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## TOWARD A METHODOLOGICAL FRAMEWORK FOR AGENT-BASED MODELLING AND SIMULATION OF SUPPLY CHAINS IN A MASS CUSTOMIZATION CONTEXT

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# Toward a methodological framework for agent-based modelling and simulation of supply chains in a mass customization context

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Abstract

In a dynamic customer-centric supply chain context, classic forecasting models turn out to have a limited applicability. In order to estimate the key performance indices of these Supply Chains and to facilitate their management, it is necessary to use more elaborate tools such as a simulation. However building simulation of customer-centric supply chains is no trivial matter. It requires the elaboration of a representative model and the execution of this model according to a set of hypotheses associated to scenarios. Due to their properties, Multi-Agent Systems seem particularly well suited for the modelling and the simulation of Supply Chains and more especially in a mass customization context. In this paper we propose an agent modelling framework for the modelling and simulation of such Supply Chains to facilitate their management. We show how this framework can be applied to a case of customer-centric Supply Chain from the golf club industry and we present an experiment plan associated.

*Keywords*: Supply Chain, Multi-Agent System, Mass Customization, Methodological Framework, Agent-Based Simulation.

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## 1. Introduction

The combination of globalization and digitalization has tremendous economic impacts and radically transforms the environment in which companies operate. The internationalization and digitalization of the markets offer companies the possibility to diversify their supply, production and distribution networks. Facing a plethoric supply, customers become more and more demanding and volatile. This induces an ever more competitive environment. Companies try to respond as precisely as possible to customer needs with highly focused products, each aiming at specific highly differentiated customer class or being personalized for a single customer.

In the aim to deal with these evolutions, companies have realized more cooperation with their suppliers and customers. This leads to the emergence of new types of organization such as the Extended Enterprise, the Virtual Enterprise and the Supply Chain. Integration of companies in these organizations provides a critical mean for value creation. It allows reducing costs, raising productivity, maximizing profits and bringing out flexibility, speed and reactivity abilities. These goals imply analysis and adaptation of existing and upcoming manufacturing and logistic systems, in terms of operations, processes, interactions and flow coordination.

Experimentations that support such analyses can hardly be realized on real systems. It then becomes necessary to decision makers to have available modelling approaches and simulation tools adapted to the nature of the considered organization.

In the aim to aid and instruct them in decision making processes, such as designing and managing organizational structures, the main objective of our works is to propose methodological elements for the design of socio-technical systems simulations. These kinds of systems are characterized by interactions between actors that necessitate decision making of different complexity. We are more particularly interested in physical system behaviour in reaction to decisions taken by the decisional system, decisions which rely themselves on the actual state of the physical system. The privileged application area of our works is the Supply Chain Management in a context of mass customization, in the aim to adequately representing systems operating in a highly dynamic environment.

The following section exposes our general research problematic: supply chain management and performance evaluation through modelling and simulation. After reminding the interest of the agent approach for Supply Chain modelling, section three introduces and compares the major works developed in this research area. Section four presents the approach and the models of the methodological framework we propose for agent-based modelling and simulation of Supply Chains. A case study is proposed to illustrate the implementation of this methodological framework. Section five details the conceptual model, its realization process, and its illustration on the case study. In section six we put emphasis on the operational model. Section seven is dedicated to the description of the simulation environment and presents some first simulations results concerning the customer demand. At last, we conclude on perspectives associated to our research work.

## 2. Research context

### *2.1. Introduction*

In the global competitive context, companies have to face numerous decisional problems related to the integration and the management of their organizations in an enterprise network. These problems, based on companies' relationships with their environment, encompass the analysis, the design and the improvement of industrial and logistic systems. The complexity of these systems and the multiple kinds of points of view to grasp, require adapted methods, models and tools, in the aim to describe, study and improve their design and management. Such a descriptive approach provides engineers and managers with analysis tools enabling the comprehension, control and improvement of their company behaviour, and subsequently of the overall networked organization. The models allow representing the physical and logical components of the industrial and logistic systems (resources, products, etc.). However, the erratic nature of the behaviour of these systems cannot be easily studied with static modelling tools. The recourse to dynamic analysis tools, for performance evaluation of industrial and logistics systems, relies on experimentation. Simulation belongs to this experimental path, and furthers the resolution of problems related to distributed decision making.

### *2.2. Supply Chain modelling*

Modelling the network organization consists in describing its functioning, in order to improve its performance and its competitive position. The models, methods and tools developed in the area of enterprise modelling are widely used for representation of manufacturing networks. This area, focused on production systems, had stretched over the limits of the company in order to grasp its organizational and operational evolutions.

Modelling frameworks such as Petri Nets [55] and IDEF [54] allow a behavioural representation of the companies' components. They are based on various concepts of activities, resources, processes, etc. They offer transversal point of views on the enterprise functions and fit with modelling methodological approaches such as CIMOSA [1], GRAI-GIM [12] and PERA [57]. They allow designing models adapted to the various facets of the studied company, relying on different modelling formalisms.

However, enterprise modelling does not allow to describe the whole set of properties related to network organizations. This approach offers a point of view that allows considering the network organization as a unique enterprise. Therefore, properties such as the distributed nature of the organizational structure, the autonomy of cooperative entities, the interaction dynamics, etc., are generally not expressed or explained.

We can add to all these properties the fact that companies have to redefine themselves and their networks for them to meet the expectations of customers and succeed to thrive in the new economy. As shown in Table 1, these transformations can be summarized by stating that network organizations have to evolve from a mass production paradigm to mass customization paradigm. This implies adjustments, alterations and transformations through the entire Supply Chain, with an emphasis on developing the flexibility, reactivity and agility of Supply Chain actors, allowing them to act as value adding coordinated collaborators helping the overall network face the environment dynamics.

Table 1

| | Mass production | Mass customization |
|---|---|---|
| **Principles** | Stability and control of the process for having an efficient production | Flexibility and adaptability to obtain customization and diversity |
| **Goals** | Design, production, marketing and delivery of low cost goods and services. Everybody can buy the products. | Design, production, marketing and delivery of customized goods and services with reasonable price. Everybody can exactly satisfy his needs. |
| **Main characteristics** | -Stability of demand<br>-Large homogeneous market<br>-Standard goods and services<br>-Uniform quality and low cost<br>-Long products development cycle<br>-Long products life cycle | -Split up demand<br>-Heterogeneous market niche<br>-Customized goods and services<br>-High quality<br>-Short products development cycle<br>-Short products life cycle |

Mass Production versus Mass Customization, source [42]

Customization expresses a chain structure defined by products/markets segments and physical flows pulled by the demand. Thus, it appears that languages and frameworks for enterprise or manufacturing network modelling, which provide graphical or sometimes formal enterprise representation, are not sufficient to explain and/or anticipate the behaviour of the network facing the environment dynamics.

### *2.3. Supply Chain modelling approaches*

In the literature we can distinguishes three main approaches for Supply Chain modelling: organizational, analytical and simulation. The organizational approaches rely on process modelling based on systems theory. The Supply Chain models issued from these approaches usually do not allow obtaining an evaluation of the dynamic system behaviour through time, when faced with stochastic environmental stimuli.

The analytical approaches rely on mathematical formalizations of the Supply Chains. The obtained models necessitate simplifying approximations, usually restrictive, and are limited for taking into account time. Two such approaches are the Control Theory approach, based on differential equations, and the Operational Research approach, which relies on optimization theories.

Supply chain modelling and simulation was originally based on System Dynamics, [15].This was motivated by the fact that the structure of the supply chain and the flow control determine its performance. Supply chain modelling and simulation was later investigated with continuous simulation and discrete event simulation. Currently discrete event simulation is the preferred mainstream method used for simulation of supply chains, [52]. The emerging trend exploiting the agent approach builds on discrete event simulation.

Supply chain simulation can be used either for descriptive or normative purposes. The former aims to help decision makers to better understand the behaviour and performance of the modelled supply chain and to foster the emergence of managerial insights. The latter uses simulation in an attempt to improve the functioning and performance of the supply chain by identifying the best decisions to take regarding structural, organizational, managerial and process transformations. Agent-Based modelling and simulation extends significantly the capabilities of discrete event simulation for both descriptive and normative purposes in the context of complex knowledge intensive supply chains.

