Improving the understanding of supply chain dynamics: Towards an intelligent simulation tool

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Abstract
This paper introduces an intelligent simulation tool that aims to improve our understanding of the dynamics of supply chain operation. The proposed added value of this tool lies in the explanation of simulation results, the support of knowledge propagation across the supply chain and the capture of supply chain communication, all of which are facilitated by using Artificial Intelligence techniques. The conceptualisation framework for modelling a supply chain, and the tool's scope and behaviour are discussed.

Keywords: supply chain modelling, supply chain simulation

Introduction
In the Knowledge Society and the Digital Economy era, Supply Chain Management (SCM) is increasingly important for gaining and sustaining a competitive advantage. It has been argued that "SCM consciousness is accelerating up the corporate agenda" (Storey et al., 2006, p. 757) and there is a shift towards Supply Chain (SC) integration (Lee and Whang, 2004). However, organisations adopt SC orientation in a limited way, and supply chains often fail to behave as one entity (Holweg and Pil, 2008). This is mainly due to the difficulty to understand the complex nature and the dynamics of SCM, and especially SC coordination (Choi et al., 2001). Moreover, we are now experiencing SC- rather than enterprise-based competition (Harrison and van Hoek, 2008; Lambert and Cooper, 2000). Hence, there is a need for assessing overall SC performance and comparing the performance of competing supply chains.

Simulation is a widely accepted method for providing an insight into the causes and effects of SC performance and assisting SCM decision-making through what-if analysis. It has been argued, however, that there is a scarcity of analytical tools that exploit the benefits of integrated SCM (Min and Zhou, 2002). Most existing SC simulation solutions do not explain simulation results (i.e. answer the why-question) and they do not support knowledge propagation. The effect of communication delays or failures on SC performance is also neglected.

With the aim of filling this gap and supporting a better understanding of the SCM domain and dynamics, a knowledge-based approach for SC modelling and simulation is suggested in this paper. The development of an intelligent simulation tool is, thus, proposed, which is envisaged to answer questions such as: What is the impact of the change of a supplier's sourcing policy on overall SC performance? Why is there a delay on order delivery at day 4? Could the current SC configuration support the manufacturer's shift to a build-to-order strategy?

The remainder of the paper is structured as follows: First, we provide background information to SCM and present existing SC simulation tools, highlighting relevant gaps. Second, the research hypothesis and objectives are described. Third, a three-phased methodology for the research is introduced, and details of the theoretical framework for the tool's conceptualisation are presented, along with the tool's scope and expected behaviour. Finally, we discuss expected results and theoretical and practical implications for the Operations Management community.

Background

A Supply Chain is defined as "all parties involved, directly or indirectly, in fulfilling a customer request" (Chopra and Meindl 2003, p. 4). The current view of the supply chain as the unit of competition emphasises the importance of managing supply chains in an effective way. In this environment, the urge for *SC integration* is becoming prominent. Organisations are now beginning to realise that a systemic and holistic view of their supply chains can benefit their individual performance. This means that the supply chain should have common mission, goals and objectives as a whole, but at the same time individual SC members can pursue their independent policies. As such, a SC can be considered as a virtual organisation (VO) (Tan, 2001). According to Storey et al. (2006), there is a shift of SCM to a collaborative model and virtuality, two basic characteristics of virtual organisations. Moreover, these two organisational forms share the same drivers: close organisational relationships and collaboration between members, coordination of activities, alignment of incentives, information sharing, process integration and trust.

Three main categories of *SCM problems* can be identified: SC planning and demand forecasting provides estimations on future demand, SC configuration specifies the system's structure, policies and processes in a static way, while SC operation refers to the SC members' actions and interactions, leading to the flow of materials, funds and information across the supply chain. These three categories are interdependent. Incorrect SC planning and demand forecasting would lead to a sub-optimal SC configuration, resulting into low SC performance and operation problems along the SC.

It is worth emphasising the significance of *coordination* of activities for SC integration, an issue closely related to the third category of SCM problems, i.e. SC operation. According to Lee and Whang (2004), workflow coordination is one of the four dimensions of SC integration, while Simatupang et al. (2002) recognize logistics synchronization as one of the four modes of coordination that affect operational performance and SC integration. Achieving coordinated workflow is not an easy task, as it requires a deep and solid understanding of the interrelation between activities of different SC members, the so-called SC dynamics. This problem is even more challenging if one considers the complex and dynamic nature of supply chains (Choi et al., 2001).

