A Multiagent System for Production Synchronization in SME Mecatronics Supply Chain

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ABSTRACT

We present in this paper the application of multiagent system (MAS) for modelling and simulation of the dynamic structure and behaviour of the supply chain in SMEs mechatronic context in Savoie. First, a short literature overview describes the context and the contribution of multiagent modelling for SMEs integration. In the rest of the paper, the supply chain concepts and their agentification are presented. On the basis of this correspondence, we propose a synchronization protocol for the operational system (production flow and resources).

INTRODUCTION

The growing need for supply chain integration between the various actors is a major strategic challenge and a strong competitive advantage. Indeed, the supply chain is a complex macro-system, first due to the variety of implicated organizational structures and the relationships between them, and secondly due to the strategic decisions it involves. A company's success lies in its ability to integrate managerial processes of the supply chain but also to coordinate with other actors (Drucker, 1998; Lambert and Cooper, 2000).

As such, Small and Medium Enterprises (SMEs) evolve in an unstable and complex economic environment. In order to survive and to be able to support supply chain's requirements and market requests, SMEs have to collaborate together to achieve their goals without losing their autonomy and identity (Julien, 1997; Villarreal Lizarraga *et al.*, 2005). According to Julien (Julien, 1997), to find equilibrium between big companies and SMEs, SMEs must maintain and even improve their competitiveness in an increasingly competitive market. This competitiveness can be achieved by the control of information and processes but also thanks to a network structure. The theory of SMEs network, which is based on collaboration, cooperation and coordination, is a crucial crossroad for its management strategy. The alliances will reduce their vulnerability and this stresses SCM integration in a global supply chain context. This philosophy is explained by Assens (Assens, 1994): "the enterprises network is based on an autonomous and independent SMEs network which interacts in the context of mutual trust relationships to reduce the uncertainty of their environment. During these local interactions, a global organization form emerges in the absence of a central regulatory entity".

In the French region of Savoie, the industrial environment consists of numerous productive SMEs of the mechatronic industry working together in a cluster to achieve a common goal in a complex global supply chain. Some economic researches defined the Savoie industrial context as a region based on sector and geographical concentration of independent SMEs which have complementary activities. This cluster's success is due to interlinking the different production units and developing relationships characterized by flow regulation, learning and coordination. According to this context description and some investigations, we have drawn three main features of the supply chain which integrates SMEs groups and especially mechatronic: (i) complexity due to the number of autonomous actors in SMEs network and the heterogeneity of their relationships (ii) decentralization due to the dispersion of the geographical production sites in the global supply chain (iii) only a local site visibility for SMEs group in the global supply chain. To fill the gap caused by these characteristics, SMEs coordinate their activities with other sites through physical and data flow (Tounsi et al., 2008).
The lack of work in this area and the growing need expressed by professionals lead us to study the structure of the supply chain essentially composed of SMEs mechatronic, and the different mechanisms of integration defining the dynamics behaviour. To fill this gap, we have studied the research advances in industrial and software engineering to find an adequate solution to the studied context. This solution is based on the multiagent approach to model and simulate the static and dynamic aspects. Indeed, the benefits of multiagent systems (MAS) are widely recognized in literature. Agent technology allows new approaches for modelling and simulation of complex distributed systems. Hence, on one hand, autonomous agents can communicate their preferences, deal objectives with other agents or coordinate together to reach their own objectives or some more global objectives (Bussman et al., 2004). On the other hand, the supply chain is composed of actors or entities which evolve in an organization and interact to achieve a collective purpose. This analogy leads to multiagent approach being a framework naturally oriented to model the supply chain.

In this paper, we focus on the description of the dynamic behaviour adopting the multiagent approach. This work is divided into three main parts. The first part discusses on one hand the different mechanisms of management integration in the supply chain domain and especially in the SMEs mechatronic field; and on another hand, the contribution of multiagent system to implement this dynamic behaviour. In the second part, we present the agentified domain metamodel which describes the static modelling of the context. The third part introduces the behaviour of the identified concepts in the physical system synchronization, before a conclusion is drawn.

