share certain risk with the buyer by offering a credit for each of his returned units, be it due to unsold, or whatever reasons (Wang and Benaroch, 2004). In general, there are two kinds of return policies: full return and partial return. The former one refunds full wholesale price for all returned products, while the latter one only refunds a portion of a unit price for the returned products. For example, Lau and Lau (1999) studied return policy of a single-period problem for a monopolistic manufacturer and a retailer. In another study, Yao *et al.* (2005) studied the case that a manufacturer provides a return policy for unsold goods to two competing retailers, who face uncertain demand.

From the reviewed studies, it could be observed that channel coordination is in fact governed by a set of rules such as price or quantity discount between the parties who get involved. However, it could be observed that the studies under review in this section are more static in nature so that the main objective is to, say, find the optimal discount policy which could not be altered in later stage. Therefore, some of them just assume deterministic demand in their models and some of them considered single- or two-period problems for simplicity. In contrast, a flexible supply contract allows the retailer to change her orders dynamically. The next section is dedicated to review related literature with respect to contract approach.

3.4 Contract Approach

In fact, all channel coordination could be shaped as contract approach so that a set of rules for the interactions, such as price or quantity discount, return policies, the common replenished epochs as discussed above, etc., between the different parties who get involved is specified in the contract. On the contrary, contract approach usually permits the retailer to change her orders dynamically in different periods. Giannoccaro and Pontrandolfo (2004) advocated that contracts are a useful tool to make several supply chain members of a decentralised setting "behave coherently among each other". Blomqvist *et al.* (2005) found that, from a case study, a good flexible contract prevents disagreements in asymmetric R&D collaboration. In short, contracting enables joint rules for the collaboration to be established because a contract restricts the participating members to carry out the actions, if they are all coordination oriented in obeying the rules. However, as suggested by Anupindi and Bassok (1998), research on the analysis of supply contracts with commitments when the buyer faces stochastic demands is a relatively new research direction.

3.4.1 Quantity flexibility

In contrast to traditional channel coordination approach, quantity flexibility exists in the form of contract which could be altered once it has been setup. The major rationale of any kind of flexibility of a system is to pick up the most recent information, and then to make adjustments accordingly if needed so that the system could be improved as compared with the situation without such flexibility. Taking supply chains as example, it is impossible to provide accurate forecast subject to unknown demand. No matter how good is the forecasting technique, the forecasted demand is still only an estimation which could deviate from the actual demand. Therefore, if flexibility could be provided in order to alleviate this problem, it is possible that supply chain members could gain benefits from such policy. In a quantity flexibility contract, the buyer usually places an order earlier, or makes a commitment for minimum quantity to be purchased, depending on different settings of a contract and the supplier, in return, provides the buyer with flexibility to adjust the order quantity later, subject to the most updated and accurate demand information (Wang and Tsao, 2006). Tibben-Lembke (2004) found that flexibility becomes more important as demand becomes more uncertain and finally, they concluded that “flexibility in contracts has proven to be a fertile area for research”. Schneeweiss *et al.* (2004) concluded that it is worthwhile to choose the contract parameters in the best possible way by considering, in particular, the specific information situation between the partners of a supply chain.

3.4.2 Real Options

Real options approach is a special case of the above flexibility contracts. For example, Nembhard *et al.* (2005) developed a real-options-based contract with flexibility to select different suppliers, plant locations, and market regions. Although it is commonly believed that flexibility could allow firms to compete more effectively, flexibility is not costless (Nembhard *et al.*, 2005). Along this line of research direction, any adjustment arises from the given flexibility would incur cost. This practice is similar to exercise a financial option. Spinler and Huchzermeier (2006) advocated that such contracts could provide supply chain members with flexibility to respond to uncertain market conditions. Cachon and Lariviere (2001) developed an option contract and concluded that “supply chain should maintain the flexibility to defer the final production decision until after the manufacturer observes demand”.

3.4.3 Revenue Sharing

Revenue sharing is another form of contract approach in order to achieve coordinated planning. Usually, the overall “extra” revenue obtained from the contract is shared among the parties who get involved, as governed by the contract. By conducting a series of numerical studies in a two-stage single buyer single supplier chemical supply chain, Corbett and DeCroix (2001) showed that such contracts could be able to increase supply-chain profits, but not necessarily lead to reduction in the consumption of indirect materials involved. They also concluded that the goals of maximizing joint profits and minimizing consumption are generally not aligned. Cachon and Lariviere (2005) demonstrated that a revenue sharing contract could coordinate a supply chain with a single retailer situation and could allocate the supply chain's profit. However, they also identified the most critical limitation of using revenue sharing contract: the supplier must monitor the retailer's revenues to verify that they are shared accordingly.

