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Modelling of a multi-agent supply chain management system using Colored Petri Nets

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Abstract

The growth of the productive sector has driven the evolution of supply chains into highly complex, dynamic and concurrent systems. Consequently, emerging structures have been developed through the integration of advances in information and hardware technologies with the aim of increasing effectiveness and efficiency, as Industry 4.0. In this context, although several works use a multi-agent approach, they offer limited information on the use of formal models to specification the system. Considering the potentially serious consequences of inaccurate integration specification, the use of formal tools to design the processes for these types of system is recommended. Considering supply chains as a system of discrete events, techniques derived from Petri Nets can be used for modelling purposes. Such techniques include Colored Petri Nets, which have been effectively tested in hierarchical modelling, analysis and control of distributed systems, characteristics suitable for the specification of a supply chain management system in an industry 4.0 scenario. In this context, this article presents a systematic procedure that integrates a group of guides, methods and techniques, to develop a representation of a system with problem solving abilities, thereby facilitating the construction of a supply chain management model with a multi-agent structure, which incorporates progressive refinements and permits specification of the desired level of detail. Finally, the advantages of the proposed model are presented via its application to a product assembly case study.

Keywords: Multi-agent, Coloured Petri Nets, Supply chain management.

1. Introduction

A Supply Chain Management (SCM) is a transformation and distribution system of products or services, provided to satisfy customer needs [1]. Considering market openings and the continued growth of the productive sector, this type of system has evolved from a sequential system to one with a distributed structure characterized by highly complex, dynamic and concurrent systems integrating advancements in information technology in an efficient and effective way [2]. Actually, the collaboration between suppliers, manufacturers and customers is crucial to increase the transparency of all the steps from when the order is dispatched until the end-of-life of the product [3]. This scenery promotes the adoption of industry 4.0 that use of big data, IoT and Artificial Intelligence (AI) as one . [3], [4] . In other words, The emergence of the Industry Internet of Things (IIoT) promoted new challenges in logistic domain, which might require technological changes such as: high need for transparency (supply chain visibility); integrity control (right products, at the right time, place, quantity condition and at the right cost) in the supply chains [4].

Although this scenery create opportunities to meet the needs of customers and also contribute to the development of logistics and SCM [5], according to [6] is necessary measurement the impacts of this approach. In [7] are reported technological impacts of the voiced key emerging trends and several answers. In addition, [8] defines that uncertainty, feedback cycles and dynamics are important challenges in the production and logistics systems, supply chains and networks of Industry 4.0. In consequences, the uses of control strategies is recommended. For example, in [9], the authors investigated researched on the design and development of multi-agent

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system for SCM. In their solution, each phase in the SMC has been developed as an agent enabling communication, coordination and negotiation among the agents to achieve intended business goals, but they do not use formal tools.

With respect to the average logistics performance of OECD members, Latin American countries, including Colombia are lagging behind in terms of logistics performance, indicating that information technologies should be integrated more strongly in this area of the economy. Consequently, technological developments and information systems are being widely used to facilitate SCM, increasing its participation in business generation strategies in order to diversify production, reduce deficits in raw materials, manpower, and time etc. [10]. Previous works suggest that multi-agent systems are informatics elements capable of perceiving, processing and executing autonomous actions, in order to identify their environment in terms of technical and social aspects [11], [12]. In such systems, the term agent represents a computational entity capable of perceiving, processing and acting within its environment in a rational manner [13]–[15].

In this context, considering the dynamics of the SCM, implementing informatics systems could result in a complex task. For this reason, the use of models to analyses and evaluate system behavior before the implementation of any physical modification is highly recommended, since inaccurate specification in this type of system could have economic and security consequences [16]. Furthermore, the use of formal models for SCM analysis allows the verification and validation of system dynamics [17]. Colored Petri Nets (CPN) are formal, analytic, graphical tools, which use high level programming languages in order to model discrete, concurrent and distributed events. They can be used to effectively represent and analyses processes for which communication synchronization and the shared use of resources are important. In a formal way, a CPN is defined as CPN = (P, T, A, C, V), where: (P, T, A) is a Petri-net structure; C is a set of attributes called colors; V is a set of free variables; a is an arc function which assigns bags of colors to arcs of CPN, a: $A \rightarrow (C \cup V) \rightarrow \{0, 1, ...\}$; these bags are in the form of expressions labelling the arcs and they determine the numbers and specific colors of tokens which are used for firing the transitions. This modelling tool can be characterized by some important structural and behavioral properties, such as, reachability, boundedness and liveness. Where, reachability answers the question: is there an executable firing sequence for a given marking from the initial marking that finally reaches it? Boundedness describes how many tokens a place may hold for a set of reachable markings. Liveness describes the possibility of a transition being enabled and then firing infinitely often. Reversibility describes the possibility of a net being able to return to a previous state. An extension of the subject can be found in [18].