Simulation approaches, sometimes introduced as analytical approaches, rely on experimentation through executable models. Simulation is a technique for understanding and predicting the behaviour of systems [48]. This type of approach offers several advantages [11]. Simulation is recognized to allow more realistic observation of the Supply Chain behaviour [41] or of complex economic models in general [7]. It allows an analysis of the Supply Chain dynamics. It leads to an observation of the Supply Chain behaviour along time, allowing concurrently, to understand the organizational decision-making processes [4], to analyze the interdependencies between the actors of the Supply Chain, and to analyze the consistency between the coordination modes and the decisional policies. Moreover simulation can be coupled with an optimization approach, allowing the validation of the relevance and the consequences of its results.

When using simulation approaches, the literature distinguishes between two main types of modelling [40], the equation-based modelling and the agent-based modelling. The former expresses the relations between the observables (quantifiable characteristics of one or more individuals) through equations. The model is executed by iteratively evaluating these equations and observing the evolution of the observables. The latter approach encapsulates in individuals, generically termed agents, the behaviour of each actor of the Supply Chain. The execution of the model is a behavioural simulation, letting the agents interact with each other and the environment, and monitoring their behaviour and the observables which are impacted by agent actions.

Thus, the agent-based simulation approach is the only one allowing an observation of the behaviour of each supply chain actor through time and of the dynamics of the chain resulting from theirs interactions

### *2.4. Conclusion*

Supply Chains are composed of autonomous companies which have roles and responsibilities defined from their competencies and from the activities they are able to realize. In order to evaluate their functioning and performances it is necessary to have behaviour analysis tools available, in particular enabling simulation. However, classical enterprise modelling tools do not take enough into account all the dimensions of the network organizations (distributed nature of the entities composing the Supply Chain, interaction dynamics, decisional autonomy, etc.). Taking into account the organizations agility when facing dynamic stochastic environments necessitates new representation capacities. These should concurrently allow a distributed point of view and enable a holistic perspective of the whole system.

Multi-Agent Systems (MAS) are particularly well suited for developing and running of such simulations. The properties which characterize MAS are adapted for the study and the representation of entities composing complex systems and of their behaviour facing the dynamics of the interactions. MAS take as reference social interactions in the aim to further the emergence of complex organizations [9]. Agent-based simulation highlights the dynamics of the enterprise network facilitating the study of coordination.

## 3. Overview of multi-agent-based modelling and simulation of Supply Chains

The properties which define Multi-Agent Systems provide a modelling framework adapted to the representation of Supply Chains. Development of simulation models must provide Supply Chain actors with tools enabling them to lead prospective studies not only on their own behaviour but also on the behaviour of the whole system in which they evolve. The definition of such studies must allow the members of the industrial network to evaluate the potential risks and the envisaged benefits. Entities that compose the Supply Chain have different goals, constraints and configurations. However, these entities are interdependent regarding the improvement of the whole system performances.

In this section we present further evidence of the relevance of the Agent approach and projects already led using this approach in the field of Supply Chain management.

### *3.1. Relevance of the agent approach*

An agent can be defined as an entity, either theoretical, virtual or physical, capable to act on itself and on the environment in which it evolves and to communicate with other agents. Its behaviour is the consequence of its observations, knowledge and interactions with other agents [14]. An agent can be characterized by its role, its goals, its functionalities, its beliefs, its decisional abilities, its communicational capacities and its learning capabilities. An agent is defined by Jennings et al. [26] in this way: "*an agent is a computer system, situated in some environment, that is capable of flexible autonomous action in order to meet its design objectives* ". Wooldridge and Jennings [58] define the following properties of an agent:

- **Autonomy**: an agent operates without human being or other direct intervention and neither the actions it realizes nor its internal state are submitted to any control.
- **Reactivity**: an agent perceives its environment and reacts in an appropriate way to the environment changes.
- **Pro-activity**: an agent must be able to show behaviours directed by internal goals, taking initiatives.

– **Sociability**: The agents interact with each other using communication languages and common sociability rules

Multiple kinds of agents can be differentiated according to their degrees of intelligence and knowledge, defining a wide continuum from reactive agents to cognitive agents. These agents vary greatly in terms of the nature and complexity of their required underlying abstract architecture, [56]. The reactive agents follow the stimulus/action law. They use reduced communication language and protocols. The cognitive agents have reasoning capabilities and have an explicit representation of the environment in which they evolve [37]. Cognitive agent systems are based on the cooperation of a limited number of agents able to perform complex operations. Agents in such a system follow a group of interaction rules organized in social laws and cooperate to achieve a common goal. Agents generally coordinate with each other in order to avoid conflicts while carrying out their tasks.

The design of Agent-Based Simulation raises a set of problems resulting from its multiple legacies. An Agent-Based Simulation is at the same time a software product, an agent-based software product and a simulation tool. Its design raises difficulties jointly coming from its three legacies.

As a software product, it necessitates the implementation of classical Software Engineering approaches which guide the development process and ensure its quality, its robustness, its sustainability and its adaptability.

As agent-based software, several Multi-Agent System development methods exists (from requirements to implementation) and are based on adaptations and extensions of Object Oriented methodologies (such as Unified Modelling Language (UML), Object Modelling technology (OMT)) or Knowledge Oriented methodologies [6] [25]. The use of a methodology is then guided by the targeted agent architecture type. In this framework, the notions of goals and organization are fundamental. The purpose is to describe or design an organization which is then more finely detailed [22] [44] [60]. These methodologies can also be based on Software Engineering development models such as waterfall [13] or spiral [10].

As a simulation tool, Multi-Agent Systems raise the problem of designing a simulation model (particularly agent-oriented) and its implementation in a simulation environment. If the development of generic simulation architecture seems to be accessible [38], a methodological needs to appear. Guiding the design process goes beyond allowing the free expression of the designers in a given formalism, toward setting a methodological point of view in order to adapt the model design in function of the system and environment to be dynamically simulated.

Agent technology is already considered as an important approach for developing distributed intelligent manufacturing systems [23]. Supply Chains includes and extends such systems. The agent paradigm has been shown to allow modelling and simulate in a distributed way the behaviour of the Supply Chain and of its members [20]. Supply Chain and Multi-Agent System show numerous common intrinsic characteristics [59].

Both MAS and Supply Chains are composed of entities which interact according to their roles and abilities inside organizational structures. Agents and Supply Chain actors have means, resources and capabilities allowing them to realize in an individual or collective way various functions, tasks or activities within different organizational structures. These analogies naturally lead to the Multi-Agent approach being a privileged way to represent Supply Chains. Specifically, it allows to easily taking into account:

– the distributed nature of Supply Chains and the non linearity of their behaviours;
– the modifications of the environments, since the agent autonomy allows the model to change by updating through addition and removal of agents;
– the decision complexity and variety, through the MAS capability to solve problems;
– a behaviour of cooperation without altruism thanks to the definition of the agents' properties through interaction modes.

*3.2. Previous Research on Supply Chain Agent-Based Modelling and Simulation*

Analysis of modelling and simulation works published in the literature shows that agents are used to model Supply Chain entities or decisional processes. MAS exploit the notion that actors in a Supply Chain have the same properties as agents.

Empirical evidence shows that MAS make easier the study of supply chains by simulation, as reported through the results of many projects of multi-agent modelling and simulation of Supply Chains [19, 21, 23, 28, 46, 47, 49, 50 and 51]. For example, the Supply Chain Demonstrator [19] allows to model and simulate complex conversations exhibiting a high level of cooperation using the COOL language. The validation of COOL is reached and the development of coordination protocols between agents for conflict resolution is realized [19]. This platform offers a great capacity for representation of communication between supply chain actors. The modelling approach based on SWARM proposed in [23] facilitates the representation of complex Supply Chains, especially owing to the recursive composition of its structure. Interactions between agents are specified from pre-established communication channels, which characterize the type of the exchanged messages. An agent-oriented simulator, MASCOT, has been used to study Supply Chain performance according to three lateral coordination policies [46]. Based on the MASCOT architecture, Kjendstad studies the effects of four management policies on the behaviour of the Supply Chain actors [28]. Following the analysis of characteristic elements derived from supply Chains, it has been proposed a library of generic structural and functional elements for the design of Multi-Agents models [50]. Table 2 presents a comparison of the most known works applying an agent-based approach for modelling and simulation of Supply Chains.