3.4.4 Miscellaneous

There are also other forms of contract that could not be classified under above categories because their scopes are too diversified. For example, Cheung and Leung (2000) studied a coordinated joint replenishment scheme between a supplier and buyer with two product types. The buyer will impose quality control procedures to decide if a lot of product received should be accepted, or rejected with corrective action. By coordinating the order quantity of both items, it was found that cost saving could be achieved because an optimal sample plan could be derived under the coordinated model. Chen and Xu (2001) studied the coordination of a manufacturer and a retailer in a supply chain for single-period products by a two-stage ordering and production system. The initial time of the first ordering and production remains unchanged as in the traditional single-stage ordering system counterpart. However, the retailer is allowed to reorder later in order to let the retailer to collect more information to reduce forecast error. Result showed that the manufacturer may not be better off or well off, although the retailer's performance is improved. They suggested that some profit compensation plans (i.e. revenue sharing as discussed above) should be incorporated so as to make both parties could be better off. Zimmer (2002) developed a coordination mechanism that allocates the cost of a two-stage supply chain through bonus and penalty cost. Zimmer (2002) found that the coordinated system could perform as well as a centralised counterpart. In a two-stage supply chain, Wang *et al.* (2004) employed continuous incentive contracts, which is a profit-sharing-based contract instead of quantity discount contract, and analysed the behaviour of the supply chain. Subject to normal demand, they tested their model through a numerical study and found that the costs of supplier, retailer, and the system could be reduced as compared with the case without coordination.

3.5 Information Sharing Approach

Information sharing is regarded as a tool to reduce the effect of bullwhip effects (Lee *et al.*, 1997, Cachon and Fisher, 2000). Information technology is certainly an enabler for supply chain members to share information quickly, accurately and inexpensively (but not at zero cost). Therefore, information exchange among supply chain members could certainly facilitate the coordination of supply chain activities. Since the scope of information sharing is also quite broad, the review in this section focuses on information sharing only in the context of coordination studies (recall that they are the two different dimensions as reviewed by Sahin and Robinson (2002)), in order to match with the overall scope of this paper. In other words, the literature that only investigated the values or benefits of information sharing will be excluded (e.g. Chen *et al.*, 2000, Cachon and Fisher, 2000, etc.), despite the fact that even information sharing alone is highly related to coordinating supply chains. For example, Chen (1999) developed a model to find the optimal policy subject to delay in material and information flows. Yu *et al.* (2001) showed that how the supply chain members could form a partnership in order to achieve a pareto improvement by sharing demand information. Karaesmen *et al.* (2002) investigated when demand information should be released in order to coordinate production planning in a make-to-stock production system. For a general review of the impacts of sharing production information with respect to supply chain dynamics, please refer to Sahin and Robinson (2002) and Huang *et al.* (2003).

3.6 Market Economics Approach

This approach based on microeconomics' view of market which consists of independent buyers and sellers in a perfect competitive market environment (Kaihara, 2003). The interaction between price, demand and production of a product in order to maximise a firm's expected profit is studied. Although this is not a dominating research direction in SCM from the operations management perspective, there are still a number of reported research in this area. To name a few, Ugarte and Oren (2000) studied a coordination mechanism regarding production and allocation decisions of a two-stage supply chain from market economics perspective with private information. They showed that decentralisation is less efficient than centralisation if private information affects operational decisions. Kaihara (2003) analysed supply chain in economic terms. Both studies aimed at finding the Pareto optimal solution of the market economics based supply chains. This is the equilibrium solution of the system so that resources are allocated in the most efficient manner. Babaioff and Walsh (2005) developed a negotiation mechanism to coordinate the buying and selling of goods across a supply chain, based on incentive auctions to encourage supply chain members to report their private information truthfully.

3.7 Observations

Above reviews summarised some recent development which employed analytical approaches to study the impacts of coordination in supply chains. This section serves to investigate and to summarise the characteristics of the quoted literature in this respect. Major attributes of the above papers are summarised in Table 1. It is not our intention to criticise the approaches being employed in these papers. The objective is to observe the current research pattern which may be helpful for researchers to conduct further research in this area.

From Table 1, it could be easily observed that most papers concern dyadic supply chain, probably due to the simplicity of this structure in analytical analysis. It is logical to ask whether future research in this domain could extend the dyadic structure for analysis or not. Secondly, demand uncertainty is still the most frequently quoted parameter accounted for system dynamics. In this connection, it is insightful to include, if possible, more stochastic variables (like suppliers' capacity) in the analysis, although it may be difficult in various mathematical approaches. As a matter of fact, other types of uncertainty may also present in any supply chains. For example, uncertainty is inherent in the market at supply side (e.g. delivered from an external supplier may differ from those requested) (Petrovic *et al.*, 1998). It is desired to consider both supply and demand uncertainty into consideration.