LITERATURE OVERVIEW

In this section, we define the different communication mechanisms to integrate the potential actors in the supply chain. We also present the common communication mechanisms in the SMEs cluster and in the global supply chain. Moreover, in the last part we introduce the contribution of the multiagent paradigm to structure the decision-making and the dynamic behaviour of the supply chain actors.

Communication mechanisms in the supply chain

The primary factor of management practices integration in a supply chain is the use of a communication mechanism to synchronize the flows (physical, informational, decisional and financial). In this work, we define a communication mechanism as a "*framework formalizing interaction between different actors in the network according to their managerial relationship characteristics*". In a supply chain, we can find several types of actor's relationships depending on the nature of their goals and their degree of involvement. Indeed, Wong *et al.* (Wong *et al.*, 2004) highlight that in a supply chain, integration is based on different types of relationships that are: *coordination*, *cooperation* and *collaboration*. In many cases, these mechanisms are used with confusion and as being similar. However, according to the literature, each mechanism has its own characteristics. Before describing a relationship between two actors in a supply chain, one must consider the criteria relating to: objectives, decision-making, risks, profits, formal exchanges and sharing product transformation.

According to Mattessich *et al.* (Mattessich *et al.,* 2001), cooperation infers a less formal relationship and involves a lower degree of commitment to join goals. A cooperative relationship entails information sharing as needed, and authority is retained by each organization so that there is virtually no risk. In this kind of communication mechanism, resources and rewarded are separately treated. The product transformation is supported individually by each organization. The second communication mechanism to consider is the coordination which is defined in literature as a process to bring into a common action, movement or condition, or to act together in a smooth concerted way. Compared to cooperation, coordination leads to more formal relationships and an understanding of compatible missions. Planning, division of roles and communication channels are well-defined. Resource allocations are mutually acknowledged, and risks and benefits may be shared or compensated. However, authority may still rest with the individual organization and the product transformation is handled individually. Finally, the third communication mechanism is the collaboration. It is defined as a mutually beneficial and well-defined relationship entered into by two or more organizations to achieve common goals. Collaboration is distinguished from coordination by its collaborative structure which determines a joined authority structure. Resources are pooled or jointly secured, and the product transformation is shared. Table 1 summarizes the different criteria for each communication mechanism.

	Collaboration	**Cooperation**	**Coordination**
Objective	Common	not grouped	Common
Decision-making	Common	Individually	Common + actor decision maker (in some cases)
Benefits	Shared	Individually	Shared
Resources	Shared	Individually	Individually (but known by others)
Formalism	Formal	Few formal	Formal
Risks	Shared	Not shared	Shared
Temporal aspect on product transformation	Shared	Individually	Individually

Table 1. Communication mechanisms (Tounsi *et al.,* 2008)

Integration of SMEs mechatronic network in the supply chain

Previously, we have identified different communication mechanisms that define the management framework of process and information. On the basis of this literature analysis, we studied the different integration mechanisms in the supply chain composed essentially of SMEs mechatronic in Savoie. So, briefly, the global supply chain is divided into many sites geographically dispersed. A cluster of some SMEs mechatronic in Savoie is integrated in this global network but only with a local visibility of the production sites. However, the SMEs cluster is not isolated and it communicates with the other nodes through the different types of flows. The study of the global supply chain and the SMEs cluster identifies two kinds of communication mechanisms according to the criteria defined before. Hence, in the mechatronic cluster, SMEs work together to achieve a common goal. Resources, benefits and products transformation are shared. So, the SMEs collaborate in cluster to reach the local objective. The collaborative process takes place according to the following scenarios:

- *Physical flow synchronization*: in the cluster, the actors will synchronize their information and their actions for production needs. This collaboration is frequent in commonly encountered situations.
- *Local Monitoring*: the monitoring and control of SMEs group will be based on the performance evaluation and the resolution of new perturbations on the physical environment which do not disturb the objectives of other parts of the SC.