Table 2
Application of Multi-Agent Systems to Supply Chains

| Simulation projects | Areas | Approached problems | Supply network modeling | Main characteristics |
|---|---|---|---|---|
| **Strader *et al.* [47]** | **Supply Chain Management** | Information sharing in a divergent products Supply Chain | 1 agent per enterprise department : 8 agents (inventory, planning , …) | Comparing management policies according to the network architecture |
| **Swaminathan *et al.* [48]** | **Design of supply networks** | Design of Multi-Agent models for Supply Chain simulation | 4 production agents<br>1 transportation agent<br>Control elements | Creation of the model from generic elements<br>Modularity - Reuse |
| **MASCOT [44]** | **Supply Chain Management** | Supply Chain coordination by planning and scheduling | 3 agents / enterprise :<br>1 planning agent<br>2 scheduling agents | Utilization of a Blackboard<br>2 interactions protocols<br>Intra-level and Inter-level |
| **ANTS [45]** | **Scheduling** | Task allocation on resources by commitments | 1 agent/resource<br>1 agent/material<br>1 agent/process | Least Commitment Scheduling engagement on capacities |
| **DASCh [39]** | **Supply Chain Management** | Propagation of forecasts to the network' actors | 1 agent/enterprise<br>1 agent/information<br>1 agent/material<br>1 agent MRP/enterprise | *Bullwhip Effect*<br>Precise forecast windows size |
| **Optimisation / MAS [20]** | **Inventory control** | Service level versus inventory level stock | 1 agent spot market<br>1 agent/network site<br>1 agent/transportation | Study of replenishment policies (reorder point, quantity, …) |

The projects studied in Table 2 have very distinct purposes, yet all of them find useful the agent-based modelling and simulation of Supply Chains. The area of the study and the considered problems influence the choice of the abstraction level for the Supply Chain representation. These factors also condition the creation of the Supply Chain model, as well as the multi-agent organization. Agents are in particular used for the representation of the entities composing the supply Chain. The specification of their behaviour is determined by the abstraction level of the model. As a matter of fact, the roles adopted by the agents and their number differ from a project to another. Agents have competences, behaviours, responsibilities, communication and decision making capacities that spread from the management of a material resource to the strategic management of a company. In most cases, the studied implementations have associated an agent to each company or each production or distribution site, and an agent to each key actor (personal, organizational or software) within the supply chains. In general the agent-based simulation approaches are different for each project. We can also note that, in these works, the demand is specified as an input parameter of the simulation model, through a demand profile. However, in a product customization context, demand and transformation activities depend on each other and become more and more difficult to forecast.

### *3.3. Existing agent-oriented simulation works versus mass customization*

Mass customization is not taken into account in the reviewed works. The intrinsic characteristics of customization in Supply Chains necessitate behaviour representation of customers in the modelling step. However, the realization process of the obtained simulation models in the presented simulation projects is not explicit. Thus this makes very difficult to take into account the product customization.

A specific methodological framework, having its roots in the research area of enterprise modelling, appears to be necessary, according to us, in order to realize agent-based simulation models of complex Mass Customizing Supply Chains. This generates an additional dimension in the representation complexity of Supply Chains, and can hardly be taken into account in the reviewed works.

## 4. A methodological framework for agent-based modelling and simulation of Supply Chains

### *4.1. Introduction*

The elaboration of agent-oriented simulation models of complex Supply Chains, in particular those characterized by mass customization, requires a specific methodological framework.

The agent-oriented methodological framework that we propose takes its roots in the area of Enterprise Modelling, and leads to the definition, the implementation and the simulation of an agent model on a specific software platform.

In this section, we first present in a general way this methodological framework, by introducing the various levels structuring it, as well as the various models which compose it and their phases. Then we present a case study relative to a Supply Chain in a mass customization context, used for illustration in the following sections dedicated to each of these models.

### *4.2. Overview of the methodological framework*

Agent-oriented simulation is based on experimenting through executable models. It allows a time phased observation of the behaviour of the system and of the entities composing it. Agent-oriented simulation is based on the notion of observables, which are quantifiable properties characterizing one or several entities. The values of these properties are changed according to actions realized by entities. The state of the system at any time results from the dynamic behaviour of every entity and their interactions.

As seen in the previous section, the agent-oriented modelling is adapted to the representation of the Supply Chains and to the study of their behaviour. The definition of observables allows an understanding of the organizational decision-making, and an analysis of the management of interdependences among actors of the supply chain.

In order to understand how the real world system reacts to some stimuli, Frantz [16] defines a generic simulation process illustrated in Figure 1. In this process, a conceptual model is first developed to obtain a representation of the real system. This model is then implemented in a simulation model which is a computer representation of the conceptual model. The simulation model is used to run scenarios defined by the users.

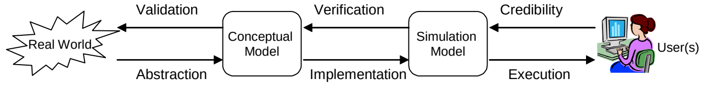



Fig. 1 : Model abstraction in the simulation process [16]

We propose using an adaptation of this methodological framework for the agent modelling and simulation of supply chains, structured according to three levels of preoccupation:

- The *conceptual level*: At this level is developed a *conceptual modelling* which constitutes an abstraction of the real system, in our case a complex Supply Chain. This modelling process is realized from knowledge extracted from Enterprise Modelling. The obtained modelling of the supply chain is crystallized in a *Domain Model*. This model is then reformulated in the agent paradigm to obtain the *Conceptual Agent Model* of the considered supply chain;
- The *operational level*: From the Conceptual Agent Model of the supply chain, this level develops an operational agent modelling, crystallized in an *Operational Agent Model*. This model has to permit to simulate the behaviour of the studied supply chain. The Operational Agent Model is a computer model and it takes into account all the constraints inherent to the simulation in a context of Agent-Based Simulation.
- The *exploitation level*: This level concerns the implementation and the integration of the previously defined Operational Agent Model on a specific simulation software platform. This level concerns also the execution of this simulation model according to different contextual scenarios.

Figure 2 presents the three modelling levels and their resulting models that jointly structure our proposed agent methodological framework for modelling and simulation of complex Supply Chains.

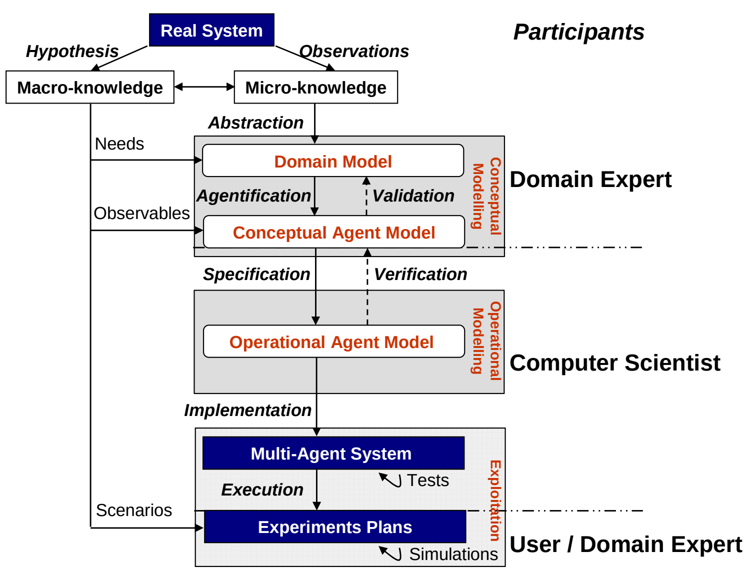



Fig. 2 : Framework for Agent-Based Modelling and Simulation of supply chains [31]

As presented in Figure 2, distinct individuals may be taking charge of the conceptual, operational and exploitation levels:

– At the *conceptual level*, the responsible participant is the domain expert. His role is to realize a knowledge based description of the real system and to define the phenomena under study. He uses formalisms from the Enterprise Modelling field to elaborate a first model of the real system: the domain model. Then he reformulates this model under the agent paradigm to get the Conceptual Agent Model. Two types of knowledge are exploited at this level. Macro-knowledge is used to develop a global view of the system and to express the phenomena to be explored, through needs, observables and scenarios. Micro-knowledge helps to identify the system's individuals and allows describing their behaviour.
– At the *operational level*, the aim is the elaboration of specifications for an agent model of simulation. These specifications are the responsibility of a computer scientist. They concern the agent-oriented software engineering, for which various specification models and associated formalisms have previously been proposed. These models and formalisms will hereafter be adapted to the particular context of the modelling and the simulation of Supply Chains.
– At the *exploitation level*, both the computer scientist and the domain expert have responsibilities, as well as decision makers and analysts. The computer scientist has to implement and integrate the Operational Agent Model of simulation on an adapted software simulation platform. The domain expert has to clarify and specify the various scenarios that are to be studied. Together with decision makers and analysts, as pertinent, he defines the different relevant experiment plans to be performed and then helps interpret and analyze the experimental results.