Supply chain modelling and simulation are perceived as effective methods for enhancing our understanding of SC dynamics, thus tackling the problem of SC coordination. SC modelling can capture SC complexities, while simulation facilitates the testing of different scenarios through what-if analysis. SC system dynamics are thus captured and an insight into the causes and effects of SC performance can be provided. Popular off-the-shelf SC simulators include Supply Chain Strategist (i2 Technologies, 2007) which incorporates IBM's former Supply Chain Simulator (Bagchi et al., 1998), Supply Chain Builder (Phelps et al., 2001), and Supply Chain Guru (LlamaSoft, 2004).

Among the strengths of these systems, we recognise the sophisticated financial reports and inventory handling, as well as the incorporation of geographical information about SC members. However, most of the existing SC simulation solutions tackle the SC configuration problem and not the SC coordination problem. They employ optimisation techniques, and then utilise simulation techniques to validate the proposed configuration. Hence, the focus of simulation is not on understanding the dynamics of SCM but rather on checking the proposed optimal SC configuration properties. This fact justifies the lack of explanation of simulation results, an important drawback if the user wishes to gain an insight into SC dynamics. Furthermore, the absence of business process analysis makes the task of improving workflow coordination difficult. This means that SC simulators suggest numerical values for SC configuration parameters (e.g. safety stock level and reorder point) but do not support their translation into SCM processes nor the analysis of these processes. Hence, the decisions on developing SCM business process models, as well as on streamlining and orchestrating activities across the supply chain need to be made by individual SC members, and no relevant assistance is provided. Moreover, the direct incorporation of business logic in the model is not allowed; in the best case, choosing among predefined policies is possible. Last but not least, communication between SC members is neglected. The SC communication process takes place during the daily operation of supply chains, and is particularly important during SC re-configuration or when the supply chain needs to deal with unexpected events (i.e. when negotiation is involved). However, the communication process has associated costs (Jagdev et al., 2008), and hence can affect overall SC performance. This effect on SC performance is even more important when communication delays or failures are involved. Therefore, the fact that existing SC simulators do not cover communication aspects is regarded as a significant gap.

Research Objectives

Recognising the importance of workflow coordination for SC integration, this paper tackles the need for better understanding of overall SC dynamics. With the aim of filling the gaps explained at the Background section, a knowledge-based approach for SC modelling and simulation is suggested. Our first objective is to provide a theoretically well-grounded SC modelling framework. Our second objective is to develop a SC simulation environment that can capture SCM dynamics in terms of SC members' actions and interactions, and explain simulation results. Experimentation with different SC configurations and strategies will be allowed, thus providing an insight into the SC coordination problem.

Our *research hypothesis* has as follows: A supply chain simulation tool using a logic-based computational model and its reasoning mechanism can help understand and explain the dynamics of SCM in a holistic way, thus assisting the improvement of overall SC performance.

Methodology

A three-phased methodology is suggested: Firstly, the SCM domain is conceptualised based on appropriate business theories; secondly, SCM constructs are formalised in logics and thirdly, SC operation is simulated. A knowledge-based *approach* is adopted throughout these phases. The rationale behind the choice of this approach is following: Knowledge is a source of competitive advantage, and the knowledge-based view is a widely accepted perspective on the SCM domain (Lavassani et al., 2008). In highly distributed environments, like supply chains, there is often hidden implicit knowledge that should be uncovered, discovered and shared among individual members. Since knowledge-oriented techniques are appropriate for this task and they are known to be useful for SCM analysis (Karacapilidis and Adamides, 2007; Manataki and Chen-Burger, 2009), a knowledge-based approach is adopted in this research. The three phases of the suggested methodology are further explained below.

SCM conceptualisation

Three basic components are selected to abstract and model the SCM domain: SC roles, SC services and SCM processes. As shown in Figure 1, a SC role provides a specific SC service through the execution of the corresponding enabling SCM processes. For example, a retailer contributes to the supply chain by selling products to the final customer through the execution of processes like receive payment.

