A multi-agent approach for dynamic production and distribution scheduling

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Abstract: In an age when enterprises are increasingly dependent on their suppliers and customers, individual companies should broaden their scope in order to include other organisations participating in the same value chain. Consequently, different parties of the chain ought to exchange information to make sound decisions in order to cut down global costs or improve customer service. This paper proposes a multi-agent approach for dynamic production and distribution scheduling in a simple supply chain. The approach is based on the continuous supervision of the active schedules and routes, in order to detect possible exceptions and apply corrective actions in a real-time and coordinated manner with other parties. Finally, the paper focuses on the design phase of the distribution stage, where the problem is mathematically formulated as a dynamic vehicle routing problem with time windows and backhauls (DVRP-TWB), and three combinatorial optimisation meta-heuristics are proposed as solving techniques.

Keywords: multi-agent supply chain; integration of production and distribution; dynamic vehicle routing problem.

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1 Introduction

In the past, companies used to apply arm's length relationships with suppliers and buyers since most supply chains were short and mainly vertically integrated. But, supply chain management changed this scenario by considering that trust relationships can be more profitable for all the parties in the chain. Christopher (2011) defined supply chain management as: "*The management of upstream and downstream relationships with suppliers and customers in order to deliver superior customer value at less to the supply chain as a whole*". So, it is essential that firms broaden their scope to include other companies. The main reasons underpinning this idea are related to the fact that today companies depend more than ever on their suppliers and customers since they often focus on their core business and subcontract the rest. Nevertheless, many companies still do not collaborate with others for fear of revealing or sharing their private information, among other things. But today, competition no longer applies to individual companies but to supply chains. This means that firms should also consider the benefits that could arise from exchanging information with other companies of the same supply chain to harmonise the global performance. As a matter of fact, in global markets, where competition is fierce, it is more necessary than ever to promote the collaboration of the different echelons of a supply chain to cut down costs or improve the level of customer service so as to enhance its global competitive position.

Many manufacturing companies must cope with changes arisen during the production stage that often make their production schedules unfeasible. This problem becomes even more complex when considered in the supply chain context since production schedules at different levels are not independent. In a similar way, distribution routes are often subject to sudden changes that should be handled efficiently. Therefore, both the production scheduling and the distribution problems must be considered dynamic.

This paper deals with two main problems in the supply chain context, i.e., the dynamic production scheduling problem and the dynamic distribution problem.

With reference to production scheduling, each company usually keeps its own independent production plans. But when considered from a wider perspective, this independence is at stake, since supply chains are subject to a dynamic phenomenon that has been dubbed ‘the bullwhip effect’. What happens is that small unplanned demand variations translate into wider swings in demand experienced by companies located further back in the supply chain (Hugos, 2006). Furthermore, faulty items or late deliveries caused by suppliers may introduce significant delays or disruptions in the active production schedules. If companies do not share demand information or react to upcoming events across the supply chain, their production schedules will often become unfeasible, thus leading to poor responsiveness.

Equally, as far as the transportation of goods to customers, the so-called vehicle routing problem (VRP) has extensively been analysed. But, it is often the case that unforeseen events happen on the way to the customer that require adjustments to be made in the distribution plans. Therefore, the dynamic vehicle routing problem (DVRP) is a more realistic approach.

This paper describes a multi-agent approach for dynamic production and distribution scheduling in a supply chain consisting of three levels, manufacturer, suppliers and customers. This approach is based on the continuous supervision of the active schedules and routes, to detect possible exceptions and apply corrective actions in a real-time and coordinated manner. Finally, the paper focuses on the design phase of the distribution stage, where the problem is mathematically formulated as a DVRP-TWB, and three combinatorial optimisation meta-heuristics are proposed as solving techniques. This paper clarifies and extends the analysis shown in the aforementioned paper (Álvarez et al., 2013) by explicitly describing the multi-agent approach selected, some exceptions handled by the system and a detailed formulation of the distribution model. The upcoming sections include: a literature review of the concerned research areas (integration of scheduling and distribution, routing problems and solving techniques), the general framework of the system, the multi-agent approach, a detailed description of some exceptions and how they are handled, the distribution problem and some conclusions.

