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Integrated Methodological Frameworks for Modelling Agent-Based Advanced Supply Chain Planning Systems: A Systematic Literature Review

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Abstract. This paper provides a systematic literature review of recent developments in methodological frameworks for the modelling and simulation of agent-based advanced supply chain planning systems. As this is a novel and promising domain with little epistemological organisation, we first propose a taxonomical classification of the main techniques and approaches employed in the field. Special attention is given to the methodological aspect of the above-mentioned systems, since they are normally implemented directly from pre-stated requirements with little explicit focus on system analysis, specification, design and implementation in an integrated manner. The second contribution of this work is a comparison of selected works by research topics, also identifying their main limitations. Among sixty suitable manuscripts identified in the primary literature search, only seven explicitly considered the methodological aspect. In addition, we noted in general terms that the notion of advanced supply chain planning is not considered unambiguously, that the social and individual aspects of the agent society are not taken into account in a clear manner in several studies and that a significant part of the works are of a theoretical nature, with few real-scale industrial applications. An integrated framework covering all phases of the modelling and simulation process is still lacking in the visited literature. We hope that our findings can contribute to open the door for new and innovative researches in this emerging field.

Keywords. Supply chain management, advanced supply chain planning systems, agent-based modelling and simulation, methodological frameworks.

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1 Introduction

The Supply Chain Management (SCM) paradigm is widely discussed today in virtually all industry sectors. A supply chain (SC) is a network of autonomous or semi-autonomous companies responsible for raw materials extraction, the transformation into intermediary and finished products, as well as the distribution and delivery to final consumers (Lee & Billington, 1993). These systems encompass several characteristics that render them quite intricate, according to the complexity's theory.

In order to cope with this complexity, modelling and simulation techniques are frequently used to understand these systems and to propose the best way to exploit them. For example, scientists and practitioners are modelling and simulating supply chains to deal with problems related to: dynamic scheduling and shop floor job assignment, planning and scheduling integration problems, supply chain coordination problems, supply chain dynamics problems (Lee & Kim, 2008), information sharing, supply chain control structures, intelligent behaviour of supply chain members, evaluation of supply chain push and pull strategies, autonomy of supply chain partners and problem-solving algorithms and methods, among several other possibilities described in the literature.

In an attempt to model and simulate these problems, many techniques emerged since the 1950's. Santa-Eulalia, D'Amours, Frayret and Azevedo (2009a) reviewed the state of the art of modelling and simulation techniques for capturing the complexity of supply chain systems. In this work, fourteen different modelling and simulation approaches were identified and organized into a novel taxonomy. One of the most preeminent categories identified is called multi-agent systems. Derived from Artificial Intelligence, this technique provides an innovative way to model and treat supply chain management problems.

To extend this previous study, this paper reviews the literature related to agent-based systems for SCM. To do so, a new taxonomy classifying different methodological frameworks for modelling SCM problems was created. This taxonomy identifies that several dissimilar methods are being employed to represent agents in a SC since the 1990's, as it will be explained in the next subsection. The present work focuses on a specific category of this taxonomy which models "agent-based systems" to perform "advanced SC planning". These agent-based systems are defined here as d-APS (distributed Advanced Planning and Scheduling systems), as proposed by Santa-Eulalia, D'Amours and Frayret (2008).

These systems represent an emergent domain, arising from the convergence of two fields of research. The first field deals with APS systems, proposing a centralized and hierarchical perspective of supply chain planning, generally treating a single company's supply chain operations planning system. The second field concerns agent-based manufacturing technology, which entails the development of distributed software systems to support the management of production and distribution systems. APS systems employing agent technology (hereafter d-APS) propose mechanisms that overcome some of the limitations of traditional APS systems mainly related to: i) the inability to create sophisticated simulation scenarios (i.e., APS only proposes what-if analysis of part of the SC); and ii) the limitation in modelling distributed contexts to capture important business phenomena, like negotiation and cooperation (Santa-Eulalia et al., 2008).

In the domain of d-APS systems there is an important research gap (Govindu & Chinnan, 2010; Santa-Eulalia, Ait-KAdi, D'Amours, Frayret & Lemieux, 2011; Santa-Eulalia, 2009), which limits researchers in fully taking advantage of simulations: in this area, simulations are normally developed and implemented directly from pre-stated requirements with little explicit focus on system analysis, specification, design and implementation in an integrated manner. Several works exist to specify and design agent-based simulation for SCM, but few approaches exist that integrate the whole development process. Moreover, the methodological aspects are not usually exploited explicitly. This results in a typical problem in agent-based systems, i.e. the engineering divergence phenomenon (Michel, Gouaïch & Ferber, 2003), where the conceptual model is incomplete or inadequate in different ways, consequently yielding outputs that are different from the stakeholder's real requirements for simulation.

In this sense, this paper aims to organize and identify the main recent advances in the domain of methodological frameworks. This will contribute to systematize and consolidate what has been done in the last years and also uncover possible interesting research gaps for future studies in this emerging field. In order to do so, a systematic approach is employed so as to guarantee a rigorous, transparent and reproducible procedure aiming to identify, select and make an analysis and a critic summary of all suitable studies that deal with this promising research area.

This paper is organized as follows. First, section 2 presents two taxonomies organizing the modelling and simulation techniques for SC, with a special attention to agent-based methodologies. Section 3 puts forward the research methodology employed. Section 4 presents the main results of this study and finally, section 5 outlines some discussions and final remarks.

2 Supply Chain Modelling and Simulation

”Modelling and simulation is the use of models, including emulators, prototypes, simulators, and stimulators, either statically or over time, to develop data as a basis for making managerial or technical decisions. The terms "modelling" and "simulation" are often used interchangeably” (DoD, 1998).

Many efforts for modelling and simulating SC systems have been made since the 1950’s. Santa-Eulalia et al. (2009a) proposed a taxonomy to organize the literature review on modelling and simulation techniques for supply chains. It represents how we understand the domain and it divided as follows:

- *SC Simulation*: represents essentially descriptive modelling techniques, in which the main objective is to create models for describing the system itself. Modellers develop these kind of models to understand the modelled system and/or to compare the performance of different systems. Several techniques were surveyed, including System Dynamics (Kim & Oh, 2005), Monte Carlo Simulation (Biwer & Cooney, 2005), Discrete-Event Simulation (Van Der Vorst, Tromp, & Van der Zee, 2005), Combined Discrete-Continuous techniques (Lee & Liu, 2002) and Supply Chain Games (Van Horne & Marier, 2005).

- *SC Optimization*: refers to normative models, i.e. models that suggest how the system should or ought to be. Modellers develop these kinds of models mainly to discover the ideal situation concerning the modelled system (optimal behaviours). Examples of the studied techniques include Multi-Echelon Inventory Systems (Ng & Piplani, 2003), Classic SC Optimization (Ouhimmou, D’Amours, Beauregard, Ait-Kadi, & Chauhand, 2008), and Statistical Analysis-Based and Non-Parametric Optimization (Chen, Yang & Yen, 2007). There are also a set of Statistical Analysis-Based techniques, which are divided into Combined Optimization – Monte Carlo (Beaudoin, Lebel & Frayret, 2007), Business Games (Moyaux, Chaib-draa, & D’Amours, 2007), Stochastic-Programming based (Kazemi, Ait-Kadi & Nourelfath, 2010) and Fuzzy Logic Based techniques (Ganga, 2010).

- *Basic Hybrid Approaches*: it is interesting to note that in between Simulation techniques and Optimization approaches, there is a basic hybrid approach called Simulation Optimization. This technique combines characteristics of both SC Simulation (i.e., descriptive models) and SC Optimization (i.e., normative models), and it is being largely discussed in the literature.

- *Artificial Intelligence*: descriptive and/or normative models, used to create models that try to mimic systems including the human behaviour for supply chain management. Modellers employ these models for describing the system, (most of the applications available in the literature) or for optimizing it, or both (like the system proposed by Frayret, D'Amours, Rousseau, Harvey & Gaudreault, 2007). This approach is explained in details in the next sub-section.

In addition, it is important to mention that there are other techniques in the literature, but they are not very common in the surveyed works. Some examples are spreadsheet simulations (Kleijnen, 2005; Chwif, Barretto & Saliby, 2002), mental simulations (Escalas, 2004; Penker & Wytrzens, 2005), case base reasoning (Kwon, Im & Lee, 2005), and traditional Queuing models (Amouzegar & Moshirvaziri, 2006). For more details about these techniques, the reader is referred to Santa-Eulalia et al. (2009a).