However, the main drawback of these studies is on the inflexible coordination mechanism (that's why some studies consider only single- or two-period problem). The major objective of these studies is still to derive an optimal solution (in terms of expected value if uncertainties are involved) subject to the distribution of the stochastic variables. Even though some studies consider system dynamics, the impacts of uncertainty has not been studied. It is desired that some flexible coordination mechanism, which will be taking the most updated situation into consideration, could be developed. Finally, one may observe from Table 1 that some papers did not take uncertainty into considerations. As discussed before, a major weakness of some analytical approaches is that it is not easy to model such uncertainty mathematically. To be fair, coordination among supply chain members does not imply the presence of uncertainty. However, it is certainly worth considering the effect of coordination subject to uncertain environment. It is interesting to note that analytical approaches could not be employed to find the absolute optimal solution, because uncertainties are always unpredictable. In other words, future events could not be forecasted without error. However, the above studies could find the optimal value in expected values, like expected cost, when the system subject to a certain probabilistic distribution.

4. SIMULATION APPROACHES

With advanced development in computing technology in the last few decades, simulation has become a very important tool to analyse complicated problems. It is a highly flexible tool that can be used effectively for analyzing complex systems, like supply chains, and enables us to model such systems in details (Van Der Vorst *et al.*, 2000; Jansen *et al.* 2001). One of the advantages of simulation is the ability to study hypothetical models as close to the real situations as possible (Sirias and Mehra, 2005). Parameters in simulation programs, i.e. dependent variables or systems' parameters, could be varied easily so that analysis of different combinations of the systems under study is affordable, and hence the cost to make decision could be reduced, and response to such modifications could be obtained very fast (Manzini *et al.*, 2005). Unlike traditional mathematical optimisation techniques, results in intermediate stages could be captured during simulation process so that system dynamics could be analysed in different perspectives. In this connection, it is not surprising that simulation has been widely utilised in supply chain studies with respect to systems dynamics. For example, Hung *et al.* (2006) presented a simulation study of a supply chain in which inventory replenishment systems and production planning had been modelled. They tested their model in a two-product divergent supply chain with uncertain demand, which was modelled by Normal distribution. The simulation model was built based on object-oriented approach for studying the dynamic behaviour of supply chain. In fact, object-oriented approach is highly related to the multi-agent approach, which will be discussed in the later section. One benefit of using such approach is that user can easily modify the simulation model to reflect changes in the supply chain.

Simulation is not only applicable to new system design. Manzini *et al.* (2005) made use of simulation to study five industrial cases in different sectors, but all are concerning material flows within the supply chain, in order to demonstrate how simulation could be employed to improve existing systems. Rabelo *et al.* (2005) employed simulation to evaluate system dynamics of a semiconductor enterprise. Their study demonstrated that how simulation could help top management to select the most appropriate options from various production decisions. As discussed previously, the scope of the papers under review is related to coordination or system dynamics in supply chains. For a general review of supply chain simulation study, please refer to Terzi and Cavalieri (2004). For a general review of simulation optimisation, please refer to Tekin and Sabuncuoglu (2004).

4.1 General Simulation Studies

By making use of controlled partial shipment in a two-stage supply chain, Banerjee *et al.* (2001) conducted a series of simulation runs to prove that such scheme could improve customer service at the retail level. Also in a two-stage supply chain, Banerjee *et al.* (2003) studied the effects of lateral (i.e. intra-echelon) shipments through simulation. Inventory replenishment decisions were made based on a coordinated common review period. Based on order-up-to policy, Ng *et al.* (2001) studied two coordinated inventory models with alternative supply possibilities between two suppliers and two retailers. They found that higher level of coordination leads to significant savings in the average total cost of supply chain. In another study, Jansen *et al.* (2001) analysed the performance of several scenarios in a multi-compartment distribution system in order to satisfy customer demands for shorter lead times. This study illustrates an advantage of simulation – the ability to analyse different configurations and to record different performance measures easily.

By considering different supply chain configurations, Garavelli *et al.* (2003) investigated the effects of flexibility in supply chain configurations. Heuristics had been developed for product assignment and the authors found that even limited flexibility could provide better performance than the case with full flexibility. Zhao *et al.* (2002) analysed the effect of forecasting model, and employed early order commitment as a coordination method in a decentralised supply chain with a capacitated manufacturer and retailers under demand uncertainty. Simulation results showed that the manufacturer would gain the maximum benefit when retailers made early order commitments. On the other hand, selection of forecasting models is less important than selection of early order commitment in determining the benefits for the supply chain members.