The proposed methodological framework for agent-based modelling and simulation of supply chains can be applied for both descriptive and normative purposes. A key driver toward adequate representation of the supply chain for both type of purposes is how are modelled the decision systems, [3, 33]. The framework allows various options for integrating decisions systems such as Advanced Planning and Scheduling (APS) systems.

At one extremity of the option spectrum, the multi-agent system is coupled with an APS system. Agents can interact directly with the APS system to support their decision making. The APS system is fed by the multi-agent system with updated simulated information. At the other extremity of the option spectrum, the APS system is not used by the multi-agent system. Teams of agents take on selected responsibilities of the APS system. To do so, APS system features are embedded in specific agents according to the simulation objectives. These features are approximated as agent behaviours. The former approach simplifies the multi-agent system but increases the integration complexity due to communication requirements between the APS system and the multi-agent system. The latter approach minimizes integration capacity, but increases significantly the complexity of agent development while it approximates the supply chain decision processes.

### *4.3. The industrial case*

The case study, which we shall use in the following sections to illustrate the application of our methodological framework, concerns a mass customizing Supply Chain in the field of the golf club industry.

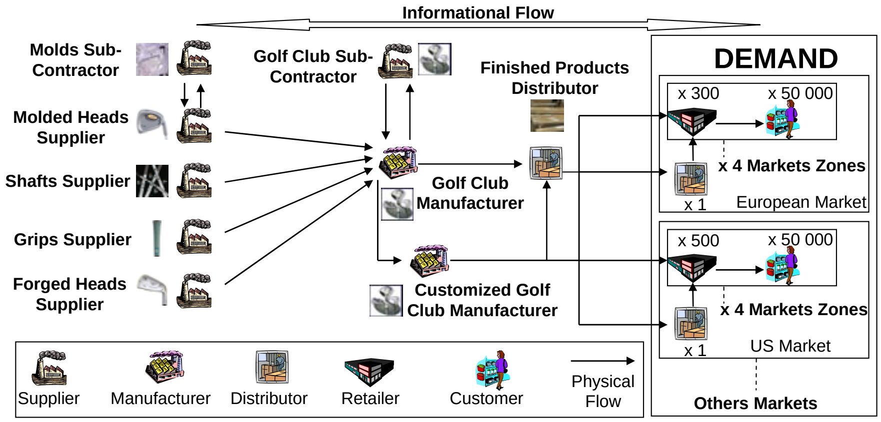



Fig. 3 : An industrial case from the golf club industry

The Supply Chain illustrated in Figure 3 is inspired from three major manufacturers [36]. This chain is characterized by combinations of specific products defined according to different levels of personalization. These products are offered to specific markets. The demand is the market response to these offers, expressed in each market in terms of customers deciding or not to purchase a set of golf clubs at specific times. Supply Chain actors are autonomous and collectively responsible to supply products on market zones.

## 5. Conceptual modelling of the case study

### *5.1. Introduction*

The conceptual modelling is performed in two steps. In the first step, we realize an abstraction of the considered Supply Chain. This abstraction is crystallized in the Domain Model of the supply chain. In the second step, according to an *agentification process*, the Domain Model has to be reformulated, based on an individual-centered approach, in order to obtain the Conceptual Agent Model of the considered Supply Chain. In this section we first detail this conceptualization process in the specific context of customer-centric Supply Chains. Then we illustrate the conceptual modelling on the case study introduced into the previous section.

### *5.2. Conceptualization process*

As introduced earlier, the conceptualization process is composed of two stages, respectively leading to the elaboration of a Domain Model and a Conceptual Agent Model of the supply chain. Figure 4 illustrates the conceptualization process with implied models and their articulations. Each of the models is described in the following sections.

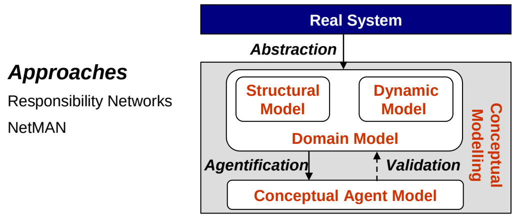



Fig. 4 : Conceptual Modelling Process

*Domain Model*

The elaboration of the domain model can be based on various modelling frameworks and formalisms from the Enterprise Modelling field, depending on the specific context and the modelling experience of the domain expert. To take into account the complexity of Supply Chain in a mass customization context, we were inspired by the modelling framework of the manufacturing networks proposed in the NetMAN project [35] [17]. We extend the use of this framework in order to better take into account the specificity of the studied Supply Chains, in particular concerning the proposed formalisms [32]. Thus, the Domain Model is composed of two complementary models:

– The *Structural Model* is based on responsibility networks [34], which are well adapted to the modelling of distributed organizations. It describes the structure of the supply chain, presents its actors and their respective responsibilities, and depicts the material flows which exist among these actors.
– The *Dynamic Model* completes the Structural Model by clarifying the coordination modes used, in particular the nature of exchanged information. The dynamic model allows defining the behaviour of each actor, and clarifying the interactions modes.

In a mass customization context, finished products are defined by the consumers from sets of options or parameters. This product personalization makes production of finished products in advance impossible. However, modules or components can be produced in advance and stored. Facing an erratic demand, the promised order-to-delivery time strongly influences the management of physical flows.

Transformation activities of products are activated at the reception of orders. The orders express the requirements of the customers and define the customer-supplier relation. For flow coordination purposes, we propose a reference model for actor coordination in supply chain. This reference model classifies activities according to eight levels of personalization (Figure 5). The actors are identified according to their competences, roles and responsibilities. They have to coordinate their activities to respond favourably to the demand.

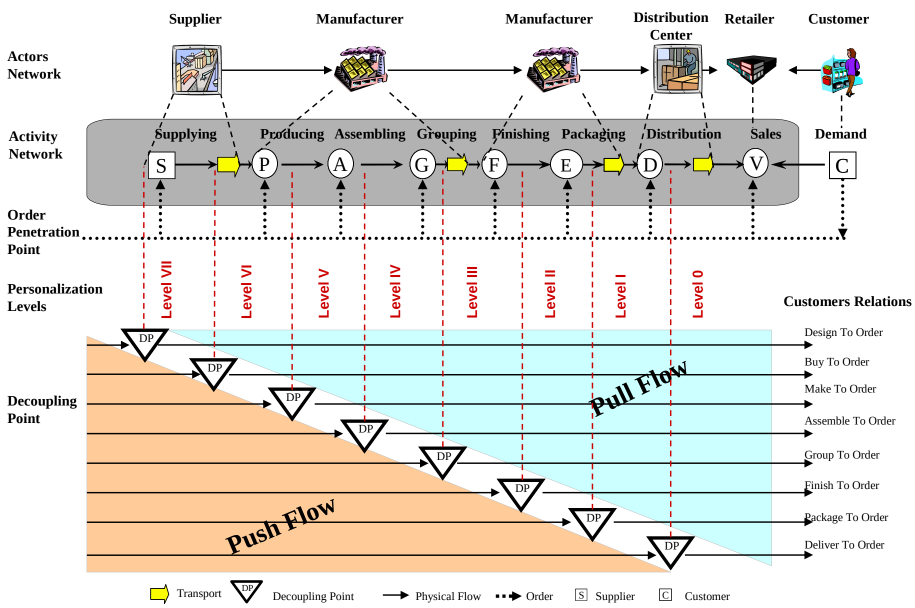



Fig. 5 : Reference model for actor coordination in supply chains [29]

An order is represented on the activity network by an order penetration point [24]. Its position determines the entrance of orders in the physical flow. The identification of the personalization level allows defining the decoupling point [8]. Its position establishes a frontier in the flow circulation, for example switching between push flow and pull flow. This point has an impact on inventory management and on the relations to establish among the actors situated upstream and downstream this point.