2.1 Multi-Agent Systems for Supply Chain Planning

From the artificial intelligence field a set of techniques fall under the umbrella of multi agent-based systems. They model systems that are composed of distributed interacting intelligent entities, called agents, which solve problems that are difficult or simply impractical for a monolithic model to solve. In this context, diverse agents work together and interact with one another to accomplish some tasks. All of the agents use their abilities and knowledge to strengthen the problem solving capacity of the whole planning system. Due to this distinctiveness, such a system is of great utility to help solving problems based on multiple methods and that have multiple perspectives (Jarras & Chaib-draa, 2002).

Multi-agents systems employ mechanisms from distributed artificial intelligence, distributed computing, social network theory, cognitive science, and operational research (Tweedale, 2007; Samuelson, 2005). Examples of these mechanisms include autonomy, pro-activeness and social ability, for example. The social capability is quite interesting in this domain; examples of these abilities include cooperation, coordination and negotiation.

In this context, software agents in SCM generally embed one or more techniques from SC Optimization and SC Simulation to support operations planning or simulation. However, agents usually go beyond by also embedding negotiation protocols (Forget, D'Amours, Fayret & Gaudreault, 2008; Dudek & Stadtler, 2005) or learning algorithms (Carvalho &

Custodio, 2005; Emerson & Piramuthu, 2004) to address other issues, such as coordination in distributed and complex contexts.

Agent-based approaches for SCM are not new. Since the early 1990's, several developments targeted the context of distributed decision-making across the supply chain using agent technology. For example, the pioneering work of Fox, Barbuceanu, Gani and Beck (1993), followed by others like Parunak (1998), Swaminathan, Smith and Sadeh (1998), Strader, Lin and Shaw (1998) and Montreuil, Frayret and D'Amours (2000), just to mention a few, have led to significant advances in the area. Nevertheless, the notion of APS systems is generally not explicitly treated. In other words, these works do not clearly address the integration of advanced planning functions with the notion of agents. Basically, APS systems address various functions of supply chain management, including procurement, production, distribution and sales, at the strategic, tactical and operational planning levels (Frayret et al., 2007; Stadtler, 2005). These systems stand for a quantitative model-driven perspective on the use of IT in supporting SCM to exploit advanced analysis and supply chain optimization methods.

More recently, agents embedding APS tools and procedures appear to consider these issues more explicitly (Santa-Eulalia et al., 2008). Defined here as d-APS, these systems model the supply chain as a set of semi-autonomous and collaborative entities acting together to coordinate their decentralized plans. The use of agent technology extends traditional APS in order to tackle negotiation and complex coordination issues. In this sense, d-APS systems may provide more modelling functionalities, hence permitting to capture a higher level of complexity in comparison with classic APS systems.

Another interesting advantage of d-APS systems is related to simulation. Agents are largely used for simulation since they naturally model the simultaneous operations of multiple agents, in an attempt to re-create and predict the actions of complex phenomena. Thus, simulating actions and interactions of autonomous individuals in a supply chain and with the possibility of assessing their effects on the system as a whole is one interesting property of this system.

To conceive, implement and use d-APS systems, a set of modelling frameworks has been proposed in the literature, as discussed in the next sub-section.

2.2 Modelling Frameworks for Agent-Based Advanced Supply Chain Planning

A set of frameworks or methodological approaches can be employed for modelling a simulation environment, varying from traditional development approaches to specific agent-oriented supply chain planning approaches. Figure 1 organizes our literature review of the main approaches that could be useful for modelling a d-APS system. This tree-classification schema adapts and extends the categorization of Bussmann, Jennings and Wooldridge (2004).

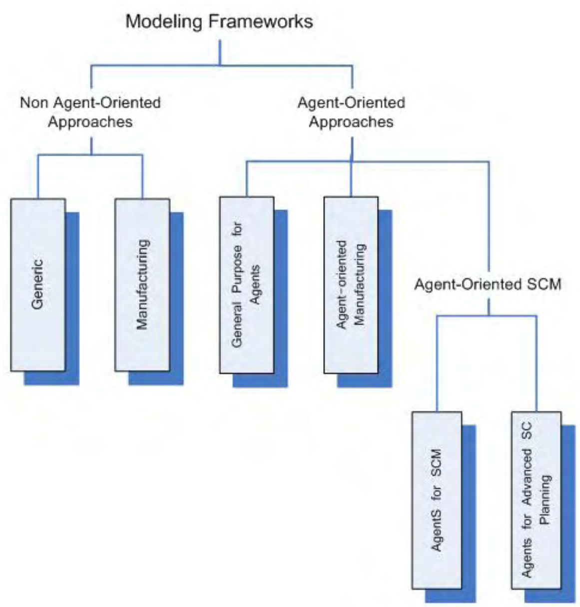

Figure 1: Modelling approaches for agent-based advanced supply chain planning.

The following categories are proposed:

- Non Agent-Oriented Approaches: refers to modelling paradigms that can be used to model diverse systems, including agent-based systems, without explicitly considering agents societies. Examples of this category include Generic Approaches such as Data-Oriented Approaches (e.g. Jackson, 1975 apud Bussmann et al., 2004), Structural Approaches (e.g., DeMarco, 1978 apud Bussmann et al., 2004)] and Object-Oriented Approach (e.g., Chatfield, Harrison & Hayya, 2006). A set of Manufacturing-oriented approaches also exists, with modelling frameworks that vary from modelling formalisms (e.g., SADT/IDEF – Structured Analysis and Design Technique/Integrated Computer Aided Manufacturing Definition – or Petri-Nets approaches) to complete modelling architectures (Vernadat, 1996) (e.g., CIMOSA – Computer Integrated Manufacturing Open System Architecture) derived from the field of Enterprise Integration.

- Agent-Oriented Approaches: Conventional methodologies have proven unsuitable for engineering agent-based systems (Karageorgos & Mehandjiev, 2004; Monostori, Vancza & Kumara, 2006). In this sense, Agent-Oriented Approaches (Brugali & Sycara, 2000) explicitly take into consideration the notion of agent. At this level, two generic classes exist: General Purpose for Agents [e.g., Tropos (Giorgini, Kolp, Mylopoulos & Pistore, 2003), Prometheus (Padgham & Winikoff, 2002), MaSE (Wood & DeLoach, 2000), Gaia (Wooldridge, Jennings & Kinny, 2000), MAS-CoMoMAS (Iglesias, González & Velasco, 1998)], which were developed for creating agent-based systems by explicitly incorporating concepts such as autonomy, reactivity, proactivity, and sociability; and Agent-Oriented Manufacturing, which provides more explicit guidelines for the identification of agents in production control, but not necessarily dedicated to supply chain problems (e.g., Nishioka, 2004; Bussmann et al., 2004; and Parunak, Baker & Clark, 2001). Although these kinds of approaches are interesting for creating simulation models for our proposed domain, they are not dedicated to the SCM context.

Derived from the Agent-Oriented Approaches, a set of techniques appears to explicitly create agents for SCM activities. Named Agent-Oriented SCM approaches, this category can be divided into:

- Agents for SCM: Agents are dedicated to supply chain management but are not specialized in the advanced planning domain. Examples of relevant projects in this domain are Labarthe, Espinasse and Ferrarini (2007), Chatfield, Hayya and Harrison (2007), Van der Zee and Van der Vorst (2005), Cavalieri, Cesarotti and Introna (2003), MaMA-S (Galland, Grimaud, Beaune & Campagne, 2003; Galland, 2001), NetMAN (Montreuil et al., 2000), ISCM (Fox, Barbuceanu & Teigen, 2000 and Fox et al., 1993), MCRA (Ulieru, Norrie & Kremer, 2000; Wu, Cobzaru, Ulieru & Norrie, 2000), CASA/ICAS (Shen & Norrie, 1999), DASCh (Parunak, 1998; Parunak & VanderBok, 1998), Strader et al. (1998) and MAIS-Swarm (Lin, Tan & Shaw, 1998). A detailed and recent comparative discussion about agent-based systems for supply chain management can be found in Monteiro et al. (2008).

- Agents for Advanced SC Planning: derived from Agent-Oriented SCM approaches, they explicitly mention the use of optimization procedures or finite capacity planning models when performing supply chain planning. The following projects can be classified as being examples of this category: Santa-Eulalia, D'Amours and Frayret (2010), Egri and Vancza (2005), SNS (Baumgaertel & John, 2003), Lendermann, Gan and McGinnis (2001), Gjerdrum, Shah and Papageorgiou (2001), MASCOT (Sadeh, Hildum, Kjenstad & Tseng, 1999), ANTS (Sauter, Parunak & Goic, 1999) and Swaminathan et al. (1998).

This work focuses on the last category of the proposed taxonomy. Special attention is given to the methodological aspects of these frameworks, as explained in the next subsection.

2.3 Methodological Aspects of the Modelling Frameworks

One important element of these modelling frameworks refers to the methodological aspect. From the software engineering domain, it is known that methodological aspects are quite important, but they are rarely taken into consideration in a clear way in the studied area.