Facing uncertain environment, it is logical to change a decision by adapting real time information after it has been realised. Pontrandolfo *et al.* (2002) developed a reinforcement learning approach to coordinate different supply chain members for decision making in global SCM. The performance of an action in a state is used to update the knowledge base until the system encounters another decision-making state. Their study showed another distinctive feature of simulation which allows iteration of some flexible algorithms. Regarding flexibility, Ferdows and Carabetta (2006) conducted a study to evaluate the impact of flexibility on inter-factory supply chain with uncertain demand. They found that flexibility in the inter-factory linkages can reduce the impact of this perturbation substantially.

As discussed in Section 3, most analytical approaches focus on two-stage supply chain. On the contrary, simulation may be employed to study multi-stage supply chains. For example, Beamon and Chen (2001) simulated a four-stage supply chain and then attempted to find out, statistically, the relationship among a number of independent variables with a number of performance measures. Also discussed in Section 3, contracting is a useful approach to achieve coordination. However, cancellation of contracts may be beneficial to supply chain members as well. Xu (2005) investigated how the supplier could choose cancellation costs that minimise her expected cost during the planning horizon. With the aids of simulation, Sirias and Mehra (2005) compared two incentive systems: quantity and lead time-dependent discounts in a two distributors and single supplier supply chain. They found that, not surprisingly, both discount policies could improve the performance of the whole supply chain.

4.2 MIT Beer Game

As discussed in the beginning of this paper, the most famous simulation study in this respect originates from Forrester's study in Industrial Dynamics (1961). Another seminal work was conducted by Sterman (1989), which is now known as "MIT beer game". These studies showed that there is a possibility that small fluctuation in end-customer demand will be amplified along a supply chain so that excessive inventory may be held in upstream members. As discussed before, Lee *et al.* (1997) coined this phenomenon as the bullwhip effect. By introducing the "time compression" concept, Mason-Jones and Towill (1997) found that stock levels could be reduced in the beer game. This could be done by transferring demand information as quickly as possible along the chain through the use of information technology. Owens and Levary (2002) supported the argument of Mason-Jones Towill (1997) by conducting another study of a food supply chain. These studies are highly related to information sharing, which will be discussed in Section 4.3.

By adopting the beer game approach, De Souza *et al.* (2000) analysed the performance of coordination by synchronising the inventory and work in process levels of each supply chain player under centralised and decentralised configurations. In a later study, Hieber and Hartel (2003) revisited the beer game and investigated the impacts of different ordering strategies on the system. They found that regardless of the ordering strategies, the last member of the chain will bear the greatest cost. By employing agent-based simulation approach, Kimbrough *et al.* (2002) proved that agent simulation could reproduce the Bullwhip Effect. They also concluded that agents do better than humans when playing the "MIT Beer Game" by using genetic algorithm to capture real world information. The major contribution of their paper is to demonstrate that agent-based modelling is able to mimic supply chain dynamics. More on agent-based studies will be presented later.

4.3 Information Sharing

With advanced information technology, information could be more visible than a decade before (Chan and Chan, 2009). Benefits of information sharing have been discussed in previous section. Undoubtedly, simulation is an effective tool for analysing the effects of information sharing. This is because some of the reported contributions could not be quantified analytically in nature. In this connection, simulation plays a vital role in this line of research. For example, Van Donselaar *et al.* (2001) analysed how to utilise advanced uncertain demand information reduce inventory level in a multi-period simulation study. In a divergent supply chain with a capacitated supplier, Zhao *et al*. (2002) and Zhao and Xie (2002) conducted simulation studies to show how forecasting models could affect the value of sharing information of the supply chain subject to uncertain demand. Reddy and Rajendran (2005) developed a heuristic approach to find out the dynamic order-up-to level, subject to different levels of information sharing.

Visibility in inventory information, or inventory accuracy in another sense, could improve supply chain performance in terms of reducing the chance of stock out or cost. Fleisch and Tellkamp (2005) simulated a three-stage supply chain with single product by aligning physical inventory information of the supply chain members. Fleisch and Tellkamp (2005) identified three factors, which are theft, unsaleables, and process quality, in their simulation model. They found that elimination of inventory inaccuracy by periodic inventory information alignment could reduce supply chain costs as well as the out-of-stock level. Apart from sharing inventory information, Yee

(2005) analysed the impact of sharing demand mix information on various supply chain performance indicators, subject to both demand and capacity uncertainty.

