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Distributed simulation of virtual workshops for the multi-site scheduling feasibility evaluation

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In this article, a distributed simulation tool for the feasibility evaluation of multi-site scheduling is proposed. The application areas concern supply chains or networks of distributed workshops based on cooperation of several independant simulation tools. The distributed simulation of workshops, called virtual workshops, generates various problems of causality and of tasks execution coordination. These problems are addressed in the proposed distributed architecture by the use of HLA protocol guaranteeing the synchronization and the chronology of events occurring in the concurrent simulations. An application to a simple case of supply chain organizing the flow between three workshops shows the effectiveness of the distributed simulation tool.

Keywords: Supply Chain; multi-site scheduling; distributed simulation; High Level Architecture

1. Introduction

The Supply Chain (SC) consists of specialized, cooperating and geographically distributed manufacturing units, and poses the problem of its performance evaluation. The principal stakes of SC are organization and management of the production distribution (Stadtler 2008). The complexity of these multi-site organizations is studied with specialized tools of production activity control such as ERP (Enterprise Resource Planning) or APS (Advanced Planning System) (Stadtler 2005), (Meyr *et al.* 2005). However, these tools are based on aggregated models of real production systems for the generation of production plans used by each enterprise of the network. The calculated plans cannot

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be suitable for real situation because of discrepancies between aggregated models and real production sites. To cure this drawback, the evaluation of plans is necessary before their dispatching in workshops. By this way, the feasibility is evaluated and if necessary ensured by the SC reconfiguration. Various methods have been proposed to evaluate the plan feasibility of the distributed workshops. In (Lee *et al.* 2002), the analytical resolution is based on a set of mathematical equations representing the considered SC model. However, incomplete modelling of the dynamic characteristics does not provide acceptable solutions for the analyzed system. As described in (Lüder *et al.* 2004), (Gupta *et al.* 2002) and (Kubota *et al.* 1999), simulation allows the SC evaluation by regarding it as a centralized company. Nevertheless, during the modelling phase, difficulties related to the significant number of entities to be modelled and to the detail level wished by companies, represent the first limits of this approach. Other drawbacks are related to the quantity of events to be simulated, the computing power, the reuse of the simulation models and the intellectual property protection. Finally, if the modelling of all SC sites remains possible, the simulation execution with one processor is not always achievable. A fine evaluation of multi-plan feasibility is difficult to obtain when being based on an aggregated model. For the SC, the feasibility is not reduced to the sum of the feasibility evaluations of each site. Taking into account these limits, the feasibility evaluation of the multi-site scheduling requires the definition of distributed simulation architecture. Several works were published on the distributed simulation of large scale production systems. A first asset in favour of the decentralization is linked to the information protection of each site which can choose to mask certain data at the time of distributed simulation. The distributed models are locally built, maintained and joined for evaluation (Mertins *et al.* 2005). Moreover, the total performance of the simulation time is improved thanks to distribution (Turner *et al.* 2000). HLA (High Level Architecture) protocol was proposed by the DMSO (Defense Modelling and Simulation Office) to synchronize simulators within a large simulation. HLA facilitates the interoperability and the reuse of simulations to reduce modelling and simulation costs and provides the means for large simulations using geographically distributed components (IEEE-Std.-1516-2000 2000). HLA implements algorithms for synchronization and respect of the chronology for simulated events and in particular those defined in (Chandy and Misra 1978). HLA enables to synchronize a federation, *i.e.* a set of federates sharing a common object model, the FOM (Federation Object Model), containing all information relating to the simulation execution. A federate is a federation component including a simulator to which an operator, a machine or a complete workshop can be associated. The RTI (Run-time Infrastructure) constitutes a data-processing implementation of the HLA interface specifications and ensures the communications between federates of the same federation by offering the HLA services for the synchronization and the management of the chronology events. In this article, the definition of the architecture model is presented in Section 2. In Section 3, the principles of distributed simulation are described studying the principal software classes. The coordination and synchronization mechanisms of messages and information are detailed. In Section 4, an application to a simple case of a multi-site SC model organizing a flow between three distributed workshops is used to illustrate modelling steps. Finally, the evaluation results of the multi-site scheduling feasibility are discussed.

2. Problem statement

2.1. *MS-R-PAC model and its limits*

The R-PAC model (Reactive Production Activity Control) conceptually represents a system of controlling and follow-up for a workshop. In this model, the MO (Manufacturing Orders) are scheduled and launched within the workshop as depicted in Figure 1. The follow-up function consists in identifying the events to establish a state of the production and of the production equipment.

