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A REVIEW OF LITERATURE IN DISTRIBUTED SUPPLY CHAIN SIMULATION

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ABSTRACT

M&S is a decision support technique that enables stakeholders to make better and more informed decisions; application of this to supply chains is referred to as supply chain simulation. The increasingly interconnected enterprise of the digital age benefit from cooperative decision making through the utilization of existing technological foundations, standards and tools (e.g., computer networks, data sharing standards, tools for collaborative working). Distributed Supply Chain Simulation (DSCS) facilitates such collective decision making by enabling simulation models of individual business processes/organizations to execute cooperatively over a computer network. The aim of this research is to identifying the advances in DSCS and its present state of play. Towards realization of this aim we present a methodological review of literature and complement this with our domain-specific knowledge in supply chains and parallel and distributed simulation.

1 INTRODUCTION

Our research lays emphasis on capitalizing on the advances in Information and Communications Technology (ICT) for the generation of added value among existing supply chain partners. It is proposed that added value is created through the process of cooperative decision making, aided by the use of M&S. The increasingly interconnected enterprise can enhance cooperative decision making by not only sharing data (e.g., those enabled through inter-organizational system linkages) but also sharing process models for distributed execution. For example, a simulation model of a logistics provider (e.g., UPS) may be logically combined with two warehouse process models belonging to customers that it serves (e.g., Amazon and DELL) and these models may be executed in different computers over a network like the Internet. Further, this distributed approach to simulation addresses the issues concerning data/information security and privacy (Mustafee et al. 2012) and supports experimenting with value constellations through the reconfiguration of roles and relationships among the supply chain players. This distributed approach to the execution of supply chain models is referred to as Distributed Supply Chain Simulation, or DSCS for short.

DSCS converges concepts from Operations Management (supply chain in particular), applied computing (distributed simulation) and Operations Research (M&S). Figure 1 illustrates this convergence through use of a Venn diagram and identifies particular stages of a M&S study where the aforementioned concepts and techniques have been applied. A M&S study comprises of several well-defined stages and most M&S users would identify with problem formulation stage (Maria 1997)/conceptual modelling (Robinson 2011), data collection, validation and verification, model implementation, model execution/experimentation, output data analysis and recommendations. Concepts from supply chain management like logistics and inventory management, value chain, facility location etc. are used in the *problem formulations stage*; M&S techniques like Agent-based Simulation (ABS), Discrete-event Simulation (DES), Spreadsheet/Monte Carlo Simulation and System Dynamics (SD) are used in the model implementation stage. In the *model execution/simulation experimentation stage* concepts from distributed computing like distributed simulation and grid-enabled simulation execution are used.