4.4 Multi-Agent Simulation

Multi-agent systems, a branch of distributed artificial intelligence, consist of more than one agent, which is defined as a “computer system, situated in some environment, that is capable of flexible autonomous action in order to meet its design objectives” (Jennings *et al.* 1998). This is a relatively new yet popular technique in analysing supply chain dynamics (e.g. Brandolese *et al.*, 2000; Sadeh *et al.*, 2001; Lin *et al.*, 2002). In supply chain, each supply chain member could be represented as an agent and hence a group of enterprises form a multi-agent system (Lau *et al.*, 2004). Kaihara (2001) stated that it is natural to model supply chains through multi-agent approach. One of the rationales behind using multi-agent system approach to model supply chains is that multi-agent system provides a communication platform for information exchange through coordination or negotiation protocol. For example, Swaminathan *et al.* (1998) developed a modelling framework using multi-agent systems for simulating dynamics supply chain. The model consists of a reusable software library which contains functional agents (such as plants, suppliers, etc.), control agents (like inventory management or demand planning), and their interaction protocols (like message types). Lin and Shaw (1998) proposed a multi-agent information approach for modelling the order fulfilment process in supply chains, and discussed how the model could apply to three different demand strategies (make to order, make to stock, assemble to order) under different configurations. In a supply chain with uncertain demand, Brandolese *et al.* (2000) showed that supply chain members are able to coordinate with each other through a pre-defined communication protocol to bid for extra capacity in the production system. Sadeh *et al.* (2001) presented an agent-based architecture for dynamic supply chain called MASCOT (Multi-Agent Supply Chain cOordination Tool). MASCOT is a re-configurable, multi-level, agent-based architecture for coordinated supply chain. Agents in MASCOT serve as wrappers for planning and scheduling modules. By modelling a supply chain network with agent-based approach, Gjerdrum *et al.* (2001) simulated how the agent system could determine the inventory control policy in order to reduce the operating cost of the system while a high level of customer order fulfilment could be maintained. In another study, Umeda and Zhang (2006) developed an agent-based simulation model to study three different operation models (reorder-point, centralised, and pull). A negotiation (or coordination) protocol was developed in finding next order volumes between operational managers and parts suppliers of the distributed supply chain. Readers can refer to Lee and Kim’s review (2008) for a general review of applications of multi-agent systems in manufacturing and supply chain applications.

4.5 Fuzzy Logic

Apart from using probability distribution to model stochastic variables, fuzzy logic is an alternative and is a useful tool to handle variables with imprecise information. There variables in supply chain could be described by vague linguistic language, and be modelled by fuzzy membership functions (Petrovic *et al.*, 1998; Grabot *et al.*, 2005). Taking demand as an example, it could be described as “demand is *high* in this week”. For example, Petrovic *et al.* (1998, 1999) made use of fuzzy logic to interpret and represent vague and imprecise information in a serial supply chain with unlimited production capacity, while the objective was to determine the stock levels and order quantities for each inventory locations at the lowest cost. System dynamics was analysed with respect to uncertain demand and uncertain supply, which were expressed in linguistic phrase. In their simulation studies, supply chain members were coordinated by sharing inventory information with adjacent members. Hu *et al.* (2001) developed a fuzzy logic based bid calculation model to determine the set of product quantity that will be stored to inventory. Hojati (2004) investigated how fuzzy logic could be employed to model non-deterministic parameters in traditional EOQ-based model, and a probabilistic-based EOQ model. Grabot *et al.* (2005) modelled the uncertainty and imprecision of the demand by fuzzy membership function before they are allowed to pass through each step of the material requirement planning cycle.

4.6 Observations

From the preceding review on simulation studies, it could be observed that majority of them, unlike analytical approach, are multi-period in nature and more performance indicators could be recorded for discussion. This is due to the capability of simulation study which can capture a variety of data during the course of simulation study, and could be employed to analyse iterative algorithm. Some other attributes are summarised in Table 2.

Regarding supply chain structures, Table 2 reveals that dyadic structure is not the most dominating structure being employed under most simulation studies. In other words, the attribute is more diversified as compared with the cases in analytical approaches. This observation is also a direct consequent of the benefits of simulation study that more complicated model could be coded and the computational time is reducing while computing power is improving over the years. Therefore, network model is more feasible in simulation study.

Nevertheless, demand uncertainty is still the major source regarding system dynamics. It could be beneficial to include more than one aspect of uncertainty into considerations as discussed in Section 3.7. However, this is not the only drawback regarding uncertainties. Most of the simulation studies only modelled them by a certain kind of probability distributions. There is a lack of study on varying the uncertainty level in order to get some insights on the impacts of them on various proposed methodologies.