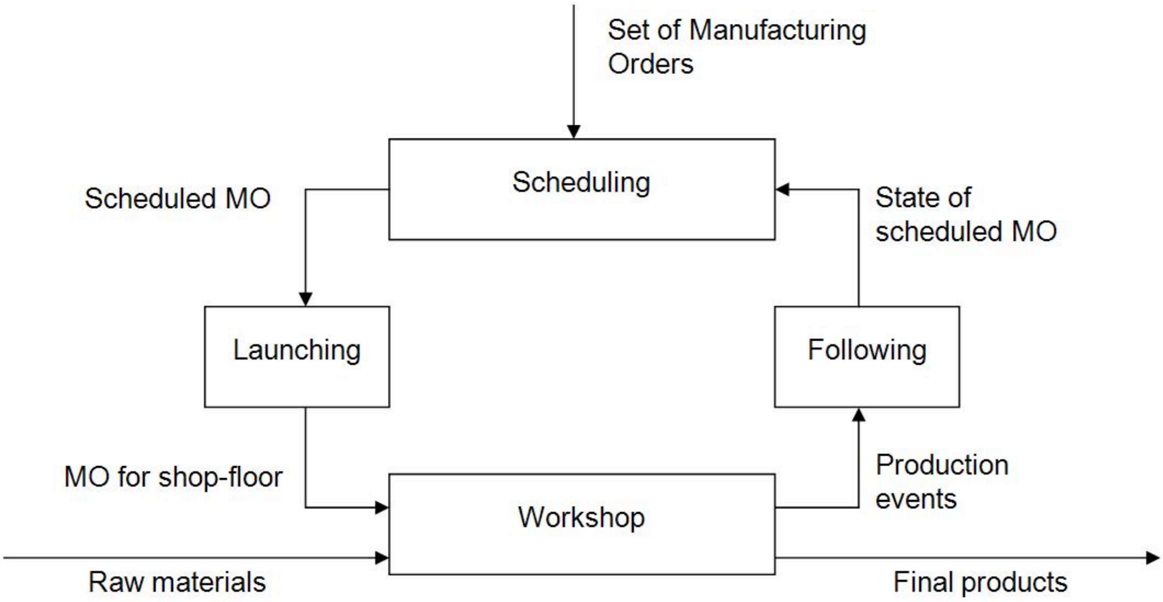

Figure 1. R-PAC conceptual model.

In (Archimede *et al.* 2003), a MS-R-PAC (Multi-site Reactive PAC) model which integrate several R-PAC was proposed to deal with the geographically distributed workshops case. This model (Figure 2) coordinates the control of several virtual workshops using a distributed scheduling carried out thanks to a protocol close to Contract Net (Smith 1980). The virtual workshop is the data-processing representation on a simulator of a real workshop. Distributed scheduling is carried out using SCEP model (Supervisor Customer Producer Environment) by indirect cooperation between the MO, *i.e.* the set of customers, and the machines agents, *i.e.* the set of producers (Archimède *et al.* 2003). The SCEP cooperative mechanism is based on a synchronous approach of negotiation under a Supervisor agent control via a ”blackboard” environment. Figure 2 shows connections between four SCEP cores (three servers and one customer). This configuration makes it possible to carry out the cooperation between three distributed sites. To drive virtual workshops, each site control is ensured by the cooperation of one SCEP core and a tasks launching module. For the monitoring, two functions are combined to follow-up and detect all the events during the production activities execution. The generation of distributed scheduling is provided with the negotiation method between four SCEP cores.

A great interest of the MS-R-PAC model is the capacity to identify easily the bad configuration of the sites and the improvement of each site independently ones of the others. The main drawback of this model lies in the inability to absorb on a site the time

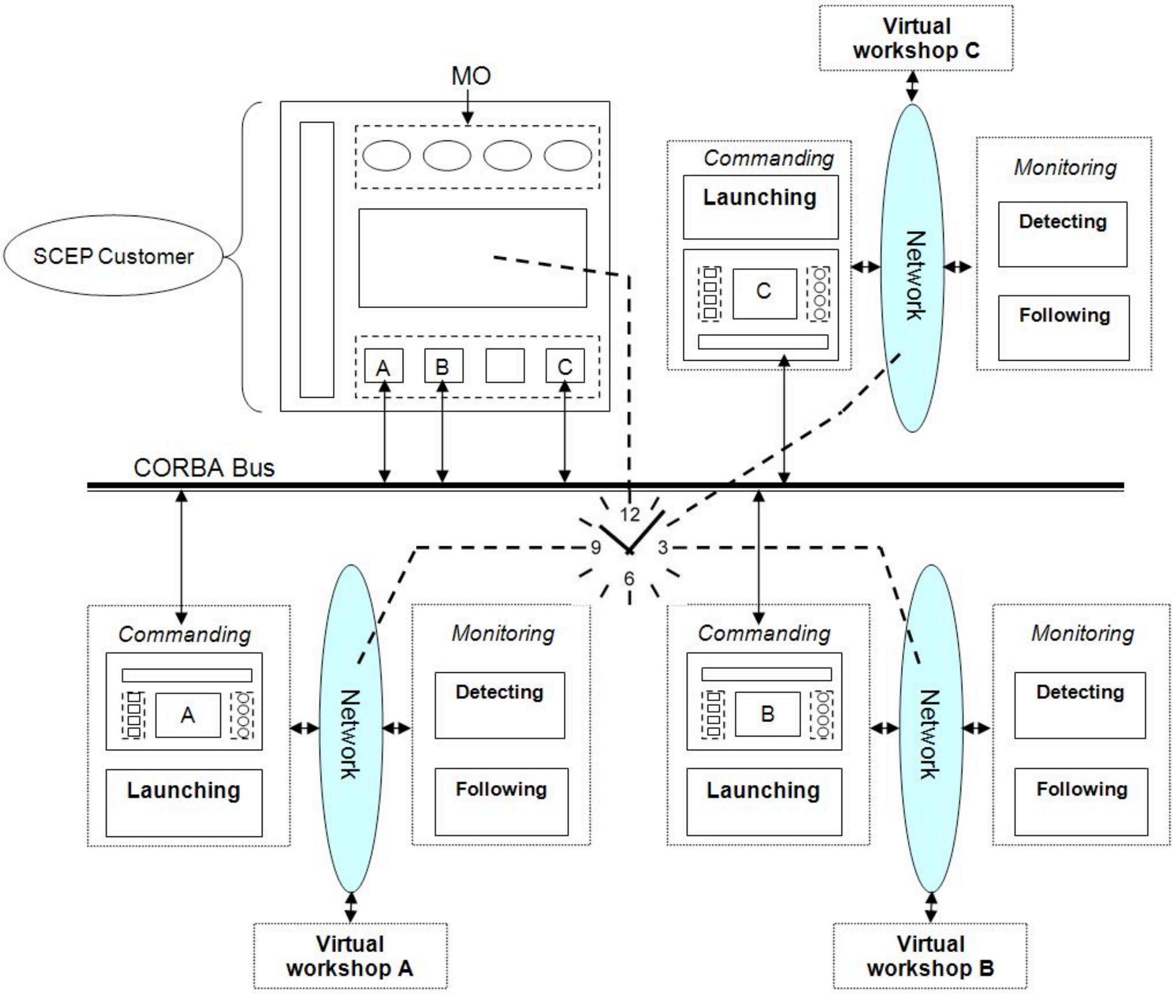

Figure 2. MS-R-PAC Model.

