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A Multidisciplinary Review of Collaborative Supply Chain Planning

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***Abstract*— Supply chains are networks of loosely coupled business units characterized by distinct, yet mutually interdependent, planning decision domains. Such networks are generally managed hierarchically through the central and aggregated control of a corporate business planning unit, or through a cascade process referred to as upstream planning. In order to improve the limitations of such hierarchical planning methods, several projects initiated in different research domains have proposed various extensions and alternatives. This paper aims at analyzing this research literature using a framework that systematically investigates their coordination process, their local decision making ability and their advanced planning tools. This paper concludes with a discussion of the complementarities of the two main methodological domains that underlie these supply chain coordination systems (i.e., operations research and agent technology).**

***Keywords*—agent technology, operations research, supply chain, distributed planning, collaboration.**

I. Introduction

Supply chains are networks of organizations that produce and deliver value in the form of products or services to the final consumer through upstream and downstream linkages [10], from raw material production, to its transformation and manufacturing into sub-components, their assembling, and their delivery to the final consumer. In the context of this review, this definition is extended in order to include the internal networks of business units of integrated companies ([26], [15]). Supply chains are thus characterized by distinct, yet mutually interdependent decision domains with independent business objectives [56]. This lack of decisional and organizational integration leads to inefficiencies related to poor coordination of production and distribution decisions, such as the bullwhip effect [41], which result in missed opportunities, delays, inefficient inventory decisions, poor capacity allocation, misuse of resources, all leading to increased cost. To achieve supply chain excellence, companies have developed best practices and standards, including *Efficient Customer Response* (ECR) in the grocery industry and *Quick Response* (QR) in the apparel industry, as well as specific business processes such as *Collaborative Planning, Forecasting and Replenishment* (CPFR) and *Vendor-Managed Inventory* (VMI) [56]. These initiatives play an important role in the development of the practice of supply chain management and ultimately in the streamlining of supply chain operations in various sectors. Yet, these efforts do not propose advanced collaborative decision processes where supply chain operations are planned simultaneously subject to the need and constraints of all supply chain partners, which is the main issue addressed in this review. This section first introduces this problem. Next, it provides a brief introduction of the various research domains that have contributed to address it.

A. Supply chain coordination problem

[15] propose to define the objective of the *Supply Chain Operations Planning* (SCOP) problem as being the "[coordination of] the release of materials and resources in the supply network under consideration such that customer service constraints are met at minimal cost". In this specific definition, the authors consider explicitly the release of materials and resources as constraints that must be dealt with simultaneously. In this review, the problem that is investigated includes various specific settings of supply chains, including the management of specific relationships such as with a logistic service provider. In other words, the problem addressed here consists in synchronizing the supply chain partners' usage of their resources in order to avoid shortage and make sure materials, components and final products flow continuously whenever needed by downstream partners, at minimal cost. This involves making decisions such as what and when to produce and deliver. In the context of virtual supply chains (i.e., supply chains assembled temporarily on-demand to meet specific needs, [8]), managing the release of materials and resources may also involve making decisions about supplier selection, which is quite often part of many approaches proposed in the literature (see section III.B.2).

An important feature of this coordination problem is its distributed nature. Decision rights in supply chains are distributed among independent companies with different operations management challenges that are directly related to the very nature of their core business strategy and processes. Therefore, companies can make any decision and follow any decision process they want to. Consequently, the most challenging aspect of this problem is to provide a solution that meets this distributed nature.

B. Multi-disciplanary domain of research

In order to contribute to solving this problem, researchers from various domains are coming forward with a growing

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number of coordination techniques, which are various in nature and scope. Three technological domains can be identified as main contributors. The review proposed in this paper includes contribution within these three domains. The first domain is *operations and logistics management*. It deals simultaneously with supply chain management and operations management. It is a branch of industrial engineering dedicated to improving manufacturing and logistics operations management through the use of specific methods and tools. Next, *Operations Research* (OR) deals with advanced mathematical modeling and algorithms to support decision making. In other words, OR provides a way to not only model supply chain decision problems, it also provides the means to solve these complex decision problems and create efficient decision support systems. It is a tool that is widely used to solve other industrial and service engineering problems, among others.