These methodological aspects include procedures and steps for developing a system. For example, a traditional way of developing a system from a software engineering point-of-view is called the waterfall approach (Pfleeger & Atlee, 2006), whereas a set of stages are depicted as cascading from one to another. These stages are analysis, specification, design, implementation, integration and maintenance. Derived from software engineering, specific approaches for agent-based software engineering appeared more recently (Dam & Winikof, 2004). For example, MaSE (Wood & DeLoach, 2000) which was originally inspired from object-oriented approaches now proposes a complete lifecycle methodology, consisting of seven iterative steps, divided into the initial system analysis and the design. An example of a recent work employing an "Agents for SCM" approach with methodological concern is Govindu and Chinnam (2010). It proposes a method for the analysis and design of multi-agents supply chain systems by integrating the Gaia methodology and the Supply Chain Operations Reference (SCOR) model. Specific works dealing with the methodological aspects will be discussed in section 4.

Now it is possible to position the present work in relation to the concerned literature. This paper focuses on new developments in the "Agents for Advanced SC Planning" area, with a major attention on methodological aspects. As it will be discussed later, this area is emerging fast and several interesting research gaps still exist.

Before presenting the main results in section 4, the next subsection summarizes the research methodology employed in this work.

3 Methodology

This section presents the general organization of a systematic review of the domain of "methodological frameworks for modelling d-APS systems". A systematic review is a review following a rigorous, transparent and reproducible procedure aiming to identify, select and make an analysis and a critic summary of all suitable studies that deal with a clearly defined question (Becheikh, 2005). Its origin was in the medical science, but it can be adapted to different domains. For example, it has recently been used in software engineering and management science.

Based on Becheikh (2005) and Kitchenham et al. (2009), the following phases were defined for the present work:

- Problem formulation: this study consists of a systematic literature review concerning scientific papers and technical reports published between 2007 and 2010 on the selected topic, i.e. on methodological frameworks for agent-based advanced supply chain systems. The last four years were covered to identify only recent advances in the field, as a previous literature review on the domain was provided by Santa-Eulalia (2009) covering the period from 1993 to 2007. The main research questions addressed by the present study are:

  Q1: How many works related to Agent-Based Supply Chain Planning systems and their methodological aspects has there been in the past four years?

  Q2: What research topics are they addressing (e.g., planning, scheduling, control, supply, distribution, etc.)?

  Q3: How many papers explicitly employ methodological aspects (see subsection 2.3) in their work?

  Q4: Are the frameworks explicitly addressing the APS functions and modules?

  Q5: Are social and individual aspects of their agents explicitly considered?

  Q6: What are the identified main limitations of these studies?

  Q7: What are the required research advances in the domain?

  Q8: Which methodological aspects are covered and which are not in the literature?

- Search strategy: the search was performed in digital works only and in the English-speaking literature. The inclusion criteria comprised i) scientific peer-reviewed articles, published in a peer reviewed journal or conference or ii) technical reports, from well established research groups, companies or professional societies. The databases employed were Academic Search Premier, Business Source Premier, Google Scholar, ABI-Inform, Proquest and SCOPUS. The final result of this stage was a list of potential articles that had to be analysed.

- Selection and evaluation of the articles: Figure 2 schematizes this process. The primary literature search (step 1) yielded 60 papers. Of these, 26 were excluded since they did not focus on agent-based systems for advanced SC planning (d-APS, as defined previously), and one was eliminated because the reference was found, but not the full paper. A search from the reference lists of relevant studies lead to eight additional studies, which were included in the review process in step 2. In addition, two references already known by the authors but not spotted by the primary search were included manually. From the 34 publications that reached step 2, 27 were eliminated because they did not present specific methodologies for modelling d-APS systems, and 7 were further evaluated in step 3. Step 2 produced a comparative table of all agent-based systems for SC planning and step 3 produced a specialized table on modelling frameworks for d-APS systems.

- Finalisation: information extraction and organization, as well as findings statement, implications, and recommendations (also for steps 2 and 3).

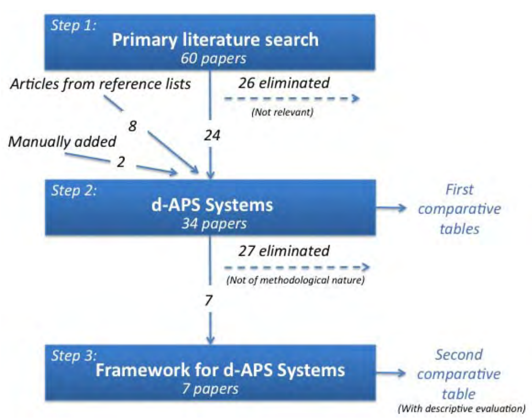

Figure 2: Papers search process.

It is important to explain the difference between step 2 and step 3. First, papers are compared in step 2 (d-APS systems) using a general description of each work. On the other hand, a specific descriptive evaluation is performed at step 3 (Frameworks for d-APS Systems) as this work is primarily concerned about the methodological aspects of the papers.

Diverse approaches from different disciplines exist for evaluating frameworks of software engineering methodologies. Together with the evaluation of general aspects, the Karageorgos and Mehandjiev (2004)'s approach was employed, inducing a descriptive evaluation method for the specific aspects of agent-based methodologies. This method includes arguing for or against certain characteristics of the evaluated framework without actually applying it, which is useful for discovering some weaknesses in the method, e.g. when desirable features are not supported. It comprises four different conceptually linked views: concepts, models, processes and pragmatics. The framework is summarized in Table 1.

View	Aspect
Concepts: concentrates on which modelling concepts are used.	**Concept definition**: refers to restrictive premise concerning the agent based architecture and type/class of agents that can be produced using the methodology. Methodologies can be classified as being open (no consideration for a particular agent architecture), bounded (consideration for specific architectures, such as BDI – beliefs, desires and intentions) or limited (highly bounded). It is preferable for a method to be open. **Design in scope**: considers whether a methodology includes steps and guidelines for the engineering lifecycle. It can be true or false. **Heuristics support**: considers whether the methodology provides a formal support for applying heuristics guidelines and tips for engineering a system. This formal support can be, in extreme cases, used to provide automation of the engineering process. It can be true or false.
Models: denotes the models used to represent different parts of the system.	**Organization settings**: concerns whether organization settings (e.g., agents' roles) are explicitly considered as design constructs. Can be true or false. **Collective behaviour**: considers whether the approach includes first-class modelling constructs to explicitly represent collective agent behaviour or not. Can be true or false. **Non-functional aspect**: regards whether non-functional aspects are explicitly considered or not. Can be true or false.
Processes: concentrates on steps that are executed to construct the model.	**Design perspective**: refers to the perspective from which the methodology is used. Can be top-down, bottom-up, or both. **Support for reuse**: considers whether the methodology supports the use of previous knowledge. It can be, for example, guidelines for creating, storing and reusing knowledge. Can be true or false. **Design automation**: concerns whether there are formal underpinnings enabling, to a certain extent, automation, and which steps could be carried out by a software tool. Can be true or false.

Pragmatics: evaluates how practical the method is for engineering real-world agent systems.	**Generality**: evaluates whether the methodology is based on restrictive premises concerning the environment and the application domain. Can be characterized as high (a generic method), medium (there are considerable restrictions, but the methodology is still wide) or low (applied for specific domains). High generality results in lower design complexity since it is easier to apply it to diverse domains. **Abstractability**: considers whether there is support to enable work at different levels of abstraction, which is considered by the authors as one of the main factors affecting design complexity. Can be true or false. **Tool support**: concerns whether the approach provides tools supporting the realization of the method, e.g. agent-based toolkits, or CASE tools. Can be true or false.

Table 1: Summarizing the Karageorgos and Mehandjiev (2004)'s framework.

Next section presents the main results of the systematic research.

4 Results

According to the research strategy defined in the last section, the research results are organized in two blocks. First, a general search (step 2) was performed covering works dealing with supply chain planning using agent-based approaches, i.e. the last category of the taxonomy described in subsection 2.2. Afterwards, the previous search was specialized in order to identify those works explicitly containing methodological aspects for modelling agent-based systems (step 3). These two research blocks are explained in the next two subsections.

4.1 Agent-Based Supply Chain Planning

34 papers dealing with d-APS systems were selected for a general comparative study. In order to evaluate theses manuscripts, some criteria were defined, according to the research questions listed in Section 3.

First of all, the studied papers were classified depending on the supply chain problem treated. Diverse problems were studied, ranging from SC planning, scheduling, collaboration to lot-sizing.

The second criterion indicated whether the work was applied or not. Papers can be theoretical (T), applied (A), or both (TA). Applied papers employ theoretical developments in real cases by providing proof-of-concepts cases, for example. To complement this discussion, the industry sector mentioned in each applied work was also surveyed. To our concern, it is important to know whether these new advances are reaching the industry or if they are mostly of a laboratorial nature.