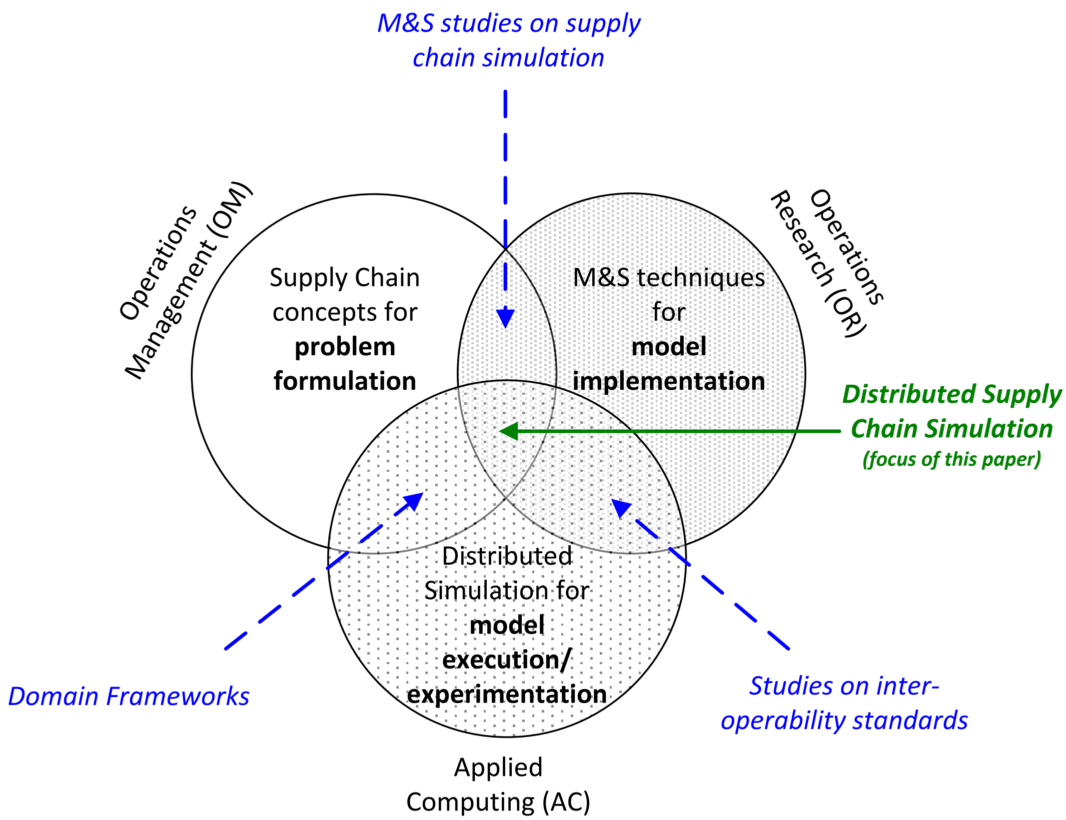

Figure 1: DSCS converges concepts and techniques from multiple disciplines.

There are several studies that have used concepts, techniques and tools from only of the three academic disciplines of OM, OR and AC. These are shown in Figure 1 by the identification of three sub-sets of intersection in the Venn diagrams; these are labelling according to the commonly identified study themes.

- Intersection of concepts from supply chain and M&S have provided a wealth of literature in supply chain simulation. There are several simulation techniques and studies have used ABS (Swaminathan, Smith, and Sadeh 1998), DES (Katsaliaki and Brailsford 2007), SD (Minegishi and Daniel 2000), Spreadsheet Simulation (Katsaliaki, Mustafee and Kumar 2014) to model supply chains, as also in supply chain pedagogy. The reader is referred to Terzi and Cavalieri (2004) for an extensive review of simulation in the supply chain context.
- Concepts from supply chain and distributed simulation have led to the development of domain frameworks for supply chain, e.g., conceptualization of distributed simulation in supply chain domain using ontology network (Gutiérrez and Leone 2013) and e- Supply Chain Operations Reference (e-

SCOR) model (Barnett and. Miller 2000). It is expected that future research will lead to the development of Supply Chain Management-specific HLA Federation Object Models. A FOM describes the objects, attributes an interactions that may be shared in a IEEE 1516 HLA distributed simulation environment (Dahmann, Fujimoto, and Weatherly 1998); it is arguable that supply chain concepts like inventory, re-order point and delivery schedule may have to be presented in a common FOM framework).

- The convergence of M&S for operations management with distributed simulation has led to studies on inter-operability standards (Taylor et al 2012); it is to be noted that these studies are not specific to a particular domain.
- Finally, the convergence of the three academic disciplines of OM, OR and AC, together with an intersection of specific concepts like supply chain management, M&S and distributed simulation, have led to the emergence of the encompassing research theme of DSCS, and which is the focus of this literature review paper.

The remainder of this paper is organized as follow. In section two we present a discussion on supply chain simulation and the M&S methods that are commonly used for implementing the same. Section three is devoted to DSCS. Following this we present the methodology for our literature review (section 4). In the next sections we present some results from the ongoing literature review and discuss some of the findings (section 5). The final section concludes with outlining the future work pertaining to the literature review.

2 MODELLING SUPPLY CHAINS

Supply Chains, from their very nature, are usually complex as they entail all the processes from procurement and manufacturing to sales and support (Stevens, 1989). Moreover, modern supply chain management approaches favor a global, holistic view in which the individual echelons share information and trust each other, rather than simply trying to optimize their own local processes independently of its neighbors (Chapman and Corso, 2005). In the context of decision support within a stochastic supply chain environment, simulation is widely regarded as a powerful analytical technique (Terzi & Cavalieri 2004) as it is a tool which can provide multi-decisional support with regard to "what-if" analysis and evaluation of quantitative benefits. In the previous section we identified four specific simulation techniques (ABS, DES, SD and MCS) that are frequently used to model supply chains from the perspective of operations management. A brief overview of these simulation techniques are presented in below.

