Supply Chains Modelling and Simulation Framework

Graph-Driven Approach using Ontology-based Semantic Networks and Graph Database

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ABSTRACT

Successful supply chains management has become a key factor for enterprises to achieve and maintain their competitive advantage. The increasing complexity and agility of supply chains are sustainably growing challenges. Simulation provides advantages over traditional analytical methods in planning and optimisation of supply chains. This paper presents a comprehensive framework for the modelling and simulation of supply chains. A graph-driven methodology is adopted considering supply chains as "Big Graphs". The research will utilise semantic networks, and develop a supply chain ontology to construct semantic-based models of supply chains. The framework proposes the use of graph databases for storing and maintaining complex supply chain models and ontologies. Furthermore, the framework will provide automatic generation of simulation models to help non-simulation experts. The applicability and validity of the proposed framework will be investigated within a case study of healthcare supply chains, during which a specific ontology for healthcare supply chains will be produced as well.

1 STAGE OF THE RESEARCH

The research can still be considered in an early stage. The initial steps included conducting a thorough literature review concerning: i) Conceptual modelling of supply chains, ii) Supply chain simulation tools and iii) Supply chain ontology. Based on the limitations and gaps exposed in the literature, the paper proposes a framework for the conceptual modelling and simulation of supply chains.

2 OUTLINE OF OBJECTIVES

The proposed framework aims at the following:

- Providing a semantic-based modelling method for supply chains that is capable of capturing and describing supply chain knowledge.
- Developing generic ontology for supply chains based on the SCOR reference model.
- Developing specific ontology for healthcare supply chains.
- Investigation of the potential advantages of using graph databases for capturing and maintaining the knowledge of supply chain models.
- Investigation of the flexibility and scalability provided by graph database in case of building complex large-scale supply chain models.
- Automatic generation of simulation models based on high-level conceptual models to help non-simulation experts easily run and modify simulation experiments using one of the state-of-the-art simulation software.
- Inspecting the applicability and validity of the proposed framework in a dynamic industry, particularly a healthcare supply chain.

3 RESEARCH PROBLEM

The complexity of supply chains continues to grow due to collaborative planning and connections among supply network participants. In addition, supply chains are required to be responsive, agile, lean, scalable, and flexible with respect to uncertain information.

Simulation is being more and more accepted to be an important part of the analysis and optimisation practice of supply chains management. However, building simulation models for supply chains involves many challenges.

Firstly, the difficulty of conceptual modelling of supply chains, involving an abstraction process, used to capture the essence of a real system into a simulation model. The literature lacks a common modelling methodology that can help describe details of a supply chain and capture essential elements and

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relationships as well as their dynamics. The need for such methodology has been acknowledged by (Gunasekaran, Macbeth, 2000), (Jain, Workman, Collins and Ervin, 2001), (Min and Zhou, 2002), (Gunasekaran, 2004) and (Zee, 2005).

Secondly, the shareability of supply chain models has become an inevitable demand since the model can be developed and shared across a network of various and distant participants. Standard supply chain ontology can help sharing models. However, the literature lacks what can be considered as a standard ontology for supply chains, especially for specific industries like healthcare or perishable goods.

Thirdly, the majority of the simulation tools produced by academia and industry for supply chains were mostly designed for simulation experts. Auto-generated simulation models can be considered as a more realistic demand due to the highly increasing complexity of supply chain models, which implies more time and costs to build simulation models.

Finally, the scalability of supply chain models is a considerable need, especially for rapidly growing supply chains. The majority of existing systems rely on XML to store supply chain models. Although XML has acknowledged advantages for information inter-changeability, document-oriented techniques might not help with model scalability according to (Chatfield, 2009), especially for more complex and large-scale supply chains.

4 STATE OF THE ART

Since the advent of supply chain management, both academia and industry have presented a significant amount of studies and tools for the modelling and simulation of supply chains. This section reviews the literature concerning the following areas:

- The conceptual modelling methodologies of supply chains.
- The simulation tools of supply chains.
- The presented endeavours for identifying supply chain ontology.