More recently, *agent technology* has emerged as a powerful technology to tackle such distributed problems [54]. It is rooted in computer science and distributed artificial intelligence and brings new capabilities and tools to deal with supply chain coordination. Because software agents are capable of sensing and reacting to changes in their environment [45], they provide the capability to adapt their behavior, and therefore their decision making process, to their planning environment. Some agents are even capable of adopting goal-driven behaviors to pursue some predefined goals. Consequently, many researchers from the domain of logistics have developed and applied these tools to design coordination techniques to the supply chain coordination problem that are radically different from pure OR-based solutions.

All these methodological domains contribute to solving supply chain coordination problems. However, some of the most interesting and flexible coordination techniques propose the use of both OR and *agent technology*. In particular, the last section of this paper compares these methodological domains in order to highlight their complementarities and their strength to address supply chain coordination problems. The remainder of this paper is organized as follows. Section II introduces a framework of analysis that is used throughout the paper to study some of the coordination techniques provided in the literature. Then, Section III proposes a review of these coordination techniques, while Section IV analyses some of their features. Finally, Section V concludes with two research issues resulting from the analysis.

II. FRAMEWORK OF ANALYSIS

In order to study such an heterogeneous body of literature, and eventually propose a classification scheme, we first propose to analyze the main challenges that any system must somehow address to provide a solution that is viable in practice. More specifically, there are three challenges to be dealt with: the design of a *coordination process*, which is used as the main entry point to our classification scheme; the design of *local decision making processes*; and the design and utilization of *advanced planning and scheduling systems*.

A. Coordination process

To address the supply chain coordination problem, a coordination process must be somehow designed. Because such a process must account for the distributed nature of the supply chain under consideration, it must involve a mechanism to coordinate the distributed entities.

In practice, the most simple coordination process involves the use of buffers. The first is a buffer of time, in the form of a lead time, which reduces the need to coordinate detailed supply chain capacity utilization. Lead times are usually calculated, or estimated, in order to leave the supplier enough time to produce the ordered goods regardless of its capacity utilization profile. Next, due to the volatility of demand and the imperfect delivery performance of suppliers, companies also build up inventories to protect themselves against the various sources of variability. These approaches lead to a huge body of literature related to inventory management and control [2].

In the academic literature, many other forms of advanced coordination techniques have been proposed, from direct supervision, to mutual adjustment, to third party mediation [22]. Consequently, according to the nature of the supply chain to coordinate, from a pair of business partners to a virtual supply chain assembled to meet a customer's need, there are several classes of coordination mechanisms that can be adopted to provide a useful and effective solution. The analysis of the literature proposed in the next section illustrates these classes.

B. Local decision process

With the introduction of agent technology, it becomes necessary to distinguish between the process of making a decision and the process of building an operations plan. Particularly, this need to consider separately both processes is necessary for agent-based supply chain coordination techniques that provide decision support mechanisms capable of adapting the agents' local decision processes to the situation. In other words, in artificial intelligence, the concept of planning is related to the agent's ability to plan its own course of actions, and thus plan/select the appropriate decision making process to apply. This concept is indeed different from the building of an operation plan, which is only one of the actions an agent can carry out. Advanced agents in this context might be able to negotiate with others, measure key performance indicators, send a request-for-proposal or a bid.

C. Advanced Planning and Scheduling systems

Advanced Planning and Scheduling (APS) systems are advanced, generally OR-based, tools developed to provide finite capacity (more generally constrained) planning functions to support companies manage their operations. This review analyzes coordination techniques that usually involve generic or specific forms of APS. Used with agent technology, APS systems provide agents with the ability to build operation plans, while agent technology provides the means to link and coordinate planning decision processes across the supply chain. Agents may also be able to configure these tools in a flexible manner to adapt their process of building an operations plan to their changing needs and constraints.

In the context of this review, one must pay attention to the potential of the proposed planning tools to be adapted to specific problem. Similarly, it is also interesting to analyze whether or not the proposed coordination mechanism can take into account the various nature of the legacy planning tools. In other words, this requires analyzing the level of dependency between the proposed coordination mechanisms and the planning tools used. Indeed, a coordination mechanism can be either general (i.e., capable of operating with any advanced planning tool), or specific (i.e., requires a specific process of operations planning). The next section exploits this framework in order to classify and analyze some of the coordination techniques provided in the literature.