SD takes a holistic view of the problem and uses stocks, flows and feedback loops to study complex systems. MCS uses a sequence of random numbers according to probabilities assumed to be associated with a source of uncertainty and thus allows decision makers to account for risk. DES is used to model systems in greater detail (when compared to SD) and with more complex temporal dependencies (when compared to MCS). It involves the modelling of a system as it progresses through time and is particularly useful for modelling queuing systems. ABS is a computational technique for modelling the actions and interactions of autonomous individuals (agents) in a network. The objective here is to assess the effects on these agents on the system as a whole (and "not to" assess the effect of individual agents on the system). ABS is particularly appealing for modelling scenarios where the consequences on the collective level are not obvious even when the assumptions on the individual level are very simple. This is so because ABS has the capability of generating complex properties emerging from the network of interactions among the agents although the in-build rules of the individual agents' behavior are quite simple.

There are two specific problem scenarios which may severely limit the application of the conventional supply chain simulation (by conventional we mean a standalone one-computer simulation execution) for decision making; (a) execution of large and complex supply chain models, and (b) execution of inter-organizational supply chain models. In relation to (a), a supply chain network can be quite large and consist of a multitude of complex, interacting elements. The computer representation of such supply chains may thus necessitate the implementation of large models that are beyond the capability of a single computer to simulate (Mustafee et al. 2009; Taylor et al. 2002; Gan and Turner 2000). With regard to (b), in recent years, the scope of supply chain management has evolved to cross the enterprise boundaries, as vertical integration is no longer the emphasis of large corporations (Archibald, Karabakal, and Karlsson 1999). In order to increase performance over the supply chain, accurate simulation models have to be built. There are generally two strategies for creating an overarching simulation model that encompasses the individual supply chain processes. The first strategy is to create a single simulation model – this is the conventional approach. The second strategy is to develop different models for the individual supply chain elements and then to use distributed simulation technology (refer to section 3) to execute the models in sync. The latter approach is arguably better equipped to tolerate the physical changes that may take place in the underlying supply chain structures (for example, a change in the logistics provider can be modelled by replacing the former logistics model with a new model that simulates the processes of the new provider, thereby alleviating the need for creating a new supply chain model). However, although such detailed models do not pose a problem when the chain involves only a single enterprise, not many participating companies are willing to share detailed model information when the chain crosses the enterprise boundaries. This is discussed next in relation to DSCS.

3 DISTRIBUTED SUPPLY CHAIN SIMULATION

Simulation models typically represent the processes associated with specific business units. However, in the case of supply chains more than one business unit may need to be modelled as different organizations may be responsible for various supply chain operations such as manufacturing, transport and distribution. Organizations can be protective about their internal processes and can have concerns regarding data/information security and privacy. Thus it could be argued that creating a single supply chain simulation model representing the various inter-organizational processes is usually not an option since this will run counter to organizational privacy. Further, issues such as data transfer, model composition and execution speed may also make a single model approach problematic (Mustafee et al. 2012). A potential solution could be to create several distinct and well-defined simulation models, each modelling the processes associated with one specific supply chain business unit, linked together over the computer network/Internet. This approach is referred to as distributed supply chain simulation. Distributed simulation techniques enable technology that allows corporations to construct a cross enterprise simulation while hiding model details within the enterprise. An informative example is given by Gan et al. (2000). As this paper concerns distributed simulation we consider it prudent to present a technical discussion on this; from Mustafee et al. (2012).

Distributed simulation can be defined as the distribution of the execution of a single run of a simulation program across multiple processors (Fujimoto, 2000). Distributed simulation software (sometimes called *middleware*) is quite complex and implements well-known distributed simulation time management algorithms to achieve synchronization between individual running simulations (Fujimoto, 1990). The time management algorithms are required for the prevention of causality errors. Causality errors happen as a result of a failure to process simulation events in increasing timestamp order. More specifically, a causality error occurs when a simulation has processed an event with timestamp $T1$ and subsequently receives another event with timestamp $T2$, wherein $T1 > T2$. Since the execution of the event with time stamp $T1$ will have normally changed the state variables that will be used by the event with timestamp $T2$, this would amount to simulating a system in which the future could affect the past (Fujimoto, 1990). For a serial simulator that has only one event list and one logical clock it is fairly easy to avoid causality errors. In the case of distributed simulation, the avoidance of causality is a lot more difficult because it has to deal with multiple event lists and multiple logical clocks that are assigned to various processors. The reason for this is explained below.