4.1 Supply Chain Conceptual Models

First, the SCOR (Supply Chain Operations Reference Model) model, which can be regarded as one of the most widely accepted reference models for supply chains. SCOR has been developed and being maintained by the Supply Chain Council (SCC) Inc. The SCOR model has been developed to describe the business activities associated with all phases of satisfying a customer's demand. The model contains several sections and is organized around six primary management processes: Plan, Source, Make, Deliver, Return and Enable, as shown in Figure 1. (Supply Chain Council, 2012)

Figure 1: The six major management processes of SCOR.

Many studies adopted SCOR as a basis for building either abstract or simulation models for supply chains such as (Jeffrey, Edward, 2003), (Samuel, Sunil, 2005), (Yuh-Jen, Yuh-Min, 2009), (Fredrik, Mirko, 2009) and (Jack, Kincho, 2010). According to (Fredrik, Mirko, 2009), the advantages of the SCOR model are:

- Providing the modeller with a solution to the problem of different levels of details in simulation model since SCOR has predefined levels of aggregation.
- Defining performance metrics for each level.

However, SCOR has been criticized in other studies. According to (Guixiu, Frank, 2004), SCOR does not provide a concrete realisation of a conceptual framework that can be integrated to a company's existing systems. Furthermore, (Chatfield, 2009) accounted the following SCOR's shortcomings:

- SCOR makes the translation of the supply chain description into an object-oriented model less than straightforward.
- The descriptions and measurements of SCOR do not have the content and detail necessary for building robust quantitative models.

On the other hand, the object-oriented approach has been also embraced in literature. (Manuel, Hin-Tat, 2003) used the UML during the object-oriented development process to analyze and visualize the design of supply chains. (Biswas, Narahari, 2004) developed DESSCOM, an object-oriented framework for supply chains modelling and decision support. Another object-oriented modelling methodology consisting of agents, jobs, and flows was developed by (Zee, 2005).

Supply chains were also modelled in terms of multi-criteria decision analysis. An ANP-based (Analytic Network Process) approach was used by (Ashish, Ravi, 2006) to model the metrics of lean, agile supply chains. However, the pairwise comparison required by ANP models can limit the numbers of decision criteria, which might be an obstacle in case of modelling more complex supply chains.

A considerable endeavour has been presented by (Chatfield, 2004) and (Chatfield, 2009) to standardise the process of modelling supply chains. The study developed an XML-based language for modelling and simulation of supply chains, SCML (Supply Chain Modelling Language). However, XML-based models can incur some drawbacks. First, since XML is double-tagged, the file length will increase, as opposed to files generated by a less strictly designed language that allows single-tagged elements. Additionally, since XML files are ASCII text files, the file size, measured in bytes of storage, will be greater than if the information were stored as binary data or as another file structure, which can impose further limitations on modelling large-scale supply chains.

4.2 Supply Chains Simulation Tools

Three main approaches used for supply chain simulation are: i) Discrete Event Simulation (DES), ii) Systems Dynamics (SD) and iii) Agent-Based Simulation (ABS). However, discrete event simulation has been largely preferred in literature. Numerous DES tools for supply chains were produced by studies such as (Ettl, Feigin, 1996), (Tomoyuki, Tetsuya, 2000), (Richard, David J., 2001), (Edward J., Ali, 2003), (Juqi, Wei, 2004), (Chatfield, 2006).

Agent-based simulation approach has received growing attention in recent studies. An agent-based modelling and simulation framework for supply chain risk management was developed by (Tiffany J., 2012). (Luis, Sophie, 2011) proposed FAMASS, a framework for providing a uniform representation of distributed advanced supply chain planning using agent technology. (Karam, Erwan, 2010) used an Operational Agent Model (OPAM) that was implemented and simulated in a specific agent-based software architecture.

The Systems Dynamics approach was mainly adopted within continuous simulation models of supply chains. For instance, (Patroklos, Dimitrios, 2005), (Vo, Thiel, 2006) and (Sameer, Anvar, 2011) used Systems Dynamics for simulating the behaviour and relationships of supply chains, and to determine impacts such as demand variability and lead-time on supply chain performance.

