6

Collaboration and Exceptions Management in the Supply Chain

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1. Introduction

A supply chain is a network of companies that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers. Over the past few decades companies have been forced to react to a multitude of changing market dynamics:

- The increasing size of companies for attending global markets results in complex, longer and costly logistics infrastructures.
- The trend towards outsourcing and off-shoring has caused a fragmentation of the supply chain.
- Globalization means companies will have to face global managerial risks: financial crisis, environmental tsunamis, political risks, terrorist attacks.
- Environmental sustainability is a key consideration in the development of future globalization strategies.

To sum up, a company is no more going to behave like an island. All companies are interconnected and the final service to the customer is the result of the participation of a set of companies. Therefore, it is necessary to adopt a holistic view in order to make good decisions.

The objective of Supply Chain Management (SCM) is managing the entire flow of information, materials and services from raw materials suppliers through factories and warehouses to the end customer (Burt et al., 2002). SCM adds value to the customer when inventory is correctly positioned, thus facilitating sales. Besides, it helps organizations to build a suitable balance between differentiation through superior customer service and cost (Christopher, 2005).

In order to manage a supply chain in a successful way, it is necessary to reduce both lead times and inventory levels, since they contribute to increase the global cost of the supply chain and harm customer service. Moreover, any delays related to a mismatch between supply and demand may cause excess of inventories and stock-outs that must be avoided. Demand variations and possible supply problems are inevitable, so it is necessary to ensure that the supply chain is responsive and flexible. Therefore, a fluent information exchange and collaboration between members of the supply chain is desirable. SCM is intrinsically linked to collaboration: not only material, information, or money flows must be managed, but also relationships that are located both upstream and downstream the chain.

The purpose of this chapter is to provide an approach for collaborative dynamic scheduling that tries to coordinate different echelons of the supply chain in order to reduce inventory, backorders and ensure production orders visibility to the customer. This approach handles exceptions that could invalidate a production plan using a wide perspective to include suppliers and customers so as to obtain feasible and optimized plans, as well as better customer service. Therefore, it analyzes the implications of disruptions affecting production schedules that occur at a certain point of the supply chain for other nodes and takes proper actions to minimize the effects.

2. Literature review

Considering the volatility of market dynamics, it is paramount that supply chains are agile in order to provide a fast response to changes. A key aspect of agile supply chains is a fast information exchange across the enterprise networks. Besides, the visibility of demand changes and disruptions throughout the supply chain is crucial if we want to obtain effective and efficient solutions.

As regards commercial solutions, Manufacturing Resource Planning (MRP II)/Enterprise Resource Planning (ERP) systems are recognized as successful solutions to integrate different functions of a company, e.g. production, purchasing, sales, accounting, etc. But at the same time, they are focused internally and do not support information exchange, let alone collaboration with either suppliers or customers. Later on, the so-called Advanced Planning Systems (APS) appeared to avoid some limitations of the MRP II/ERP systems such as infinite capacity or fixed lead times. The APS systems provide a centralized management of the supply chain activities and processes in real time. In recent years, the ERP II concept emerged in order to support the idea of integrating both internal and external business processes, enabling a direct data interchange between companies. But most commercial solutions have an important limitation, i.e. they are not affordable for SMEs.

The basic operational problem that causes disruptions in the supply chain is the difficulty to match supply and demand. On the demand side, changes may derive into excess of inventories and stock-outs. Unplanned demand oscillation can cause distortions in the supply chain when the different nodes do not interchange information. These distortions are commonly known as the "bullwhip effect" (Forrester, 1961). This effect has been extensively analyzed and has been a key issue of many scientific publications due to the negative implications it has in terms of excess of inventory, shipping cost increase and quality problems. There is a common agreement that information sharing is a crucial factor in order to obtain global benefits in the supply chain level. Therefore, a fluent flow of information throughout the supply chain is necessary. The CPFR model offers a general framework by which a buyer and a seller can use collaborative planning, forecasting and replenishing processes in order to meet customer demand. Buyers and sellers are involved in four collaboration activities: Strategy and planning, Demand and Supply Management, Execution and Analysis.

On the supply side, late deliveries and quality problems often incur an interruption of the manufacturing processes. In order to implement the just-in-time philosophy (JIT), new collaboration concepts arose such as vendor-managed inventory (VMI) where orders disappear and vendors have access to real demand information, thus reducing costs and enhancing service. This means that the supply network must be responsive to these demand and supply variations (Hu, 2010).

Furthermore, the so-called CO-OPERATE project (Azevedo et al., 2005) aims at improving the overall goal of the supply chain by creating a communication infrastructure between companies. This infrastructure enables a collaborative production planning, multi sourcing coordination, process visibility and exception handling reducing the "bullwhip" effect thanks to information sharing. But some authors (Viswanathan et al., 2007) showed, that in order to enjoy the full benefits of collaboration, practitioners should focus more on synchronization than just on information visibility. Therefore, the SCOR and CPFR models provide suitable tools to reduce the bullwhip effect and best meet customer demand. Besides, the CO-OPERATE project enables collaborative production planning and exception handling by means of a common information infrastructure in the supply chain. But despite all the contributions in this research area, there is a lack of studies that focus on synchronizing local scheduling solutions in real time in order to improve the decision-making processes.

2.1 Problem scope

Managing information in an inter-organizational context has become critical and it is necessary not only to exchange information but to synchronize the production plans at the different echelons of the SC.

The system works with the following assumptions:

- Information is only exchanged with immediate suppliers and customers, this means that a basic supply chain will be considered rather than an extended one (Hugos, 2006).
- The company has several plants that are independent in the sense that they are not connected through assembly operations. But they have alternate resources at different plants that can opportunistically be used in case of unavailability problems. In Fig. 1, a representation of the entities included in our research is shown.

The control system is distributed and decisions are made at each node but taking into consideration information exchanged with other nodes. This means that each plant will

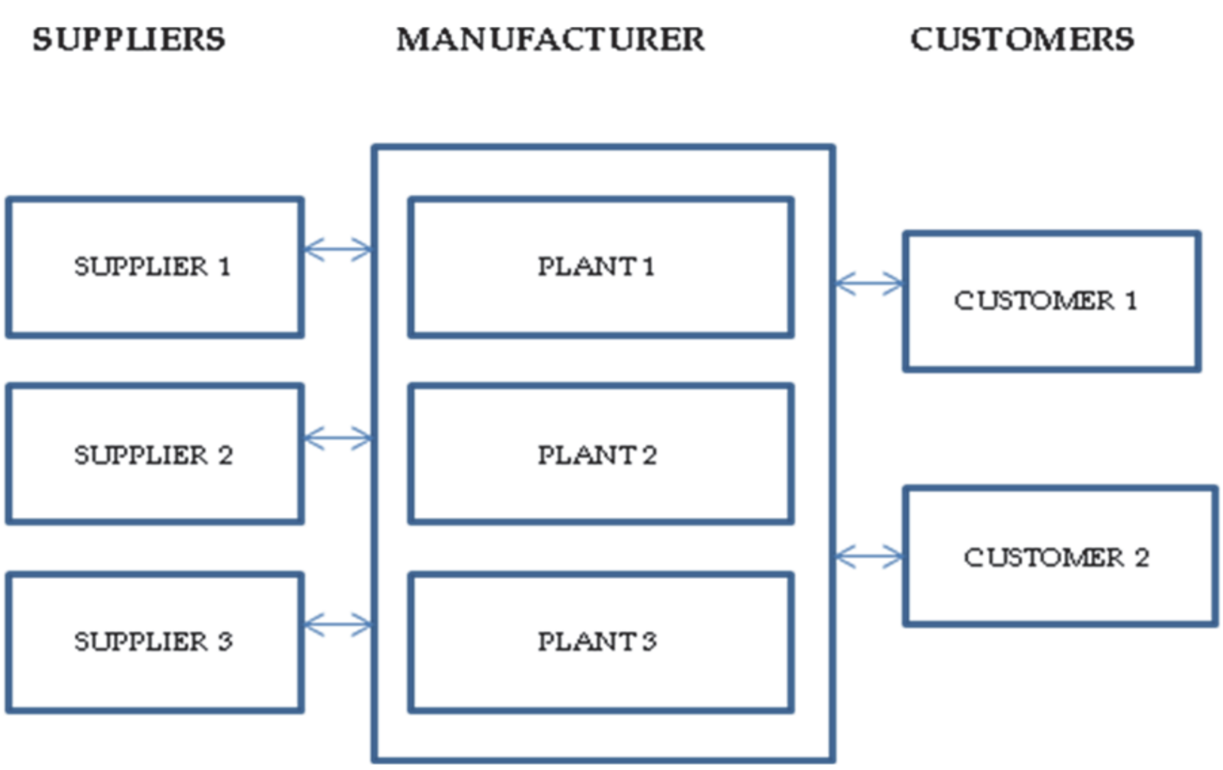

Fig. 1. The supply chain structure

be autonomous as regards decision making in terms of production management but, at the same time, will take advantage of information coming from other nodes in order to allow a dynamic collaboration and a better global solution.