The system being modelled may be composed of a number of physical processes. In a distributed simulation, each physical process is usually mapped to a logical simulation process running on a separate machine. In the context of supply chains, the physical processes may characterize the activities of manufacturing organizations or they may represent processes associated with storage, transport and logistics. All the interactions between the physical processes (e.g., material movement from one supply chain component to the other) are modelled as messages that are exchanged between their corresponding logical processes. Each message will have a time stamp associated with it.

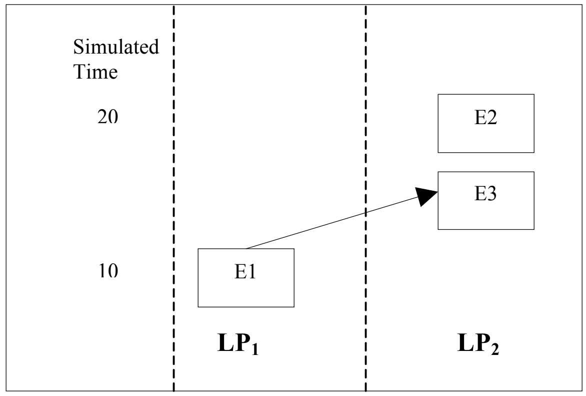

Figure 21: Execution of events in a distributed simulation (adapted from Fujimoto, 1990).

In Figure 2 above, the simulation represents a physical system that has two physical processes, say, PP_1 and PP_2. Logical simulation processes LP_1 and LP_2 model the two physical processes. Each of these logical processes have their own simulation engine, simulation clock and an event list. During simulation initialization the event lists of both LP_1 and LP_2 are populated with the events *E1* and *E2* respectively. The timestamps for *E1* and *E2* are 10 and 20 respectively. It will be possible for LP_1 to process event *E1* without any causality error since the timestamp of *E1* < timestamp of *E2*. But LP_2 will not be able to execute event E2 at time 20 because causality error may then occur. The reason for this is that execution of *E1* might schedule another event *E3* for LP_2 at time 15. In such a case, if LP_2 had been allowed to execute *E2* at simulated time 20 then it would have resulted in a causality error because the time stamp of *E3* < the time stamp of *E2*. Different synchronization protocols are proposed for distributed simulation that prevent or correct such causality errors.

In the subsequent sections of this paper we identify several technical characteristics of the DSCS studies that have been selected for the review. This includes, but is not limited to, the programming languages/libraries used for the implementation of distributed simulation middleware and/or the choice of existing middleware (the middleware implements one or more synchronization protocols).

4 LITERATURE REVIEW METHODOLOGY

Our literature profiling methodology consists of the *"Paper Selection"* stage which describes the methodology used for the purpose of selecting papers for inclusion in this study and the *"Information Capturing"* stage which identifies the information that is captured from papers that have been included in the study.

Paper Selection Stage: We have undertaken a search for relevant articles using the *Web of Science®* and SciVerse *Scopus* citation and journal databases, *ACM Digital Library* and *IEEE Explorer*. To identify articles which would be incorporated in our study's dataset the following criteria were used: inclusion of the words: *"distributed"* and *"simulation"*, and the words *"supply"* and *"chain"* in the title, abstract or keywords of the published paper. The search identified publications written in the English language from 1970 until 2011 (inclusive). Results from this sampling search strategy generated more than 400 papers in total. The abstracts of all the papers, including full-texts in many cases, were reviewed. This led to the exclusion of several papers from the database. However, new papers were also identified from the reference lists of the reviewed papers. Subsequent to the paper selection stage we were left with 113 papers, which formed the dataset for our literature review exercise.