Next, it was identified whether specific implementation toolkits that enable individuals to develop agent-based applications, such as NetLogo, Swarm, Repast, AnyLogic, Maillorca, JADE and others, were employed. This helped to identify if modelling toolkits were associated to any methodological development.

Another important criterion employed refers to the methodological aspects of the frameworks. As the main objective of this work is to treat this aspect, it was verified whether they were explicitly considered. Papers are identified as “Yes” when they put forward the methodological aspects (in this case, the kind of contribution they provide is indicated), as “Some” when only a few elements are considered, or “NI” (i.e., not identified) when it was not possible to detect this criterion for the studied work.

The notion of APS being clearly treated in the paper was also verified, such as when the authors noticeably identify a set of modules/applications/functionalities/agents for planning and scheduling supply chains. These elements can be at different decision levels (strategic, tactical, operational, control), for different parts of the supply chain (procurement, production, distribution, sales), from the source of raw material to final consumption and return (Stadler, 2004). Again, the notation “Yes”, “Some” and “NI” was employed. This allowed us to identify whether a complete analysis of APS systems was conducted, or if the planning and scheduling approaches were treated partially for specific/dedicated problems.

Finally, two additional criteria related to agents’ society were surveyed. The first one refers to social aspects, which are associated with how the society is organized (for example, using autonomous, federated, or hierarchical societies – Shen, Norrie & Barthès, 2001) and what the agent’s relationships are. Also, social aspects can be related to social protocols, i.e. a set of rules governing connections between agents, defining syntactic, semantics and approaches for synchronizing interactions. The second agent-based criterion refers to individual aspects of the society. They stand for different individual roles that agents can play within the society, such as planning and scheduling, controlling, learning, knowledge management, interfacing, and so forth. Sometimes individual aspects comprise internal agent architectures. The objective in analysing social and individual aspects is to identify if the agent paradigm is really employed, or if it is employed arbitrarily or partially. Again, the notation “Yes”, “Some” and “NI” was used.

The next four tables (Table 2, Table 3, Table 4, and Table 5) summarize the main findings of this first research bloc according to a chronological sequence.

Authors	Approach /Project	Contribution	SC problem	Theoretical or Applied	Application Sector	Specific Implementation Toolkit	Methodological approach	APS modules	Social Agent Organization	Individual Agent Organization
Andreev et al. (2007)	Adaptive Planning Toolset	An architecture for performing an adaptive SC planning	SC Planning	TA	Airport logistics, factory planning, laundry scheduling and pharmaceutical logistics	NI	NI	NI	NI	NI
Andrews, Benisch, Sardinha, and Sadeh (2007)	NI	Inspection of games from one bracket of the 2006 TAC (Trade Agent Competition) semi-finals in order to isolate behavioural features that distinguished top performing agents in this bracket	SC Planning (requests to suppliers, offers to customers, and a production plan)	T	NI	NI	NI	NI	NI	NI
Chen and Wei (2007)	SCMAS (Supply Chain Multi-agent Systems)	A multi-agents architecture dedicated to negotiation and to production planning and dynamic scheduling	SC Scheduling; Negotiation	T	Computers industry	Yes (JADE)	NI	NI	Some (a negotiation approach is proposed)	Some (agents have defined individual roles)
Feng, Helaakoski, Jurrens and Kipinä (2007)	SteelNet	A coalition framework for business and manufacturing networks comprising an ontological engineering environment and a multi-agents architecture. The d-APS is just part of a larger architecture, including other elements such as CAPP and CAM, for example	Manufacturing and SC Integration	T	Steel products	Yes (JADE)	NI	NI	Some (some interaction mechanism are studied)	Some (an internal agent architecture is proposed)
Frayret et al. (2007)	The experimentation on planning platform	A generic software architecture for development of an experimentation environment to design and test distributed advanced planning and scheduling systems	SC planning	TA	Forest products industry	No (C# - Microsoft.NET - and with ILOG CPLEX and ILOG SOLVER)	NI	Yes (agents are specialized in different APS planning areas)	Some (some agents interactions protocols are identified)	Some (agents planning capabilities)
Ivanov and Kaeschel (2007)	Decentralised Integrated Modelling Approach (DIMA)	Multi-disciplinary approach to model flexible application of various modelling frameworks (analytical, simulation and heuristics) as well as their combinations in the context of agile production networks.	SC Integration - named collaborative and agile networks	T	NI	NI	Some (some methodological aspects are considered, as the definition of conceptual models, mathematical models and simulation tools)	NI	Yes (some general schema of agents interactions)	Yes (some functional agent model for describing active elements)

Table 2: Studied works for the year 2007.

Authors	Approach/Project	Contribution	SC problem	Theoretical or Applied	Application Sector	Specific Implementation Toolkit	Methodological approach	APS modules	Social Agent Organization	Individual Agent Organization
Ivanov, Arkhipov and Sokolov (2007)	NI	It elaborates principles for creating complex quantitative models for SC and Virtual Enterprises using concepts from control theory, system theory, operations research and distributed artificial intelligence	SC Planning and Control	T	NI	No (partially implemented using C++)	Some (some methodological aspects are considered, as the definition of conceptual models, mathematical models and simulation tools)	NI	NI	Some (meta-models for SC planning and control)
Jankowska, Kurbel and Schreber (2007)	Mobile Agent-based SCEM System (MASS) SCEM stands for Supply Chain Event Management	An architecture for a mobile SC event management system based on mobile agents, Auto-ID technologies and mobile computing for linking SC planning and SC execution	SC Planning and Execution (SC Event Management)	TA	Bicycle Industry, but no details are provided	Yes (JADE)	NI	NI	NI	NI
Labarthe et al. (2007)	NI	An agent-based methodological framework for modelling and simulation of SC	General problems related to SCM	TA	Golf club industry	Yes (AnyLogic and Majorca)	Yes (the proposed framework is of methodological nature)	NI	Yes (a specific interaction schema is proposed - structural and dynamic model)	Yes (agent roles - cognitive and reactive - are explicitly defined)
Lee and Kumara (2007)	NI	A decentralized coordination approach for dynamic lot-sizing in distribution networks	Coordination, information sharing and lot-sizing in distribution networks	T	NI	No (they used a Discrete-Event Simulator - not identified - and LINDO)	NI	NI	Some (coordination mechanisms based on auctions/bidding strategies)	Some (a lot sizing approach)
Monteiro, Roy and Anciaux. (2007)	NI	An heterarchical architecture for coordinating decisions in a multi-sites environment	Coordination, SC planning, Negotiation	TA	Bronze tap production system	NI	NI	NI	Some (cooperative negotiation models)	Some (a Planner Agent and a Negotiator Agent)
Orcun et al. (2007)	SCOPE (Supply chain optimisation and protocol environment)	A rapid-prototyping environment for simulating SC planning scenarios employing APS technology	SC planning, collaboration	TA	Consumer packaged goods industry	No (they employed Excel with Visual Basic and Crystal Ball and they also employed ILOG CPLEX)	NI	Yes (Agents are specialized in different APS planning areas)	NI	Some (different planning approaches for each agent)
Shin (2007)	Collaborative coordination of distributed production planning (DPP)	Collaborative coordination mechanism/heuristics based on information sharing and on a coordinator/mediator for a distributed system	Coordination, production planning	T	NI	NI	NI	NI	Some (for coordination and collaboration only)	Some (production planning model)

Table 2: Studied works for the year 2007 (continued).

Authors	Approach / Project	Contribution	SC problem	Theoretical or Applied	Application Sector	Specific Implementation Toolkit	Methodological approach	APS modules	Social Agent Organization	Individual Agent Organization
Venkatadri and Kiralp (2007)	DSOPP (Distributed Simulation Order Promising Platform)	An agent-based architecture for order promising in a distributed network employing optimization technology	Order promising, SC planning	T	NI	No (OPL Studio 3.7 and Visual Studio 6.0)	NI	NI	Some (order promising interaction schema)	NI
Yain-Whar, Edmond, Dumas and Chong (2007)	UMTac-04	Comparison of two different strategies in SCM, namely buy-to-build and build-to-order using an agent-based platform in the context of the TAC SCM	SC Planning	T	Computers industry	NI	NI	NI	NI	Some (different planning strategies)

Table 2: Studied works for the year 2007 (continued).