2.2 Description of the model

The model of the industrial factory that has been selected for our research corresponds to a discrete manufacturing environment that is often subject to disruptions. An entity-relationship semantic model has been used in order to represent the elements of the industrial factory.

The main components of the database are the following (Álvarez & Diaz, 2010):

1. *Plant*. The company can have several plants. Each production plant has its own production schedule that has been generated independently.
2. *Reference*. A product reference is related to an end product that can be manufactured at a specific plant. Some attributes of the product reference are the code, batch size, cost and unitary manufacturing time.
3. *Work order*. It is related to the orders the system has and refers to only one reference, for which there can exist one or more process plans.
4. *Material*. Each reference needs a set of raw materials that must be transformed into end products (references).
5. *Operation*. The operation types are the different possible operations that can be performed by the machines of the plant. Besides, each machine can perform several operations at different individual speeds.
6. *Characteristic*. They are related to the possible product features of the company. In addition to that, they define the sequence-dependent set-up times.
7. *Customer*. Entity that receives the end products of the company.
8. *Supplier*. Entity that provides materials to manufacture end products of the company.
9. *Operator*. Human being that is in charge of executing jobs at a plant.

3. Software architecture

It is very important to preserve the necessary level of autonomy of each node when they belong to different companies. Therefore, we consider that a distributed approach is more suitable than a centralized one, where the exceptions that occur at a certain node can be solved in a collaborative way with other nodes of the network.

Most decentralized planning solutions use agent-based models. An agent is a software system that communicates with others in order to solve a problem that exceeds the capacity of each individual software module. Agent-based technology is considered a suitable approach for the development of distributed planning and scheduling systems (Hao et al., 2006). Lu et al. (2005) propose a collaborative production framework based on agents, where production orders, subassemblies, production lines and cells are represented as agents that interact among them in a collaborative way. A supply chain is composed of several agents, such as vendors, wholesalers, manufacturers, retailers and customers. These agents must share information and coordinate the physical execution of their operations to ensure a smooth flow of materials, services, information, and cash through the chain.

The general framework of the system is based on a decentralized multi-agent architecture that will be used in order to coordinate the different production plans, where each agent will represent a node of the supply chain. Production will be scheduled at each plant, independently from other nodes. But when exceptions arise, other nodes will also be at stake. For example, when new orders arrive at a plant and there are not enough raw materials available at that plant to manufacture them, the affected node will ask for materials to one or several suppliers, which might have to communicate with their own suppliers. Whenever an exception arises, the affected node will reschedule all the affected operations taking into account the capacity available at the active production schedule and will also check the feasibility of the solution externally. The solution will then be transmitted to the customer who generated the new order. Possible interactions between nodes of the supply chain will be analyzed and relevant information will be communicated to the affected ones.

In fig. 2 the software architecture with all the modules of the system is shown, as well as the relationships among them. The modules are the following: Data Capture (DC), Internal Events Manager (IEM), Plant Scheduler (PS), Suppliers Module (SM), Customers Module (CM), Plants Coordinator (PC) and Events Monitoring and Management (EMM). The exchange of information among agents is mainly represented by three subsystems of information: (i) a communication subsystem inside the plants (IEM module), which will manage the unforeseen events that may lead to a rescheduling of part or the entire production plan, (ii) an inter-plants communication subsystem (PC module), which will manage the events produced in a plant that may affect other plants and (iii) a supply chain communication subsystem (EMM module), which will manage events occurred in a plant that can affect suppliers and/or customers (Álvarez & Díaz, 2011).

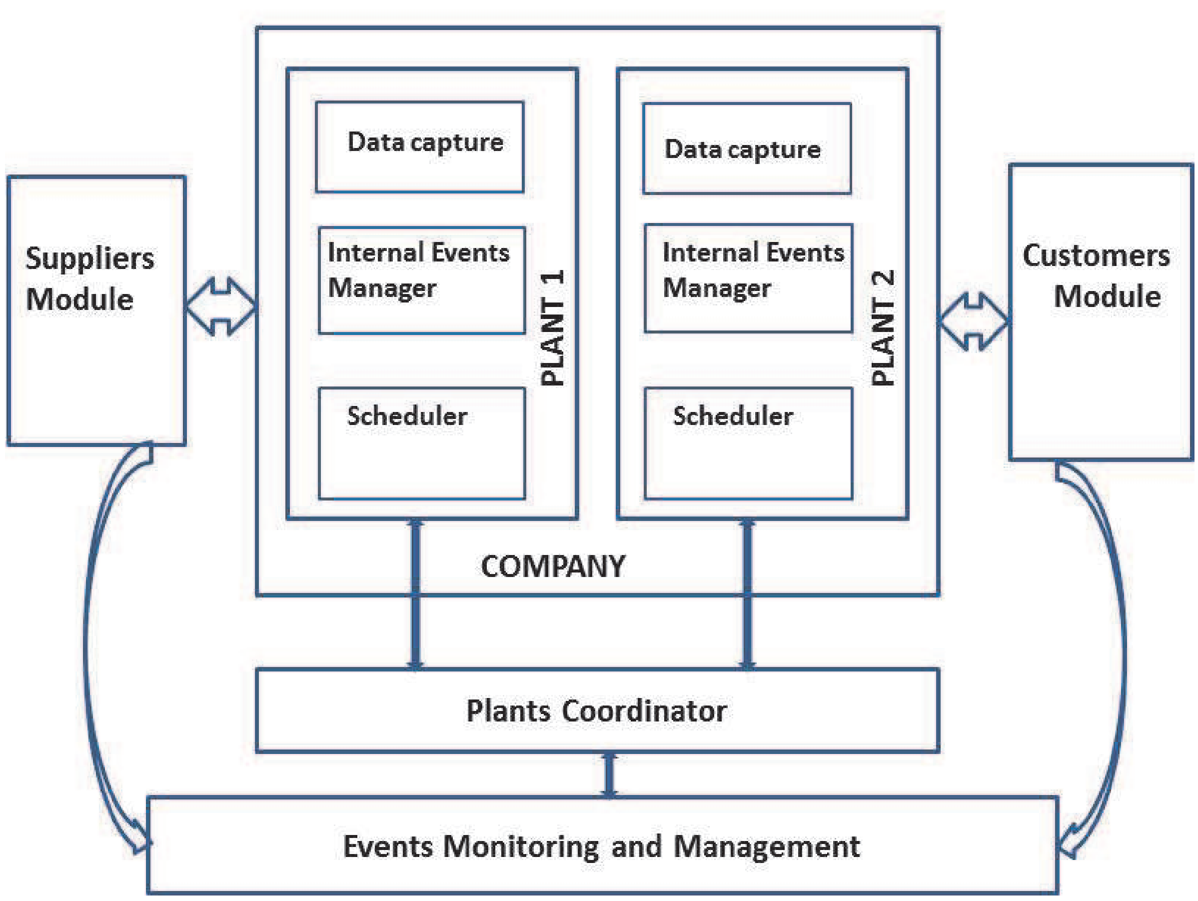

Fig. 2. Software architecture.

4. Exceptions

Exceptions can be classified into two main groups: internal and external. The latter can also be divided into two subgroups: exceptions related to customers and exceptions related to suppliers (see table 1).