Information Capture Stage: We have complemented the aforementioned *search, retrieve and read* process with our domain-specific knowledge in DSCS, and have identified four categories of variables that would be captured from our readings of the 113 papers. These are, (a) variables related to the general metrics of the selected papers, (b) variables which provide insights on the problem definition and context, (c) variables pertaining to the technical characteristics of model development and implementation, and (d) variables that would help us identify the outcome and the contribution of a study. Each category further consists of a number of variables/subcategories that attempt to describe the key aspects of the study being reviewed, for example, under the category general metrics (a) we have variables that capture the article type, the source of the publication (conference, journal), etc.; variables on motivation for research, application sector, supply chain echelon, etc. are present under the category problem definition (b); the category model development (c) includes variables on M&S technique used, the choice of distributed simulation middleware, etc.; we have variables pertaining to outcome of study (d) like the contribution of research, whether the solution was implemented and future research directions. In the following section we present the results for a sub-set of these variables and discuss their findings. The complete synthesis of our literature review exercise, which will take into account the data captured for over 20 variables, will be presented in a subsequent publication.

5 RESULTS AND DISCUSSION

5.1 General Metrics - Publication Frequency

The first paper in our dataset was published in 1997 and more than 90% of the papers were published from 2002 onwards. This comes as no surprise since the distributed simulation protocols only date back to 1997 (Dahmann, Fujimoto and Weatherly 1997); these were developed by the military and for military applications. The first book that is a comprehensive guide for the implementation of distributed simulation was published in 2000 (Fujimoto 2000). So it is only in the last 15 years that distributed simulation has become the focus of interest in the scientific society starting from the defence sector and moving to civilian domains with societal and business orientations. The maximum number of DSCS papers were published in the year 2006 (15 papers), followed by 14 papers in 2002. Between 2000-2011 (both years inclusive) a minimum of five papers were published on DSCS every year.

5.2 General Metrics - Publication Outlet

The majority of the articles were published as conference proceedings. Overall, the dataset consisted of 72 *conference papers* (64%), 35 *journal articles* (31%), 4 *books* and 2 *book sections*. From our database it was found that the 113 selected papers were published in 62 publishing outlets. The most popular publishing outlet for DSCS papers is the *Winter Simulation Conference* with a representation of 32% (36 papers), followed by the journal *Simulation-Transactions of the Society for Modeling and Simulation International* follows (5 papers) and the *International Journal of Production Research* (3 papers).

5.3 General Metrics – Article Type

We distinguish between a research paper, a review, a survey and a discussion paper. Research papers develop an idea, software/model improvement, present results of experiments, discuss case studies (generic or real) and present validity and applicability; a research paper may consist of one or more of the aforementioned elements. Review papers focus on synthesis of literature and is usually based on an underlying literature review methodology. Survey papers use a variety of research methods (literature review, case studies) and/or research instruments (interview, questionnaires) to conduct scientific enquiry into a specific research theme; such papers may also provide directions for future research. Discussion papers present the thoughts and the philosophical positioning of experts in the field. Our dataset consists of *four review papers*; two on multi-agent systems (Lee and Kim 2008; Moyaux, Chaib-Draa and

D'Amours 2006), one on the use of simulation in supply chain context (Terzi and Cavalieri 2004), one on DSCS frameworks (Bandinelli et al. 2006). We have identified *two survey papers*; both use case studies to present a discourse on the need for distributed simulation in real-world manufacturing and logistics problems (Lendermann 2006) and for interoperability issues with COTS simulation packages (Taylor et al. 2009). We have three *discussion papers*, two of which focus on the use of distributed simulation in industry (Taylor 2002; Lendermann 2007) and one on COTS distributed simulation (Taylor et al. 2003). The remaining 104 papers are *research papers*.

5.4 Problem Definition/Problem Context – Motivation for Research (top 5)

The top five motivations for research in DSCS is presented according to the frequency of its occurrence in underlying dataset. Thus, the motivation reported in the maximum number of papers is presented first, followed by the second most identified motivation, and so on so forth. It is to be noted that most papers articulate more than one motive (advantage) for using DSCS.