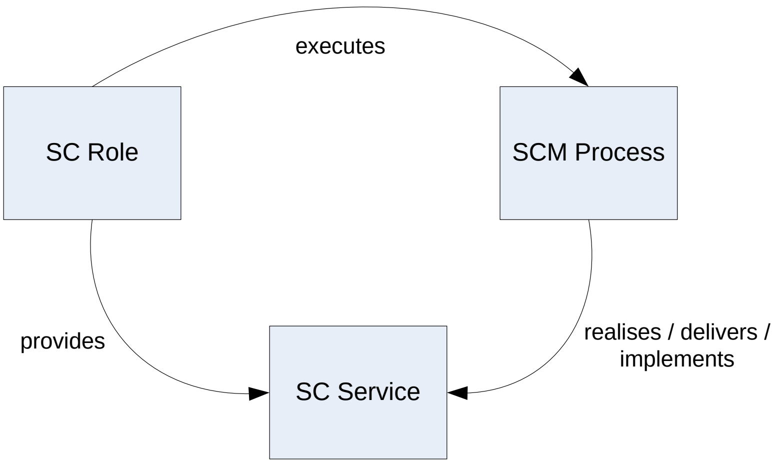

Figure 1: SCM conceptualisation components

A *SC service* is defined as an archetypical function that supports the flow of products requested by the final customer. SC services can be better understood when adopting the holistic view of SCM: An integrated supply chain has the goal to satisfy the final customer while maximising its overall performance. In order to achieve this goal, several steps are involved, such as collecting the raw materials or components of the product, assembling the final product, transporting unfinished or finished products between sites, selling the products to the final customer, etc. Each of these steps or functions are conceptualised in our methodology as SC services.

A *SC role* is defined as the combination of two parameters: i) the archetypical service of a SC member towards the SC (and hence the corresponding position in the SC network) and ii) its business model. The first parameter deals with the part or character that a SC member plays in the supply chain network. For example, a computer manufacturer and a retailer play different roles in the supply chain in order to provide the final customer with the computer, thus delivering two different SC services: The manufacturer assembles the computer, while the retailer sells the computer to the final customer. This also implies a dependency between the two – the retailer cannot sell the computer if it hasn't been first assembled, thus the manufacturer precedes the retailer at the SC network. The second parameter is introduced as the business model of a SC member affects its SC behaviour. The business model typology by Weill et al. (2004) is adopted, consisting of four basic business model archetypes: creator, distributor, landlord and broker. Hence, through the combination of the two parameters, we recognise SC roles such as supplier-creator, supplier-distributor, manufacturer and retailer. Note that a certain company may undertake multiple SC roles in a supply chain (e.g. Dell is known to be both the manufacturer and the retailer for its PCs). Also, an organisation can be a member of numerous supply chains, possibly undertaking different roles.

A *SCM process* is defined as a SC role's business process supporting the flow of the requested product to the final customer. Receive product, send invoice and consolidate order are examples of SCM processes. Considering Figure 1, a SCM process is regarded in our methodology as a SC role's business process towards delivering the assigned SC service, and thus towards the fulfilment of SC goals. It is important to distinguish between high-level SC services and lower-level SCM processes: The former are archetypical SC-wide (global) functions, while the latter are more SC member-specific (local) operational business processes. The way a SC service is translated into a SCM process model depends on the SC member, thus different companies may have a different orchestration of SCM processes for delivering the same SC service.

The underlying framework for the choice of the three above constructs is grounded on the application of Organization Design theory on supply chains. As discussed at the Background section, a supply chain can be viewed as a virtual organisation, where the theory of Organization Design can hence be applied. In our conceptualisation we adopt Galbraith's (1995) star model of organization design, which identifies five major components: strategy, structure, processes, rewards and people. Among those, processes and structure are regarded as the prominent ones; as Galbraith (1995, p.14) argues, "if structure is thought of as the anatomy of the organization, processes are its physiology or functioning". Structure is further decomposed into power and authority, reporting relationships, and organizational roles (Galbraith et al., 2002). But since supply chains are generally known to have a chain VO topology or structure with respect to power and authority and reporting relationships (Katzy and Löh, 2003), it is reasonable to minimise SC structure to the SC role dimension. Furthermore, and as already explained, SC roles are derived from basic SC services. The above reasoning leads us to the conceptualisation of SCM through SC roles, services and processes.