This reference model allows identifying the level of personalization associated to an order. This allows to place the decoupling point, and thus to define the coordination mode associated to the needs expression. The domain expert defines these needs in order to study rules and organizational structures of Supply Chain.

*Conceptual Agent Model*

The Conceptual Agent Model is the result of the agentification process. This process is a unified reformulation according to an individual-centered approach. Indeed, from the two Structural and Dynamic Models a unique agent model is elaborated. The Conceptual Agent Model specifies the agents, the objects and their interactions. We distinguish two main types of interactions: informational (message) or physical interactions.

To perform the agentification process rules have been defined. Each actor of the supply chain specified in the Dynamic Model generates a specific agent. Any activity of an actor of the chain generates a specific agent in close interaction with the agent associated to the actor concerned, regrouped in a same partition. Any exchange of information specified in the dynamic model generates a message based informational interaction. Any material flow in the dynamic model requires an object to represent a physical product and leads to a physical-type interaction.

At this conceptual modelling level, the focus is put on the identification of the agents, the objects and the nature of their interactions. The nature of the agents, the nature of the objects, their specification, their software architecture, as well as the detailed specification of their interactions will be defined during the operational modelling.

### *5.3. Illustration on the case study*

#### *5.3.1. The Domain Model*

The Domain Model proposes a representation of the real supply chain under study. It is composed of two models, The Structural and Dynamic models. These are conceived according to the abstraction level adopted to fit the needs of simulation study.

*Structural Model*

The structural model is built around a set of actor types including producers, assemblers, processors, fulfillers, distributors, retailers and customers [34].

Producers have the responsibility to produce parts and components from materials. Processors are responsible for performing specified operations on parts and products. The Assembler and the Fulfiller have as responsibilities to transform sets of materials, parts, and/or components into modules and/or final products, the difference lying mostly in the fact that fulfillers make personalized products, strictly to order, while assemblers can assemble standard products to stock or to order. Once these transformation steps accomplished, final products or modules are delivered to Distributors and Retailers. In general, distributors have the mandate to decouple the supplier and the client, and to provide to the latter the products on demand. Distributors may be providing final standard products to Retailers, while fulfillers may provide personalized products. Retailers have the responsibility to satisfy the client needs by selling him final products. Physically implemented retailers form a physical interface between the Customers and the Supply Chain. Web-enabled virtual retailers do not have a physical presence and thus offer a marketing and transactional interface. The number of Retailers is specified by market zone. A Customer belongs to a market zone.

The responsibility network of Figure 6 represents the Structural Model of the supply chain studied (inter enterprises level).

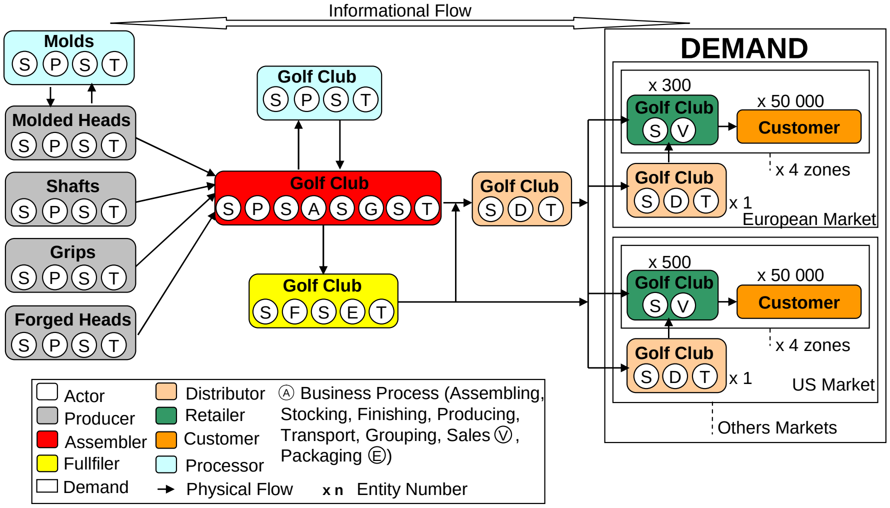


Fig. 6 : A Structural Model at the Inter-Enterprise level

*Dynamic Model*

The dynamic model depicted in Figure 7 at the inter-enterprise level is based on a part of the responsibility network described in the structural model. It includes a Shaft Producer, a Golf Club Assembler, a Golf Club Fulfiller, Distributors, Retailers and Customers. Customers express their needs by placing orders at Retailers. These needs rise up along the responsibility network to the appropriate decoupling point.

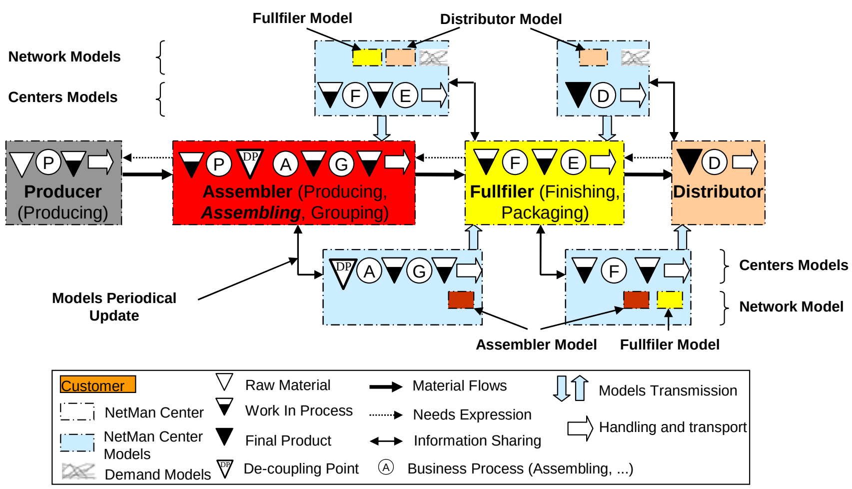
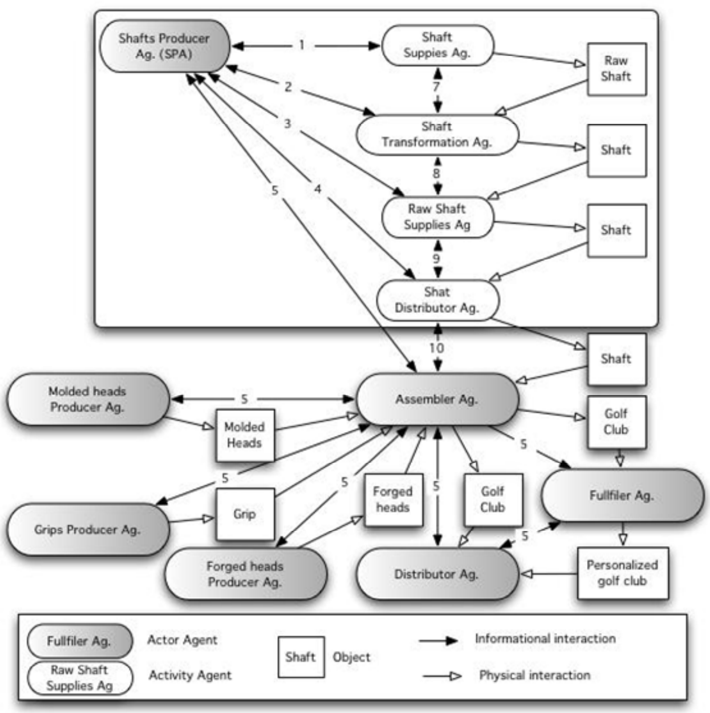


Fig. 7 : A Dynamic Model at the Inter-Enterprise level

The Customer-Retailer relationship described in Figure 7 is an “Assembly To Order” relationship. The decoupling point is situated at the Golf Club Assembler. Transformation activities are then made in a pulled flow from the de-coupling point to the Customer. Customers can purchase popular products stored at the Retailer or place an order for a personalized product fitted to his specifications.