delay caused by another site without adapting the manufacturing plans. When there is a time delay in one of the sites, it is sent to the SCEP customer. In order to absorb the time delay, all the sites should be directly informed. On the other hand, important causality problems, due to the load and/or the speed of the various simulators, can appear. The causality principle and the respect of the chronology of the events issued of each site cannot be guaranteed. However, synchronization problems can appear in the MS-R-PAC model. Starting from a synchronization point, a simulator processing at each time step numerous events on a high speed processor may need a more important processing time to meet an assignation date than a simulator lower loaded by events which are computed in parallel on a machine with a lower speed processor. As depicted in Figure 3, some foreseen events, overcoming at the due date in the temporal repository of the most loaded with simulator that must start before other foreseen events overcoming at the due date in the temporal repository of the least loaded with simulator, can be observed after these last ones in the repository of a human observer and thus in past of the least loaded with simulator. Indeed, during the execution of the simulation, an overlapping of two successive operations of the same project executed on two different sites can be observed in repository temporal of a human observer while every site respects perfectly the foreseen plan.

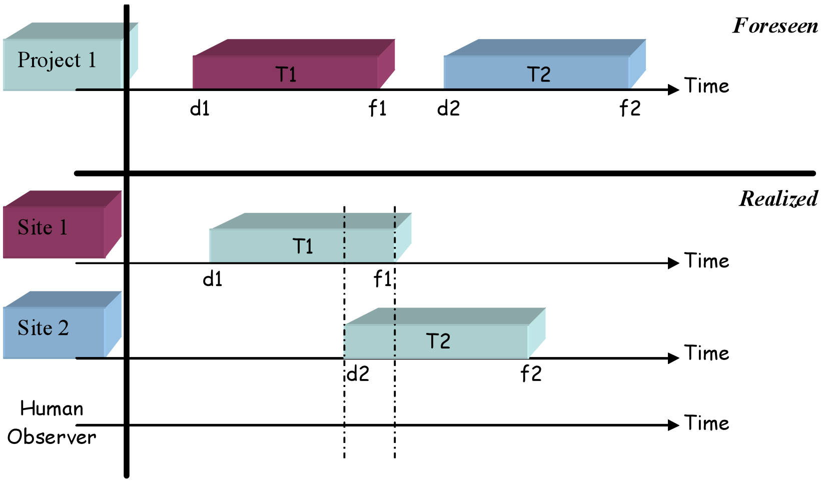

Figure 3. Causality problem example.

2.2. *F-R-PAC model*

In order to satisfy these requirements and to take into account the causality problem, a new model F-R-PAC (Federation of R-PAC) (Figure 4), associating a federate R-PAC on each site, was defined. F-R-PAC is conceived to carry out a multi-site plan of production, resulting from an external scheduler, in a network virtual of production workshop. A federate R-PAC consists of four main functions which are Communication, Monitoring, Commanding and Synchronization. The Commanding function, encapsulates a simulation function of which role is the management of the virtual workshop. Commanding controls the plan execution and the task dispatching in the virtual workshop. Monitoring carries out the follow-up of the production and enables the detection of events linked to the start or the end of operations resulting from the virtual workshop. Communication ensures the connection between the external scheduler and the two functions Commanding and Monitoring. Synchronization defines the linking interfaces with the other sites. F-R-PAC architecture enables to easily take into account any modification of the corporate network; any change in real workshop requires an adaptation of the corresponding virtual workshop. The distributed simulation consists in synchronizing a set of R-PAC enabling the execution of any kind of multi-site scheduling in virtual workshops. The sites can indifferently represent workshops, machines, operators or transportations. A distributed scheduler calculates the multi-site planning and sends it to the R-PAC federates using an adequate communication network protocol.

In Figure 5, the R-PAC federate is a component software which makes it possible to model the sites partners and consists of four managers and one encapsulated simulator: the Dispatching Manager (DM), the Flow Shape Manager (FSM) and the COMmunication Manager (COM) and the SYnchronization Manager (SYM). The DM, whose algorithm was detailed in (Enjalbert *et al.* 2004), controls the plan execution and the task dispatching in the virtual workshop and makes it possible to access via SYM to the functionnalities of HLA by the mean of two Ambassadors RTI_A and FED_A, *i.e.* entities providing the interface with HLA. It can encapsulate any discrete events simulator. The FSM carries out the follow-up of the production and enables the detection of events linked to the start or the end of operations resulting from virtual workshop. The COM ensures the connection between the external scheduler and DM or FSM.