III. DISTRIBUTED SUPPLY CHAIN COORDINATION

As explained previously, the supply chain coordination problem is concerned with reducing the inefficiencies that arise from the decentralized nature of supply chains. In other words, it is the distributed ownership of information and the inherent division of decision rights that constrains the coordination of a supply chain and limits its performance.

Philips Electronics is one of the first companies to have implemented an advanced collaborative planning process that directly addresses this problem [16]. Their collaborative process involves the operations managers of several production and assembly facilities through weekly virtual meetings where they exchange information, evaluate alternative plans of materials release using a central advanced planning tool, so as to select a plan that is agreed upon by all supply chain members. Although this collaborative process is mainly carried out by operations managers, it provides a significant breakthrough for the many approaches in the literature that propose to automate the functions required to build a collaborative supply chain operations plan.

In the academic community, the research efforts to improve supply chain coordination can be classified into several types. A first classification scheme was introduced in [5] to differentiate between the inter-function coordination, referred to as the general coordination problem, and the multi-plant coordination of the same function. The general coordination problem is then subdivided into three classes of coordination problems, namely *supply and production planning*, *production and distribution planning*, and *inventory and distribution planning*. The review of the literature presented in [58] deals with the coordination of these functions, while the review in [5] focuses on the multi-plant coordination problem.

The review of the literature that is proposed in this paper deals indifferently with both coordination problems. However, the classification is made according to the coordination process in order to emphasize the technology over the problem definition. In this review, we propose 3 main classes of coordination techniques: *coordination heuristics*, *agent-based coordination* and *mathematical decomposition*.

A. Coordination heuristics

The main principle of coordination heuristics is to create a distributed decision process where supply chain partners exchange structured and specific information to build coordinated operations plans. These processes can be simple (greedy) or more advanced and iterative. Table I provides an overview of these approaches.

The most simple coordination heuristic, generally used in practice, consists in a simple, one way information exchange, referred to as *upstream planning* ([5], [17]). In brief, *upstream planning* requires each supply chain partner to define its operations plan to meet local customer demand, then derive from this plan its own dependant demand, which is then forwarded to the appropriate suppliers, and so on in a cascade. The first class of coordination techniques presented here involves various extensions of this fundamental coordination process.

1) Greedy heuristics and information sharing

The first type of coordination heuristics extends the idea of *upstream planning* using various forms of greedy mechanisms or specific modeling approaches to improve its basic performance. For instance, [59] propose that the customer regularly send its own demand forecast overtime, on a rolling horizon, and a penalty mechanism that the customer must pay for any forecast error. Here, the supplier is committed to deliver whatever the customer forecasts, but it is protected from any error or opportunistic behavior of the customer. Another approach, proposed in [49], involves the partial centralized optimization of sub-networks within the overall supply chain. Similarly, [53] use an advanced form of information sharing which involves the sharing of the upstream partner's decision model in order to improve the downstream planning decision process with an anticipation of its partner's decision process. In the context of natural resource, [23] propose a two-phase planning process that allows partners to communicate both demand targets and supply capacity constraints. Finally, [24] propose a solution that involves information sharing throughout the supply chain with a supply chain manager.

2) Distributed local search

More advanced coordination heuristics involve an iterative information exchange between supply chain partners, during which they progressively adjust their own initial plan through some form of local search (i.e., small incremental deviations). Such procedures allow the partners to mutually adjust their plans according to the constraints or capabilities of their partners. This form of coordination techniques requires the design of a convergence mechanism to guarantee the improvement and the feasibility of the collective plan, as well as termination conditions in order to stop the incremental process of mutual adjustment. Some systems only deal with the coordination of two partners ([17], [35], [36]), while other coordination heuristics encompass more partners, or even the entire supply chain [55]. Furthermore, some heuristics are rooted in the understanding of the process of adjustment of an operations plan ([17], [35], [36]), while [55] is inspired by a meta-heuristic, ant colony optimization, configured to be used in a distributed setting. This idea could be extended to other meta-heuristics (e.g., simulated annealing, taboo search).

3) Distributed search with constraint propagation

The use of a distributed search procedure to coordinate supply chain operations is a rather novel approach recently proposed by [25]. In this approach, the coordination space of the many heterogeneous planning problems of a linear supply chain is modeled as a tree. In this distributed and asynchronous process, agents must decide whether to produce an alternative solution to a customer demand plan for which they have already found a solution (i.e., an operations plan), or to produce a first solution to a demand plan for which they have not produced any solution. In an advanced form of search, the authors have also investigated the possibility of using learning to help agents decide the most appropriate action to take.