This article proposes a multi-agent model using Colored Petri Nets for supply chain management, using the case study of a product assembly system (PAS), located at the National Learning Service, SENA (for its initials in Spanish - Servicio Nacional de Aprendizaje), Cali, Colombia. In this context, several theories and formal tools were integrated in the modelling of a supply network according to the public and private policies on productivity in developing countries.

The article is divided into three sections. In section two, the methodological procedure is described. Each phase of the methodological procedure is extended in section three, using the SENA product assembly system case study. Finally, conclusions are made.

2. Methodological procedure

For the development of the productive system models the proposals presented in [12] are integrated. A set of guides, methods and techniques are established to develop a formal system with problem solving ability, allowing construction of an SCM model which includes progressive refinements, enabling attainment of the desired level of detail.

2.1. Information gathering

At this stage, field visits should be made to identify and select the system to be modelled, in order to fully understand the operation and identify the components, such as physical devices (sensors, actuators, hardware, etc.), informatic technologies, as well as the environment and goods to be produced. Additionally, it is necessary to define the enterprise resource Planning. Boundaries in the production and management systems must also be delineated.

2.2. Definition of variables and system behavior

The gathered information is analyzed and system variables are established. For this, the relation between the component of proposed architecture must be analyzed, the use of conceptual maps and workflows which describe SCM processes are recommended.

2.3. Conceptual and functional modelling

The relationship between the system components is conceptually described (interaction between modules), and the functions that define variable behavior during process flow are established. Synoptic Flow diagrams, amongst others, are used to define the conceptual models, whilst formal tools, such as Colored Petri Net (CPN), are used to develop functional models, allowing system dynamics to be simulated and compared with the behavior of the current system - in the next stage.

2.4. Model validation

Based on the information gathered in stages 2.1 to 2.3, a validation of possible real time scenarios is done. To validate system characteristics and behaviour at the macro level, the SCM is mapped in relation to the requirements and properties of the CPN representation, such as: reachability, vivacity, repeatability, limitations, etc. Examples of parameters used to define simulation scenarios include:

- Level service indicator (LS): a written agreement between a service supplier and its client, in order to set an agreed level for the quality of service – it represents the expected probability of not reaching a stockout situation.

- Time frame of the product on the supply chain (TFPSC): the time that a product remains in raw material (RM) form until it undergoes transformation into a final product and is delivered to the retailer link.
- Connection communication time between links (CCT): the time required to transmit a successful message from one link to another inside the SCM.
- Average inventory indicator (AI): the average among the existent values in the inventory and the new purchase values.

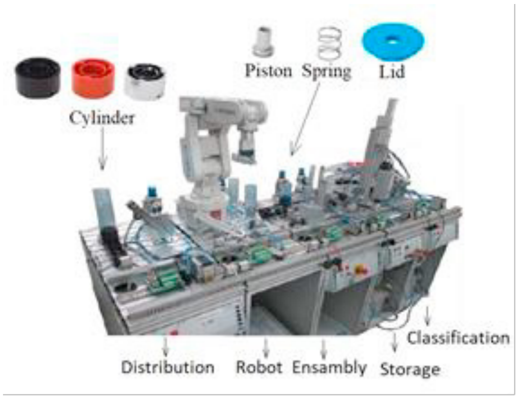
3. Case study

This section describes the application of the proposed methodological procedure to the modelling of a multi-agent system for supply chain management, using the product assembly system (PAS) case study.

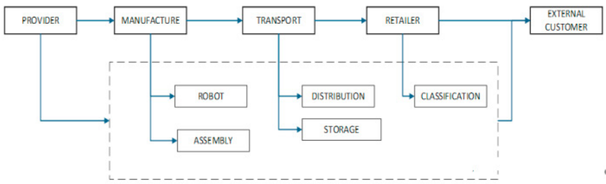
3.1. Information gathering

The SCM presented as a case study corresponds to the SENA product assembly system simulation bank (PAS). It consists of five production modules; where each one of its modules was considered as a supply chain link, see Figure 1(a). The PAS was chosen due to the availability of information, its flexibility for different SCM configurations and the possibility of integrating communication technologies.