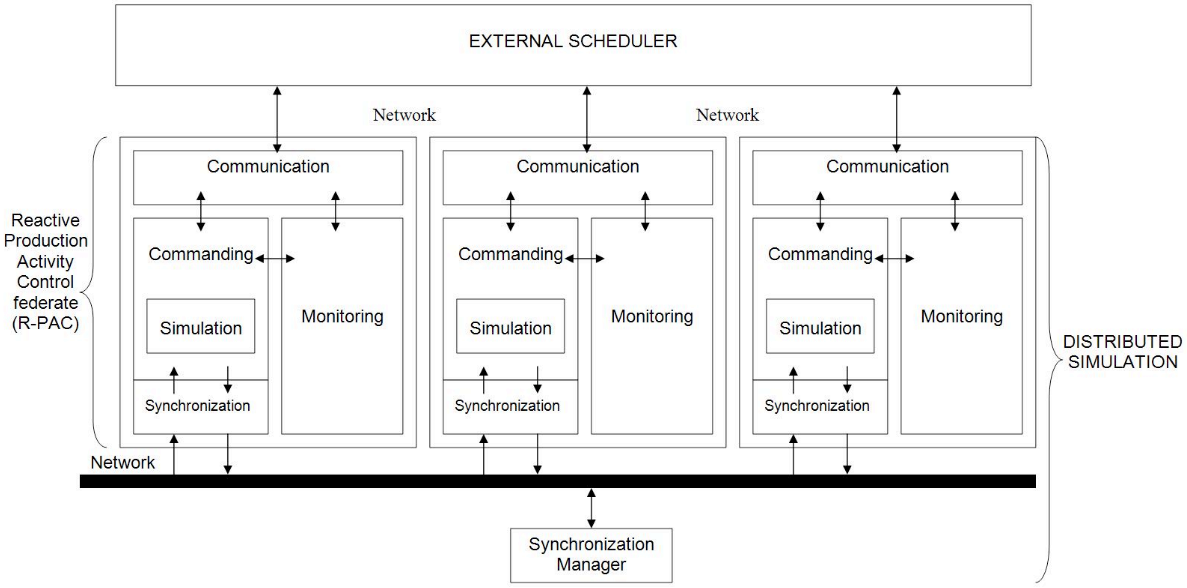

Figure 4. F-R-PAC federation.

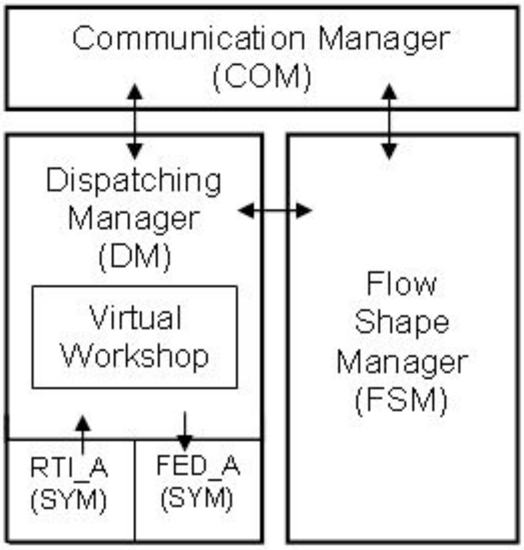

Figure 5. R-PAC federate.

3. F-R-PAC implementation

In Figure 6, a UML class diagram details the principal functions of the distributed simulation in F-R-PAC architecture. There are five principal classes. CSimulator models the DM and encapsulates the controlled simulator. CFlowShopManager carries out the follow-up of the production operations through flow-shape functions. COrdoAmbassador is the class which manages the connection with scheduling. CShopFederate enables the federate synchronization R-PAC to reach HLA mechanisms. CWorkshop represents database feeding the various classes.

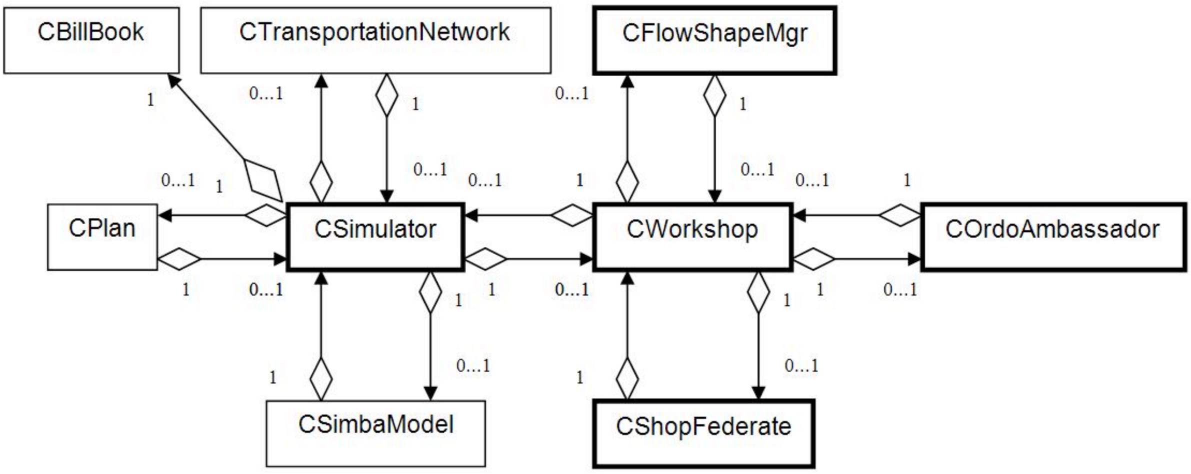

Figure 6. UML class diagram of F-R-PAC.

3.1. *Dispatching Manager*

The DM controls the MO execution in the virtual workshop. CSimulator is related to classes allowing the recovery of information on the simulator behavior (CPlan, CBillBook, the DM scheduling and CTransportationNetwork, to facilitate transportations). The CSimbaModel class implements the simulator encapsulation. In this study, the virtual workshop is implemented using SIMBA, an event-driven simulation software of Lanner Group. CSimulator ensures the control of the plan execution in the virtual workshop.