In other words, such a procedure provides a means of searching the coordination space to find a set of local plans that are collectively better in terms of the supply chain performance indicator that is optimized. One of the strengths of this approach is to only require the exchange of minimal information such as demand and supply plans. This coordination process is also independent from the planning tools that are used to produce agents' local operations plans.

TABLE I. COORDINATION HEURISTICS

Ref	Main features
Upstream planning extensions and information sharing	
[23]	Upstream planning with retro-propagation of supply constraints in a context of natural resource transformation.
[24]	Suppliers provide capacity constraints per period to the supply chain manager who plans production and transportation operations.
[48]	Hierarchical operations management (aggregated and detailed) with web-based operations plan sharing.
[49]	Upstream planning with partial centralized optimization.
[53]	The downstream company anticipates the upstream company's decision making in order to send an improved demand plan.
[59]	Upstream planning with forecast sharing and an incentive mechanism to guarantee accurate information sharing.
Distributed local search	
[17]	Coordination of a manufacturer-supplier system with local decisions supported by linear programming and coordinated through iterative adjustments of requested quantities to account for current supplier's availability.
[35], [36]	Iterative heuristic for the coordination of a manufacturer and a third party logistic/distributer. Local decision making is supported by linear programming, and only available supply quantities and distribution plans are exchanged.
[55]	Operations coordination of a production network based on a distributed extension of ant colony optimization (ACO). The information that is exchanged is the pheromone matrix specifically created during the local decision process.
Distributed search with constraint propagation	
[25]	Distributed discrepancy search procedure where agents collectively search the supply chain coordination space modeled as a tree by forwarding alternative demand plans as a means to propagate demand constraints.

B. Agent-based coordination

Agent-based coordination involves a set of techniques that are rooted in agent technology (see Table II). Therefore, they use various concepts of artificial intelligence (AI) to propose a rich and heterogeneous family of coordination approaches.

1) Knowledge-based coordination

Knowledge-based coordination approaches involves the explicit representations of specific knowledge that can be used by a software agent to coordinate its activities with others.

Protocol-based coordination: In a supply chain context, the most frequently used approach of knowledge-based coordination uses explicit representation of how to interact with other agent (i.e., interaction protocols) in specific situations, and, in the case of deliberative agents, how such interaction protocols can contribute to the goals of the agents. An interaction protocol is often modeled as finite-state machine graphs (e.g., [11]) or Petri nets (e.g., [46]). Such protocols model all possible states and outcomes of a given interaction, defining at the same time all possible actions that can be performed by the agents within this interaction, according to their role in the interaction and the actions performed by the other agents. In a given active state of an interaction, an agent generally has a rather small set of actions that it can perform. Reactive agents usually have a pre-determine series of internal actions to perform in order to continue the interaction (e.g. [23]). This approach is the most common in agent-based coordination. On the contrary, deliberative or multi-behavior agents ([19], [20]) plan or, respectively, select their own course of actions according to, for example, specific goals to reach or a utility function to maximize.

Argument-based coordination: In a supply chain context, companies may have to influence their partners' agreement space, or how they assess value over that space, to reach an agreement. Argument-based coordination similarly involves the construction and exchange of arguments that agents believe will make their counterpart look more favorably upon their proposal [31]. Arguments are information that is added to an offer sent by an agent in order to influence its counterpart. In other words, this aims at identifying or creating new opportunities in the coordination space, or modifies how agents value their counterparts' offers, in order to facilitate the coordination process. Although it is not a technique that is widely used in the supply chain context, some researchers are investigating this approach. For instance, [27] introduce an argument-based negotiation approach for conflict resolution for the extended enterprise. Along the same line, [9] proposes an argument-based technique in the context of a logistic service provider to dynamically solve conflicts in operations management.

2) Market-based coordination

In virtual supply chains, where partners are selected or assembled when needed to meet a specific opportunity, market-based coordination techniques allow supply chain members to select one or many suppliers according to their ability to meet particular needs. Many of the techniques reported here are based on the contract-net protocol [14] or auction theory.