Authors	Approach / Project	Contribution	SC problem	Theoretical or Applied	Application Sector	Specific Implementation Toolkit	Methodological approach	APS modules	Social Agent Organization	Individual Agent Organization
Forget et al. (2008)	Multi-Behaviour Agents for SC Planning	An agent-based model employing multi-behaviour strategies for SC planning, which are able to react differently according to the stimuli from the business environment	SC planning; Coordination	TA	Lumber industry	No (generic programming tools and optimization used ILOG SOLVER and ILOG CPLEX)	NI	NI	Some (two different coordination schemas were studied)	Yes (different agent behaviours for SC planning)
Jung, Chen and Jeong (2008)	NI	A decentralized supply chain planning framework based on minimal-information sharing between the manufacturer and the third party logistics provider	Planning, Collaboration, Information Sharing	T	NI	No (only ILOG-OPL Studio)	NI	NI	Some (a simple information sharing schema)	Some (some decision models for distribution and production planning)
Lau, Li, Song, and Kwok (2008)	NI	A multi-agents system where agents are subject to an adjustable autonomy, which is changed during runtime as a response to uncertainties from the environment. Also, a coalition formation approach is employed to establish global coherence through negotiation	SC adaptability for entities' autonomy	TA	Defence industry	NI	NI	NI	Some (a coalition formation approach)	Some (individuals' autonomy)
Lin, Kuo and Lin (2008)	NegoGA (Negotiation and Genetic Algorithm)	A distributed coordination mechanism that integrates negotiation techniques with genetic algorithm to plan quasi-optimal order fulfilment schedules	Coordination	T	Mould manufacturing	Yes (JADE)	NI	NI	Some (a negotiation approach)	NI
Paolucci et al. (2008)	Supply Chain Operations Planning (SCOP) System	A d-APS framework for Small and Medium Enterprises	SC Planning (S&OP)	T	NI	NI	NI	NI	Some (a bidding approach with a negotiation mechanism based on Contract-Net Protocol)	Some (some decision variables are explicitly used by the mediator)
Santa-Eulalia et al. (2008)	NI	A conceptual framework for modelling agent-based simulation for SC planning	SC planning	TA	Lumber industry	No (generic programming tools and optimization used ILOG SOLVER and ILOG CPLEX)	Yes (The main contribution is of methodological nature)	Yes (the notion of d-APS is identified)	NI	NI

Table 3: Studied works for the year 2008.

Authors	Approach / Project	Contribution	SC problem	Theoretical or Applied	Application Sector	Specific Implementation Toolkit	Methodological approach	APS modules	Social Agent Organization	Individual Agent Organization
Benisch, Sardinha, and Andrews (2009)	CMieux	An agent approach called CMieux in the context of theTAC SCM (Trading Agent Competition). It implements adaptive strategies to support the integration of procurement, bidding and planning functionality. They performed some experiments to demonstrate empirically the performance of their approach	SC planning; Coordination	T	Computers industry	NI	NI	Some (they explain some traditional modules, such as procurement, scheduling, inventory projection and forecasting)	NI	Some (agents mechanism for SC planning)
Cid-Yanez, Frayret and Léger (2009)	(FEPP) FORAC Experimental Planning Platform	Analysis of some demand-driven planning approaches that propagate demand information upstream the supply chain	SC Planning	TA	Lumber industry	No (C# - Microsoft.NET - and with ILOG CPLEX and ILOG SOLVER)	NI	Yes (Agents are specialized in different APS planning areas)	NI	Some (different planning approaches for each agent)
Gaudreault, Frayret, Rousseau and D'Amours et al. (2009)	NI	Three agent-specific mathematical models to plan and schedule a softwood SC composed of sawing, drying and finishing activities. Specific coordination mechanisms are also proposed to assure that the resulting plans are coherent with each others	SC planning; coordination	TA	Softwood lumber	No (C# - Microsoft.NET - and with ILOG CPLEX and ILOG SOLVER)	NI	Some (specific modules for three SC entities at the operational level)	Some (a coordination mechanism)	Some (specific modules for the three SC units)
Ivanov (2009)	DIMA (decentralized integrated modelling approach)	A novel approach for comprehensive multi-disciplinary modelling of distributed large-scale business systems with decentralized decision-making and control.	SC planning and control	T	NI	NI	Yes (a macro approach covering conceptual modelling, mathematical modelling, and software development)	NI	NI	NI
Lemieux, D'Amours, Gaudreault, and Frayret, (2009)	(FEPP) FORAC Experimental Planning Platform	A multi-agents simulation environment for SC planning	SC Planning	TA	Lumber industry	No (C# - Microsoft.NET - and with ILOG CPLEX and ILOG SOLVER)	NI	Some (they developed some operational planning modules)	Some (conversation mechanisms are proposed)	Some (different planning approaches for each agent)
Pan, Leung, Moon and Yeung (2009)	NI	A UML-based modelling approach for representing SC and a genetic algorithm and fuzzy inference mechanism for determining a reorder point in uncertain contexts	Coordination, order promising	T	Fashion industry	No (Matlab)	NI	NI	Some (interactions are indicated in general terms)	Some (a model is created for calculating reorder points)

Table 4: Studied works for the year 2009.

Authors	Approach / Project	Contribution	SC problem	Theoretical or Applied	Application Sector	Specific Implementation Toolkit	Methodological approach	APS modules	Social Agent Organization	Individual Agent Organization
Santa-Eulalia et al. (2009b)	(FEPP) FORAC Experimental Planning Platform	Testing different SC strategies in an agent-based environment	SC Planning and Control	TA	Forest products industry	No (C# - Microsoft.NET - and with ILOG CPLEX and ILOG SOLVER)	NI	Some (Agents are specialized in different APS planning areas)	Some (a coordination mechanism)	Some (different planning approaches for each agent)
Silva et al. (2009)	NI	Proposes a distributed optimization framework for SC planning based on a meta-heuristic called ant colony optimization	Cooperation	TA	Computers industry	No (Matlab)	NI	NI	Some (specific information sharing schemas)	Some (agents dedicated to supply, logistics and distribution were defined)

Table 4: Studied works for the year 2009 (Continued).

Authors	Approach / Project	Contribution	SC problem	Theoretical or Applied	Application Sector	Specific Implementation Toolkit	Methodological approach	APS modules	Social Agent Organization	Individual Agent Organization
Chan & Chan (2010)	NI	An adaptive coordination strategy for improving fill rate while reducing costs without using information sharing	Coordination	T	NI	No (Java)	NI	NI	Some (coordination mechanisms)	Some (decision models for two-echelon SC)
Ivanov et al. (2010)	A-SCM (Adaptive SCM)	A multi-structural framework (models and tools) for the planning and control of adaptive SC using principles from control theory, operations research and agent-based modelling	SC planning, coordination	T	They mention that it was applied to special machinery building and textile branches, but these cases are not discussed in the paper	Yes (Anylogic)	NI	NI	Yes (a multi-structural process)	Some (specific roles and goals of modules)
Karam, Tranvouez, Espinasse and Ferrarini et al. (2010)	NI	A methodological framework for modelling agent-based simulation for SC planning based on conceptual and operational models	General problems related to SCM	TA	Golf club industry	Yes (Majorca and Analogic)	Yes (The main contribution is of methodological nature)	NI	Yes (several interactions possibilities are explicitly mapped)	Yes (different agents' roles are identified conceptually)
Kim & Cho (2010)	NI	Negotiation approach for SC formation using mediators. They compared their approach with a heuristic and centralized one	Negotiation	T	NI	No (C/C++, ILOG CPLEX)	NI	NI	Some (a negotiation approach is proposed)	Some (scheduling models for agents)
Santa-Eulalia et al. (2010)	FAMASS (FORAC Architecture for Modelling Agent-based Simulation Supply Chain Planning)	A methodological framework for modelling agent-based simulation for SC planning applied in the forest products industry	General problems related to SCM and agents	TA	Lumber industry	No (generic programming tools and optimization used ILOG SOLVER and ILOG CPLEX)	Yes (The main contribution is of methodological nature)	Yes (A specific modelling schema is proposed, which is called SC cube)	Yes (a specific modelling schema is proposed)	Yes (a specific modelling schema is proposed)

Table 5: Studied works for the year 2010.

The next sub-sections discuss the main criteria surveyed.

4.2 Main Contributions

Contributions in the domain cover dissimilar topics. For example, several papers propose agent-based architectures (e.g., Frayret et al., 2007; Andreev et al., 2007; Feng et al., 2007; Monteiro et al., 2007; Venkatadri & Kiralp, 2007), some deal with the famous TAC – Trade Agent Competition (e.g., Andrews et al., 2007; Si, Edmond, Dumas & Chong, 2007; Benisch et al., 2009), certain approaches propose coordination and information-sharing mechanisms (e.g., Lee and Kumara, 2007), others focus on mathematical models for agents (e.g., Gaudreault et al., 2009), a number use an agent-based environment only as a testbed to test SC strategies (Cid-Yanez et al., 2009; Santa-Eulalia et al., 2009b), and finally some propose agent-based methodological frameworks (e.g., Karam et al., 2010; Santa-Eulalia et al., 2010; Labarthe et al., 2007).