Despite the many simulation tools developed in academic research, they have not been widely embraced, as evident from the current status and usage of those tools. Furthermore, the literature lacks recognition that supply chains are neither completely discrete nor continuous but a mixture of both, therefore should be modelled appropriately to reflect this. The need for constructing supply chain models with discrete-continuous aspects has been recognised by (Young, Min, 2002), (Mustafa, Theopisti C., 2007) and (Dmitry, Alexandre, 2012).

4.3 Supply Chain Ontology

An ontology can provide a formal explicit specification of shared knowledge, which can offer practical grounded solutions for designing and modelling supply chains. However, the adoption of ontologies in supply chain modelling has been given little consideration in the literature.

(Fayez, Rabelo, 2005) presented supply chain simulation ontology based on the SCOR model. The ontology was developed using Protégé tool and encoded with the RDF standards.

(Y. Ye, D. Yang, 2008) presented an ontology-based architecture for implementing semantic integration of supply chain management. The ontology was developed with no specific industry focus and consisted of ten top-level classes: Supply_Chain, SC_Structure, Party, Role, Purpose, Activity, Resource, Transfer_Object, Performance and Performance_Metric.

(Yan, Dong, 2008) developed a supply chain ontology called Onto-SCM. They utilised the IDEF5 schematic language to visually represent core concepts and relationships in Onto-SCM. The precise syntax and formal semantics of Onto-SCM were defined with Ontolingua, a mechanism for writing ontologies in a canonical format.

On the other hand, ontologies of general enterprise modelling were previously used for supply chains models. For instance, TOVE ontologies by (J. Lin, M.S. Fox, 1996), Enterprise Ontology (EO) by (M. Uschold, M. King, 1998) and IDEON ontology by (Madni, W. Lin, 2001).

Based on the ontology literature, it is believed that the literature has the following limitations:

- Apart from (Fayez, Rabelo, 2005), the ontology mainly addressed the strategic level of supply chains, giving less consideration to the tactical and the operational levels.
- Many of the developed ontologies were not built on a standard basis that can help sustainable development in the supply chain community.
- The ontologies apparently lacked classification of the defined attributes into continuous and discrete, which could help build combined discrete-continuous simulation models.
- The literature lacks industry-specific ontologies,

for example in the healthcare domain. Generic ontologies might not be adequate for describing more detailed processes at the tactical and operational levels.

5 METHODOLOGY

The proposed framework is fundamentally based on a graph-driven methodology for the modelling and simulation of supply chains. The methodology considers the supply chain as a big graph that forms a complex network of connections. Accordingly, the methodology utilises the potentials of semantic networks and graph databases to construct supply chain conceptual models and ontologies. Figure 2 demonstrates the main components of the framework.

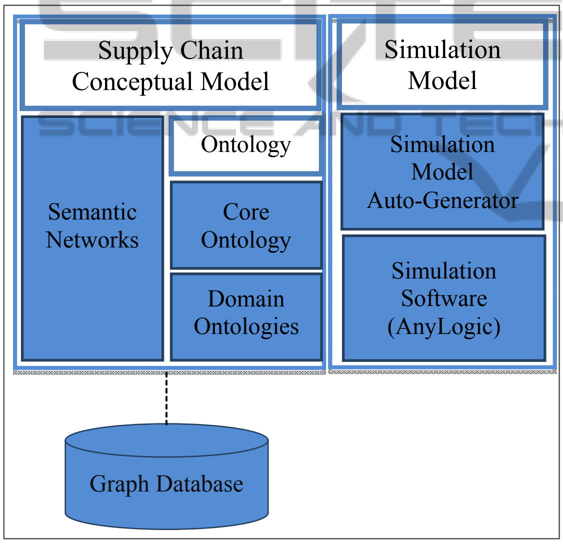

Figure 2: Main components of the proposed framework.