In addition, probability distributions other than Normal distribution (e.g. exponential) are employed in some simulation studies to model some stochastic variables. This is a good practice and is encouraging to conduct such sensitivity analysis. Nevertheless, it is relatively easier to change the probability function of a particular parameter in a simulation study than in an analytical study. This could result in more robust simulation results, which can compensate the deficiency of simulation studies in terms of their ability to produce robust analytical solutions.

5. CONCLUDING REMARKS

This paper aims at reviewing recent literature regarding coordination and system dynamics in supply chains. Section 3 and Section 4 provide a summary of the studies under two categories: analytical approach and simulation approach, respectively. Attributes of each category had been presented at the end of each section. Although both approaches are equally popular in solving supply chain coordination problems, there are some more interesting observations that could be shared as below. Table 3 summarises some key different aspects regarding the two approaches in this field of study. Some of them are elaborated in the subsequent sections.

5.1 Analytical Approach or Simulation Approach?

The main contrast between analytical models and simulation models is that the latter normally do not aim at optimising the problems under study. Instead, behaviour of the supply chains under study is the main focal point for investigation. In addition, simulation studies tend to include more performance indicators for discussion. This is certainly a benefit as a result of the simulation capability. However, this is also the weakness of simulation study that a robust optimal solution could not be guaranteed. In other words, simulation studies are more focusing on whether the developed algorithm could deliver a good result (rather than the optimal result), and the trend of the simulation results. It is quite unfair to say this is the shortcoming of simulation study, but, as a matter of fact, this is a limitation of simulation study. However, if the focus of a study is put on system dynamics, and stochastic variables are presented so that the optimal solution seems non-existent. Under this situation, it is straight forward to consider simulation study as a promising tool in relation to such study.

In this review, the number of simulation studies under review is slightly less than that number of analytical studies under review. It could be concluded that even though simulation is useful in many facets of supply chain studies, analytical approaches are still a widely accepted tool, especially for well-defined problems. It is not the intention of this study to judge which approach is the best methodology in supply chain research. From the attributes of the two sections, it could be concluded that they attract different pools of study and could be complementary to each other. Insights or algorithms observed in analytical studies could be modified as more sophisticated, and / or iterative, and / or even interactive algorithms to be studied by simulation. When system dynamics is the main concern, however, it seems that simulation could be more powerful in analysing the problem subject to different sources of uncertainties.

One important issue is noticed in the reported simulation studies, it is not uncommon that output analysis is omitted. Some of the reported literature only report the trend of the simulation results and this is, to a certain extent, inadequate. Simulation output data by employing statistical techniques (like paired-t test for testing the output of two or more different systems, subject to the same conditions) could be imperative in analysing, interpreting, and using the simulation results (Law and Kelton, 1991). Law and Kelton (1991) also advocated that some variance-reduction techniques should be considered to reduce the variances of the output random variables of interest, which is overlooked in some simulation studies.

5.2 Flexibility in Coordination

In fact, there is a drawback which could be observed from the review. Most of the proposed methodologies do not take flexibility in the coordination methodologies into considerations while system dynamics presents. Although some authors have attempted to add flexibility into their study (e.g. Tsay (1999) for quantity flexibility, Barnes-Shuster *et al.* (2002) for real options, Cachon and Lariviere (2005) for revenue sharing, etc.), they are restricted to single- or two-period problems. It is believed that flexibility in general provides a competitive advantage to firms, and allows them to compete more effectively when demand and / or price are uncertain (Nembhard *et al.*

2005). If production is inflexible such that production quantities are varied frequently, significant costs will be incurred and this will degrade any inventory policies (Dejonckheere *et al.*, 2004). In addition, flexibility seems decoupled from information sharing and adaptability characteristic. Interaction of them could be a new research direction in the future, especially if simulation approach is adopted (e.g. Chan and Chan, 2009).

5.3 Uncertainties

As discussed at the end of Section 4, there is a lack of study on varying the uncertainty level in order to gain insights on the impacts of such stochastic variables. This is also a focus of system dynamics, especially if simulation is adopted as the optimal solution could not be found. No matter how good a coordination mechanism could be developed, if it is only useful under certain situations, effort is required to further refine the model subject to different level of uncertainties.

Unsurprisingly, Normal distribution is popular choice for modelling stochastic variables (e.g. demand), which is still the main stream of research pattern. Apart from its simplicity, researchers have conducted some sensitivity analysis on using normal distribution to represent stochastic demand and concluded that this is a robust approximation (Tyworth and O'Neil, 1997). If fact, the Central Limit Theorem is widely quoted as a proof in approximating stochastic parameter by Normal distribution (Dekker *et al.*, 2000; Brandolese, *et al.*, 2001; Chou *et al.*, 2001; Chen and Lin, 2002; Kim *et al.*, 2003). Therefore, using Normal approximation is still a reasonable approach to modelling stochastic variables. However, as discussed above, sensitivity analysis could be carried out on different levels of uncertainties.