It was observed that the terms framework, architecture, approaches and methodology were very frequently employed in many studies to define the contribution of the papers, but no definition was provided for them. For example, in the modelling area (particularly in the Enterprise Modelling – Vernadat, 1996), these terms can have different meanings, but the surveyed works mostly neglect to precise the nature of their contribution. This is probably an indication that the surveyed area still is an emerging domain requiring some organization.

4.2.1 SC Problems

Several SC problems were identified: general problems related to SCM, manufacturing and SC integration, SC planning, scheduling, control and execution, cooperation, coordination, negotiation, information sharing, SC adaptability, order promising, and multi-levels lot-sizing.

It is possible to affirm that three macro categories exist in this area, covering most of the papers: 1) Relationships in SC, including the following categories: coordination, cooperation, information sharing, negotiation and integration; 2) Production Planning and Control, comprising the following sub-categories: SC planning, scheduling, control and execution; 3) Others, including papers that related to general problems in SCM and agents, as well as one about SC adaptability.

When considering possible repetition (i.e., when a paper can be classified in more than one macro category), it is possible to see that: 17 papers (50%) are in the macro category Relationships in SC (including Chan and Chan, 2010; Lin et al., 2008; and Lee and Kumara, 2007); 22 papers (65%) are related to Production Planning and Control (such as Lemieux et al., 2009; Jankowska et al., 2007; and Orcun et al., 2007); and finally, there are only 4 papers (12%) in the third macro category (i.e., three papers related to general problems – namely Karam et al., 2010; Santa-Eulalia et al., 2010; and Labarthe et al., 2007 – and one paper about SC adaptability, i.e. Lau et al., 2008). Figure 3a summarizes these findings.

This led us to believe that d-APS researchers are focusing mostly on two mainstreams subjects (Relationships in SC and PPC), and that there is some interesting room for other domains. For example, problems related to SC governance, sustainability, adaptability, network design and other domains are lacking in the recent literature.

4.2.2 Applications

Among the selected 34 papers, 18 (53%) are of a theoretical nature (e.g., Ivanov, 2009) and 16 (47%) provide real applications (e.g., Cid-Yanez et al., 2009). Seven of the theoretical papers (21%) also illustrate their approach through conceptual (not real) industrial applications (e.g., Si et al., 2007).

Despite the fact that applications are usually considered relevant for having papers published in prestigious journals and conferences, more than half of them (18) do not provide real applications and 12 (35%) do not provide any at all. Among those manuscripts presenting some kind of application, most of them (28) are demonstrations (e.g., proofs of concept) that are not linked with an industrial-scale situation. None of the papers present mature applications being commercialized or close to the market. This indicates that so far d-APS systems are mostly at laboratorial stages and that many efforts need to be done in order to gain more practical insights.

The last four tables also surveyed the application sector of the 16 concerned studies, which are: airport logistics, laundry, pharmaceuticals, forest products, bicycles, golf club, defence, bronze tap, packing, computers and toys. In the case of theoretical papers employing conceptual industrial cases, the following sectors were found: computers, steel, mould and fashion. It is interesting to note that 8 manuscripts are about the forest products industry. This indicates that the application is quite diversified, hence enriching the domain, although many applications are of an academic nature.

4.2.3 Toolkits and Methodologies

Modelling toolkits are not employed massively, since only 7 manuscripts (20%) out of 34 utilize a known toolkit: 4 use JADE, 1 works with AnyLogic and 2 employ together Majorca and Anylogic.

Among those works not mentioning any specialized agent toolkit, it was observed that generic languages are usually employed (mainly C#, C/C++, and visual basic) connected to some optimization system (e.g., ILOG SOLVER and CPLEX). Other technologies used for implementation are ILOG-OPL Studio, LINDO, Excel, Crystal Ball, some discrete-event simulation tool, and Visual Studio. No correlation was identified between the methodological aspects and the agent toolkits.

In terms of methodological aspects, 27 papers (79%) out of 34 do not explicitly mention the use of them. On the other hand, a small quantity of 2 (6%) papers (Ivanov et al., 2007a; and Ivanov et al., 2007b) present some indications that they were inspired by methodological aspects, such as the definition of conceptual models, mathematical models and simulation tools. Only 5 (15%) papers explicitly present methodological elements and 4 contributions are of a methodological nature (Karam et al, 2010; Santa-Eulalia et al., 2010; Ivanov, 2009; and Labarthe et al., 2007). The methodological aspects of these 5 works will be detailed in subsection 4.3.

4.2.4 APS Functions and Modules

Despite the fact that the studied works being reviewed can be classified as dealing with d-APS systems according to our definition, few articles (i.e., 9 out of 34, representing 26%) detail (i.e., Yes and Some) APS modules. Some of them present agents specialized in traditional APS modules, such as procurement, scheduling, inventory and forecasting (e.g., Benisch et al., 2009); others present agents specialized in specific industrial domains (e.g., operational planning for sawing, drying and finishing operations, such as Cid-Yanez et al., 2007, Lemieux et al., 2009, and Gaudreault et al., 2009); and in one specific case a specialized modelling schema is proposed to explicitly represent a d-APS system (Santa-Eulalia et al., 2010).

The evaluation of this criterion allows us to believe that a complete and integrated view of d-APS is still not properly covered in the reviewed literature. Most of the works do not intend to propose a generic architecture for d-APS systems, specialized in specific domains. At the present time, almost all of the papers deal with agent-based SC planning and scheduling using optimization approaches without explicitly declaring that APS (or d-APS) technology is being used. This indicated that d-APS still is a new research domain which is not uniformly defined.

4.2.5 Social and Individual Agents Issues

When dealing with d-APS, two facets of these systems have to be considered: social and individual abilities of the multi-agents system.

In terms of the social aspects, it was not possible to clearly identify them in 10 manuscripts (29%). Despite the fact that in some cases terms such as communication and conversation are mentioned, they do not provide any approach for modelling social aspects of the agent society. For example, Jankowska et al. (2007) is much more dedicated to the layered technical architecture and the main computing technologies it integrates.

On the other hand, 20 works (59%) are classified as proposing “some” discussion about social aspects. They do not provide any complete modelling approach to identify and simulate several different types of social structures or social protocols, but they address these aspects somehow; sometimes one paper just mentions or uses one or two social aspects in a limited way; occasionally they take one specific aspect (e.g., negotiation) and thoroughly explore it by proposing protocols, for example. For instance, Kim & Cho (2010) present an approach based on cooperative relationships, information sharing and negotiation.

Finally, 4 papers (12%) are classified as “yes” because they propose a dedicated set of modelling schemas to capture different social facets of d-APS systems. Karam et al. (2010) provide an appropriate set of abstractions to identify, develop and describe the organizational structure of a SC as well as the dynamic relations between the entities that make up a SC. Santa-Eulalia et al. (2010) also present a specialized modelling schema, called Social Agent Organization Analysis, to capture different social structures and protocols. Ivanov et al. (2010) discuss an approach for coping with a multiple structure design and changeability of structural parameters due to different factors at all the stages of the supply chain life cycle. Labarthe et al. (2007) created a dynamic and structural model based on responsibility networks in SC.

Using exactly the same logic employed for the social aspects, the 34 surveyed papers revealed that the individual aspects of the agent society are not considered in 7 (21%) manuscripts. For example, Andreev et al. (2007) propose a concept called Open Demand

and Resource Networks, which dynamically matches demands and resources. This can be used to define a variety of individuals in a network, but their individual aspects (e.g., roles, internal architectures, etc.) are not identified.

In 22 papers (65%) out of 34, some individual aspects were treated. For example, some works approach one (or more) individual aspects of each agent, such as Lau et al. (2008), who propose an approach to manage the agent's individual autonomy according to environmental changes.

A more complete solution suggesting detailed ways of modelling several individual aspects of SC was found in only 5 papers (15%). Karam et al. (2010) provide some abstractions to define agents' behaviours that can be of reactive, deliberative or hybrid nature. Santa-Eulalia et al. (2010) also propose a specialized modelling schema, called Individual Agent Organization Analysis, to capture different individual characteristics. Ivanov et al. (2010) put forward functional agent models for describing active elements. Based on the actor agent paradigm, Labarthe et al. (2007) suggest two individual roles for agents, i.e. cognitive and reactive, with some encapsulation principles and a behavioural representation method.

It is interesting to note that 3 out of 4 papers covering social and individual aspects of agents' society also deal with methodological approaches. The exception is Ivanov et al. (2010), but these authors do use methodological elements in some of their previous works.

Figure 3 summarizes the main findings of the studied works.