### *5.3.2. Conceptual Agent Model*

The Conceptual Agent Model is a reformulation in agent paradigm of the Domain Model. Conceptual Agent Model specifies the agents and their interactions. We have to distinguish two main types of interactions: message based information interactions or physical interactions. As seen before, specific rules supporting the agentification process have been defined. Figure 8 presents a Conceptual Agent Model. In this example, a Shaft Producer actor, who performs five activities is represented by six agents, an agent for the actor and an agent by activity.




1- Supply Plan
2- Production Plan
3- Inventory Levels
4- Deliver Plan
5- Coordination Mode

7 - Inventory Levels / Production Schedule
8 - Production Schedule / Inventory Levels
9 - Inventory Levels / Deliver Plan
10- Deliver Plan / Supply Plan

Fig. 8 : Conceptual Agent Model

## 6. Operational Agent Modelling of the case study

### *6.1. Introduction*

The operational agent modelling step has for objective to build a computer model in order to simulate the behaviour of the studied supply chain. The Operational Agent Model is obtained from the Conceptual Agent Model using a number of derivation rules. It specifies the multi-agent system which will be implemented on a simulation platform. These specifications can be expressed through existing agent-oriented software engineering models and formalisms. In this section we first detail the *operationalization* process, leading to the specification of the Operational Agent Model.

*6.2. Operationalization process*

The *operationalization* process is performed in two steps. In the first step, we define the software architecture of the multi-agent system as well as the internal architecture of the agents. It leads to the elaboration of diagrams and graphs derived from the Conceptual Agent Model. In a second step, we specify in detail the knowledge, the behaviour and the interactions between agents. Different agent-oriented software engineering diagrams are then developed. All these specifications define the Operational Agent Model for the integration of the multi-agent system in a simulation platform. Figure 9 presents the steps followed during this *operationalization* process.

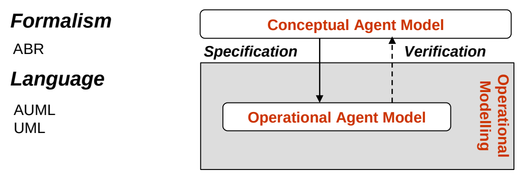



Fig. 9 : Operational Modelling Process

*Multi-agent system architecture*

The definition of the software architecture involves differentiating the agents of the Conceptual Agent Model. The conceptual agents are named according to the nature of their activity within the supply chain (e.g. production planner for assembly centre A). Then we define for each conceptual agent an internal software architecture.

We distinguish two types of activities realized by conceptual agents: decision-making or operating activities. Decision-making or deliberative activities are based on decision models or procedures requiring informative interactions with other agents. Operating activities consist in executing an action not requiring information exchange.

To build the software architecture of the multi-agent system, the decision-making activities and the operating activities of the conceptual agent are differentiated and affected to specific software agents. Each conceptual agent will be associated to a generic software architecture established from cognitive agents and reactive agents. This generic architecture, named "Agent Actor" [30], is illustrated in the Figure 10.

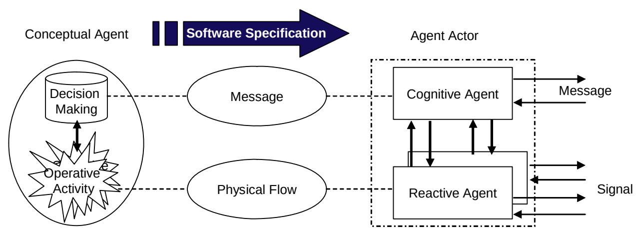



Fig. 10 : Agent-Actor software architecture

These software agents, reactive and cognitive, differ from each other on their functional mode and on their representation of the environment:

- The cognitive agents communicate by messages exchange. A downward message corresponds to an information request or to an order emission.
- The reactive agents have behaviours defined by their states. These states specify the actions they realized further to the reception of messages resulting from cognitive agents or from signals emanating from the environment.

A conceptual agent is transposed into a software agent composed by a cognitive and/or one or several reactive agents in the Operational Agent Model. These software agents, which compose the architecture of the multi-agent system constitute of two agents' societies in interaction, a society of cognitive agents and a society of reactive agents.

*Specification of software agent*

Once the basic software architecture is achieved, the next step is to specify the knowledge and the behaviour of each agent, as well as the interactions. The basic architecture is then enriched by software agents more directly associated to the technical execution of the simulation. In this software specification, various diagrams from agent-oriented software engineering are developed. The cognitive agents and the reactive agents require specification formalisms in line with their behavioural capabilities:

- The reactive agents can be based on state-based reflex-type agent models [45]. In general a reactive agent allows to represent its simple behaviour through the specification of a series of defined rules.
- The cognitive agents can be based on Beliefs-Desire-Intention (BDI) agent models [27]. Their behaviours can be specified using the Agent Behaviour Representation (ABR) formalism [53], which is presented in the Figure 11.

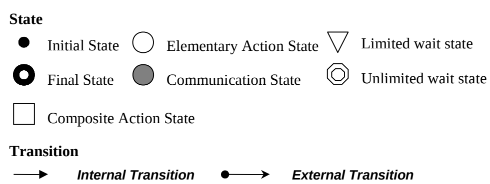



Fig. 11 : Agents Behaviour Representation (ABR) formalism [53]

The ABR formalism is presented as a strongly typed statechart graph. To a state is associated an action realized by the agent. States are interconnected by arrows representing transitions (event) conditioning the passage from a state to another. The internal transitions describe the realization of a local action by an agent. The external transitions translate the arrival of a message resulting from another agent.

The behaviour of cognitive agents is described with Behavioural Plans according to two models: individual and social. These plans can be expressed in the form of statechart graphs according to the ABR formalism. The individual models represent the autarkic behaviour of the agent. It deals with local plans, nor requiring interactions with the other agents to reach their purposes. A social model involves the social behaviour of an agent. It develops the role protocols. It thus specifies how an agent interacts with others through message passing, as well as the actions leading and resulting from these interactions. The set of Behaviour Plans of an agent defines its ability to react and solve problems.

All these specifications define the Operational Agent Model. They have to allow the integration of the multi-agent system in a dedicated simulation platform. The specificities of the simulation platform will be taken care of at the experimentation level.

### *6.3. Illustration on the case study*

#### *6.3.1. Multi-agent system architecture*

The Operational Agent Model is directly derivate from the Conceptual Agent Model. It is composed by two agents' societies in interaction, a society of cognitive agents and a society of reactive agents. The Figure 12 presents a part of this architecture restricted to the software agent issued from the conceptual agent « Agent Shaft Producer ».

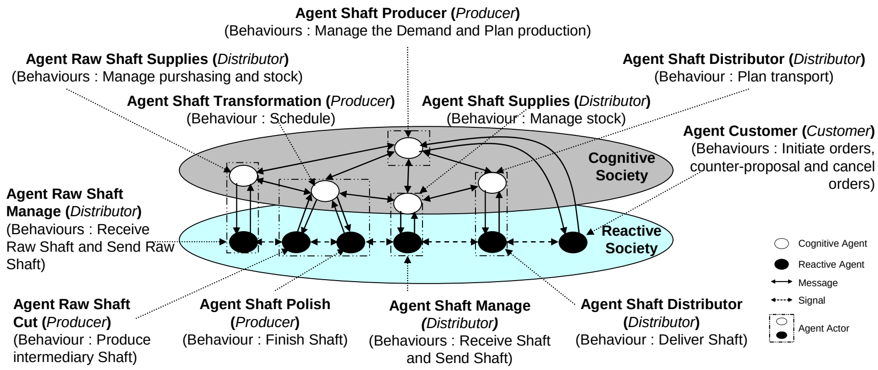


Fig. 12 : The multi-agent system

*6.3.2. Specification of each software agent*

In order to gives a detailed view of the different agent roles and the connections between the roles we use class diagram defined in Agent UML [39], based on the Unified Modelling Language UML [5]. Class diagrams can conceptually model a problem domain and they can model the implementation of classes guiding the computer scientist. As define in [2] we decompose the class diagram in five sections. The first concerns the name and the role of the agent. The second presents the attributes of the agent. The next reviews the behaviour of the agent. The section "methods" describes actions realized by the agent and the attributes concerned. The section protocol concerns the role played by the agent. The class diagram of the Agent Customer is presented Figure 13.