SCM formalisation

Formalising SCM involves the creation of libraries for each SCM construct, thus providing instances to be used in the simulation phase. Interesting properties are captured for each instance, such as the business model and network position of a certain SC role. It is worth mentioning that the SCM process library is based on the Supply Chain Operations Reference (SCOR) model (Supply Chain Council, 2008), as it is a well-established standard of the field. The libraries are formalised using methods of symbolic Artificial Intelligence, i.e. first-order predicate logic. The predicate for defining SC roles is provided below, along with an illustrative example for a retailer. As the retailer's example shows, a retailer is a SC role providing the SC service "sell product to final customer", with a "distributor" business model and placed "downstream" at the SC network.

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SCrole(ID, Name, Service, BusinessModel, NetworkPosition)
SCrole(r4, retailer, sell_product_to_final_customer, distributor, downstream)
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SCM simulation

This phase involves the development of a computational model to simulate SC operation and measure overall SC performance. SC operation is simulated in terms of SC members' actions and interactions, thus providing an insight into SC dynamics.

The *scope* of the proposed simulation tool should first be explained. The subject of the simulation is a supply chain system, consisting of three types of entities: SC members, the market for the SC's final product and the products moving downstream. SC members perform activities, which can be SCM processes or communicative actions (i.e. sending or receiving messages). The SC system is considered as closed with respect to its environment. This means that other supply chains (e.g. competing supply chains), companies that are currently not members of the studied supply chain, as well as aspects of the wider business environment, as shaped by political, economic, social, technological, environmental or legal factors, do not appear in the system. Two levels of SC operation are recognised for the tool's granularity: the global level of SC-wide operation and the local level of individual SC members' actions and interactions. Furthermore, the tool is designed to simulate supply chains of different sizes and structures, i.e. supply chains with various echelons and echelons of varying depth. For reasons of simplicity, individual SC members' organisational structure and softer business aspects, such as culture, trust and leadership, are not captured in the simulation models. Moreover, it is worth clarifying that tackling the SC operation/coordination problem, the focus of simulation is on the extrinsic behaviour of SC members (i.e. actions and interactions) rather than their intrinsic planning procedure. Predefined SCM decisions (e.g. how much to buy at a certain point) will be incorporated in the model in the form of business rules, but the decision-making process itself is beyond the scope of the simulation tool.

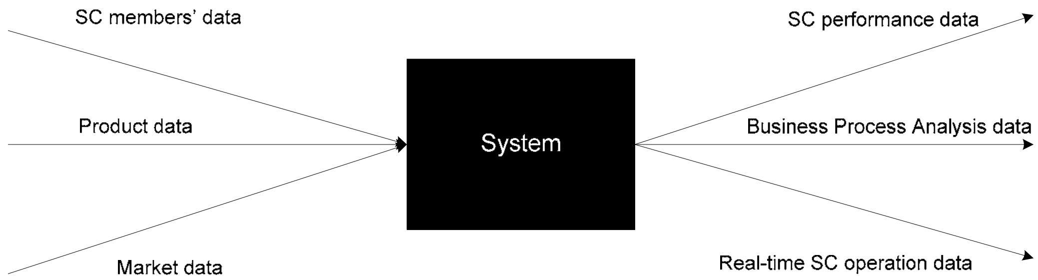

Figure 2: Simulation tool's inputs and outputs

The tool's *inputs and outputs* are shown in Figure 2. The tool is fed with information about each SC member (e.g. SC role, position in the SC network, contributing product or service, strategies, business rules, SCM processes and initial state), product information (e.g. attributes, bill of materials, etc.) and market information (e.g. average order amount and order frequency). Figure 3 presents a mock-up screen for the simulation tool's inputs. Once the system is fed with this information, simulation starts. During simulation real-time information is provided to the user in terms of processes being executed and messages being exchanged between SC members. Figure 4 illustrates the tool's real-time behaviour in a graphical way. After simulation is completed, overall SC performance is measured in terms of time (i.e. order lead-time and percentage of on-time deliveries) and cost (i.e. total cost, manufacturing cost, total inventory cost and total distribution cost). The choice of these metrics is based on the performance measure frameworks suggested by Beamon (1999) and Gunasekaran et al (2001). Business process analysis information is also provided to the user, including possible bottlenecks, deadlocks, unreachable points or critical paths detected throughout the process model of the entire SC.