The supplier and the customer are externally represented by a buffer of raw materials at the beginning of each process and a final product buffer at the end of the respective process. In addition, the manufacturer links are represented by the distribution module, a robot and assembly module, the transportation link by the storage module and the distributor is represented by the classification module. Figure 1(b) shows the current architecture of the SCM PAS, where each link is related with the bank modules.



(a)



(b)

Figure 1: SENA's product assembly system, (a) SCM structural model (b) Current architecture.

The PAS capacity allows the assembly of a final product composed of a cylinder, piston, spring, and lid, respectively. The cylinders and lids have three different presentations (red, black and silver), each combination of colours between the cylinder-lid represents a different product. The SC links (Modules) will be hereby described. 1) *Distribution module:* In this module the cylinders are supplied from the initial storage and transported by a rotating actuator, which is responsible for positioning them at the entrance ramp. 2) Robot: This module is in charge of product assembly, adding to the cylinder the following components: piston, spring and lid according to the production order. The robot moves the cylinder from the entrance ramp to the assembly position, then the robot goes to the storage of each element. Then, in the manufacture station the robot assembles the cylinders. Finally, the robot transports the assembled product towards the storage module. 3) *Assembly module:* In this module two elements act independently; the first element is the storage of the lids and the second is the spring storage. Both supply the robot module with the elements required for product assembly with the cylinder that comes from the distribution module. In the event of a shortage of elements in storage, this module sends a supply order to the suppliers. 4) *storage module:* This module has two tasks, the storage and dispatch of finished products. For the storage, the module has three available buffers which classify the product according to the color. For dispatch, the module processes a dispatch command and sends a request to the robot for the product's transportation. 5) *Classification module*: When the finished products are received by this module a control activity is carried out. To achieve this, a sensor checks the color, if it is confirmed by the dispatch command, the product is taken to a conveyor belt which classifies it depending on the product colour.

Figure 2 presents the representation of the Current SC in the CPN. Each link (transition) corresponds to a PAS module. In the upper part of the image, the information flow between links (places) is shown, and in the middle the flow of products (places) is displayed. The link of the external customer represents a flow of information as well as products with the retailer (lower part of the image).

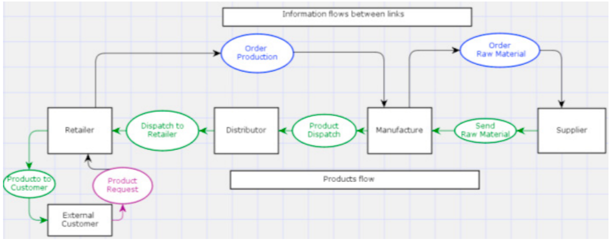


Figure 2: CPN architecture of the traditional SC PAS

3.2. Definition of variables and system behavior

In order to model a multi-agent architecture based on an actual system, the current system variables and behavior were defined. Due to space limitations, only variables and architecture from the proposed multi-agent system will be discussed. In essence, the variables and behavior of both systems (current system and multi-agent system) are similar. The difference lies in the addition of "agents" to the proposed system.

Figure 3 shows the multi-agent architecture proposed for the SC PAS. Two computational entities or smart agents were added to the current model, which was explained in the previous section. The first one, the operator logistic agent, is in charge of the management of the distribution process, internal inventory management, Manufacturer storage, selection and dispatch of the vehicles to the Retailer, and the information associated with these processes. The second one, the integrator agent, is responsible for the information management of all the SC links, except that of the external customer.

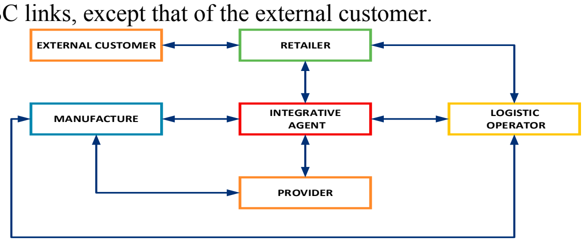


Figure 3: Architecture proposal.