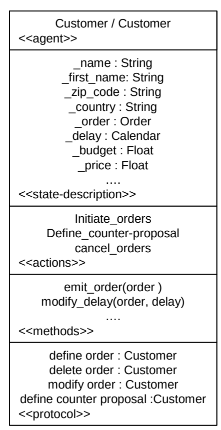


Fig. 13 : AUML class diagram of the Agent Customer

Behaviours for reactive agents are represented by statecharts. For cognitive agents a higher level formalism such as the ABR formalism should be used. The Agent *Raw Shaft Supply* is responsible for the purchase, the receiving, the distribution and the inventory control of raw shafts. It has a Distributor role. Figure 14 illustrates the *Raw Shaft Purchasing* Behavioural Plan.

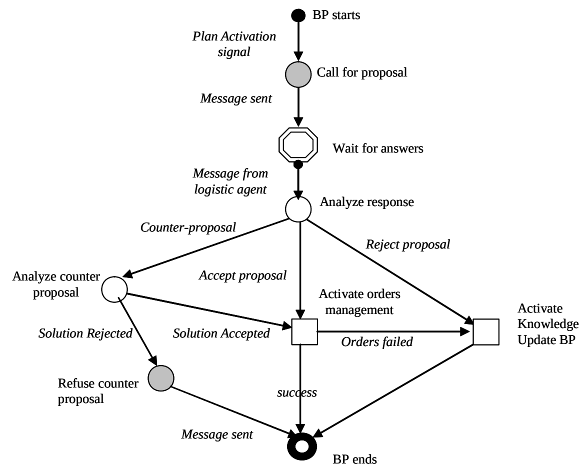



Fig. 14 : Raw Shaft Purchasing Behavioural Plan for the Agent *Raw Shaft Supply*

## 7. Exploitation of the agent modelling for the case study

This section concerns the exploitation level defined in the methodological framework that is proposed in section 4. The exploitation necessitates the use of a computer environment to implement and to simulate the Operational Agent Model (OAM) under a scenario based set of operating hypotheses. To simulate the OAM specified in the previous section, a dedicated software system has been developed. Figure 15 presents the steps of the exploitation process as well as the computer resources used.

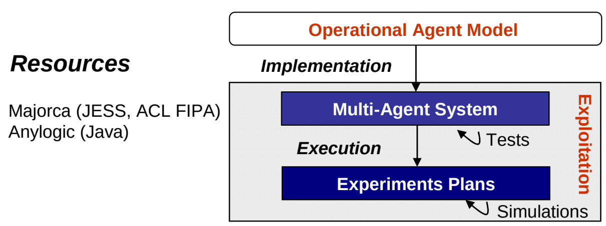



Fig. 15 : Exploitation process

This section first presents the implementation of the Operational Agent Model in two interacting software platforms. Then, for illustrative purposes, an experiment plan adopted for customer simulation related to the case study is presented.

### *7.1. Implementation*

The implementation activity transforms the agents obtained during the operational modelling process by integrating them within a computer environment. In the implementation process, the cognitive agents are implemented in the MAJORCA platform developed in our laboratories [53]. This platform, written in Java, integrates the JESS rule engine [18] and complies with the FIPA (Foundation for Intelligent Physical Agent) Agent Communication Language standard. The reactive agents are implemented in the Anylogic© simulation software for the development of discrete systems. Figure 16 presents the computational agent architecture chosen for the OAM implementation in the two software platforms which are interacting through message exchanges.

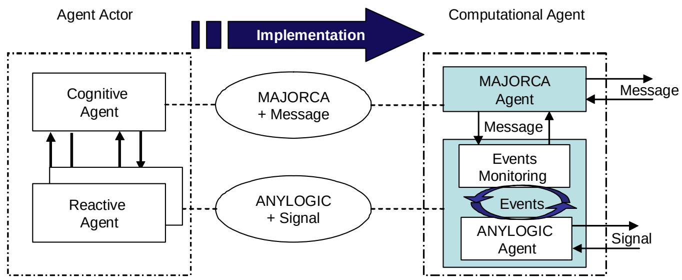



Fig. 16 : The “Computational Agent” architecture

To develop a multi-agent system (MAS), it is not sufficient to put several agents in the same environment. These agents have to interact. To support these interactions, auxiliary agents or services agents are necessary. In a simulation context, there are several kinds of service agents: i) the White Pages Agent or Agent Name Server Agent (ANS-Agent), ii) the Yellow Pages Agent or Register Agent (R-Agent), and, iii) the Event Scheduler Agent (ES-Agent). The ANS-Agent lists the agents occurring in the MAS, by loading in memory their name and the address insuring the following of the messages exchanged. The R-Agent is a repertory agent responsible to interact with agents so as to maintain an up to date list of agents, stating their names and skills. The ES-Agent insures the synchronization of the events and the time between the agents of the AOM.

Figure 17 presents the integration of the OAM of the Golf Club case study in these two software platforms in order to study the coordination modes. The OAM represents the entities that realize coupled decision-making and/or operative activities.

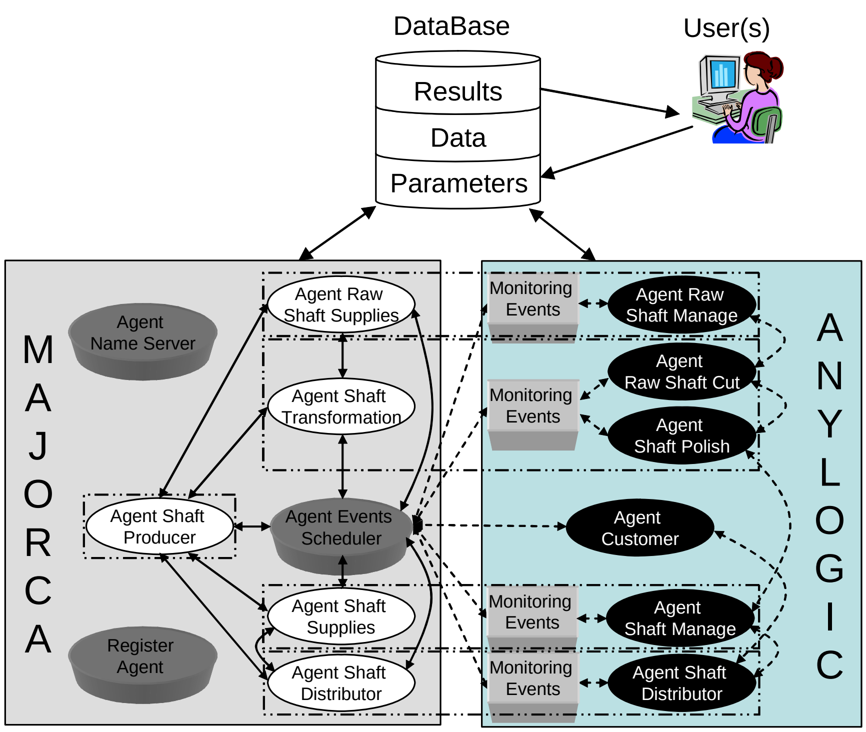



Fig. 17 : An implemented multi-agent platform

The implemented simulation environment consists of services agents (ANS-Agent, R-Agent, ES-Agent and of simulation engines (JESS inference engine, Majorca, Anylogic libraries). The simulation environment has to facilitate the understanding of results via a user interface, which assist users in the decision-making. The software Anylogic is used to develop graphic interfaces to support user interaction during the simulation sessions, for instance the setting of the reactive agents and objects defined in the OAM. Others interfaces permit to realise the setting of cognitive agents.

The database also constitutes an interface between the simulation environment and the users. It is used for the setting of the model to simulate; the memorization of the data in the course of execution; and the saving of the simulation results. The OAM parameters clarify the characteristics of the system according to the needs of the study to be realized and phenomena to simulate. The following section is dedicated to the description of these needs and these phenomena in the context of mass customization.