3.2. *Flow Shape Manager*

The FSM is implemented in the CFlowShapeManager class and provides mechanisms for checking, at each event occurrence, if the running plan execution is correct. A flow-shape function for the workshop is generated according to the foreseen scheduling, available in CWorkshop. During simulation, the time stamped data concerning the task execution are processed and a comparison is carried out in order to detect the discrepancies. Figure 7 illustrates a flow-shape function generated from the occurrences of beginning and ending of operation dates. The level represents the sum of the tasks, expressed in minutes, whose dispatching is planned in the workshop. An increasing level expresses that the total load of the workshop is growing whereas level zero means no task is planned.

In practice, the production plan always differs from the effective plan because schedule modelling is based on a simplification of reality. The differences between the foreseen and the followed flow-shape functions are analyzed for each event occurrence in order to evaluate the plan performances. The flow-shape functions of the same workshop are aggregated according to a mechanism described in (Archimède *et al.* 1993), reducing detection times.

3.3. *Communication Manager*

The COM manager implements a communication layer between the distributed simulation and the distributed scheduling. The COM is described in the COrdoAmbassador class and enables to send to the scheduler information on production or transportation

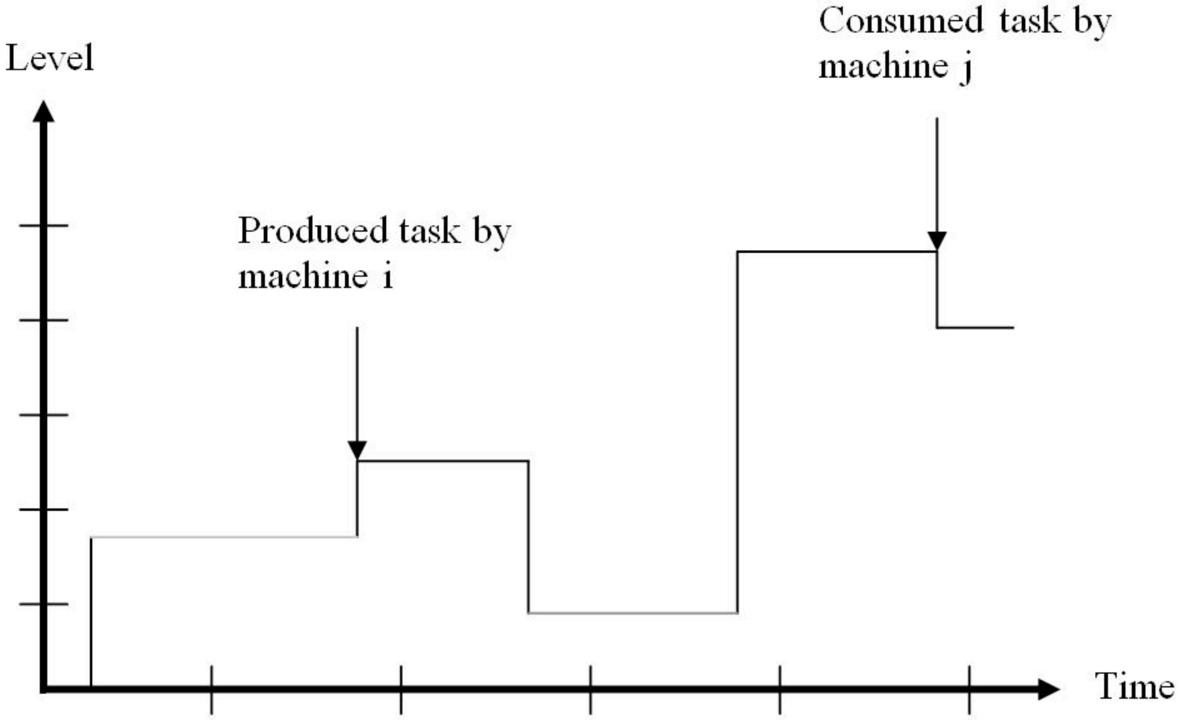

Figure 7. Flow-shape function between two machines i and j.

detected disturbances. Moreover, COM is waiting from the scheduler to receive a new scheduling at any moment. CWorkshop class recovers all simulation information and stores them in its databases. CWorkshop requires information on initial scheduling by its connection with COrdoAmbassador. The time stamped messages are available for the CShopFederate in HLA formalism. In the same way, a database can be accessed by the DM via the CSimulator class in order to supply the simulator with data. Finally, CWorkshop is linked with CFlowShapeManager to give information on the predicted scheduling to build flow-shape functions. CWorkshop makes available simulation information necessary to the federate synchronization.