Below are described the variables and restrictions associated with the links of the proposed SCM PAS, see Table 1. These variables correspond to the information that must be transmitted by the actuators involved in the production process, and the restrictions are the imposed boundaries for each of the links of the SC in this particular case study.

Table 1: Variable definition and restrictions (OA, IA)

SC links	Variables	Restrictions
Logistic operator agent (OA)	- Number of vehicles available for product dispatch. -- Vehicle load capacity	- The logistic OA doesn't transport the commodity without prior integrator agent authorisation - The commodity moves by the disseminated trucks of the company - Limited truck capacity. - For this model the following parameters are not considered: Incidental events (strikes, Natural disasters, Collisions, etc.) Scheduled events, such as: maintenance, load and unload time frames
Integrator Agent (IA)	- Central warehouse with inventory control inside the manufacturer. - Production order and approval - Product delivery confirmation -Processes the information generated by other SC links, such as - Commodities in warehouse.	Through this agent there is no physical flow of products and it requires updated information on each and every one of the previously established processes. The processed information is distributed to each of the output ports and will be received in the input ports connected with the links of the SC.

3.3. Conceptual modelling

In this phase, the functional relationships of each of the SCM processes are defined, whereby system activity flow is described using the proposed architecture. A flowchart for the external customer and retailer, where each block represents an activity within the process, and a number stipulates the sequence where the operation is executed.

3.4. Definition of variables and system behavior

On Figure 4 the proposed global functional PAS model is shown. The numbers 1 to 6 on the net transitions denote the SC links, and the places below the integrator agent represent information flux between the integrator and the other links. Places between links (in the middle) are products and raw materials. The direction of the information flow and products are represented by net arcs.

This article will emphasise the integrating agent (IA) CPNs.

Figure 5 displays the Integrator agent; the agent contains five individual modules (transitions) with a specific function. The integrator agent updates the process status and is also in charge of coordinating, performing, reporting and authorising the execution of production orders, raw materials requests and their reception, product dispatch and inventory updates.

New orders are transmitted to the manufacturer (manufacture order module) and a bidirectional information channel between the IA and the manufacture link is established.

This sub-net, see Figure 5, has five net “modules” with specific functions. For instance, “Prioritization criteria module”, which selects production orders and prioritises production based upon previous orders, available raw materials and product number. The “Reports module” integrates SC information and sends reports to each link, except the external customer.