2 Literature review

Both dynamic production and distribution problems are gradually attracting more interest, owing to their closeness to real-life situations and potential benefits for companies. The integration of production–distribution problems has scarcely been studied in the literature (Park and Hong, 2009; Safaei et al., 2010; Bilgen and Günther, 2010). In general terms, these models handle some simple assumptions and work only statically, which means that they are neither realistic nor useful for companies. Xu et al. (2005) concluded that the most effective approach is the coordination and integration of intercompany activities by using information technology and, in particular, web-based supply chain management, taking into account its affordability for all kinds of companies. Furthermore, the use of a multi-agent architecture seems to be one of the most promising approaches to implement distributed environments such as supply chain networks (Hao et al., 2006; Kumari et al., 2013). In particular, some authors (Bruccoleri et al., 2005) propose the use of a multi-agent approach for handling exceptions in production environments.

The VRP is one of the most widely studied problems in the combinatorial optimisation field (Christofides, 1976). Because of its complexity, and, above all, its applicability to real life, the VRP is used in many works annually (Marinakis and Marinaki, 2010; Laporte et al., 2013; Osaba et al., 2013a; Lin et al., 2014). Having a fleet of vehicles, a set of clients (each one with its own demand) and a fixed depot, the objective of the VRP is to find a number of routes with a minimum cost such that each route starts and ends at the depot, each customer is visited exactly by one route, and the total demand of the customers visited in a route does not exceed the capacity of the vehicle that performs the route.

To better represent real problems, many variants of the VRP have been proposed over the years. Some of them are the so-called vehicle routing problem with backhauls (VRPB) (Goetschalckx and Jacobs-Blecha, 1989), the vehicle routing problem with time windows (VRPTW) (Taillard et al., 1997; Bräysy and Gendreau, 2005) and the DVRP (Psaraftis, 1995).

Backhauls is a feature that allows customers to request either delivery or pick-up of materials (Toth and Vigo, 2000). In this problem, the vehicle capacity becomes an extremely important factor. A well-known real application for this type of problem is the grocery industry. The Interstate Commerce Commission estimated that, with the introduction of backhauling, in the USA the savings in the grocery industry had reached 160 million dollars (Golden et al., 1985).

The VRP with time windows has extensively been studied throughout history (Bräysy and Gendreau, 2002; Cordeau et al., 1999). This feature allows each customer to have a time window associated [ei, lj]. This time range has a lower limit and an upper limit that trucks must respect. This means that vehicles have to meet customer demand within that time window. In the vast majority of studies in the literature, these windows are understood as hard constraints. Therefore, in these cases, a route will not be feasible if a vehicle arrives to any customer after the upper limit. By contrast, a vehicle can arrive at a client before the lower limit. In this case, the client cannot be served before this limit, i.e., the vehicle will have to wait until that time. Another alternative is to use flexible time windows, called soft time windows. In this case, time constraints can be skipped, carrying a penalty in the objective function. The penalty function could change according to the study, the higher the penalty, the less tolerance to accept non-fulfilments, and vice versa. One reason why it is so interesting is its dual nature, since it can be considered as a two-phase problem. The first phase is concerned with vehicle routing, whereas the second one, however, is concerned with customer scheduling. In addition, this characteristic is very easy to adapt to real world, because in the great majority of distribution chains, customers have hard temporal constraints that have to be fulfilled. For example, in the distribution of the press or of perishable foods, these windows are really necessary (Hsu et al., 2007).

Finally, dynamism in VRPs is a relatively new field, which many researchers have been studying in recent years (Pillac et al., 2013; Beaundry et al., 2010). Dynamism can force to update previously planned routes. This fact can be caused either by possible disruptions or by the arrival of some information that was not available in the beginning.