5.4 Research Gap

By reviewing the two observations (Section 3.7 and Section 4.6) and Table 1, the authors found that related research are polarised into two extremes. Nowadays supply chain practitioners are competing in a turbulent environment in which flexibility and fast response is a pre-requisite for survival. They witnessed the increasing complexity of coordination problems in supply chains. Although analytical approaches could provide us with a robust and closed form mathematical solution, there is a need to fill the research gap by studying agile (with flexibility) and networked supply chains. The authors advocate research with mixed-mode study in gaining the benefits from both approaches. That is, to develop an analytical based simulation modelling so that a robust analytical solution, with the ability to response to changes fast. In so doing, a proper sensitivity analysis has to be carried out in order to maintain a high level of robustness of the study.

To conclude, this is not an exhaustive review regarding SCM ss addressed in the beginning of this paper. The focus is put on coordination and system dynamics of supply chains. Nevertheless, the authors hope that readers of this study could gain insights from this paper in carrying out their research in the related areas in the future, especially when they are struggling in selecting a proper methodology for solving their problems.

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Table 1. Attributes of analytical studies under review

Approaches		Attributes	Uncertainty		Distribution				Structure			
			U1	U2	D1	D2	D3	D4	S1	S2	S3	S4
Control Theoretic		Dejonckheere *et al.* (2003)	√		√				√			
		Dejonckheere *et al.* (2004)	√		√				√			
		Disney and Towill (2002)	√		√					√		
		Riddalls and Bennett (2002)	√			√				√		
		Sourirajan *et al.* (2008)	√	√	√					√		
Channel Coordination	*Discount Policy*	Boyacı and Gallego (2002)									√	
		Cachon (1999)	√		√			√			√	
		Chen *et al.* (2001)									√	
		Karabatı and Sayın (2008)									√	
		Klastorin *et al.* (2002)	√				√				√	
		Li and Liu (2006)	√		√					√		
		Mishra (2004)									√	
		Munson and Rosenblatt (2001)							√			
		Qi *et al.* (2004)	√					√		√		
		Shin and Benton (2007)	√		√					√		
		Viswanathan and Piplani (2001)									√	
		Weng (1999)	√			√						
	Return Policy	Lau and Lau (1999)	√		√					√		
		Lau *et al.* (2000)	√		√					√		
		Lee and Rhee (2007)	√			√				√		
		Wang and Benaroch (2004)	√				√			√		
		Yao *et al.* (2005)	√		√						√	
Contract Approach	*Quantity Flexibility*	Anupindi and Bassok (1998)	√		√					√		
		Bassok and Anupindi (1997)	√		√					√		
		Jung *et al.* (2008)								√		
		Schneeweiss *et al.* (2004)	√				√			√		
		Tibben-Lembke (2004)	√		√					√		
		Tsay (1999)	√		√					√		
	Real Options	Barnes-Shuster *et al.* (2002)	√		√					√		
		Cachon and Lariviere (2001)	√			√				√		
		Lee and Kumara (2007)										√
		Nembhard *et al.* (2005)		√		√						√
		Spinler and Huchzermeier (2006)	√		√					√		
		Wang and Tsao (2006)	√				√			√		
	Revenue Sharing	Cachon and Lariviere (2005)	√				√			√		
		Chiou *et al.* (2007)									√	
		Corbett and DeCroix (2001)	√					√		√		
		Giannoccaro and Pontrandolfo (2004)	√		√				√			
		Jaber and Goyal (2008)										√
		Zhang *et al.* (2008)	√		√					√		
	Others	Chen and Xu (2001)	√		√					√		
		Chen and Liu (2008)									√	
		Cheung and Leung (2000)	√					√		√		
		Mathur and Shah (2007)	√				√			√		
		Wang *et al.* (2004)	√		√						√	
		Zimmer (2002)								√		
Information Sharing		Chen (1999)	√			√			√			
		Karaesmen *et al.* (2002)	√			√				√		
		Lee (2001)	√			√				√		
		Weng and McClurg (2003)	√				√			√		
		Yu *et al.* (2001)	√		√					√		
Market Economics Approach		Babaioff and Walsh (2005)		√				√				√
		Kaihara (2003)										√
		Ugarte and Oren (2000)	√			√					√	

Notes:
1. "U1" is marked if demand is the only uncertainty; "U2" is marked if there is uncertainty other than demand, unmarked if no uncertainty exists, i.e. all parameters are all deterministic;

2. “D1” is marked if uncertainty is modelled by Normal distribution, “D2” is marked if uncertainty is modelled by non-specified Stochastic distribution, “D3” is marked if the uncertainty is modelled by uniform distribution, “D4” is marked if uncertainty is modelled by other distributions, unmarked if no uncertainty exists;
3. “S1” is marked if the supply chain structure is serial, “S2” is marked if the supply chain structure is dyadic (i.e. one to one), “S3” is marked if the supply chain structure is divergent (one supplier to many retailers), “S4” is marked if the supply chain structure is network.