- *Faster simulation execution:* A reduction in the time required to execute the large and complex models of supply chains by using larger number of processors and more memory;
- *Interoperability:* realizing enhanced functionality between multiple, disparate, heterogeneous models, by 'hooking together' simulation models into a single simulation environment, subsequent to the DSCS frameworks and inter-process communication (IPC) formalisms having been established.
- *Data hiding & sharing:* Participating component models of each organizational unit can perform independent runs without sharing sensitive information and without knowing in detail the state of any other models taking part in the distributed simulation.
- *Reusability:* The model of each organizational unit is reusable in the same DSCS when the supply chain configuration changes over time therefore reusability of legacy federate code is achieved which is platform neutral and independent of federate modeling approaches.
- *Geographically-distributed architecture:* Inter-organizational communication is attained by coordinating the configuration and invocation of geographically distributed models.

5.5 Problem Definition/Problem Context – Supply Chain Sector

The majority of the DSCS studies (45 papers) are related to the *manufacturing sector* in general terms, by which we mean that they do no refer to a specific product but they use a standard set of production plants, retailers, etc. to demonstrate the application of distributed simulation. Eleven papers describe a supply chain in the *semiconductor industry*. The *automobile industry* closely follows with 10 papers of which 40% are real case studies. The *logistics* category has nine papers that are related to logistics network and the transportation part of the supply chain. In our *healthcare category* we have four papers and this is followed by sectors pertaining to *aerospace, business, computers and energy* – each of which has two papers. Finally, we have identified more than 20 other categories that are referenced by only one paper; these include industries pertaining to *food, chemicals, petroleum, railways, robotics* and *e-Commerce*.

5.6 Problem Definition/Problem Context – Supply Chain Echelons

The papers name from 2 to 7 echelons in the supply chains which describe. By echelons we mean the number of stages present in a supply chain, for example, supplier, assembly facility, distribution and retailer are examples of such echelons. We have identified the number of echelons from the problem context that is presented in the DSCS papers. In each of these echelons more than one actor/player may exist. Most papers report between two to four echelons and since a good portion of the papers refer to the supply chain with generic data they provide nonspecific echelons, e.g., *customers-suppliers*; *company A, company B*; *supplier-manufacturer-distributor-retail-consumer*. Papers which present detailed description of the supply chain sector (unlike, for example, the general reference to the manufacturing sector – refer to section 5.5) usually provide specific details related to the echelons, e.g., *blood service - hospitals*;

wafer fab - assembly & test-fulfillment - center-warehouse - customers; *source – sawing – drying – finishing – delivery – customer*. Finally, the minimum number of echelons identified is two and the maximum is seven.

5.7 Problem Definition/Problem Context – Real World Problem and Stakeholder Involvement

The next variable refers to papers which describe a clearly defined real world problem, i.e. the analysis of a specific or representative supply chain scenario or DSCS research strongly motivated by a specific or representative supply chain scenario. In our dataset we identified 18 articles that identify a real world problem. This is 16% of the dataset. Extending this further, we then classified on the basis of a clearly identifiable stakeholder (i.e. a specific supply chain). 10 articles were identified (9% of the dataset). These figures could indicate that most DSCS research is not relevant to the real world. However, DSCS research ranges from analyzing supply chain issues to the development of the underlying technology to support DSCS. Many of the articles in our dataset fall into the latter category and present useful research results that contribute towards generalizable DSCS approaches. Many of these do motivate their research general overviews of supply chain issues. A positive view of this could be that these articles represent important groundwork towards a general approach. A negative view could be much DSCS research is irrelevant and misinformed as it does not address real world supply chain issues. In most fields one might expect research articles to address a balance of theoretical and practice issues. A review of real world impact of simulation papers published in leading simulation, Operational Research and Manufacturing journals (Taylor, et al. 2009) found that 10% of the articles were motivated by real world problems and had clearly identifiable stakeholders. This shows that although 16% appears to be low, comparing this figure to the wider survey shows that this figure is slightly better. The same is true for stakeholder involvement. One might therefore conclude that DSCS research is as applied as wider simulation research.

5.8 Model Development and Implementation – M&S Techniques

The majority of M&S techniques used in the context of DSCS are DES, ABS and SD. The vast majority of the papers report DSCS with the use of DES (61 papers), this is followed by ABS with 21 papers. SD is only identified in four DSCS studies and only as a hybrid method together with DES. There is also one example of a hybrid model using DES and ABS. Two studies have identified simulation games for training and perti-nets. Finally we have identified single occurrence of studies that have used symbiotic simulation, numerical optimization, simulation-optimization and interoperable simulation.