Exceptions		
Internal	External	
Repeat parts Machine failure Machine recovery Material shortage Arrival of material Absence of operator Presence of operator	Related to customers	Related to suppliers
	Shortening due date Extension of due date New urgent order Order quantity increase Order quantity reduction Order cancellation	Return of materials Partial materials delivery Delayed delivery Defective delivery Cancelled delivery

Table 1. Types of exceptions

4.1 Internal exceptions

Main internal exceptions are related to the availability of machines, operators and auxiliary resources, as well as quality related events. If an exception occurs at a shop floor, the affected operations at the current production schedule will be identified and the feasibility of the solution will be verified. Nevertheless, these internal exceptions can generate external exceptions if they affect either suppliers or customers. These exceptions will contribute to synchronize and optimize the entire supply chain.
Here is a list of all the possible internal exceptions that are going to be managed by the system:

- *Repeat parts*: whenever there is a quality reject that can be repaired through reprocessing, the user will introduce this event.
- *Machine breakdown*: this event can be manually introduced through the user interface, or automatically by the shop floor Data Capture module, and will allow the system to know that this machine is out of order. Besides, if possible, an estimated duration of the unavailability interval will be input to the system.
- *Machine recovery*: this is the opposite event of the previous one, informing the system that the broken-down machine has been repaired and is fully operative again.
- *Material shortage*: through this option, the user can specify a single lack of material affecting only one order, or a global lack of material affecting each order consuming that material.
- *Arrival of material*: this is the opposite event of the previous one, meaning that the orders affected by the material shortage can be processed.
- *Absence of operator*: this event informs about an unexpected temporary absence of a needed operator.
- *Presence of operator*: this is the opposite event of the previous one, meaning that the absent operator is available again.

4.1.1 Absence of operator

The absence of operator event is handled according to the process described in fig. 3. When the Data Capture module of a plant detects that an operator is missing, the Internal Events

Manager module will calculate the percentage of operations affected, and based on that percentage it will assess the severity of the event.
If the absence of the operator is not serious, the event will finish. Otherwise, this module must check whether there are other operators in the plant that could replace him/her. Sometimes, in multi-plant environments, it may happen that some operators work in different plants (e.g., one week in one of them and the next week in another). When this kind of situations happens, we should look at the possibility that an absent operator is replaced by another that is working at the same plant or at a different one on condition that

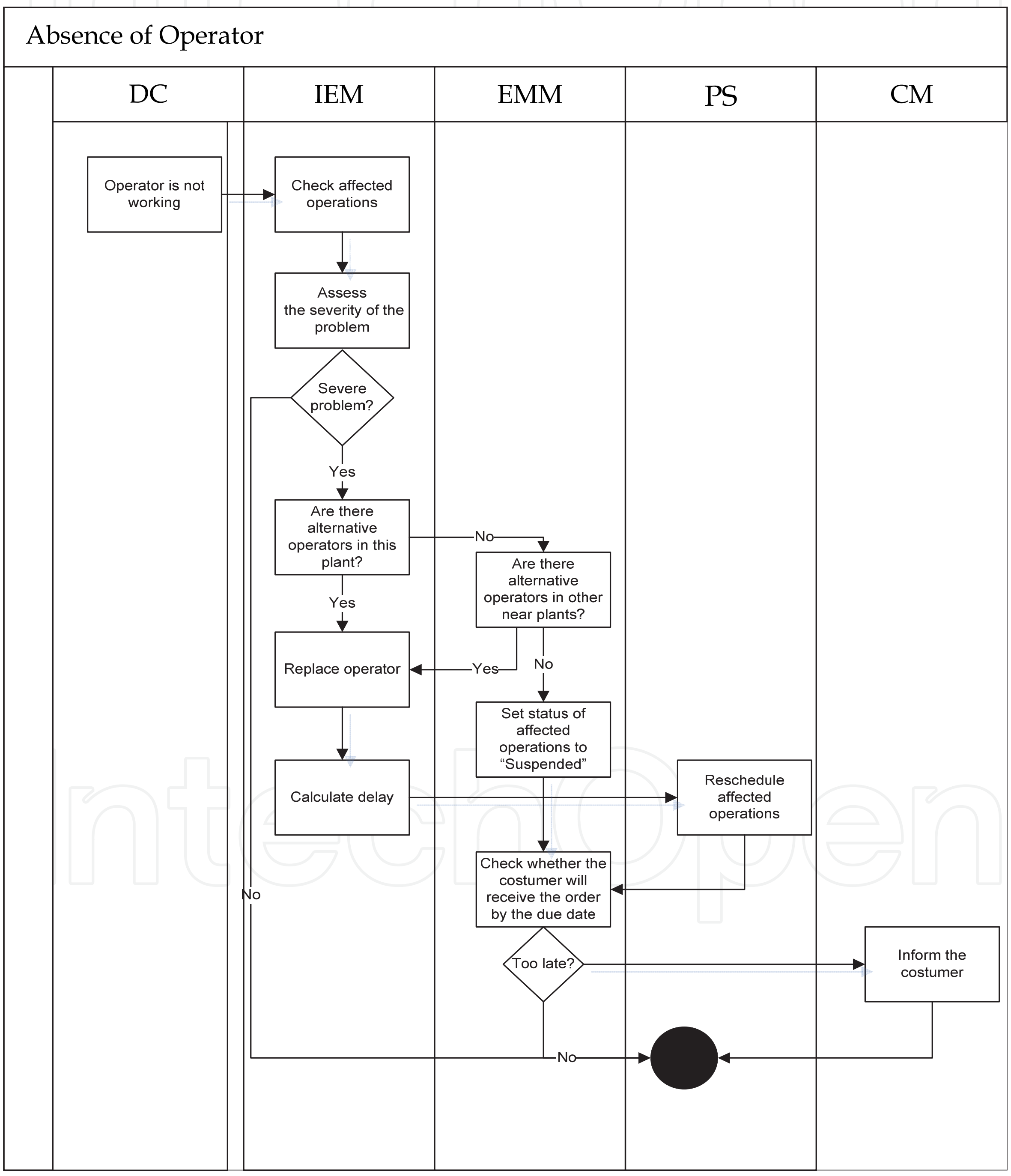

Fig. 3. Flowchart of an unexpected absence of operator event.

he/she has enough time to travel from one plant to the other and to make these operations.This event could launch a re-planning process, caused by an operator who is not in his/her place. The field Available_Flag, in the table OPERATOR, indicates the availability or not of and operator in real time. When a non-programmed unavailability of an operator happens, this flag would be set to 'N'. This means that it would not be possible to consider any operator whose flag is 'N'.

In principle, since every plant is going to have a scheduler (PS), it will be necessary to determine the compatibility between machines and operators. So, if an operator is free during a certain period of time and is compatible with the machines that must be used for the affected operations, he/she will have to move through the plant or even to come from another plant. In this case, we should also consider an estimation of the travelling time between plants.

In order to see whether there are other operators available, it is necessary to search for workers that could operate that machine and are free. If so, the operator will be replaced, else the same search will be done in other plants. If there are no operators available in any plant, the flag of the affected operations will be set to "Pending" until the operator returns to his/her place.

Finally, the Event Manager Module will check whether the modification of the plan affects the client, mostly because of the delays. If so, the client will be informed about that modification, otherwise the event will finish (dot symbol).

4.2 Exceptions related to suppliers

Here is a list of possible exceptions that are generated at the suppliers' side:

- *Return of materials*: If the supplier has delivered defective parts that are detected during the manufacturing process, the affected batches will be taken away.
- *Partial materials delivery*: It means that the supplier is not able to deliver the total amount requested, but just a part of it. Problems will arise if there is not enough level of on-hand inventory to replace it.
- *Delayed delivery*. It means that the supplier informs the company that a certain order will arrive late. An explanation of how this event is handled by the system is provided in the next section.
- *Defective delivery*. A supplier detects a defective lot once it has already reached the customer.
- *Cancelled delivery*. This means that a supplier is not be able to make a delivery at all, not even partial. This may imply that some manufacturing orders cannot be produced due to lack of materials.