Nevertheless, the SMEs cluster will coordinate its activities in order to achieve the global supply chain objectives. At the global level, each node has a limited perimeter of influence. For this reason, a cluster needs to communicate with the other actors to face the environment disturbance by coordinating their activities and local objectives in order to achieve the global objective. This coordination takes place according to the following scenarios:

- *Initial configuration of the system*: the actors of the network interact in order to set and coordinate their goals in the global supply chain.
- *Environment perturbation affecting all goals*: if a perturbation occurred in a cluster's environment which requires a modification of its local objective and which affects other nodes objectives, the coordination between supply chain sites is necessary in order to find an appropriate solution to the problem.
- *Reconfiguration of the system*: if the actors recognize that the current system configuration cannot achieve the global objective, the interaction between the sites is required to set new objectives according to their experience.

In this paper, we implement the second scenario of the coordination mechanism and the two identified collaboration scenarios.

Multiagent approach for supply chain dynamic modelling

In supply chain modelling and simulation there are two main types of approaches: the equation-based modelling approach and the agent-based modelling one. Parunak *et al.* (Parunak *et al.*, 1998) have proven that multiagent systems and agents are more suitable to model the dynamics behaviour of the complex network manufacturing system and to study the impact of flow management between different entities than the equation-based modelling. In fact, agents are more suitable for applications that are decentralized, changeable, ill-structured (dynamic structure) and complex (Parunak, 1998). The multiagent approach provides a framework naturally oriented to model the supply chain. By comparing the supply chain and the multiagent system characteristics, similar concepts and the same organizational practices arise. In fact, both are composed by actors or entities which evolve in an organization and interact to achieve a collective purpose. This analogy leads to multiagent approach being a privileged way to model supply chain systems.

In literature, several research works propose different protocols based on multiagent system for modelling the dynamic behaviour of the supply chain. Most often, these protocols extend the Cooperative Problem Solving model (CPS) proposed by Wooldridge and Jennings (Wooldridge and Jennings, 1999). The CPS defines an abstract way to structure a collective decision-making process in which a group of autonomous agents choose to work together to achieve a common goal. In more details, this model is deployed in four stages:

- *Recognition*: in which an agent identifies the potential for interaction.
- *Team formation*: in which an agent solicits assistance.
- *Plan formation*: in which the newly formed collective attempts to construct an agreed joint plan.
- *Execution*: in which members of the collective play out the roles they have negotiated.

In the following, we describe the implementation of the different collaboration and coordination processes defined previously. These protocols apply the CPS abstract model and structure the interaction between the domain concepts in order to simulate the physical system synchronization.

AGENTIFIED DOMAIN METAMODEL

First, it is necessary to describe the architectural and functional properties of the domain concepts. In this section, we present the agentified domain metamodel which merges the domain concepts with multiagent concepts. The domain metamodel generation and its agentification are based on ArchMDE (Architecture Model Driven Engineering) development process which draws its metamodelling steps in MDE (Model Driven Engineering) approach. MDE (Kent, 2002) promotes the separation and combination of models in order to control the software development in its different phases (from the analysis to the implementation). In fact, in our research context, we identify two metamodels related to ArchMDE approach. The first one describes the functional concepts and properties of SMEs Mechatronic supply chain. The second one defines a multiagent metamodel. A combination of the two metamodels will generate an agentified domain metamodel (see figure 1). Only the main results of this approach are outlined in this section. More details can be found in (Tounsi *et al.* 2009a).