3.4. *Federate synchronization manager*

The virtual workshops communicate independently of the COM via HLA bus thanks to the CShopFederate class including all HLA information necessary to the federation execution. The F-R-PAC behavior requires the management of two kinds of synchronization: inter-federate and intra-federate synchronizations. The first one, managed by HLA, rests on a publication/subscription mechanism. During simulation, R-PAC federates cooperate and react to events which are conveyed on the network using time stamped messages. These time stamped messages ensure a regulated and constrained behavior for all federates. Intra-federate synchronization between the DM and the controlled simulator is based on the assignation points to which the simulator must go to be synchronized by the DM algorithm. The difficulty rests in these two synchronization mechanisms coexistence. The DM must ensure that an assignation point is not too distant to guarantee synchronization of the simulator. In Figure 8 the effectiveness of the time management and the causality rule implementation is illustrated. In order to guarantee the good execution of the plan the DM determine the nearest event date according to information received from the simulator and information drawn from its own scheduling. The next assignation to a desired date is fixed by the DM according to local information. This date can be a planned operation or a beginning or ending transportation, or a date corresponding to a waited and delayed event. Then, the federate requires the RTI authorization to advance the simulator to this date (NER: Next Event Request). If the RTI considers that until this date no external event will appear to disturb the federate, then it authorizes the time advance (TAG: Time Advance Grant) of the simulator. On the contrary, if the RTI refuses the desired assignation date advance, a new assignation point on a lower date corresponding to the next external event concerning the federate is proposed. Until the assigned date was reached, several stops and resumes can be necessary. The DM updates the scheduling, transmits time stamped messages on its state to the RTI, and starts a new cycle by proposing a new assignation date.

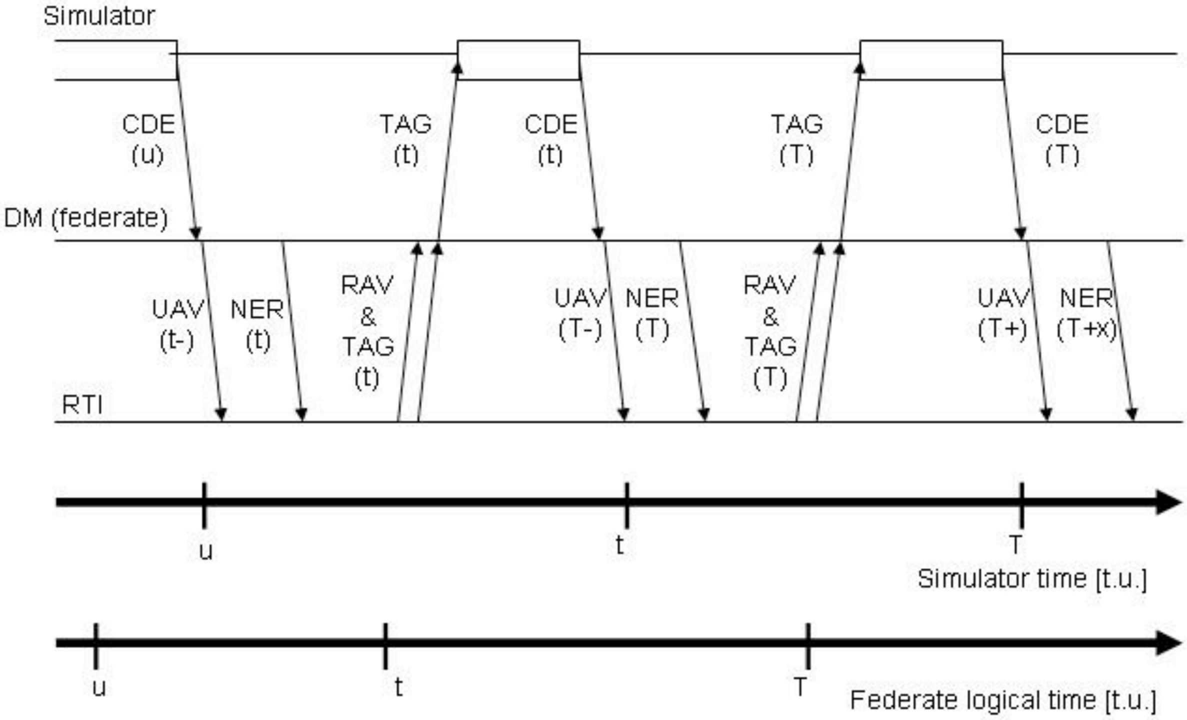

Figure 8. Communications within a R-PAC federate.

In Figure 8, the first synchronization is done at date u expressed in time units. A CDE (Current Date Event) is sent by the simulator to the DM, corresponding to an appointed assignation date. The federate transmits to the RTI messages concerning the state of objects locally simulated, (UAV: Update Attribute Value). Then, a new time advance towards the next assignation desired date is asked. The time advance request must drive the simulator to date t. The RTI makes sure beforehand no event will be able to interfere before the appointed date t for the federate. When the authorization is granted (TAG) and after having received messages concerning the state of the objects simulated by other federates (RAV: Reflect Attribute Value), the DM transmits information to the controlled simulator which can advance at date t. The mechanism is renewed until the complete simulation of all planned events.

Table 1. Routings.

MO	Activity	Duration
MO1	Turning	36 min
	Milling	33 min
	Turning	48 min
	Milling	48 min
	Assembling	48 min
MO2	Turning	33 min
	Milling	36 min
	Turning	18 min
	Assembling	24 min
MO3	Turning	30 min
	Milling	36 min
	Turning	24 min
	Milling	24 min
	Assembling	42 min

Table 2. Machines and activities.

Location	Machine	Activity
Tarbes	M1	Milling
	M2	Milling
Pau	M1	Turning
	M2	Turning
Lourdes	M1	Assembling

Table 3. Inter-site transportation durations.