4.2.1 Delayed delivery

The process associated to a delayed delivery event is described in fig. 4. Firstly, the Internal Event Manager module will change the order status as "delayed" by modifying that field of the database. Then, the level of inventory will be checked. If there is enough inventory to compensate for this delay, the event will end (dot symbol). Otherwise, the Internal Event Manager module will check whether the event is severe or not, considering the delay interval indicated by the provider and the impact on the current production schedule. If the impact is small, the plan will be changed and the event will finish (dot symbol). Then, if this change affects any order, the affected clients will be informed. However, if the impact is big,

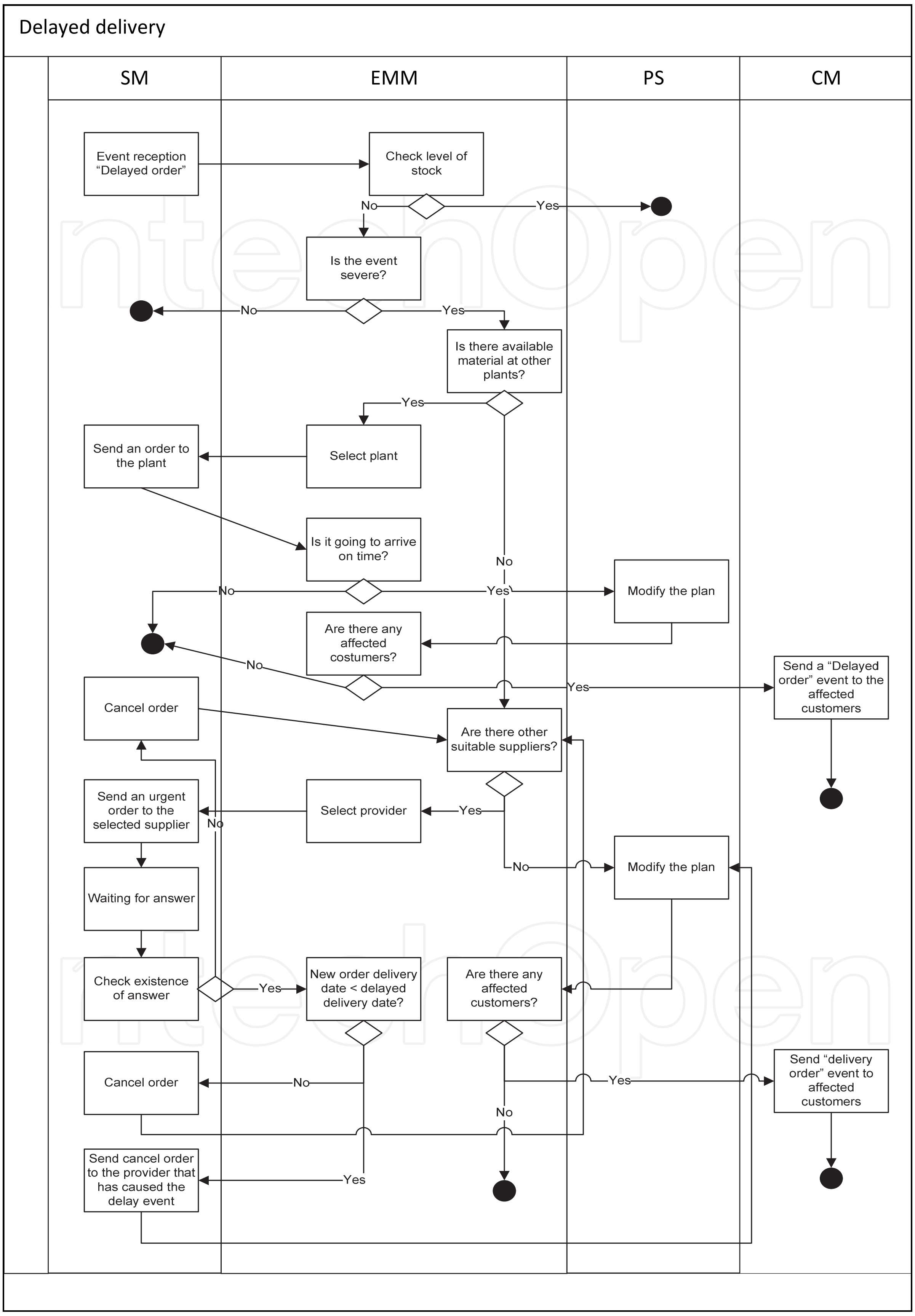

Fig. 4. Flowchart of a delayed delivery event.

the module must check in the database whether any other plant has the materials that are needed. If so, a request will be sent to the plant that is going to provide the material.
If the estimated arrival date of the material (to do that, the matrix of distances between plants must be checked) is earlier than the date of the first operation affected by the delayed order the event will finish. Else, the plan must be modified and customers must be informed by sending to them a “Delayed order” event and then the process will finish. In case the raw materials cannot be moved from another plant, a negotiation process with the suppliers will start, following a repetitive structure. Firstly, the table Material Provider of the database will be checked, regardless of which supplier generated the exception that is being handled. Then, the most suitable provider will be selected, if there exists one.
Since the system will be working in real-time, when it is necessary to search for a different supplier, only a small set of suppliers will be considered for selection. This set of suppliers should have shown a sufficient level of quality, price and service in the past. The candidate that accepts the order and offers the best combination of cost and service will finally be selected. Next, the Suppliers Module will take the control and will send an urgent order event to the provider. Later, the SM will wait for a certain interval, defined by a constant. If the provider does not answer before the time expires, the iteration will start again. Otherwise, the SM will send a reply to the Internal Event Manager module, which would compare this new delivery date with the delay date of the provider that generated the exception. If the delivery period is shorter than the delay period, the Suppliers Module will send a confirmation message to the new provider and a message to cancel the order will be sent to the provider that caused the delayed delivery event.
Consequently, the database must be updated, setting the delayed order status to “cancelled”, and adding the new order. Then, it will be checked whether the delivery date of the new order is earlier than the initial delivery date of the delayed order. If so, the event will finish, else the plan will be modified by adding the new delivery date. Once the plan is made, the Internal Event Manager module will check the orders that do not fulfil the due dates and the Customers Module will inform those clients affected by the delay. Then the process will end.

4.3 Exceptions related to customers

The most important events in this category are the following:

- *Shortening due date*. This means that the manufacturing operations of the work order must be moved backwards in time.
- *Extension of due date*. This is the opposite situation meaning that the manufacturing operations must be moved forwards in time in order to comply with the new due date.
- *New urgent order* or *order quantity increase*. This event will involve an order promising process in order to check material limitations or real-time capacity in the active schedule to include the added units. This event will include an ATP (Available to Promise) check and possibly a CTP (Capable to Promise) check. The ATP information is based on the on-hand inventory or planned production of the MPS available for commitment to customers’ orders. On the other hand, the CTP information refers to the resource time available that can be used to meet customer demand over a certain time interval (Viswanathan et al., 2007). Consequently, the urgent unplanned demand coming from customers will often mean an availability check of the supplier network. With this information, it will be possible to promise a realistic due date to customers.
- *Order quantity reduction*. If the customer decides to cancel a part of the order, it will request a reduction in the materials order quantity to the supplier, else the whole

purchasing order will be received. Furthermore, the plant will reduce the work order to the exactly quantity required and therefore, some slack times will be introduced in the schedule.

- *Order cancellation*. The jobs of the order will be eliminated and the corresponding capacity will be released at the assigned resources.

5. Plant Scheduler (PS)

Exceptions management usually implies rescheduling operations in the affected plant or plants. This task is done by the Plant Scheduler module. We have developed a finite-capacity scheduling system that operates in different plants and works with multiple optimization criteria, and besides, it can generate both static and dynamic schedules. It allocates jobs to machines in order to minimize production cost, delivery delays, machine idle time and, in case of rescheduling, maximize similarity with original schedule.

5.1 Main features of the scheduler

The job-shop scheduling problem on manufacturing environments presents the following general features:

- An industrial plant (shop-floor) has as main objective the production of a set of different parts. The manufacturing of every part is done by means of a process plan composed by one or more processes, which can be sequential or take place in parallel.
- The plant has a set of material and/or human resources to do the manufacturing processes of the parts.
- There exists a set of production orders of the different parts, each one referred to a single part with its corresponding quantity. The production orders can either be make-to-order or make-to-stock.
- The production of every order generates as many manufacturing operations as processes in the process plan of the corresponding part. Precisely, the resolution of the problem consists of obtaining a schedule that specifies the necessary resources and time intervals to do these manufacturing operations.
- There exists a number of constraints that must be satisfied totally or partially in order to achieve a valid schedule. This way, there can be constraints related to the process plan of any part (precedence in the accomplishment of the processes), constraints related to the resources (limitations in the operability and capacity of the machines, availability of operators and tools), and constraints related to the orders (release dates and due dates).
- The aim of production scheduling is to decide the assignments of resources to the different operations of the production orders with their corresponding time intervals, preserving the constraints, optimizing the use of resources, and minimizing costs and times.