5.1 Supply Chain Modelling Approach

The first principal objective of the proposed framework is to provide the conceptual modelling methodology that can effectively describe and capture the knowledge of supply chains. The modelling methodology should involve an abstraction process for determining what part of the real-life system will be modelled and at what level of detail. Conceptual modelling was described as the "art" in the science of simulation according to (Jain S., Workman R., 2001). The modelling methodology should address two main points:

- Conceptually, how should supply chain knowledge be represented?
- How can the conceptual models facilitate the shareability of supply chain knowledge?

5.1.1 Supply Chain Big Graphs

The supply chain comprises a virtual complex network of participants including suppliers, manufacturers, wholesaler, retailers and customers. The network participants are connected through upstream and downstream linkages in the different processes and activities to produce some service or product. Apparently, it can be conceivable to consider modelling supply chains as constructing "Big Graphs".

Accordingly, the framework adopts a graph-based method to model and capture the knowledge of supply chains. Furthermore, graph modelling provides a suitable form for sharing models with diverse sorts of experts or decision makers.

5.1.2 Modelling Supply Chains as Semantic Networks

A semantic network is a graph structure for representing knowledge in patterns of interconnected nodes and arcs (Shapiro, Eckroth, 1992). The proposed framework utilises the common graph-based nature of supply chains and semantic networks to build semantic-driven supply chain models. Hence, the supply chain participants are modelled as nodes (entities) that are interconnected via arcs (predicates) that can represent properties or relationships. Those predicates will be explicitly described by ontology. Figure 3 depicts a simple example of a semantic network.

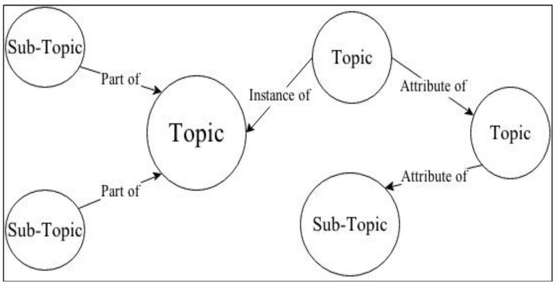

Figure 3: Example of a Semantic Network.

Semantic networks have the advantage of being a declarative graphic representation of knowledge. In addition, semantic networks can be understandable by human and machines as well. Various semantic models have been built based on the concept of semantic networks, the RDF model for instance.

5.1.3 Supply Chain Ontology

Developing supply chain ontologies is a pivotal element to provide expressiveness and semantics to capture comprehensive supply chain knowledge. The framework adopts ontologies to provide standards of information, shared vocabulary and conceptualisation of problem-oriented data for supply chains. The ontology will consist of two main categories:

i) Generic Ontology:

Initially, the framework will use a SCOR-driven process to define classes, subclasses, properties, and instances that can represent the various supply chain levels. The adoption of the SCOR model is due to being the most shared and widely accepted concept within the supply chain community, and it has been largely used in literature to describe and model supply chains.

A hierarchy of concepts will be driven from the SCOR processes and performance measures to describe the taxonomy of supply chain knowledge. The top level of the ontology hierarchy should represent primary processes of a supply chain in a strategic aspect. The generic ontology is based on the six primary management processes defined by SCOR: Plan, Source, Make, Deliver, Return and Enable. Moreover, a 'Hybrid' process was added to provide more flexibility. Figure 4 outlines the main classes of the generic ontology.

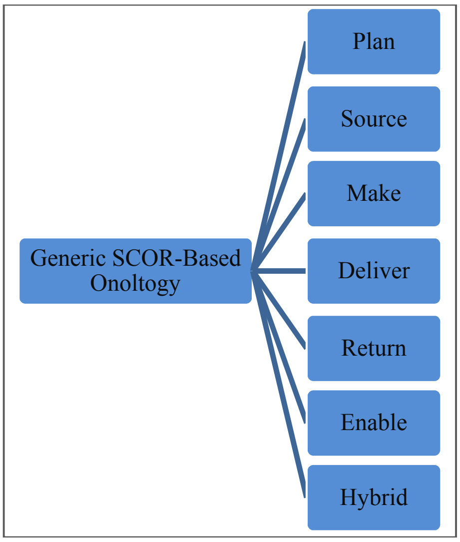

Figure 4: Main classes of the SCOR-based generic ontology.