From/To	Tarbes	Pau	Lourdes
Tarbes	-	24 min	30 mmin
Pau	24 min	-	18 min
Lourdes	30 min	18 min	-

4. Application to a simple supply chain case

A simple application illustrating the case of a corporate network cooperating for manufacturing three products is detailed herein. The three MOs necessary to carry out its manufacturing, MO1, MO2 and MO3, are offered at the possible suppliers. Associated routings and durations of each activity are summarized in Table 1. Three sites of production located at Tarbes, Pau and Lourdes are selected as partners for this manufacturing project. The site of Tarbes provides basic preparation of the feet as well as plates. The site of Pau prepares turning activities. The site of Lourdes is in charge of assembling and painting. Associated machines and activities are described in Table 2. Inter-site transportation durations are defined in Table 3 while intra-site transportation were neglected. For this example, a distributed scheduling was carried out using the software R@mses (Re@ctive Multi-agent System for Scheduling). Based on model SCEP defined previously, R@mses puts in competition the MO which are negotiated for the sites (Archimede and Coudert 2001). In Figure 9, a bar chart recapitulates the whole of the MO distributed on the three sites. We note that the first three orders proceed in Pau. Transport is represented each time that an activity of a MO requires a change of site. The three parts corresponding to the three MO thus are successively transported from Pau towards Tarbes. The activities and transport follow one another thus until the scheduling of all the activities.

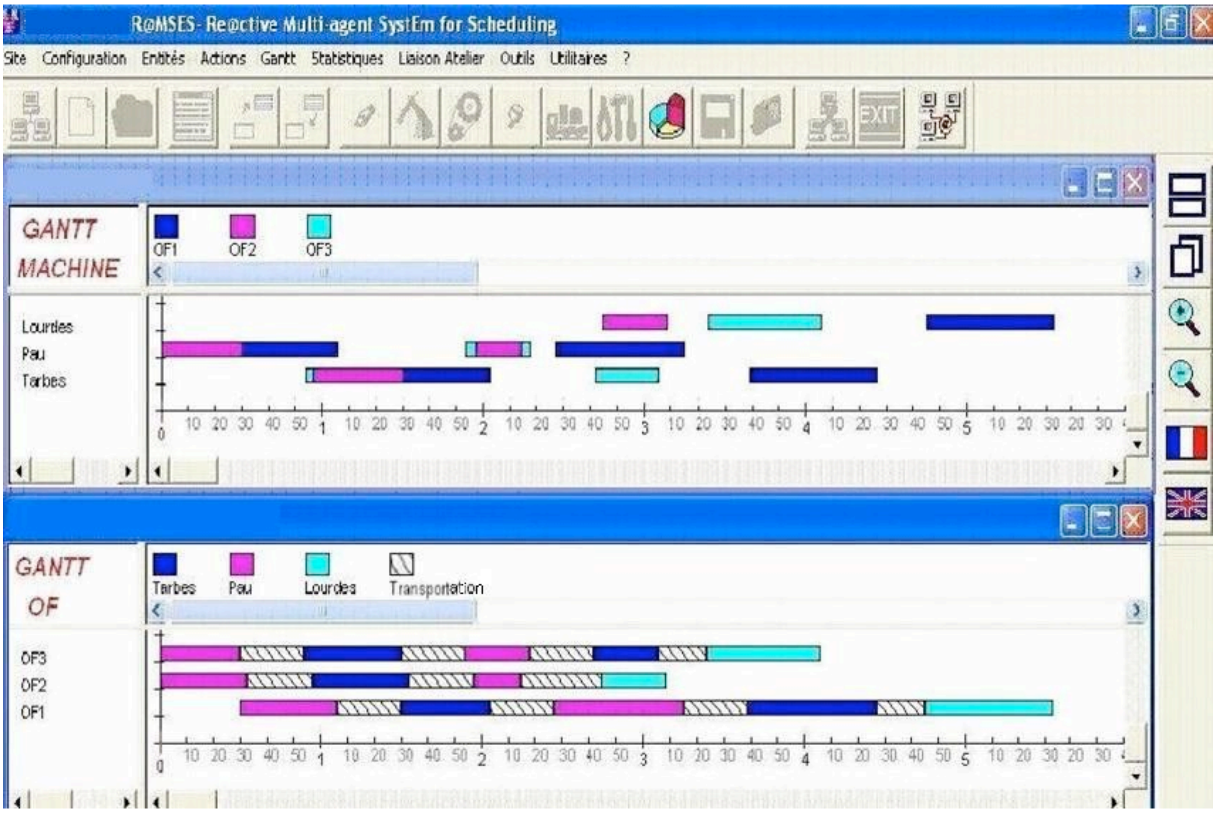

Figure 9. Gantt chart of the multi-site MO.

During this period, road works are in progress on axes connecting the sites and traffic is limited. An arbitrary direction of traffic is then imposed. The course of delivery joins successively the sites of Tarbes, Lourdes and Pau before to be back in Tarbes. Initially, only one truck able to transport only one part per way at the same time is considered. Thereafter, when several trucks are available, as soon as an operation requires a transportation, a request is sent to the trucks. The first available one accomplishes transportation. In order to evaluate the feasibility of this multi-site scheduling, several workshop configurations according to transportation capacities are studied. Simulation was initially carried out with one then two trucks to determine the better configuration of distributed workshops able to take into account the described constraints linked to traffic.

In Figure 10, the flow-shapes resulting from scheduling and simulations are represented. Level are expressed in ten minutes. The aggregated flow-shape functions scheduled for the sites (a) Tarbes, (b) Pau, and (c) Lourdes are used as input data for simulation. The first simulation was done with one transportation resource. Results are represented in Figure 10 by flow-shapes of the sites (d) Tarbes, (e) Pau, and (f) Lourdes. After several simulations, finally the case of three trucks is presented for the sites (g) Tarbes, (h) Pau, and (i) Lourdes. For the site of Tarbes (a), (d), and (g), until to *85 min*, the three flow-shapes are similar because no MO is dispatched and no part is coming from Pau.