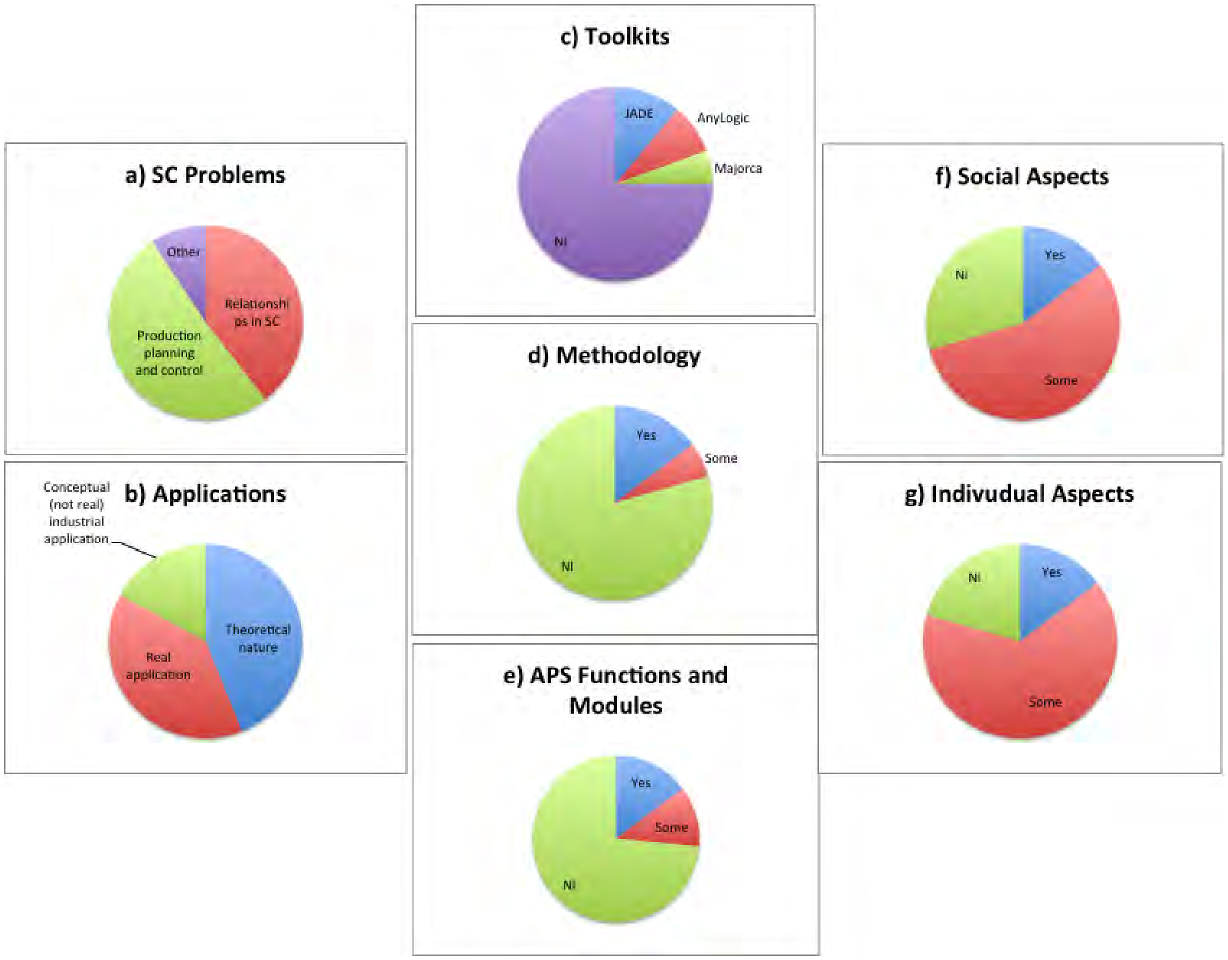

Figure 3: Summarizing the main findings of the studied works.

4.3 Methodological Frameworks for Modelling d-APS

This section discusses the papers classified as somehow tackling methodological aspects. In order to do so, specific aspects to perform a descriptive evaluation were identified. They are:

- *Modelling Phases*: it was verified whether the framework adheres to the methodology for simulation of distributed systems developed by Galland et al. (2003), comprising the following traditional development phases: i) *analysis*: an abstract description of the modelled supply chain planning system containing the simulation requirements, in which the functionalities of simulation are identified and described in general terms; ii) *specification*: translation of the information derived from the analysis into a formal model. As the analysis phase does not necessarily allow the obtaining of a formal model, the specification examines the analysis requirements and builds a model based on a formal approach; iii) *design*: creation of a data-processing model that describes in more details the specification model. In the case of an agent-based system, design models are close to how agents operate.

- *Modelling Levels*: the modelling levels comprises two issues: i) *supply chain*: refers to the supply chain planning problem, i.e. the business viewpoint; ii) *agent*: the supply chain domain problem is translated into an agent-based view; i.e. the technical viewpoint.
- *Descriptive Evaluation*: this part of the evaluation follows the Karageorgos and Mehandjiev (2004) approach, as explained in subsection 3. In this case, only 8 out of 12 proposed criteria were evaluated, since 4 of them were not present in any surveyed work. They are: heuristics support, non-functional aspect, design automation, and tool support.
- *Modelling Formalism*: the integration of specific modelling formalisms in the methodological frameworks was verified.

Previously in step 2, 7 works proposing methodological frameworks were identified. Due to their similarities, these works were assembled into four groups: Karam et al. (2010), FAMASS (Santa-Eulalia et al., 2010 and Santa-Eulalia et al., 2008) DIMA (Ivanov 2009; Ivanov et al., 2007a; and Ivanov et al., 2007b), and Labarthe et al. (2007). Table 6 summarizes the descriptive evaluation.

	Methodological Phases			Modelling Levels		Descriptive Evaluation (Karageourgos et al., 2004)				
Approach	**Analysis**	**Specification**	**Design**	**Domain models (SC Planning and Control)**	**Agent models**	**Concepts**	**Models**	**Process**	**Pragmatics**	**Modelling Formalisms**
Karam et al.	NI	The phase called Conceptual Modelling generates models for roles and organization, which are not of executable nature	The phase called Operational Modelling generates the executable models	NI	Three models: CROM (Conceptual Role Organization Model), CAOM (Conceptual Agent Organization Model) and OPAM (Operational Agent Model)	Only three types of agent architectures are allowed: cognitive, reactive and hybrid. The methodology proposes three modelling steps with specific modelling rules	Agents roles and collective behaviours are explicitly identified	Design perspective is top-down, with no support for reuse	Generality is high. Abstractabily is present, with three major abstract levels (conceptual, operational and exploitation)	AUML, RCA (Tranvouez, 2006)
FAMASS	This is the main contribution of this work. Several reference models are provided to define functional requirement s for simulation	They do not propose dedicated models for specification, but they employ Labarthe et al.'s (2007) to generate specification models from the stated requirements. A set of conversion rules are proposed to derive specification models from their analysis	Similarly to specification, they propose a set of conversion rules to translate analysis requirements into design models in accordance with Labarthe et al. (2007)	Two approaches are proposed: one for defining the simulation problem and another one for identifying functional requirements for the distributed planning system	Two approaches are also proposed: one covering the social organization (structure and protocols) and another for the individual agents' abilities	It does not limit the agent architecture one can employ. It proposes four phases with several steps and dedicated modelling guidelines	Agents roles and collective behaviours are explicitly identified	The design perspective is mostly a top-down approach, but a bottom-up is allowed. There is no support for reuse	It presents high generality in d-APS context. Also, abstractability is present through four modelling levels (domain, agent, infrastructure and simulation)	UML, AUML
DIMA	NI	The separation between specification and design phases is not clear. However, they propose modelling approaches for network design, adaptive planning and control, and network control. These approaches can potentially support specification and design phases	Two contributions can be identified as being part of the design phase: i) a general indication on how the decision models work for planning, monitoring and reconfiguration; ii) a macro schema for the MAS architecture	They propose conceptual models for decision-making, including planning, execution and stability recovery/reconfiguration	It proposes a functional agent model for describing active elements, a general schema for agents' interactions for customer order execution. Also, a general MAS functional architecture is proposed	Open architecture, no agent type is favoured. Only general engineering lifecycle phases (conceptual model, mathematical model, and simulation tool)	Some agent roles are formally identified (for adaptive planning and control). A collective behaviour is not explicitly detailed, only general indications are provided	The design perspective is not clear. There is no support for reuse	It is specialized in virtual enterprises and collaborative networks (defined as a special type of SC), but almost all notions can be generalized to traditional SC. Three abstraction levels are proposed: concept, model and software	Only mathematical modelling, but the authors mention that some dedicated formalisms are under development
Labarthe et al.	NI	The Conceptual Level, leading to the elaboration of the Domain Model and the Conceptual Agent Model	The Operational Level, which delimits how the agent-based system will work on a simulation platform	A specific Domain Model is proposed for SC and mass customization	A Conceptual Agent Model and an Operational Agent Model are specific agent-dedicated modelling approaches	Only two types of agent architectures are allowed: cognitive and reactive. The methodology proposes three modelling steps with specific modelling rules	Agents roles and collective behaviours are explicitly identified	Design perspective is top-down, with no support for reuse	The generality is between medium to high, since it is dedicated to mass customization, but almost all concepts can be generalized. Abstractabily is definitively present, with three major abstract levels (conceptual, operational and exploitation)	Responsibility Networks , ABR (Tranvouez, 2001), AUML and some own formalisms

Table 6: Studied methodological works organized into four groups according to the project.