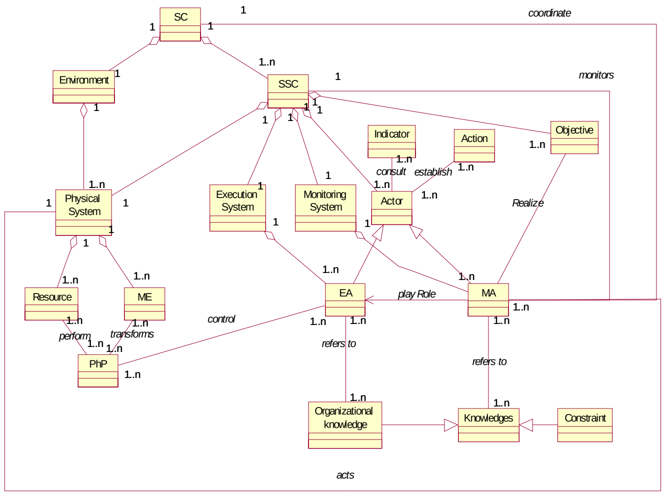

Figure 1 Domain metamodel (top-down)

The domain metamodel is an UML class diagram which represents the concepts defining the architecture and the properties of the global supply chain and the SMEs group (Tounsi *et al.*, 2009b).

- *Supply chain (SC)*: this concept defines the root of the domain modelling. All the other concepts will detail this one.
- *Environment*: this concept models the space allocated to the product flow and management through the internal resources as well as the external elements able to influence the activities of the supply chain.
- *Sub Supply Chain (SSC)*: the SSC represents a group of SMEs which collaborate to achieve an internal aim and/or the overall objective of the supply chain. The SSC is

responsible for the management of the product flow in a certain stage of its life cycle. The SSC is composed of 3 layers involving some particular concepts and playing a specific role.

These 3 first concepts define the abstract framework of the context. Thus, according to the domain metamodel a supply chain (SC) is composed of one or more organizations (SSC) and a physical environment. SSC at this level represents a SMEs group. A Detailed presentation of the internal architecture of the SSC and its perimeter of influence (visible part of the environment to the SSC) follows. These concepts represent the second level of the domain metamodel.

- The *Monitoring System* models the intelligent layer of the SSC. It controls and monitors the two other layers through the information provided by the Execution System. The *Monitoring Actors (MA)* are the main elements of this layer. They model the intelligent actors of SSC and establish metrics to evaluate the performance of the group and consequently act on the two other layers. Therefore, the MAs are the components responsible for the control and decision-making in SSC but also for the coordination activity in the global supply chain.
- The *Execution System* is the reactive layer of the SSC. It deals with two main roles: (i) it ensures the synchronization of the physical flow according to the information gathered from the *Physical System*, (ii) it observes and corrects the *Physical System* if a perturbation occurs. In abnormal situations, the *Execution System* refers to the *Monitoring System* for coordination and decision-making. The *Executive Actors (EA)* are the principal entities of this layer. The EAs mainly model the reactive actors and occasionally MAs having reactive behaviour in this layer.
- The *Physical System* is the visible part of the environment from the SSC. It corresponds to the influence perimeter of the SSC. This layer is composed of passive elements controlled by the two other layers of the SSC. Two main concepts are identified: the *Moving Entity (ME)* modelling the product in circulation and the *Resource* modelling the production means.

Finally, the following concepts considered as data support, allow some other concepts to play their roles in the metamodel:

- The *Physical Process* (PhP) describes the sequences of processing stages of the product. The PhP is a concept to be integrated within a domain metamodel in order to define the tasks that can be handled by the *Execution System*.
- The *Indicator Base* represents a database recording the indicator measures. The EA detects a Physical System deviation according to the gathered information within this database.
- The *Action Base* represents a database that stores the actions to apply when facing an indicator deviation.
- The *Objective* models the global goals of the supply chain or of the SSC ones.
- The *Knowledge Base* represents a database including all knowledge needed by the actors to make the right decision. A n element of the Knowledge Base can be an organizational knowledge or a constraint.

At this step, the domain metamodel describes the supply chain in SMEs mechatronic context. This metamodel is merged with a multiagent metamodel in order to obtain a correspondence between each domain concept and multiagent one. The agentified domain concept implements the structural properties and dynamic behaviour of the multiagent one. Figure 2 draws the multiagent metamodel according to the "vowel approach" introduced by Demazeau (Demazeau, 1996).