Auction-based coordination: As defined in [44], an auction is "*a market institution with an explicit set of rules determining resource allocation and prices on the basis of bids from market participants*." In agent technology, thanks to the contract-net protocol, auctions and request-for-proposal (RFP) are common to coordinate resource allocation. Therefore, many different ways have been proposed to apply auction and market mechanisms to the supply chain coordination problem. A central supply chain manager is sometime involved to evaluate and synchronize the incoming bids, and ultimately make a selection decision to allocate the jobs throughout the entire supply chain (e.g., [12]). Furthermore, a bid can involve a single offer that is evaluated (e.g., [1], [6], [28]), or several alternative offers from which the partners can choose [12]. Finally, [40] propose a hierarchical (cascade) auction structure to coordinate the allocation of jobs in a distributed manner.

TABLE II. AGENT-BASED COORDINATION

Ref	Main features
	Knowledge-based coordination
[1]	Supplier provides min and max durations of a production stage if carried out at a given time. A supply chain manager plans the order with penalties for being late or early.
[3]	Multi-agent systems for order planning in a make-to-order environment. Enables interactions with users, other companies' agents and legacy systems.
[7]	Multi-agent architecture for operations coordination in a distribution system.
[9]	Argument-based coordination technique for conflict resolution between a manufacturer and a logistic service provider.
[11]	Commitment-oriented approach of coordination based on interaction protocols.
[20]	Functional decomposition of the supply chain with inter-agent negotiation to coordinate their planning activities.
[21]	Generic framework for production network modeling and operations coordination through negotiation protocols and optimizations tools.
[27]	Argument-based negotiation approach for conflict resolution in the extended enterprise
[29]	Agent-based interaction protocols to coordinate resource capacity synchronization in a production network.
[46]	Multi-site operations coordination supported by distributed software agents linking internal functions of legacy information systems with external coordination function.
	Market-based coordination
[1]	Multi-agent architecture using contract-net to selection and coordinate supply chain members.
[6]	Supply chain planning using request-for-quote coordination schemes and optimization tools for bid evaluation and operations planning.
[12]	Supply chain level planning via the selection and coordination of multiple suppliers. Suppliers provide bids with alternative offers from which a central manager choose the set of bids that is the most economic.
[28]	Using the contract-net, a supply chain manager announces quantities to supply. Suppliers provide bids for part of these quantities, until the original order filled.
[30]	Open tender mechanism using a blackboard architecture for supplier selection.
[34]	Supply chain task allocation using a modified contract-net to manage several interdependent suppliers simultaneously.
[39]	Distributed operations scheduling using an extension of the contract protocol.
[40]	Distributed auction systems to allocate inventory in a distribution network. Local decision making supported by linear programming models. Involves cost function and capacity information sharing.
[42]	Supply chain coordination using contract-net and case-based reasoning to avoid unnecessary communication.

Price-based coordination: Instead of being inspired by auctions or by the contract net protocol, price-based coordination techniques are rather inspired by spot market mechanisms. This type of coordination techniques is typically illustrated by [37] where each supplier proposes a price for its goods, which he iteratively adjusts according to market conditions. For instance, if a quantity of goods has been purchased on the market, the supplier will increase the price of the goods at the next round of transactions. On the contrary, if no goods have been purchased, then the price of the goods is iteratively decreased until it is sold or taken out of the market.

C. Mathematical decomposition

Coordination techniques inspired by mathematical decomposition are mainly rooted in OR with little reference, if any, to agent technology although similarities can be drawn. The main idea is to exploit a mathematical decomposition method is order to create distributed APS systems, where integration and coordination is carried out according to the same method (see Table III). In other words, mathematical techniques, which have been developed to solve large combinatorial problem, are used to resolve the supply chain coordination problem in a distributed manner. The main decomposition approach that is used for such a purpose is Lagrangean decomposition. Its principle is to develop a central supply chain planning model; relax the binding constraints of natural sub-problems (typically the material flow constraints between supply chain partners); and develop a distributed and synchronous iterative process to adjust the penalty of these relaxed constraints to converge toward a feasible solution (a set of operations plans that mutually respect each other's output). Generally, a central master problem is used to calculate and adjust synchronously these penalties according to the current state of the local optimization processes. However, [43] propose an asynchronous and decentralized adjustment process for these penalties.