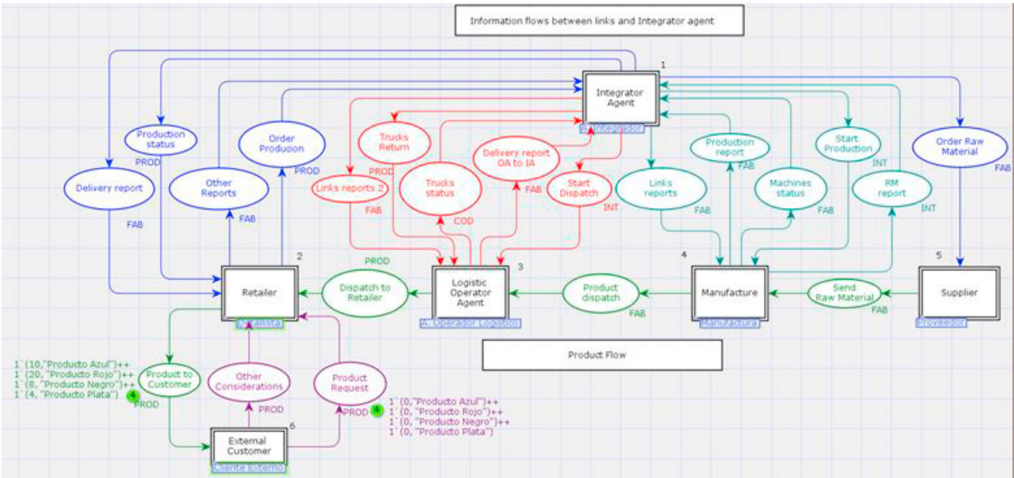


Figure 4: Proposed SCM from CEAI-SENA Global functional model

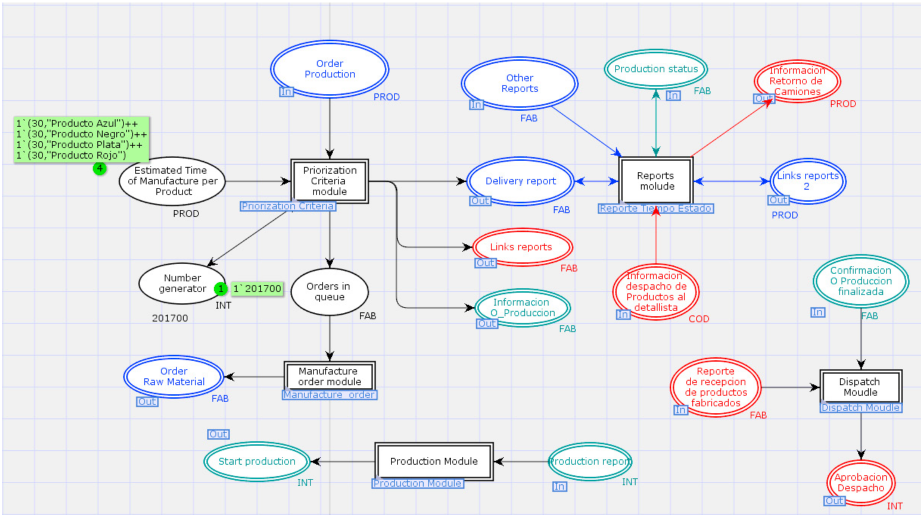


Figure 5: Integrator agent CPN

Model validation

This section details the validation of the initial model (current SC PAS) and the proposed multi-agent model. Additionally, two subsections are presented, where the results are shown from a qualitative and quantitative validation. The first section details the qualitative validation, which verifies the SC dynamics and the established parameter fulfilment using the proposed multi-agent architecture. The second section presents a quantitative application, which compares the proposed SCM performance to the current SCM. Seven scenarios were validated, see Table 2.

Table 2 Validation scenarios.

Scenarios of validation	Description	Modification of production rate	IA addition
Scenario 0	Current SCM	-	-
Scenario 1	Modification of production rate	X	-
Scenario 2	Product mobilisation from manufacturer to retailer	-	-
Scenario 3	Effect of the communication level on the process	-	X
Scenario 4	Combination scenarios 1 and 2	X	-
Scenario 5	Combination scenarios 1 and 3	X	X
Scenario 6	Combination scenarios 2 and 3	-	X
Scenario 7	Combination all scenarios	X	X

Qualitative validation description

Table 3 exhibits the initial conditions for each link in the supply chain. Additionally, it was verified that the proposed model satisfies the SC link requirements based on the multi-agent architecture and features inherent to the multi agents.

Table 3: Initial condition of each link

SCM Links	Current Model	Proposed model
External customer	This SCM link represents the consumer of the resources found in the retailer.	This SC link represents the consumer of the resources found in the retailer
Supplier	Receives the entire product sent from the manufacturer, no matter the storage capacity and also sells the product to the external customer.	The production order generator (O.P). It sends the requirements to the integrator agent and includes only the orders that the market needs (bought by external clients).
Manufacturer	The following are not considered: * Manpower of the production process. - The production status update. - The initial conditions are optimum for the simulation. - Production continues until the raw materials are depleted, independent from the market needs.	Uses SCM existent physical distribution links from CEAI-SENA. The following parameters are not considered: - Machinery warm up - Unexpected events, such as strikes, delays, natural disasters. - Scheduled events, such as maintenance and calibrations. - It doesn't have an inventory of the raw materials.
Suppliers	- Delays on raw materials delivery are not considered. - The supplier has unlimited products access to the previously selected resources - For each item a single provider is considered.	- Delays on raw materials delivery are not considered. - The supplier has unlimited access to products of the previously selected resources. - For each item a single provider is considered
Integrator agent	- Integrator agent is non-existent; however, a person is assigned to perform the communication to replace the integrator agent.	An information administrator, in charge of receiving signals, processing them and sending generator signals to each necessary SC link, except the external customer link.

Qualitative validation results and analysis

In Table 4 the aspects that were validated in the proposed CPN model, considering each SCM link are displayed. In the proposed model the same activities as the current model were validated. Additionally, multi-agent incorporation and the strengthening of some link aspects were considered.