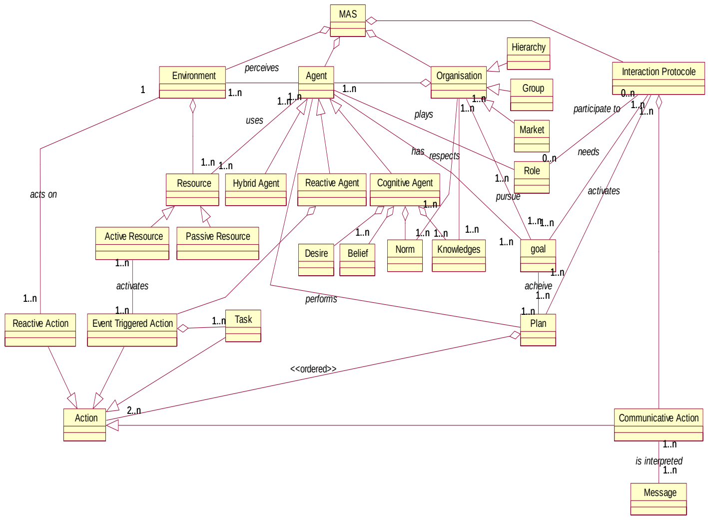

Figure 2 Multiagent metamodel (Tounsi et al., 2009a)

So, according to these two metamodels, the following table highlights the correspondence between the domain concepts and the multiagent ones.

Domain concepts	***Multiagent concepts***	***Description***
Supply Chain (SC)	MAS	By analogy, the root of the domain metamodel corresponds to the root of the multiagent system.
Environment	Environment	In the two metamodels, environment is the space defining all things external to agents and necessary to manage the SC.
Sub Supply Chain (SSC)	Organization	It is an organization composed of two groups of agents.
Physical System	Resource	It is all needed resources for one agent or a group of agents to manage the group (perimeter of influence).
Resource	Passive Resource	It is an allocated resource to the agent to perform its task.
Moving Entity (ME)	Active Resource	It is the product in circulation. ME activates the behaviour of the reactive agents.
Physical Process (PhP)	Task	It is a task or a physical activity to be handled by

		reactive agents.
Monitoring System	Group	It is a group of cognitive agents which collaborate in the SSC and also coordinate the activity of the organization with other organizations.
Execution System	Group	It is a group of reactive agents which collaborate in the SSC.
Actor	Agent	An actor can be a cognitive agent or a reactive agent according to its decisional granularity.
Executive Actor (EA)	Reactive Agent	EA perceives physical system and acts on it according to the observation.
Monitoring Actor (MA)	Cognitive Agent	According to the collected information and the historic of situation and action, MAs group monitors the SSC to reach a goal and achieve its activity.
Objective	Goal	A SSC have a goal to reach. This goal is coordinated with other nodes' goalss.
Indicator	Belief	The agents act on the environment according to the indicator measures. However, a MA monitors the SSC according to the historic of these measures.
Action	Plan	It is an action or a plan to apply when facing a perturbation.
Knowledge	Knowledge	It is all needed knowledge to the agents to act in appropriate way.
Organizationa l knowledge	Knowledge	Each agent owns a list that contains the information about other agents from the same SSC or the global SC. This list stores knowledge about the name of the agent, the task that it performs and its resources.
Constraint	Knowledge	The MAs take decision according to their objectives and their beliefs. In the same time, there's some constraints (about product, or other SC where the group involves) that MAs group must take into account in decision-making.

Table 1. Correspondence domain concepts and multiagent ones

PHYSICAL SYSTEM SYNCHRONIZATION

The SSC is responsible for the synchronization of the involved Physical System to achieve its task. This activity consists in applying a communication protocol according to the nature of the interaction framework. In this section, we describe the collaboration and coordination processes to implement in the Execution System and Monitoring System in order to synchronize the Physical System. These protocols are built according to the CPS abstract model.