In a different approach presented in [50], the authors have adapted Benders decomposition to such a supply chain coordination problem. Although Lagrangean decomposition has quite been adapted to this context, these approaches by mathematical decomposition remain largely underutilized. For instance, column generation still remains totally unexplored to solve such a complex planning context in a distributed manner.

TABLE III. MATHEMATICAL DECOMPOSITION

Ref	Main features
	Lagrangean decomposition
[4]	Lagrangean relaxation is used to decouple the imbedded distribution and production sub-problems, and sub-gradient optimization is implemented to coordinate the information flow between the production and distribution facilities through a centralized planner.
[18]	Supply chain activity coordination using a Lagrangean relaxation procedure and an auction theoretic approach. Uses a central coordinator.
[32], [33]	Distributed decision making mechanism using functional agents and a Lagrangean relaxation procedure to coordinate interdependent problem solving agents.
[38]	Distributed resource scheduling based on Lagrangean relaxation interpreted as a combinatorial auction. Uses a central coordinator.
[43]	Supply chain operations coordination through Lagrangean decomposition of the supply chain planning problem and the asynchronous, distributed and iterative adjustment of the marginal cost of violating flow conservation constraints.
[47]	Function-based Lagrangean decomposition of multi-partner supply chain planning using a procedure with an adjustable penalty mechanism to enforce convergence of local problems.
[52]	Multi-agent model for intra-organizational logistics management based on Lagrangean relaxation
	Benders decomposition
[50]	Distributed decision making framework based of the L-shaped method to coordinate local distributed problems to near-optimality.

IV. Discussion

The proposed classification scheme is develop to distinguish between the coordination processes proposed in the literature. However, other issues are also useful to improve our understanding of this new research domain. This section first proposes to investigate the two other aspects of the framework presented in Section II. Next, we investigate the complementarities of OR and agent technology by analyzing their dynamic, their structure, their capacity to evolve and tolerate faults, and their convergence and stability.

A. Analysis of the literature

As presented in Section II, the second element of the framework is the local decision process.

1) Local decision process

Agents' ability to carry out advanced forms of interaction with other agents makes them the perfect tool to implement almost any form of coordination mechanism. However, because they are also capable of advanced AI planning, it becomes clearer that software agents can provide a flexible way to adapt local decision processes to the needs of the situation, which generally lack in pure OR-based solutions. For instance, [19] propose a framework to develop a multi-behavior agent that is capable of adapting its behavior and the usage of its tools to a situation. Along the same line, [51] provides a mixed-initiative problem solving approach to create a joint environment of human users, advanced planning decision systems and expert systems for supply chain coordination. Other solutions, such as proposed in [20], involve learning capabilities to let the agent learn the best action to perform in various situations. However, most coordination techniques proposed in the literature do not present advanced capabilities in terms of behavior adaptability and flexibility. To the extent of the author's knowledge, there is no study reported involving the development of an agent capable of automating some of the functions carried out by operations managers, including the expert adjustment of a schedule proposed by a traditional APS system. This largely remains a future topic for research.

2) Advanced planning and scheduling systems

Similarly, the flexibility and adaptability of advanced planning and scheduling systems is not really part of any discussion in the literature. In other words, most coordination techniques involve the use of very specific planning tools, which tends to reduce the domain of application of the approach. Some even oversimplify the problem. Furthermore, the structure of the planning tools used in these coordination techniques is generally tightly linked to the coordination process itself. Consequently, it is almost impossible for a supply chain member willing to adopt such solutions to independently select a coordination process and an advanced planning and scheduling system. However, some of these coordination techniques (e.g., [46]) make an explicitly reference to the use of planning tools and legacy systems, which dramatically improves the odds of ever seeing such a solution implemented in a company.

B. Towards integration of OR and agent technology

The analysis of the contributions studied in this paper reveals that the two main methodological domains contributing to the development of distributed supply chain technology are OR and agent technology. A further analysis of these two domains highlights that both have complementary qualities.

1) Dynamic:

The prime characteristic of an agent is reactivity. In other words, it is the agent's ability to sense changes in its environment which induce it to act in a goal-driven or predefined manner to carry out a specific function. This consequently involves a more or less intelligent form of feedback control, which gives agent-based systems their ability to adapt their local decision processes to their environment. From this perspective, OR-based systems do not involve the same level of control, if any. The notion of environment in an OR context can be translated into the elements that constitute the decision problem to be solved (i.e., an objective function, constraints, and parameters). However, the concept of changes in the environment is not explicitly part of an OR-based system, although it may be important for its user who could be interested in decision robustness or sensitivity analysis. It thus appears that OR-based systems and agent technology are two complementary technologies from this dynamic point of view. OR provides a way to solve complex decision problems and agent technology provides a way to monitor an environment and trigger an appropriate decision making process in response to an event whether it is external to the agent or internal in pursuit of a local goal.