Formally, the problem can be described with the following elements:

- Set of problem variables, $X = \{(x_{11}, x_{12}), (x_{21}, x_{22}), \ldots, (x_{n1}, x_{n2})\}$, where each variable pair (x_{i1},x_{i2}) represents a job/machine combination.
- Solution space, $S = (OP \times M)^n$, being $\#S = (nm)^n$.
- Set of feasible solutions of the problem, $S' \subseteq S$.
- Objective function, $f : S' \to \Re$, where four main goals are included in terms of cost:

$$\sum_{i=1}^{n} Cm(OP_i) + \sum_{i=1}^{m} \left(Cdd(OR_i) + Chd(OR_i)[+Cjit(OR_i)] \right) + \sum_{i=1}^{q} Cid(M_i) + \left[\frac{k \cdot w}{n} \sum_{i=1}^{n} Cm(OP_i) \right]$$

where:

- n is the number of manufacturing operations scheduled.
- m is the number of work orders.
- q is the number of operative machines in the plant.
- $Cm(OP_i)$ is the manufacturing cost of operation i. It is equal to the unitary manufacturing cost of a part at the assigned machine multiplied by the number of parts to be manufactured in the operation.
- $Cdd(OR_i)$ is the delay cost with respect to the due date of order i. It is equal to a delay cost per day multiplied by the number of days the order is delivered late.
- $Chd(OR_i)$ is the delay cost with respect to the scheduling planning horizon of order i. It is equal to a delay cost per day multiplied by the number of days the order is finished late.
- $Cjit(OR_i)$ is the cost due to early completion of the order i with regard to the due date (in case of JIT scheduling). It is equal to an early completion cost per day multiplied by the number of days the order is finished before the due date.
- $Cid(M_i)$ is the idle time cost of machine i.
- k is the number of manufacturing operations in the schedule, whose machine or sequence in the machine has changed with respect to the original plan.
- w is an influence factor that is decided by the user.

Apart from this basic definition, some important information related to the plant model must be considered to start the calculations:

- Alternative process plans for every manufacturing part.
- Standard batch size for every part.
- Preference levels for machines.
- Sequence-dependent set-up times for machines.
- Maintenance plans for machines.
- Priority levels of the work orders.
- Critical auxiliary resources (operators and tools).
- Working calendar for each plant.
- Weekly working shifts for every resource (machines, operators, tools).

5.2 Evolving algorithm

The algorithm designed for this job-shop scheduling problem is based on the general procedure of an evolving algorithm, EA, combined with a specific heuristic adapted to the problem. This heuristic is applied in the generation process of organisms at the initial population, as well as in the recombination of genes to build new organisms at the successive generations. The aim is to generate feasible organisms, that is, solutions that satisfy all the problem constraints. This means that all the production schedules obtained can be applied to the actual plant situation, since they satisfy all the existing constraints.

5.2.1 Basic structure of the evolving algorithm

The input information of the EA is composed of all the entities integrating the model of the industrial plant (parts, machines, processes, part characteristics for set-up times calculation, work orders, jobs, calendars, etc.). In particular, starting from all the operations in the system, the EA schedules those operations that have not yet been assigned to any manufacturing resource, but keeping the machine and time assignments of the scheduled operations.

The EA is not affected by the origin of non-assigned operations to be scheduled, i.e., non-assigned operations can be all the operations in the system, or just a subset of them that must be rescheduled due to an unexpected event or exception. As previously explained, the dynamic exceptions that are supported by the system (machine failure, return of materials, new urgent order, etc.) are processed before the execution of the EA. This process implies selecting the operations to reschedule, and changing the plant information affected by the exception. This independence and generality of the EA makes it suitable to build both static and dynamic production schedules.

Firstly, we implemented a configurable software application to support a general-purpose genetic algorithm using an object-oriented methodology, and later we transformed it into an evolutionary heuristic algorithm adapted to the problem. The general procedure of this algorithm is the typical one of the genetic and evolving algorithms.

In order to carry out the tests of the proposed EA in the job-shop scheduling system, we have chosen the following characteristics and configuration parameters:

- The number *p* of organisms in the population (50), as the main goal of the tests is to check the optimization quality of the solutions with the different evolving selection criteria.
- The fitness function *f* of every organism $\mathbf{x}_k$ ($k = 1,...,p$) used by the EA is calculated as the inverse of the objective function described in section 5.1:

$$f(\mathbf{x}_k) = \frac{1}{\sum_{i=1}^{n} Cm(OP_i) + \sum_{i=1}^{m} \left(Cdd(OR_i) + Chd(OR_i)[+Cjit(OR_i)] \right) + \sum_{i=1}^{q} Cid(M_i) + \left[\frac{k \cdot w}{n} \sum_{i=1}^{n} Cm(OP_i) \right]}$$

- The selection of reproductive organisms is done using a deterministic criterion that allows the reproduction of all organisms in the current population.
- The generation of new organisms is done only by mutation of existing organisms (no crossover), i.e. the proposed algorithm is of evolving type.
- The selection of surviving organisms is done by means of fourteen evolving selection criteria: a deterministic elitist scheme, a mixed elitist - random scheme, three schemes of proportional selection, three schemes of hierarchical selection, three schemes of selection by tournament, and three schemes of disruptive selection.

5.2.2 Solution coding

We use the typical structural model of genetic and evolving algorithms to represent the problem: population, organisms (feasible solutions of the problem), chromosomes (homogeneous groups of variables in a solution) and genes (variables of the problem). Every organism of the problem is formed specifically by n+m+q chromosomes, where n is the number of open and in-progress operations that exist in the system, m is the number of open and in-progress work orders, and q is the number of machines at the plant.

To support the scheduling information of operations, relative to machine and time interval assignments and to objectives and constraints, every operation-chromosome possesses 17 attribute-genes:

- *Genes[0]*. It indicates the number of the operation in the list of operations of the plant.
- *Genes[1]*. It indicates the number of the machine assigned to the operation in the list of machines of the plant.
- *Genes[2]..Genes[6]*. They indicate the scheduled starting date of the operation in the format *Year-Month-Day-Hour-Minute*.
- *Genes[7]..Genes[11]*. They indicate the scheduled finishing date of the operation in the format *Year-Month-Day-Hour-Minute*.
- *Genes[12]*. It indicates the previous operation-chromosome in the batch/order.
- *Genes[13]*. It indicates the following operation-chromosome in the batch/order.
- *Genes[14]*. It indicates the previous operation-chromosome in the assigned machine.
- *Genes[15]*. It indicates the following operation-chromosome in the assigned machine.
- *Genes[16]*. It indicates the production cost in cents of the operation in the assigned machine.

To support the scheduling information of work orders, relative to time interval assignments and to objectives and constraints, every order-chromosome possesses 14 attribute-genes:

- *Genes[0].]*. It indicates the number of the work order in the work orders list of the plant.
- *Genes[1]..Genes[5]*. They indicate the scheduled starting date of the work order in the format *Year-Month-Day-Hour-Minute*.
- *Genes[6]..Genes[10]*. They indicate the scheduled finishing date of the work order in the format *Year-Month-Day-Hour-Minute*.
- *Genes[11]*. It indicates the due date delay cost in cents of the work order.
- *Genes[12]*. It indicates the scheduling horizon delay cost in cents of the work order.
- *Genes[13]*. It indicates the due date advance cost in cents of the work order (valid only in case of JIT scheduling).

To support the scheduling information of machines, relative to objectives and constraints, every machine-chromosome possesses 4 attribute-genes:

- *Genes[0].]*. It indicates the number of the machine in the list of machines of the plant.
- *Genes[1]*. It indicates the maximum working time of the machine in the scheduling horizon.
- *Genes[2]*. It indicates the effective working time of the machine, i.e., the total duration of the jobs assigned to the machine.
- *Genes[3]*. It indicates the idle time cost of the machine in cents.

6. Tests

6.1.1 Description of tests

We have designed a set of tests on an instance of limited size of the industrial plant, with the main goal of testing and showing in a simple and clear way the performance of the production scheduler and of the evolving algorithm that sustains it in the collaborative system of exceptions management in the supply chain. This instance of the plant has the following components:

- Number of parts: 3.
- Number of machines: 6.
- Number of processes: 3.
- Number of part characteristics: 3.
- Number of work orders: 4.
- Number of batches: 6.

- Number of operations (jobs): 18.

The tests have been done considering three different scheduling situations:

- *Static Scheduling*. A complete schedule is generated for a scheduling horizon of 15 days in which machines and time intervals are assigned to the 18 operations.
- *Rescheduling due to a machine failure*. A machine failure exception has been simulated, which forces a rescheduling of the subset of manufacturing operations that were assigned to the damaged machine during the foreseen unavailability period.
- *Rescheduling due to a new urgent order*. A new urgent order event is simulated, which forces a rescheduling.