Table 4: Validation of the proposed model with the SCM multi agent architecture model

PROPOSED MODEL		
	Fulfilled	**Not fulfilled**
Supplier		
Raw material Supply	X	
Entries		
Information management (purchase order)	X	
Raw materials for processing	X	
Process		
Raw material entry	X	
Product manufacture	X	
Finished product storage	X	
Information management (request order)	X	
Output		
Finished product	X	
Production report	X	
Consumers		
Finished product	X	
Sale service	X	
Multi-agent		
Self sufficiency		X
Sociability	X	
Interaction	X	
Contextualisation	X	
Reactivity	X	
Initiative		X
Rationalism	X	
Learning		X
Mobility		X
Communication capacity	X	
Benevolence	X	
Strengthened aspects		
	Modified	**Not modified**
External customer		X
Retailer - Information management - Inventory limitation - Product request depending on demand	X	
Logistic operator agent - Order processing - Warehouse storage - Product transport	X	
Manufacture - Information management - SCM integration	X	

In comparison to the current model, the proposed model integrates information technologies. This addition gives self-sufficiency to the links and support is provided from the integrator agent, which manages the SCM according to market needs. The management consists of inventory limitation depending on market demand, and information handling (product request, information processing, SCM integration, supplier selection, OP generation, updating the information for each link). Furthermore, the proposed multi-agent model was verified to incorporate inherent properties, such as sociability, interaction, contextualization, reactivity and communication capacity.

Simulation was conducted to confirm that each CPN module would fulfil the properties of reachability, vivacity, repeatability and bordering. The functional behavior of the model according to the real system requirements and all modules were verified to avoid blocks or misfire, among other properties.

Quantitative validation description

Three parameters were defined to qualitatively validate the proposed SCM model and four indicators were responsible for evaluating system performance; indicators directly related to the established parameters. These indicators are service level (LS), manufacturing time for a product in the supply chain (TFPSC), communication connection time between links (CCT) and average inventory (AI). All indicators were evaluated for each scenario.

Quantitative results validation and analysis

Table 5 shows results for the different indicators in each simulation scenario, in each case a simulation with an order of fifty products was considered.

Table 5 Results obtained from evaluated scenarios.

Scenario	LS		TFPSC		CCT		Inventory security	AI
	Units	*%*	*hour*	*%*	*frequency*	*%*	*Units*	*units*
0	41	81,34	8	Ref	1	Ref	71	100
1	42	84,32	7.5	6,25	1	-	71	100
2	43	86,64	7.5	6,25	1	-	70	100
3	44	87,03	6.79	15,13	Necessary	50	60	80
4	45	90.05	7.08	11,50	1	-	70	70
5	47	92,79	6.43	19,63	Necessary	50	60	60
6	46	91,92	6.11	23,63	Necessary	83.33	40	40
7	49	98,07	5.71	28,63	Necessary	83.33	40	40

When scenario 0 was simulated it was verified that the model fulfils the activities of the current SCM. Table 5 shows the simulated scenarios. The first scenario does not add meaningful suitability to the SCM system. The scenarios with the addition of the intelligent agent (2nd and 3rd scenarios), obtained a reduction in production time, nevertheless acting separately they would not bring about meaningful improvements to supply chain management, which has repercussions on the permanency of the product in the system. The 6th Scenario involved the use of both agents, a combination which led to remarkable improvements. For instance, it accomplishes the SCM product permanency time goal, and in consequence improves service quality, significantly reducing communication time between links in the SCM and the average inventory drastically reduces. Finally, the result of the 7th Scenario, derived from the combination of the proposed modifications from the 1st, 2nd and 3rd scenarios, indicates that when the communication process is reinforced and standardised, information quality is also improved, as represented by an overall SCM improvement of 98.07%.

4. Conclusion

System analysis using a Coloured Petri Nets model allows the evaluation of variable behaviour. With the obtained information on the relation between the variables at each stage, the multi-agent is capable of managing the production process and controlling information flow. The results obtained from the simulation of scenarios 1, 2 and 3 indicate that the use of the integrator agent contributes to an overall system improvement of 42.47%. If integrated with another attribute, the improvement would be significant, as shown when two agents are integrated, going from a local improvement of 81.34% to 91.92%, which represents an increase of 10.58%.

The model has strategic value since it reduces the risk associated with complex decision making, facilitating effective SC task implementation. The use of agents enables flexibility, agility and efficiency of resource management.

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