2) Structure

Agent technology is generally implemented in a distributed manner (several types of structures have been developed for this purpose, [54]) to solve various management problems from information system integration to complex distributed decision problems. The structure of a multi-agent system defines the roles of each agent, their decision and information access rights, their level of autonomy as well as the way they interact together and exchange information. From a technological point of view, such a structure may also include how agents interact with legacy information systems and human users. Differently, OR technology is generally implemented as a single more or less complex algorithmic thread (or several tightly coupled threads). Consequently, OR-based systems are usually used to solve large combinatorial decision problems in a centralized manner. In a context where the decision problem is naturally distributed, such as in a multi-enterprise supply chain planning context, this characteristic makes it generally impossible to exploit OR centrally, especially with respect to sensitive information sharing and decision rights overlap. Consequently, as seen in sub-section III.C, several authors have explored various distributed approaches to implement OR technology using adapted mathematical decomposition approaches such as Lagrangian decomposition and Benders decomposition. The design of such coordination techniques provides a first and interesting approach to bridge the gap between agent technology and OR.

3) Capacity to evolve and tolerante fault

Because agent technology applications are made of loosely coupled and concurrently acting software agents, it is theoretically possible to shut down an agent, or replace an agent by another one, or add more agents, without impeding the function of the other agents. However, some agents have a role that provides a unique or central function to the other agents. Therefore, shutting down this kind of agents can have additional negative impacts to their function both locally and collectively. Similarly, the importance of the consequence of an accidental shutdown or a failure of an agent is related to how important the function of that agent is. OR-based systems generally follow a different paradigm of decision support which involves a stronger dependency with the user in terms of control. On the one hand, OR-based systems in operations management do not generally operate as automated sense-and-response systems. Consequently, the impact of an accidental shutdown will only limit the user's ability to make a good decision. On the other hand, such a failure may have a strong impact on the other decision making processes that are hierarchically dependent on the failing system. Finally, the evolution of an OR-based system requires the entire system to be taken offline and replaced. This also requires the need to develop, if needed, an interface with the legacy systems which may provide information.

4) Convergence and stability

Convergence can be defined as the ability of a system to provide efficient decision support in a reasonable amount of time, when it is needed by the user. Hence, in OR-based systems, the time required to reach a solution is tackled through the algorithmic efficiency of the system, which is systematically part of most OR development. The quality of the solution in terms of an objective function is also of paramount importance. In agent-based systems, because each agent only contributes partially to the search for a decision support solution, the lack of central or self-control can lead to convergence problems. This is often addressed in agent-based manufacturing and supply chain systems through the use of conflict management techniques, such as behavior-based self control [57] or by adding a central coordination process to limit the propagation of conflicts. In terms of solution quality, the ability of an agent-based system to provide a good solution is usually linked to the quality of the agent coordination process, which directly influences their ability to coordinate themselves.

V. Research Issues

The analysis proposed in this paper highlights several important aspects of the development of collaborative supply chain planning systems. The first aspects addressed here concern the need to further extend the integration of OR and agent technology. The second aspect deals with the need to develop collaborative planning standards.

A. Integration of agent technology and operations research

As previously discussed in Section IV.B, OR and agent technology are two complementary technologies that bring fundamental functionalities to the development of collaborative supply chain planning systems. Along this line, [13] propose different examples to show different ways to integrate these technologies. This discussion should be extended and more approaches developed in order to improve our understanding of how to use OR and agent technology in conjunction.

B. Development of collaborative planning standards

From a technical point of view, companies use different tools to plan their own operations. Because supply chain coordination requires some forms of information exchange that are embedded within the coordination process, these tools must be interoperable at the information exchange level, but also at the decision support process level. These decision processes must be compatible and complementary. Consequently, the development of collaborative planning standards is required to guarantee the compatibility of advanced planning tools developed by two different software companies. Also, such systems require openness from companies because they tie their decision support process with the systems of other companies.

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