Table 2. Attributes of simulation studies under review

Approaches	Attributes	Uncertainty		Distribution				Structure			
		U1	U2	D1	D2	D3	D4	S1	S2	S3	S4
General Studies	Banerjee *et al.* (2001)	√		√						√	
	Banerjee *et al.* (2003)	√				√				√	
	Beamon and Chen (2001)	√	√				√				√
	Ferdows and Carabetta (2006)	√		√							√
	Garavelli *et al.* (2003)	√					√				√
	Hung *et al.* (2006)	√		√						√	
	Jansen *et al.* (2001)	√					√		√		
	Ng *et al.* (2001)		√				√				√
	Pontrandolfo *et al.* (2002)	√		√							√
	Rabelo *et al.* (2005)	√					√	√			
	Rabelo *et al.* (2008)	√	√				√				√
	Sirias and Mehra (2005)	√		√						√	
	Van Der Vorst *et al.* (2000)	√					√			√	
	Xu (2005)	√		√					√		
	Zhao *et al.* (2001)	√		√						√	
MIT Beer Game	De Souza *et al.* (2000)	√					√	√			
	Helo (2000)	√		√				√			
	Hieber and Hartel (2003)	√		√				√			
	Holweg and Bicheno (2002)	√					√	√			
	Kimbrough *et al.* (2002)	√	√	√			√	√			
	Li *et al.* (2005)	√		√				√			
	Mason-Jones and Towill (1997)	√					√	√			
	Owens and Levary (2002)	√					√	√			
Information Sharing	Chiang and Feng (2007)	√	√	√						√	
	Elofson and Robinson (2007)	√	√	√							√
	Fleisch and Tellkamp (2005)	√	√	√				√			
	Reddy and Rajendran (2005)	√		√				√			
	Van Donselaar *et al.* (2001)	√					√		√		
	Yee (2005)	√	√	√							√
	Zhao and Xie (2002)	√		√						√	
	Zhao *et al.* (2002)	√		√						√	
Multi-Agent Simulation	Allwood and Lee (2005)	√					√	√			
	Brandolese *et al.* (2000)	√					√				√
	Chan and Chan (2009)	√	√	√							√
	Gjerdrum *et al.* (2001)	√		√							√
	Lau *et al.* (2004)	√		√						√	
	Lin *et al.* (2002)	√					√				√
	Sadeh *et al.* (2001)										√
	Umeda and Zhang (2006)	√		√							√
Fuzzy Logic	Hojati (2004)		√				√		√		
	Hu *et al.* (2001)	√					√				√
	Grabot *et al.* (2005)	√					√	√			
	Petrovic *et al.* (1998)	√	√				√	√			
	Petrovic *et al.* (1999)	√	√				√	√			
	Yazgı Tütüncü *et al.* (2008)	√					√		√		

Notes:

1. “U1” is marked if demand is the only uncertainty; “U2” is marked if there is uncertainty other than demand, unmarked if no uncertainty exists, i.e. all parameters are all deterministic;
2. “D1” is marked if uncertainty is modelled by Normal distribution, “D2” is marked if uncertainty is modelled by non-specified Stochastic distribution, “D3” is marked if the uncertainty is modelled by uniform distribution, “D4” is marked if uncertainty is modelled by other distributions, unmarked if no uncertainty exists;
3. “S1” is marked if the supply chain structure is serial, “S2” is marked if the supply chain structure is dyadic (i.e. one to one), “S3” is marked if the supply chain structure is divergent (one supplier to many retailers), “S4” is marked if the supply chain structure is network.

Table 3. Key Differences between Analytic Approach and Simulation Approach in Coordination Studies

Key Aspects	Analytic Studies	Simulation Studies
Main objective	To find the optimal solution	To study the supply chain behaviour
Coordination Algorithm	Statics	Dynamic and iterative
Supply chain structure	Dyadic in most cases	Network
Parameters and Decision Variables	Deterministic in most cases	Can be uncertain
Time span of study	Single period in most cases	Multi-period
Flexibility attribute	Limited	Enabled
Performance indicators	Limited (single in most cases)	Multiple