For every described situation the evolving algorithm has been executed on a population of 50 organisms using binary tournament survival selection operators, and the corresponding statistics and performance measures of the best found solution have been calculated, i.e., the organism with the best fitness value obtained as a result of the evolving optimization process. With regard to the execution efficiency of the algorithm, the generation of the complete static program takes less than one second, so it looks promising for instances of the industrial plant with hundreds of manufacturing operations to schedule. In these cases, an execution time that would range from some seconds and a few minutes is foreseen.

6.1.2 Analysis of tests

With regard to the static schedule, table 2 shows the set of assignments done by the production scheduler, whose schematic representation corresponds to the Gantt chart of fig. 5.

Order	Batch	Operation	Machine	Starting date	Starting time	Finishing date	Finishing time
ORD-1	1	OP-1	M1	2011-1-2	19:0	2011-1-3	11:40
		OP-2	M4	2011-1-5	14:50	2011-1-7	8:30
		OP-3	M5	2011-1-8	20:50	2011-1-12	8:10
	2	OP-4	M1	2011-1-2	9:0	2011-1-2	19:0
		OP-5	M4	2011-1-2	19:0	2011-1-3	20:0
		OP-6	M5	2011-1-3	20:0	2011-1-5	22:0
ORD-2	1	OP-7	M1	2011-1-3	12:25	2011-1-4	13:25
		OP-8	M4	2011-1-4	13:25	2011-1-5	14:25
		OP-9	M6	2011-1-5	14:25	2011-1-9	1:45
ORD-3	1	OP-10	M2	2011-1-2	9:0	2011-1-3	13:0
		OP-11	M3	2011-1-3	13:0	2011-1-5	0:0
		OP-12	M5	2011-1-5	22:25	2011-1-8	20:25
ORD-4	1	OP-13	M1	2011-1-4	14:0	2011-1-5	23:20
		OP-14	M4	2011-1-7	9:5	2011-1-9	19:25
		OP-15	M6	2011-1-9	19:25	2011-1-13	6:45
	2	OP-16	M1	2011-1-5	23:20	2011-1-6	12:40
		OP-17	M4	2011-1-9	19:25	2011-1-10	18:45
		OP-18	M6	2011-1-13	6:45	2011-1-14	16:5

Table 2. Static schedule

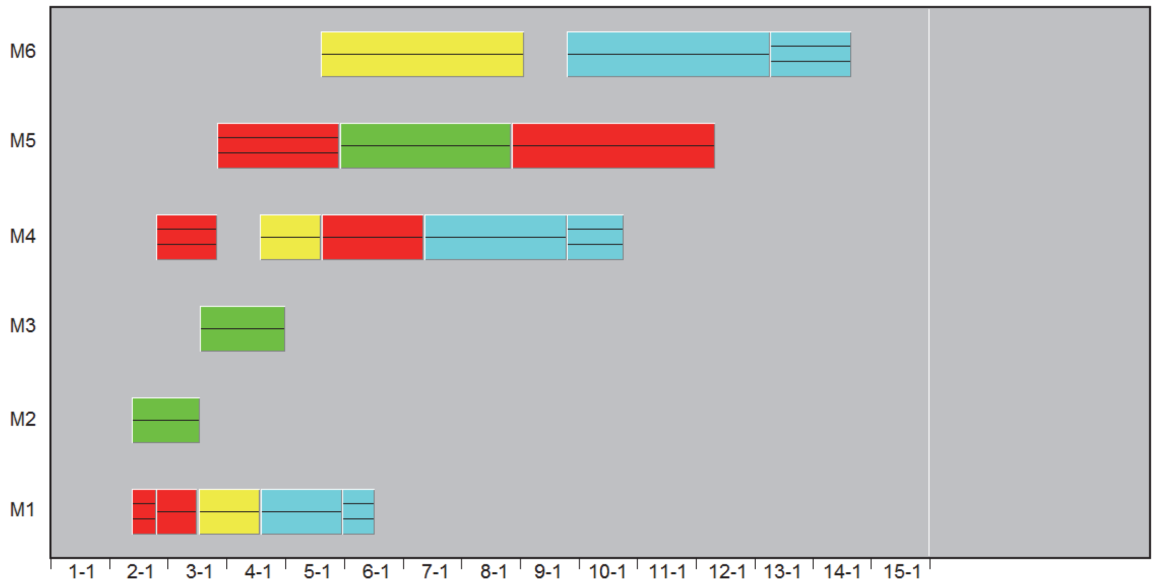

Fig. 5. Gantt chart of the static schedule

In the Gantt chart the operations corresponding to the same order are represented by blocks of the same colour (order 1 red, order 2 yellow, order 3 green, order 4 cyan). Likewise, the number of horizontal lines drawn in the interior of the block that represents every operation indicates the number of the work order batch to which the operation corresponds. The white vertical line to the right of the diagram indicates the limit of the planning horizon of the fixed scheduling time interval (15 days).

Table 3 contains the performance measures obtained for the previous static program, which will be used as reference for the comparison of results in the different cases of rescheduling. As it is observed, the work load of the plant is not excessive, and only one order (ORD-3) presents a due date delay. Besides, no order has been scheduled late with regard to the end of the planning horizon of the plant. Precisely, the due date delay of order ORD-3 relative to its foreseen manufacturing interval is 6.76 %, with an associate cost of 607.63 Euro. Note also that the average percentage of occupation of the machines is 34.17 % with a total cost derived from machine idle time of 2504.39 Euro.

With regard to the rescheduling due to machine failure, table 4 shows the set of assignments of machine and time interval calculated by the production scheduler for every order/lot/operation of the system in response to the exception. Likewise, in fig. 6 and 7 the Gantt charts of the operations appear before and after the rescheduling process respectively.

As it is observed in fig. 6, the machine that generated the failure exception is M4, which remains inoperative during a foreseen period of 3 days (5-1, 6-1, 7-1). Therefore, the three affected operations (OP-2, OP-8, OP-14) are initially eliminated from the schedule. In this case, the exception manager checks the existence of an available alternative machine (M3) that can execute these operations, so that they can be rescheduled and not remain pending. In the rescheduling process, the assignments of machine or time intervals of the operations started before the current date (event date) are not modified. Likewise, the machine assignment of the remaining operations is not changed, though these operations can be moved forward in time, as a consequence of the optimization process. Indeed, other operations might be considered, apart from the three directly affected by the event, for

STATIC SCHEDULE - GLOBAL PERFORMANCE IN TERMS OF COST	
Total cost (objective): 105412.02	**Production cost:** 102300.00

PERFORMANCE RELATED TO WORK ORDERS					
	throughput time	**due date delay**	**due date delay cost**	**horizon delay**	**horizon delay cost**
Order 1	14350	0	0	0	0
Order 2	8000	0	0	0	0
Order 3	9325	625	607.63	0	0
Order 4	14525	0	0	0	0
Maximum	14525	625	-	0	-
Average	11550	156.25	-	0	-
Σ	-	-	607.63	-	0

PERFORMANCE RELATED TO MACHINES			
	allocated operations	**usage percentage**	**idle time cost**
Machine 1	5	27.31	418.66
Machine 2	1	7.78	553.33
Machine 3	1	9.72	780.00
Machine 4	5	48.15	448.00
Machine 5	3	56.48	131.60
Machine 6	3	55.56	172.80
Average	3	34.17	-
Σ	-	-	2504.39

Table 3. Static schedule performance

relocation during the rescheduling process (by simply annulling the machine assignment of the operation before the scheduler is launched), but this possibility has been avoided taking into consideration the general aim of minimizing the changes with respect to the previous schedule.

Table 5 contains the performance measures for the schedule obtained after the event of machine failure. As it is observed, after the rescheduling process three orders (ORD-2, ORD-3, ORD-4) present a due date delay, with an associate cost of 16489.57 Euro. Even one of them (ORD-4) is scheduled late with respect to the end of the planning horizon of the plant, with an associate cost of 272.36 Euro. Note also that the average percentage of occupation of the machines is 35.32 % with a total cost derived from machine idle time of 2444.39 Euro.