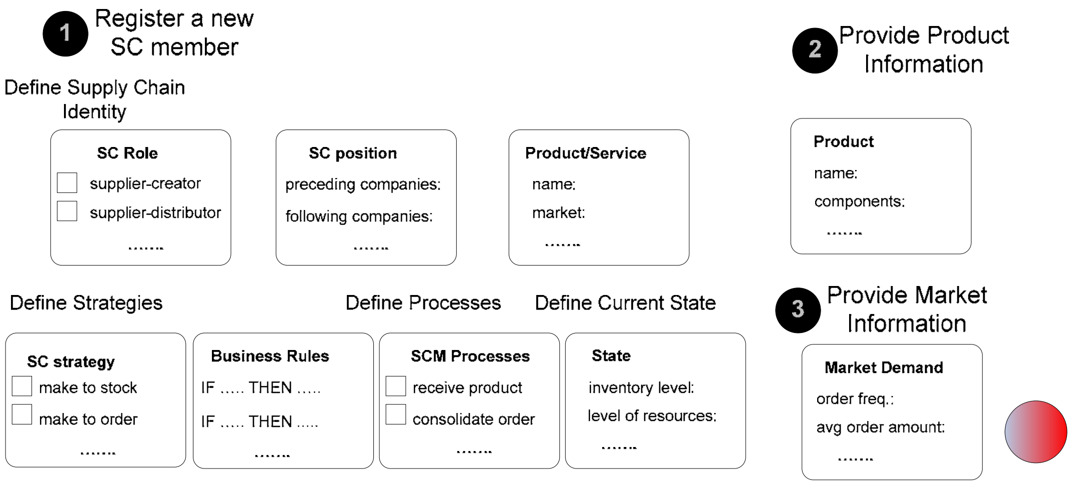

Figure 3: Simulation tool's mock-up screen for inputs

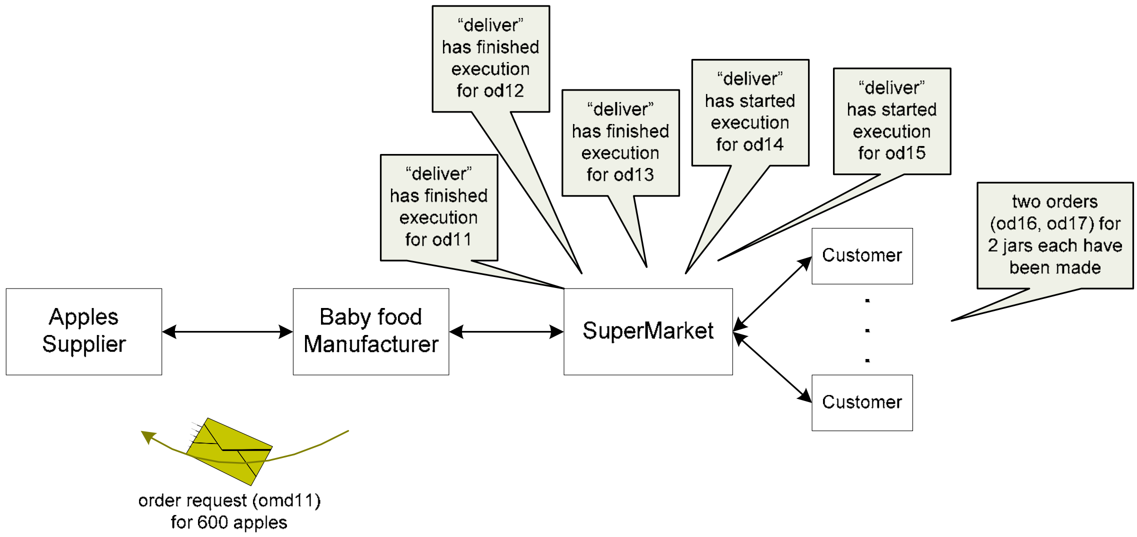

Figure 4: Visual SC simulation results

As far as *technologies* are concerned, the proposed simulation tool utilises recent advances of Artificial Intelligence. Particularly, each SC member is represented in the tool as an Intelligent Agent that can think, act and interact with other SC members. The thinking capabilities of a SC member are captured through the corresponding Business Rules, while its acting capabilities are represented with the use of Semantic Business Process Modelling, the execution of which is enabled through a Workflow Management System. In order to facilitate the explanation of simulation results, a knowledge-based approach is adopted.