Karam et al. (2010) present an organization oriented methodological framework for modelling and simulation of SC. It allows observations of different levels of details while reproducing the SC behaviour. This methodological framework is structured according to a conceptual and an operational abstraction levels. At the conceptual level, the modelling is based on a Conceptual Role Organizational Model (CROM), which is then refined into a Conceptual Agent Organizational Model (CAOM). At the operational level, modelling is mainly based on the Operational Agent Model (OPAM). This framework permits the study of the impact of a specific SC organizational structure and its related management policies on SC performance.

The FAMASS (*F*ORAC *A*rchitecture for *M*odelling *A*gent-based *S*imulation for *S*upply chain planning) framework (Santa-Eulalia et al., 2010; Santa-Eulalia et al., 2008) is inspired from theoretical contributions found in the field of simulation, systems theory, distributed decision making and agent-based software engineering. It proposes a conceptual framework for modelling simulation requirements in d-APS systems. At the conceptual level, FAMASS proposes a schema for defining the simulation problem and translate it into a distributed model. Next, at the agent level, one can convert the distributed model into an agent-based system comprising social and individual aspects. The framework is pretty much dedicated to the analysis phase, but indications on how to transform analysis models into specification and design ones are provided.

The DIMA (Decentralized Integrated Modelling Approach) (Ivanov, 2009; Ivanov et al., 2007a; Inavov et al., 2007b) introduces a new conceptual architecture for multi-disciplinary modelling of structural planning and operations of adaptive SC with dynamics considerations, employing concepts from control theory, operations research, and agent-based modelling. The main objective is to establish a basis for SC modelling where partial models and algorithms of SC planning and control can be created. In their approach, conceptual business models, mathematical models and software architectures are matched with each other taking into account specific SC features related to dynamics and agility.

Labarthe et al (2007) propose an approach for modelling customer-centric supply chain in the context of mass customization. They define a conceptual model for supply chain modelling and show how multi-agents systems can be implemented using predefined agent platforms. After creating the Domain Model, the Conceptual Agent

Model and the Operational Agent Model, a Multi-Agent System is implemented and a set of experimental plans supports the realization of simulation experiments.

Three of these projects are somehow connected. Inspired from the agent-based software engineering school, Labarthe et al. (2007) strongly influenced Karam et al. (2010), and it is largely employed in the FAMASS approach for the specification and design phases. On the other hand, the DIMA approach follows a different school, more influenced by the system and control theory.

Table 6 helps us to understand some issues. First of all, in terms of methodological phases, one can note that the unique work dealing explicitly with the analysis phase is FAMASS, in which a dedicated set of theoretical models combined with specific guidelines and formalisms are proposed to support analysts in mapping function requirements of d-APS systems. The remaining works do not mention the analysis phase. As for the specification and design phases, excluding the FAMASS approach, all works can be used for specification and design. Although they do not state it, the proposed frameworks contain elements to do so. For example, the conceptual and operation models of Karam et al. (2010) and of Labarthe et al. (2007) provide guidelines to define formal (specification phase) and executable (design phase) models. Perhaps the most complete work for specification and design is Labarthe et al. (2007), although it is not formally dedicated to d-APS systems, since no APS functions and modules are explored. In fact, the sole approach covering entirely this issue is the FAMASS framework.

As for the modelling level, it is interesting to note that Karam et al. (2010) do not provide domain models for defining SC planning and control mechanisms. The other three approaches provide one or more artefacts to do so. For example, FAMASS provides a specific set of models for defining the simulation problem as well as the distributed SC planning functions. Also, DIMA proposes some decision-making models for SC planning, control and reconfiguration. Additionally, Labarthe et al. (2007) provide several modelling objects to create a SC system. Despite their significant differences, all the four approaches contain elements for defining agent models. The only approach dealing superficially with this issue is DIMA, in which agents are only generally defined.

The descriptive evaluation according to Karageorgos et al. (2004) indicates that the surveyed works have several elements of a complete agent-based methodology, but many are still lacking some. As identified previously, each approach deals with heuristics support, non-functional aspects, design automation, and it proposes a tool support. In terms of concepts, FAMASS and DIMA do not limit the agent architecture one can use, while the other two favour two classic types (i.e., cognitive and reactive ones). In terms of “design in scope”, all of them provide specific modelling steps and rules, although this is not totally clear in DIMA. As for the “models” perspective, agents’ roles are clearly identified in all of them. In terms of “process”, it can be said that most approaches follow basically a top-down approach, even if FAMASS would also allow for a bottom-up logic. This criterion is not totally clear in the DIMA approach. In terms of “pragmatics”, although Labarthe et al. (2007) is dedicated to mass customization in SC and DIMA is for dynamic SC (mainly virtual enterprises and collaborative networks), their “generality” can be considered high, as well as their “abstractability”.

Finally, apart from DIMA, which employs only mathematical modelling, all of them use specific software engineering formalisms, notably derived from UML.

5 Discussion and Final Remarks

To model complex supply chain planning processes, a set of modelling techniques and approaches exist. In an attempt to organize the literature review in the area, a taxonomical organization was proposed. This indicates that a variety of ways exist to capture SC behaviours, understand, organize, represent d-APS problems and later implement and use d-APS solutions.

Based on this classification, this work focused on the methodological aspects of the agent-based frameworks for d-APS systems, a specific category of the existing modelling and simulation approaches (see subsection 2.2). Two comparative analyses were done: first, a general search covering works dealing with supply chain planning using agent-based approaches was performed; later it was channelled into discussing the approaches explicitly containing methodological aspects for modelling agent-based systems.

The first comparative analysis indicated that the main contributions of the surveyed works cover several topics, but many propose modelling structures (e.g., modelling frameworks, architectures, approaches and methodologies) without formally defining what these structures are. It is known that these labels can have different meanings and implications, but this is not clearly considered in the concerned literature. In terms of "SC problems" being treated by these manuscripts, a trend to focus on two aspects was noted: "SC relationships" (i.e., coordination, cooperation, information sharing, negotiation and integration) and "production planning and control" (i.e., SC planning, scheduling, control and execution). There is some interesting room for other domains, such as SC governance, sustainability, adaptability, and network design, for instance. In terms of applications, despite the fact that some were found in several domains (such as pharmaceuticals, forest products, bicycle, golf club, defence), more than half of the works are of a theoretical nature, with few real-scale industrial applications. In terms of technical aspects, it was found that: agent-based "modelling toolkits" are employed in less than 20% of the identified works; in almost 80% of them no methodological aspect is formally treated; "APS architectures and engines" are not considered unambiguously in almost all papers; the "social and individual aspects" of the agent society is not taken into account in a clear manner in many of the selected papers. By exploring this first comparative analysis, one can see that many approaches are highly specialized in specific domains and cannot properly capture the complexity of a d-APS system in general terms. One of the most important findings is that most of the literature fails to understand "methodological concerns" and does not provide answers to simple questions, regarding what type of models and simulations can be performed for treating different SC planning problems.

This conclusion led us to an additional comparative analysis that focused on the methodological aspects of some of the works. It was identified that only 21% address methodological concerns. Among them, only one paper is dedicated to the "analysis phase", and none of them covers all the developed process in an integrated manner. The most complete work integrating "specification and design" is not formally dedicated to d-APS systems, since no APS functions and modules are explored. Additionally, the sole approach that clearly covers d-APS systems entirely (with specialized entities) does not propose an integrated modelling process from analysis to experimentation. In general terms, it is possible to affirm that different "modelling levels" and "agent models" are identified in the selected works. On the other hand, the descriptive evaluation using the Karageourgous and Mehandjiev (2004)'s approach indicates that the surveyed works have many elements of a complete agent-based methodology, but many issues are still lacking, including heuristics support, non-functional aspects, design automation, and tool support proposal. The remaining elements are treated somehow by the papers, with different degrees of details and completeness.

All these findings indicated that the domain is flourishing and that many interesting opportunities exist. We believe that the present work can collaborate to shed light on this emerging field and pave the way for new and innovative researches towards a complete methodological framework for d-APS systems, thus permitting academics and practitioners to develop and use such systems to improve the SC planning domain.

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