Order	Batch	Operation	Machine	Starting date	Starting time	Finishing date	Finishing time
ORD-1	1	OP-1	M1	2011-1-2	19:0	2011-1-3	11:40
		OP-2	M3	2011-1-7	3:20	2011-1-8	4:20
		OP-3	M5	2011-1-8	4:20	2011-1-11	15:40
	2	OP-4	M1	2011-1-2	9:0	2011-1-2	19:0
		OP-5	M4	2011-1-2	19:0	2011-1-3	20:0
		OP-6	M5	2011-1-3	20:0	2011-1-5	22:0
ORD-2	1	OP-7	M1	2011-1-3	12:25	2011-1-4	13:25
		OP-8	M3	2011-1-5	0:40	2011-1-7	2:40
		OP-9	M6	2011-1-7	2:40	2011-1-10	14:0
ORD-3	1	OP-10	M2	2011-1-2	9:0	2011-1-3	13:0
		OP-11	M3	2011-1-3	13:0	2011-1-5	0:0
		OP-12	M5	2011-1-11	16:5	2011-1-14	14:5
ORD-4	1	OP-13	M1	2011-1-4	14:0	2011-1-5	23:20
		OP-14	M3	2011-1-8	4:45	2011-1-11	7:45
		OP-15	M6	2011-1-11	7:45	2011-1-14	19:5
	2	OP-16	M1	2011-1-5	23:20	2011-1-6	12:40
		OP-17	M4	2011-1-8	0:0	2011-1-8	23:20
		OP-18	M6	2011-1-14	19:5	2011-1-16	4:25

Table 4. Schedule obtained after rescheduling due to machine failure

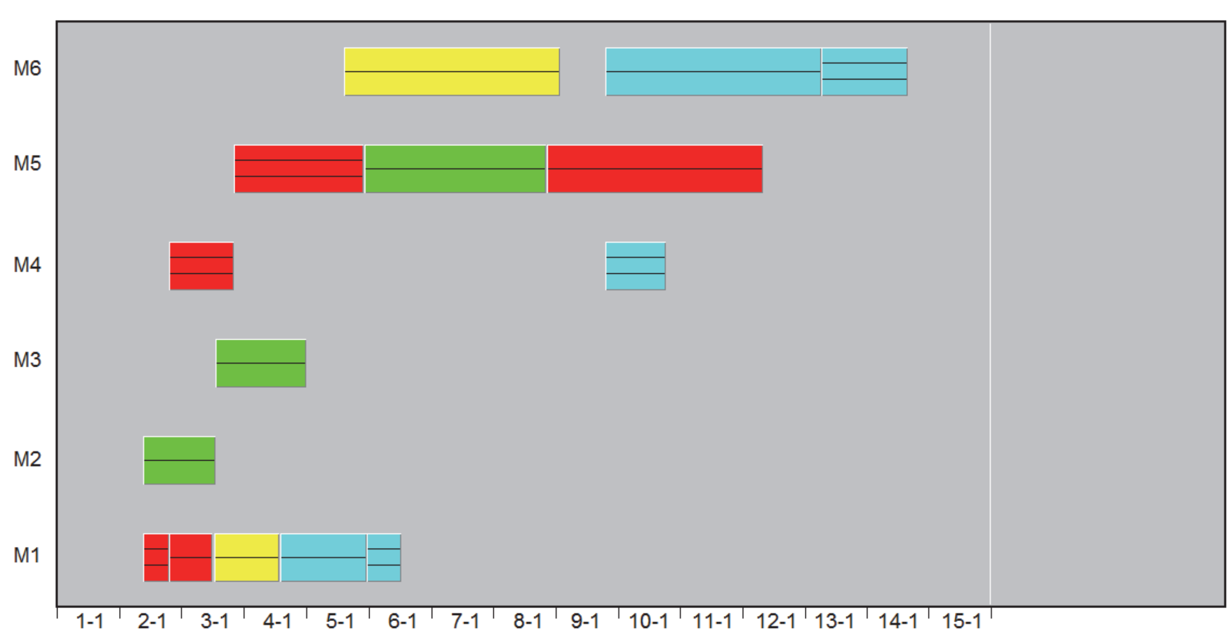

Fig. 6. Gantt chart of the schedule affected by a machine failure event before rescheduling

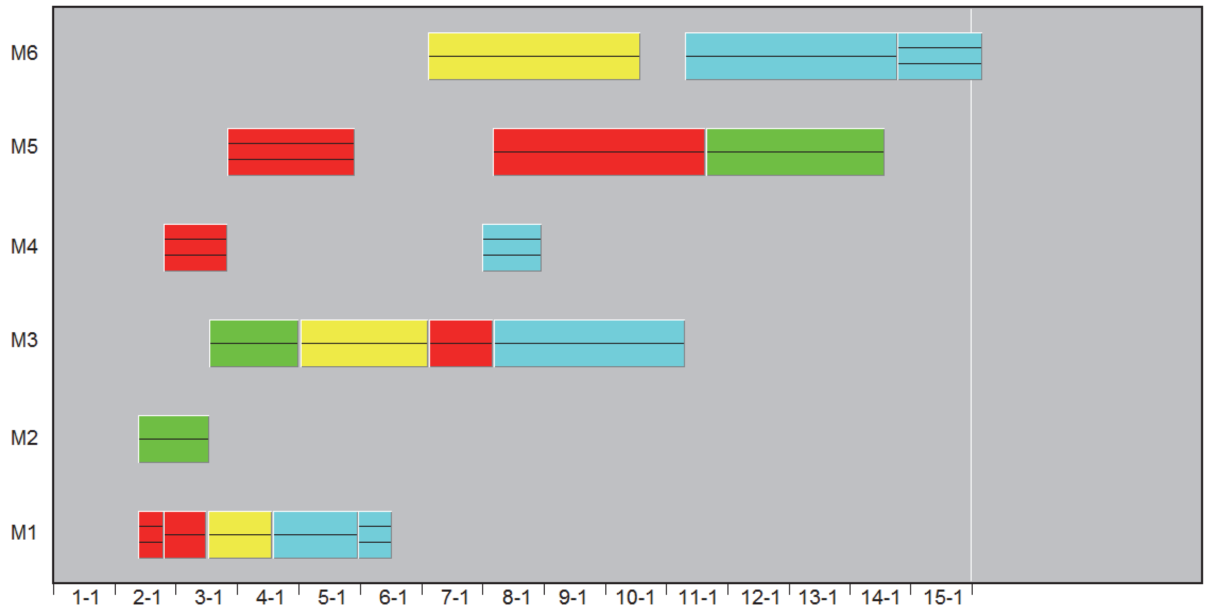

Fig. 7. Gantt chart of the schedule affected by a machine failure after rescheduling

RESCHEDULING DUE TO MACHINE FAILURE - GLOBAL PERFORMANCE IN TERMS OF COST	
Total cost (objective): 127506.32	**Production cost:** 108300.00

PERFORMANCE RELATED TO WORK ORDERS					
	throughput time	**due date delay**	**due date delay cost**	**horizon delay**	**horizon delay cost**
Order 1	13360	0	0	0	0
Order 2	10175	1680	5950.00	0	0
Order 3	17585	8885	8638.19	0	0
Order 4	16705	925	1901.38	265	272.36
Maximum	17585	8885	-	265	-
Average	14456.25	2872.5	-	66.25	-
Σ	-	-	16489.57	-	272.36

PERFORMANCE RELATED TO MACHINES			
	allocated operations	**usage percentage**	**idle time cost**
Machine 1	5	27.31	418.66
Machine 2	1	7.78	553.33
Machine 3	4	51.39	420.00
Machine 4	2	13.43	748.00
Machine 5	3	56.48	131.60
Machine 6	3	55.56	172.80
Average	3	35.32	-
Σ	-	-	2444.39