In accordance with the agentified domain metamodel, the Execution system is responsible for the synchronization of the physical process (PhP) in common situations. Indeed, Executive Actors (EAs) which are reactive agents, synchronize PhP by taking into account the availability of resources. Then, on the basis of the agentified domain concepts, the synchronization protocol in the Executive System is shown in Figure 5:

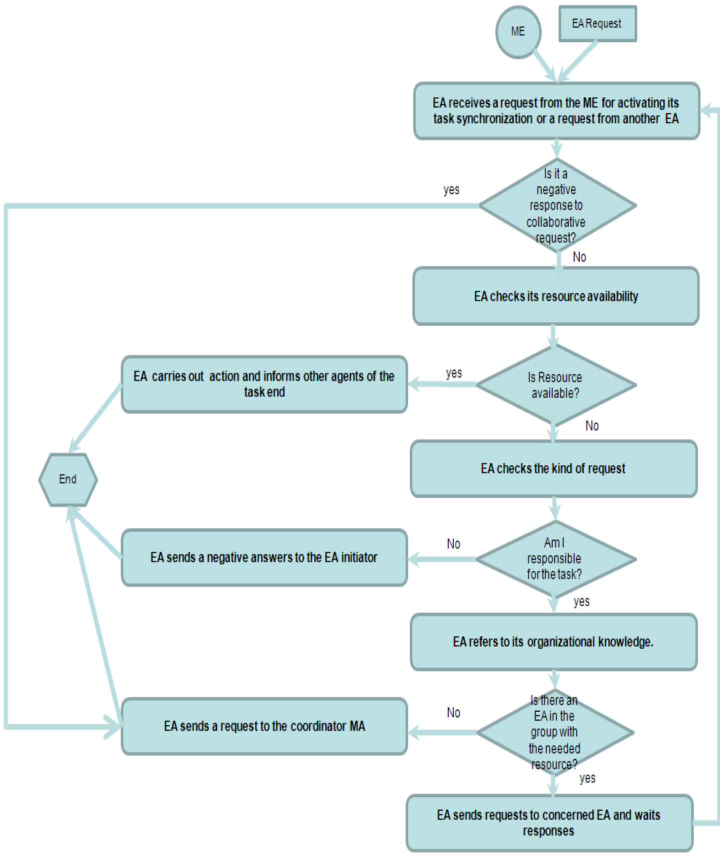

Figure 3. EA Synchronization Behaviour (Tounsi et al., 2009b)

- An Executive Agent (EA) receives a request and reacts according to its type. Three kinds of request can be distinguished: a ME request, a collaborative request from another EA or a negative response to a collaborative action initiated by the agent itself.
- If the request is a negative response to a collaborative demand that the EA initiated: the EA sends a request to the coordinator agent of the monitoring system.

- If the request is a synchronization need coming from the Moving Entity (ME) or a collaborative request from another initiator agent, EA checks the availability of the concerned resources.
- If the resource is available, the EA carries out its task, updates the state of ME and informs the other agents from the executive system and the coordinator agent of the end of action.
- If the resource is unavailable and the EA has been solicited by another executive agent to achieve the task, it sends a failure request to the initiator.
- If the resource is unavailable and the EA is in charge of the task then it seeks in its organizational knowledge an agent from the Execution System of the SSC that might have the needed resource.
- If the agent finds into its organizational knowledge an agent that can handle the task, it delegates the responsibility of the task. In this case, the collaboration process of the concerned agent will be activated and follows the same sequence.
- If the agent does not find another agent having the needed resource to handle the task, it sends a request to the coordinator agent. This agent is a monitoring agent (MA) that receives requests from the Execution System. MA sends the information to other monitoring agents of the SSC in order to find a solution.