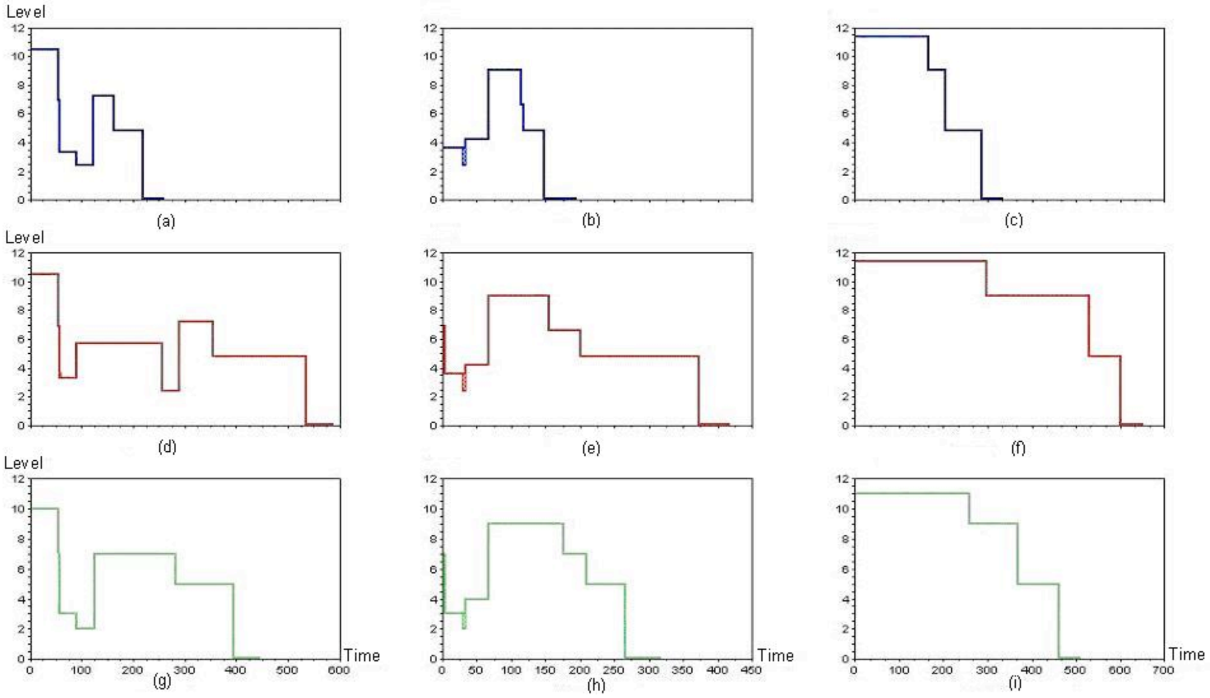

Figure 10. Foreseen aggregated flow profiles for (a) Tarbes, (b) Pau, (c) Lourdes, followed with 1 transport for (d) Tarbes, (e) Pau, (f) Lourdes and followed with 2 transports for (g) Tarbes, (h) Pau, (i) Lourdes.

At time *85 min*, the level of (d) increases because new tasks are planned but not carried out. The site is waiting for the deliveries from Pau. The delivery delays increase and the flow-shape (d) is stretched. The load level of the workshop awaited by (a) at time *120 min* is reached only around time *270 min* for (d). Simulation is complete at date *840 min* for (d) against *305 min* as initially predicted for (a). In time *85 min*, the second and third trucks supply quickly enough the site (g) avoiding a load increase. The level awaited by (a) at time *130 min* is reached only at date *180 min* for (g) because three trucks resource is not sufficient to carry out all transportation at the same time. When a great number of MO are located at the beginning of routings, the cumulative delays are without any consequences as shown in (b), (e), and (h). After initialization, the three flow-shapes are identical until date *115 min.* For (e), the level decreases at time *170 min* whereas for (h) this decrease begins only at time *145 min.* In the case of a single transportation, the flow-shape for (e) ends at date *330 min* against *165 min* for (b) as initially predicted. The MOs of Lourdes are located at the end of routings. The predicted operations are ended at time *350 min* for (c), at time *440 min* for (i), and at time *440 min* for (f). As soon as inter-site transportations are required, the truck availability, its geographical localization and the traffic direction are the main constraints not taken into account in the multi-site scheduling. The use of only one truck to supply the various sites introduces a delivery delay. In this manufacturing project, the scheduling quality depends on the transportation organization. The two trucks transportation case was simulated but the resulting improvement is not significant in comparison to the three trucks case. The tool for distributed simulation of virtual workshops enables to evaluate the feasibility of multi-site scheduling and to adapt the resources in order to correspond as well as possible to the predicted plan. In this manufacturing project, three inter-site trucks and one intra-site transportation lead to the best result. This example was sized to show the software tool efficiency and the effectiveness of the feasibility evaluation of multi-site scheduling. For an increasing example size, the simulation time remains correct regarding to complexity and to the production volume of studied networks. When supply chain takes into account a large number of partners, a centralized architecture can fail into simulating too many events at the same time whereas the use of the HLA protocol implemented in the software tool guarantees large scale simulations. Moreover, information about each partner is kept private. This method guarantees autonomy and confidentiality among cooperating simulations partners.

5. Conclusion

A tool for distributed simulation able to guarantee the synchronization and the causality of production operations for a distributed workshop network was presented. The simulation tool deals with any kind of distributed scheduling by preserving the independence of each partner. The dimensioning of transportation resources can be evaluated when a manufacturing project is dispatched. By this way, the feasibility evaluation of multi-site scheduling enables the adaptation of the supply chain configuration or the improvement of the plan. Next objectives will concern the use of transportation resources without constraint and the definition of variable size of transportation containers.

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