### *7.2. Experimentation and simulation results*

The simulation prototype currently developed has to permit the integration of the Operational Agent Model (OAM) and its simulation. The aim of this prototype is to constitute a software tool providing assistance for the design and the management of mass customization supply chains. It particularly has to enable the rigorous study of coordination modes between actors, as well as the study of the operating strategies put in place to cope with the highly stochastic, dynamic and personalized demand.

The experimentation and simulation results presented below concern only the simulation of the customer actors of the OAM. This simulation is conducted with market zone specific personalization offers. Using the personalization framework of [43], the offers can be combinations of popularization, varietization, accessorization, parameterization, and tailoring options. The customer demand given a personalization offer in a market zone is considered as being one of the essential elements forming the dynamics of the environment of the networked organization.

The personalization level is defined according to the relation between the customer and the supply chain. Customers can either acquire products at physical retailers, generating orders in case of unavailability or when selecting a personalized product), or place orders via the e-commerce web interface of virtual retailers. Retailers can correspond to sport shop, hypermarkets, franchises, or specialized shop in golf clubs.

Table 3
Offers versus personalization option

| **Canadian market** | | **Number of options per parameter** | | | |
|---|---|---|---|---|---|
| **Parameters for iron sets offer** | Popularizing | Varietizing | Accessorizing | Parametering | Tailoring |
| **Club head models** | 2 | 4 | 4 | 4 | 4 |
| **Metal alloy** | 1 | 1 | 1 | 2 | 4 |
| **Availability both sides per model** | 2 | 2 | 2 | 2 | 2 |
| **Lofts per model** | 1 | 1 | 1 | 3 | 7 |
| **Lie angles per model** | 1 | 1 | 5 | 9 | 13 |
| **Sole grinds per model** | 1 | 2 | 2 | 3 | 6 |
| **Shaft type/flex per model** | 3 | 12 | 20 | 40 | 60 |
| **Length per shaft** | 1 | 1 | 5 | 15 | 30 |
| **Adjusted weight per shaft** | 1 | 1 | 5 | 5 | 19 |
| **Grip types per shaft** | 1 | 3 | 10 | 20 | 35 |
| **Grip size per grip** | 1 | 1 | 2 | 6 | 6 |
| **Number of iron set combinations** | 12 | 576 | 800 000 | 466 560 000 | 125 483 904 000 |
| **Service Offer** (average figures) | | | | | |
| **Delivery delay (days)** | 1 | 3 | 5 | 10 | 30 |
| **Delivery reliability (fulfill rate)** | 95% | 95% | 90% | 90% | 75% |
| **Penalty for late delivery (per day late)** | $20 | $10 | $10 | $10 | $25 |
| **Price** | $850 | $900 | $1 000 | $1 200 | $2 000 |

The number of retailers is specified by market zone. A customer belonging to a market zone can for example choose to acquire a popular product off-the-shelf in a retailer, or to specify a personalized product and order it at the retailer. The retailer can express a need for some product to another retailer or to the golf club manufacturer, dependent on established business rules. An Agent Customer represents a human customer of a market zone. This agent generates an order if an offer made to him by a physical or virtual retailer satisfies his needs and meets his expectations. The offers made to him vary depending on the market zone and the expression of his needs. The Table 3 computes the number of product combinations offered in the case study to the Canadian market for each personalization option, through the combinatorial multiplication of their intrinsic product components. For every personalization option, an appropriate mix of products is proposed. Table 4 provides an example of demand data input, showing expected demand average and standard deviation per quarter for each personalization offer.

Table 4
Demand per quarter per personalization offer

| | Qrt1 | | | Qrt2 | | | Qrt3 | | | Qrt4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Canadian market forecasts** | **Qt** | **Avg/dy** | **Std dev** | **Qt** | **Avg/dy** | **Std dev** | **Qt** | **Avg/dy** | **Std dev** | **Qt** | **Avg/dy** | **Std dev** |
| **Popularizing** | 12 500 | 139 | 5% | 18 750 | 208 | 5% | 7 500 | 83 | 5% | 2 500 | 28 | 10% |
| **Varietizing** | 5 500 | 61 | 10% | 8 250 | 92 | 5% | 3 300 | 37 | 10% | 1 100 | 12 | 15% |
| **Accessorizing** | 5 000 | 56 | 15% | 7 500 | 83 | 10% | 3 000 | 33 | 10% | 1 000 | 11 | 20% |
| **Parametering** | 1 250 | 14 | 20% | 1 875 | 21 | 15% | 750 | 8 | 20% | 250 | 3 | 25% |
| **Tailoring** | 750 | 8 | 40% | 1 125 | 13 | 30% | 450 | 5 | 40% | 150 | 2 | 50% |
| **total** | 25 000 | 417 | 18% | 37 500 | 625 | 13% | 15 000 | 250 | 17% | 5 000 | 83 | 24% |

We obtained as first results of simulation, the generation of the demand for all the personalization levels according to the behavioural characteristics of the customers from the different market zones. These first results constitute inputs for the other actors of the supply chain during the complete simulation of the chain. Saved in the database, these results allow the user to obtain an aggregated vision of the demand. This step is validated by the *operationalization* of customer's behaviour represented by reactive agents. The demand is the number of products which can be specified for example by quarter, by personalization level and by market estimated through some appropriate probability distribution (e.g. a Normal distribution). The figure 18 presents the estimated demand for Canadian Market per personalization level.

Demand simulation represents a mere first step in our experiments. It has been shown here to make explicit the depth of modelling involved when simulating personalized supply chains. Describing the entire model and experimental results is way beyond the scope of this current paper. Through the illustrative examples provided in the paper we have attempted to allow the reader a glance of the agent-based models we developed for our simulation purposes. Our research agenda necessitates the definition of various alternative models to investigate the impact of supply chain coordination modes and decoupling point locations in a mass customization context.

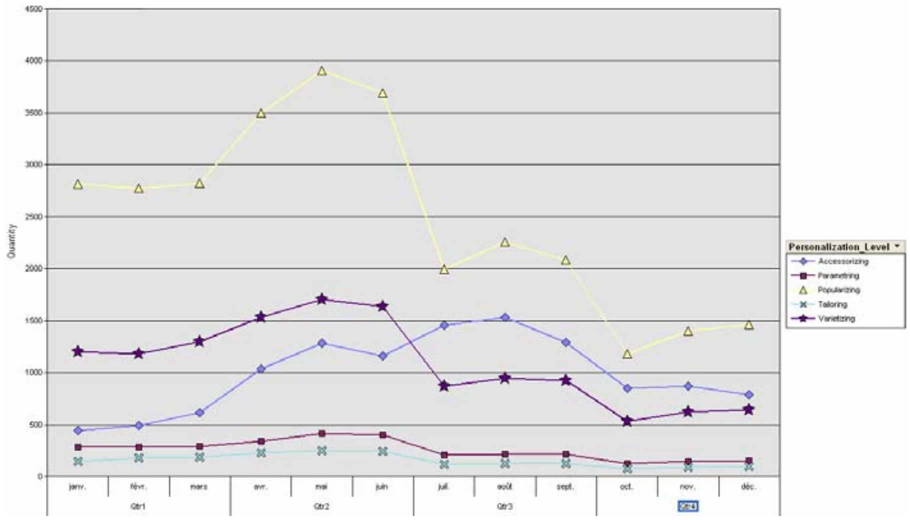



Fig. 18 : Estimated demand for Canadian Market per personalization level

**8. Conclusion**

Our research stems from the need for defining new tools for the design and management of complex mass customizing supply chains. In this paper we have proposed a methodological framework for the modelling and the simulation of complex supply chains based on the agent paradigm. This methodological framework takes its roots in the Enterprise Modelling field. It leads to the definition, the implementation and the exploitation of an agent-oriented simulation model in a specific software environment.

The methodological framework is structured according to three levels of preoccupation: conceptual, operational and experimental. For each level we defined specific models as well as their elaboration processes. A case study relative to a supply chain in the field of the golf club industry allowed us to illustrate the application of this methodological framework, from the conceptual modelling to the execution of the agent-oriented simulation model.

The simulation is performed with an original software architecture exploiting collaboration between cognitive and reactive software agents. Some first simulation results are obtained, concerning the generation of the customer demand for all the personalization levels according to the behavioural characteristics of the customers from the different market zones. These first results constitute inputs for the other actors of the supply chain during a complete simulation of the chain.

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