Further ontology attributes are extracted based on the performance attributes defined by SCOR. Those attributes can describe process details at the tactical and operational levels of supply chains. In addition, the extracted attributes should be classified into discrete or continuous attributes. Table (1) presents the main categories of performance attributes defined by the SCOR model.

Table 1: The SCOR performance attributes.

Performance Attribute	Definition
Reliability	Reliability focuses on the predictability of process outcomes. Examples: On-time, the right quantity, the right quality.
Responsiveness	The speed at which a supply chain provides products to the customer. Examples: cycle-time metrics.
Agility	The ability to respond to external influences such as marketplace changes to gain or maintain competitive advantage. Examples: Flexibility and adaptability metrics.
Costs	The cost of operating the supply chain processes. This includes cost of labour, material, management and transportation. Example: Cost of Goods Sold.
Asset Management Efficiency	The ability to efficiently utilise assets. Examples: Inventory days of supply and capacity utilization.

ii) Domain Ontologies:
The framework is concerned with covering one of the gaps in literature accounted for the lack of specific-industry ontologies for supply chains. Therefore, industry-specific ontology is developed, healthcare supply chain in particular.

5.2 Storing Supply Chain Models and Ontologies using a Graph Database

Based on the graph-driven approach, the framework utilises graph databases for storing both the supply chain model and the defined ontology. A graph database is a storage engine which supports a graph data model backed by native graph persistence, with access and query methods for the graph primitives (Robinson, Webber, 2013).

5.2.1 Storing Supply Chain Models

Graph database can provide a flexible schema to store and map the nodes and edges of the supply chain graph. Accordingly, the graph data model of graph databases can help build and store more complex large-scale supply chain models. Furthermore, the graph-based data storage provides a considerable advantage for model scalability over traditional XML-based documents.

5.2.2 Storing Supply Chain Ontology

Graph database can provide a suitable environment for storing, maintaining and querying supply chains ontology due to the following reasons:

- Graph database can handle storing complex ontologies because of the flexible graph-based model.
- Graph database is a schema-less data store, which is ideal for scalability.
- Graph database models are typically faster for associative datasets.
- Graph database provides a robust model to query ontologies.
- The common graph-based manner of graph databases and the RDF model helps export the ontology with RDF-based format, which is important for the model shareability.

5.3 Automatic Generation of Simulation Models

A tool will be developed that can automatically generate simulation models. The tool translates the high-level conceptual models of supply chains into simulation models ready to run experiments. The purpose of the auto-generation is to help non-simulation experts build and modify simulation models with different scenarios.

5.4 Simulation Software

It is not planned to produce a new simulation tool, however the framework will work along with one of the state of the art simulation software. The literature review included surveying the available simulation tools provided by academia and industry in order to select the appropriate tool.

AnyLogic simulation software was selected for that purpose. AnyLogic was considered for the following:

- The capability of providing a multi-perspective simulation approach, including Discrete Event Simulation, Systems Dynamics and Agent-Based Simulation.
- Supporting seamless integration of discrete and continuous simulations.
- Providing Java-based simulation models, which helps model extensibility.
- Providing an extensive statistical distribution function sets that provide a platform for simulating the uncertainty inherent in supply chains.

6 EXPECTED OUTCOME

In principal, the framework will present a graph-driven methodology to address the modelling and simulation of supply chains. The framework is expected to provide the following:

- Semantic-based modelling of supply chains that can improve the flexibility of building supply chain models.
- Higher shareability of supply chain models through visual graph-based models.
- Flexibility for modelling complex large-scale supply chains using graph database.
- Generic ontology for supply chains.
- Specific ontology for healthcare supply chains.
- Classifications of ontologies into discrete and continuous attributes, which can help build combined discrete-continuous models.
- Flexibility and scalability for developing, maintaining and querying ontology based on graph databases.
- Helping non-simulation experts by automatic generation of simulation models ready to run experiments using one of the state-of-the-art simulation software.

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