The *added value* of the proposed simulation tool, when compared to existing SC simulation solutions, lies in the explanation of simulation results, the support of business process analysis across the supply chain and the capture of SC communication. An example will now be introduced in order to illustrate these advantages: Consider the simplified supply chain for apple-based baby food presented in Figure 4, consisting of the baby food manufacturer, an apples' supplier and a supermarket. The supply chain is modelled according to the framework presented in the previous sections, and thus each SC member's processes and business rules are captured for simulation. A scenario for this supply chain's operation is simulated over a period of 10 days. Let's firstly assume that simulated SC performance involves a 90% rate of on-time deliveries. If the user is interested in discovering why a certain order to the supermarket was delayed, the tool can provide an explanation, e.g. order delay propagated through an order delay of apples to the baby food manufacturer, caused by the sudden disease of certain apple trees (i.e. a violation of the corresponding manufacturing business rule). Secondly, the tool analyses processes across the supply chain, and could thus identify a possible bottleneck at the manufacturer's packaging process. Lastly, let's assume that the simulation scenario involves unexpectedly high market demand, and hence some negotiation for additional orders needs to take place between SC members. In this case there is a cost versus time trade-off (i.e. a quick agreement of a responsive supply chain as opposed to a beneficiary agreement of a low-cost supply chain). By capturing communication aspects, the proposed tool can distinguish between the two cases, and calculate the corresponding SC performance.

It could be argued for this simplified SC example that the reason for the order delay, the bottleneck at the packaging process, and the effect of SC communication duration on overall SC performance could be studied without the use of simulation, but by observing the actual system behaviour or by discussing with the SC members. However, in a more complex supply chain, where numerous SC members are acting and interacting, it would be difficult to track the interrelation of events and thus understand how these dynamics affect SC performance, and it would also be difficult to discuss with all SC members. Hence it is especially in complex SCM cases that the three above-mentioned aspects of the tool's intelligence would be valuable, generating previously unknown knowledge.

Furthermore, the simulation tool is designed to facilitate what-if analysis, thus assisting the SCM decision making process. In the above-mentioned simplified SC example, if at a certain period the apple trees are perceived to be vulnerable, the baby food manufacturer might consider keeping higher inventory of finished products. The tool can be used to experiment with such a scenario and measure SC performance, thus highlighting the feasibility and related cost of such a decision. Making the business rationale transparent throughout simulation is also an important aspect of this artificial intelligence-enabled tool. Unlike other simulation tools that require SC members to translate their business logic into one of the available predefined policies, the actual reasoning behind business decisions is incorporated in the tool proposed in this paper.

Expected results and evaluation

Being at the third phase of the presented methodology, the simulation tool is currently under implementation and evaluation will follow. It is expected, however, to provide an insight into complex SC dynamics and help improve SC coordination. The tool is planned to be empirically evaluated across soundness, completeness and coverage, taking into account its aims and scope. This means that the operation of a real-world supply chain will be simulated, and the simulated SC behaviours will be compared to actual SC behaviours. With respect to the three above-mentioned evaluation criteria, the following questions will be asked: i) Do individual SC members act and interact as expected? Does the supply chain as a whole exhibit the expected behaviour? Are the estimated SC performance and the business process analysis correct? ii) Are all necessary concepts and functionalities of SC simulation covered? iii) Can all important SC scenarios be simulated through the use of this tool? Up to which level of SC complexity can be simulated and explained?

Conclusions

Recognising the need for a better understanding of complex supply chain dynamics, a knowledge-based approach for SC modelling and simulation was suggested in this paper. A theoretically well-grounded SC modelling framework was introduced, recognising SC roles, services and processes as the basic components of the SCM domain. The design of a SC simulation environment adopting a knowledge-based approach was also explained. The use of state-of-the-art Artificial Intelligence for its development is expected to enable the explanation of simulation results, a unique capability among other SC simulators.

The work presented in this paper is envisaged to contribute to the Operations Management (OM) field in the following ways: Firstly, the simulation environment is expected to help SCM practitioners understand the dynamics of their SCs, and assist them with decision-making. Secondly, experimentation with the simulation tool could lead to new theoretical findings, thus contributing to OM theory. Lastly, the introduced methodological framework for modelling, simulating and analysing SCs with the use of Intelligent Agents and Semantic Workflow Systems is envisaged to illustrate how the Operations Management field can utilise and benefit from Artificial Intelligence techniques.

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