Table 5. Rescheduling performance due to machine failure

Order	Batch	Operation	Machine	Starting date	Starting time	Finishing date	Finishing time
ORD-1	1	OP-1	M1	2011-1-2	19:0	2011-1-3	11:40
		OP-2	M4	2011-1-4	9:0	2011-1-6	2:40
		OP-3	M5	2011-1-10	10:45	2011-1-13	22:5
	2	OP-4	M1	2011-1-2	9:0	2011-1-2	19:0
		OP-5	M4	2011-1-2	19:0	2011-1-3	20:0
		OP-6	M5	2011-1-3	20:0	2011-1-5	22:0
ORD-2	1	OP-7	M1	2011-1-3	12:25	2011-1-4	13:25
		OP-8	M4	2011-1-6	2:55	2011-1-7	3:55
		OP-9	M6	2011-1-7	3:55	2011-1-10	15:15
ORD-3	1	OP-10	M2	2011-1-2	9:0	2011-1-3	13:0
		OP-11	M3	2011-1-3	13:0	2011-1-5	0:0
		OP-12	M5	2011-1-13	22:30	2011-1-16	20:30
ORD-4	1	OP-13	M1	2011-1-5	10:20	2011-1-6	19:40
		OP-14	M4	2011-1-7	4:30	2011-1-9	14:50
		OP-15	M6	2011-1-10	15:25	2011-1-14	2:45
	2	OP-16	M1	2011-1-6	19:40	2011-1-7	9:0
		OP-17	M4	2011-1-9	14:50	2011-1-10	14:10
		OP-18	M6	2011-1-14	2:45	2011-1-15	12:5
ORD-5	1	OP-19	M1	2011-1-4	14:10	2011-1-5	10:10
		OP-20	M3	2011-1-5	10:10	2011-1-7	2:10
		OP-21	M5	2011-1-7	2:10	2011-1-10	10:10

Table 6. Schedule obtained after rescheduling due to a new urgent order

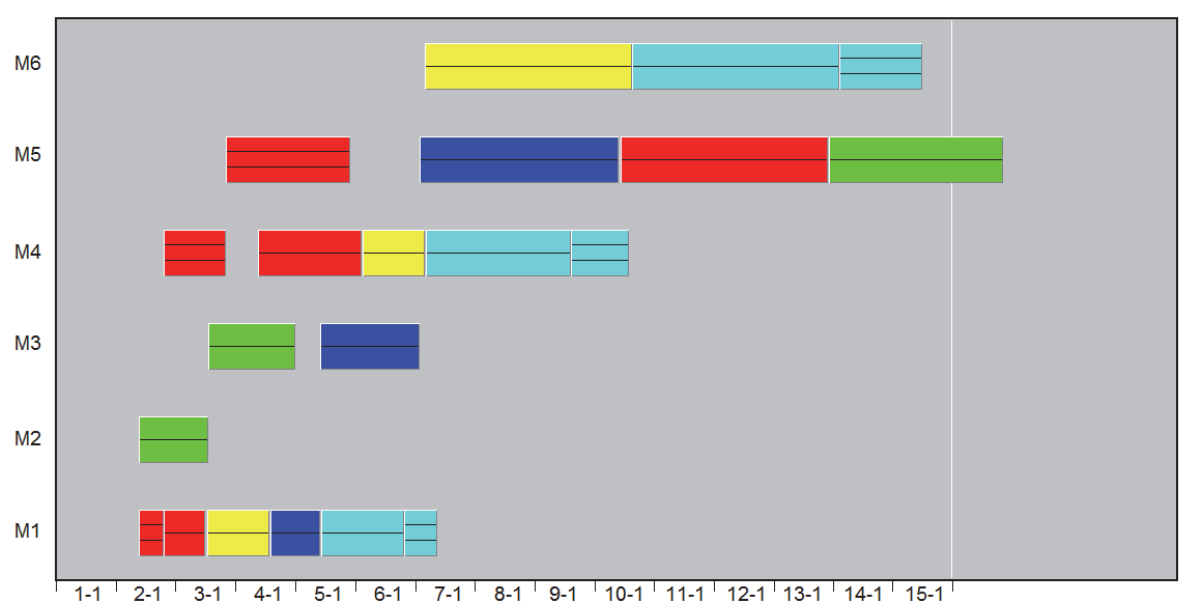

Fig. 8. Gantt chart of the schedule affected by a new urgent order after rescheduling

With regard to the rescheduling process due to a new urgent order, table 6 shows the set of assignments of machine and time intervals calculated by the production scheduler for every order/lot/operation of the system in answer to the exception. Likewise, in fig. 8 the Gantt

chart of the operations after the rescheduling is presented. In this case, the Gantt chart previous to the rescheduling is that of the static schedule (fig. 5).
As it is observed in fig. 8, the new urgent order (ORD-5) is represented by blocks of blue colour and only comprises one batch and three operations to be scheduled. In case the new work order has a high priority level, its operations are allocated as soon as possible so that they could finish before the due date, moving forward in time other operations if necessary.
Table 7 contains the performance measures for the program obtained after the exception of a new urgent order. As it is observed, after the rescheduling process three orders (ORD-1, e

RESCHEDULING DUE TO NEW URGENT ORDER - GLOBAL PERFORMANCE IN TERMS OF COST	
Total cost (objective): 142717.85	**Production cost:** 118300.00

PERFORMANCE RELATED TO WORK ORDERS					
	throughput time	**due date delay**	**due date delay cost**	**horizon delay**	**horizon delay cost**
Order 1	16625	1325	3238.88	0	0
Order 2	10250	1755	6459.37	0	0
Order 3	20850	12150	11812.50	1230	597.91
Order 4	14505	0	0	0	0
Order 5	8400	0	0	0	0
Maximum	16625	12150	-	1230	-
Average	14126	3046.00	-	246	-
Σ	-	-	21510.75	-	597.91

PERFORMANCE RELATED TO MACHINES			
	allocated operations	**usage percentage**	**idle time cost**
Machine 1	6	32.87	386.66
Machine 2	1	7.78	553.33
Machine 3	2	20.83	684.00
Machine 4	5	48.15	448.00
Machine 5	4	78.70	64.40
Machine 6	3	55.56	172.80
Average	3.50	40.65	-
Σ	-	-	2309.19

Table 7. Rescheduling performance due to a new urgent order

ORD-2, ORD-3) present a due date delay, with an associate cost of 21510.75 Euro. Even one of them (ORD-3) is scheduled late with regard to the end of the planning horizon of the plant, with an associate cost of 597.91 Euro. On the contrary, the new urgent order fulfils all the time constraints and does not generate any delay costs. Note also that in this case the average percentage of occupation of the machines is 40.65%, with a total cost derived from machine idle time of 2309.19 Euro.

7. Conclusions

In this chapter a proactive tool that manages unforeseen events in different plants of the same company is described, using a wide perspective that includes suppliers and customers. The study helps to reach a competitive advantage in the extended enterprise, since it analyzes the implications of the changes happened in a specific point of the supply chain for other nodes. This means, for example, that in case demand increases and there are not enough materials in the plant, the possibility of urgently requesting orders to suitable suppliers is explored, in order to generate a feasible production schedule. In addition, if a disruption affects the customers, these are warned early about possible service problems, and this way they will be able to take correct decisions that will benefit both their companies and their own customers.

This research proposes to incorporate collaborative capabilities to real-time production scheduling. This way, the objective of SCM is better met by a dynamic and fluent coordination of the different organizations that produce value to the customer. Therefore, this tool not only allows for information exchange with other nodes but it also contributes to collaborative production scheduling and synchronized production, thus leading to globally optimized solutions that reduce costs and increase customer satisfaction.

A description of the problem is provided identifying the key assumptions used in the model. Besides, the different exceptions supported by the system are categorized and explained. Finally, the software modules are identified, and a wide description of the Production Scheduler module of the plant is provided.

With respect to this Production Scheduler module, the study shows the possibility of successfully applying an advanced technique of optimization, the genetic and evolving algorithms, to the job-shop scheduling problem, working with a complex model of a multi-plant company and obtaining always feasible solutions that verify the constraints of the problem. The latter characteristic is achieved thanks to the incorporation of a specific heuristic of the problem in the generation process of the initial organisms and in the mutation of organisms in successive generations. This heuristic consists of supporting the operations to schedule in a sequential list that respects the precedence restrictions between processes, to assign them in the order marked by this sequential list, first the machines and then the dates. Thus, the search procedure of time intervals for the operations is done forward and without undoing previous assignments, which gives the joint algorithm an outstanding rapidity of execution.

The characteristics and complexity of the developed system can be extended in different directions, which can become condensed briefly in the following lines of development:

- Analyze the behaviour of the system on JIT scheduling environments, which are also supported in the developed software.

- Realize a rigorous analysis of the evolving algorithm of production scheduling from the point of view of the quality of the solutions, with plant instances of big size, and contrasting the different implemented techniques of survival selection, as well as other basic techniques of combinatorial optimization, such as taboo search and simulated annealing.
- The elements of the supply chain that can be most affected by decision variables subject to dynamic constraints are production and distribution. Due to that, it would be very interesting to develop an approach that aims to integrate these elements of the supply chain (manufacturing and distribution) into a single model of optimization that would simultaneously act on the decision variables of several objective functions.

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