5.9 Model Development and Implementation – Distributed Simulation Middleware

A distributed simulation middleware is a software component that implements the conservative and optimistic algorithms to achieve synchronization between the individual running simulations. Examples of such middleware include, Aggregate Level Simulation Protocol (ALSP) (Wilson and Weatherly 1994), Distributed Interactive Simulation (DIS) (Miller and Thorpe 1995), IEEE 1516 High Level Architecture – Run Time Infrastructure (HLA-RTI) (IEEE 2010), FAMAS (Boer 2005), GRIDS (Taylor et al. 2002) and CSPE-CMB (Mustafee 2004). For the purposes of the study presented in this paper, we do not discriminate among the alternative distributed simulation frameworks that may have been used to model supply chains. However, we would like to draw the readers' attention to a few of our observations: (a) Distributed simulation middleware like ALSP and DIS have been used widely in defence training simulations. However, there has been no reported application of these technologies to civilian simulations; (b) The HLA, although originally proposed to address the need for interoperation between existing and new simulations within the U.S Department of Defense, is now generally accepted as the de-facto standard for distributed simulation. It is now an IEEE standard. There are several examples of using the HLA standard and the accompanying middleware (HLA-RTI) for creating distributed simulation in the civilian sector; (c) Several middleware have been developed in the academia with the objective of facilitating distributed simulation in the industry, e.g., GRIDS, CSPE-CMB and FAMAS . However, much of this software is developed for a specific project and is not available for download. One exception to this is the Service-Oriented HLA-RTI (Pan et al. 2007), SOHR for short, that has been developed by the Parallel and Distributed Computing Centre (PDCC), Nanyang Technological University, Singapore.

5.10 Outcome of the Study – Agenda for Future Research

We have identified a total of 87 papers that report future work (approximately 77% of the 113 papers analyzed). Information pertaining to future work was collected by reading the concluding section of the papers and by a full-text search of the keyword *'future'* (in the context of future work). The work that was reported was either general/broad-ranging (e.g. grand challenges, new research direction, inter-disciplinary research, methodological improvements applicable to a field, new tool/language development) or they were specific to work being reported by the authors (e.g. extension/enhancement to the algorithm/architecture presented, further implementation of research artefact, further experimentation and validation, extending the modelling approach to a larger supply chain with more players involved, application of the proposed approach to other problems in either the same domain or a different domain). A quarter of the papers report both general and specific future research in their concluding sections. A frequently repeated future direction for research is on the need for further work aimed at improving time synchronization algorithms.

6 CONCLUSION AND FUTURE WORK

We hope that our literature review in DSCS will be a useful source of reference for researchers, stakeholders in supply chains, simulation practitioners, distributed systems' programmers, etc. as to the *state of the art* in distributed simulation of supply chains. We hope that this would enable those interested in modelling such supply chains to refer to the existing studies with the objective of identifying the most suitable modelling techniques, the underlying technologies and the expertise required and its potential advantages. This utility derives not only from general observations about the resulting statistics, but also from questions that arise and which may need to be considered as the research in distributed simulation in the industry continues to evolve. The limitations and the trade-offs associated with this distributed modelling approach must be realized and meaningful solutions should to identified for overcoming the barriers that leave this technique still unutilized by the industry.

Future work relates to the analysis of additional variables that have already been collected for the purposes of the literature review. We hope to present these results in a subsequent publication. Some of the variables that we will be analyzing are as follows (please refer to variable category information presented in section 4):

- *General Metrics* – variables pertaining to the stage of the M&S study that is identified in the DSCS papers (for e.g., does the study present a conceptual design, implementation, experimental scenario, case study?), clustering of papers based on emerging research themes, technologies, research groups, etc.
- *Model Development/Implementation* – variables which have captured data on the tools and programming languages that have used for the implementation of distributed simulation middleware, interfaces between middleware and COTS simulation packages, the test beds that have been used for executing the experiments, etc.
- *Outcome of the Study* – the contribution of the study, solution implementation.

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