However, in unusual situations, the Executive System refers to the Monitoring System. In this case, MAs group evaluates the situation according to the defined objective and establishes an actions plan. If the objective is not reached, the MA needs to consult other SSCs to find a suitable solution. So, the synchronization protocol in the Monitoring System can be described according to the follow steps:

- In the Monitoring System, a Monitoring Actor (MA) has the responsibility to check all the received requests and diffuses them to other MAs in the layer. Three kinds of requests can be distinguished: EA request, answer to a help request or a help request from another SSC in the global supply chain.
- If a MA coordinator receives an EA request then it diffuses the information to other MAs. In this case, according to the objective, the group evaluates the situation. Two cases may arise: the problem has no impact on satisfying the SSC objective or the objective is deviated.
- If there is no impact on the objective, the MA tries to find an internal solution according to its desire, belief and constraints. If a solution can be found, the MA coordinator spreads the actions plan to the Executive System.
- If the objective is deviated or an internal solution can not be reached. The MA group sends a Help Request to other SSCs through the MA coordinator and waits responses.
- If all responses are received, the MA coordinator classifies them by a reception date of help. The selection will be diffused in the Monitoring System. According to their beliefs, desires and constraints, MAs group chooses the suitable answer and diffuses the action plan to the Execution System. In this case, the EA updates the ME state.
- If the request is a Help Request from another SSC, the MA coordinator spreads the request to the Monitoring System. In this case, the Monitoring System evaluates the demands according to internal criteria (Objective, Constraint, Belief, and Desire). If the SSC can provide assistance, it makes an offer to the SSC initiator or it sends a negative response.
- SSC initiator chooses the suitable offer and sends a confirmation to the selected SSC and a cancellation response to other bids.

The following figure shows the sequence of messages between the SSCs. This diagram represents the coordination process in the global supply chain in order to synchronize the physical flow in the case of a perturbation case (SSC cannot reach the internal aim).

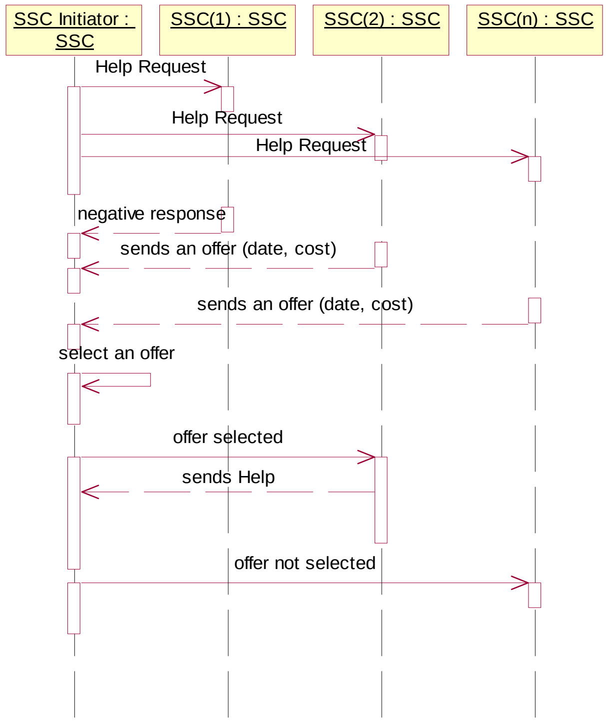

Figure 4. SSC coordination process

CONCLUSION AND PERSPECTIVES

The present research work focuses on the integration of mechatronic SMEs into the global supply chain. These SMEs clustered in group are localised in Savoie, a French region. Communication protocols for physical environment synchronization are proposed. These protocols describe the dynamic behaviour of agentified domain concepts, since the modelling solution is based on multiagent paradigm. The multiagent system defines the behaviour characteristics of the domain concepts and consequently the establishment of communication protocols. Thereby, this article introduces a stage from a global solution. Now, our research work focuses on the implementation of the performance evaluation processes in the SMEs group and in the global supply chain. All the concepts and processes will be encoded within a simulation platform.

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