To solve the VRP problem and its variants, the most widely used meta-heuristics are genetic algorithms (GAs) (Holland, 1975) and tabu search (TS) (Basu and Ghosh, 2008). Genetic algorithms are mainly aimed at solving combinatorial optimisation problems. GAs are based on the law of the evolution of species, proposed by Darwin, and on the genetic process of living organisms. In real world, populations evolve according to natural selection and survival of the best adapted specimens. GAs try to emulate this evolutionary process. The basic principles of this technique were proposed by Holland, even though its practical use for solving complex problems was shown by De Jong (1975) and Goldberg (1989). The success of GAs is given by their robustness and their capacity to adapt to a wide range of fields, for example, transport (Moon et al., 2012), software engineering (Martínez-Torres, 2012; Li et al., 2012) or industry (Chen et al., 2012; Osaba et al., 2013b).

On the other hand, TS was proposed by Glover (1986) and quickly became one of the best and most widespread local search methods for combinatorial optimisation. TS is a trajectorial technique, which works with only one solution and is iteratively modified during execution time. In this technique, successive ‘neighbours’ of the current solution are examined, and the best one is selected. To prevent cycling and avoid local optima, solutions that were recently examined are forbidden and inserted in a constantly updated tabu list. Glover (1989) and Glover and Laguna (1997) provided a very good insight into TS while other authors focus on the application of this meta-heuristic, which covers a wide range of fields (Bozejko et al., 2013; Paquette et al., 2013; Talbi and Belarbi, 2013).

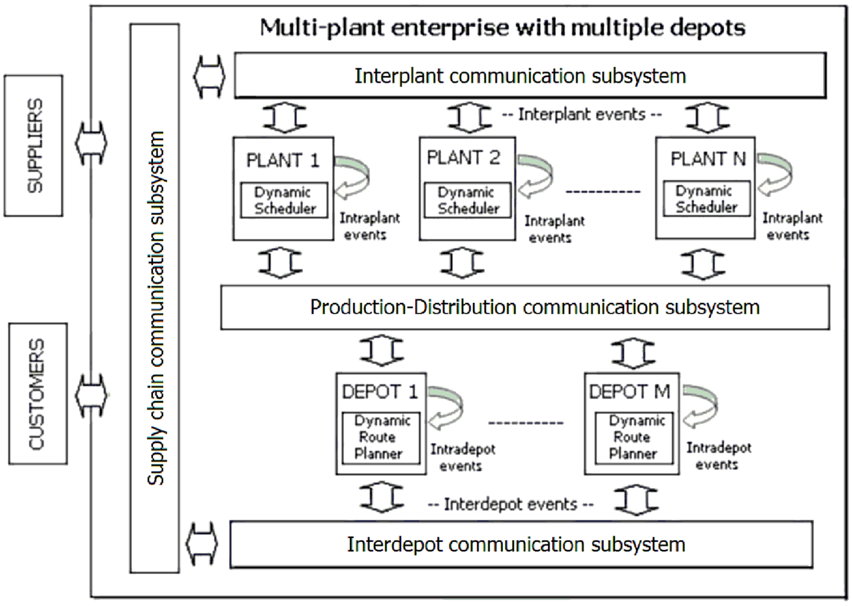
3 General framework of the system

The company that has been selected for this project has multiple plants that operate autonomously and independently, but are also able to share information and work together in case unexpected events occur. The manufacturing plants belong to the job-shop manufacturing type. In addition, the enterprise has multiple independent and autonomous local depots, which also share information with others and can work together if it is necessary. Finally, we assume that production schedules are generated off-line at the different plants and routes are also available for the different vehicles before the distribution process starts.

The communication framework comprises the following four subsystems (see Figure 1):

- The intra-plant communication subsystem, in which unexpected events that may cause partial or complete production schedule reprogramming are handled. In the same manner, at the intra-depot communication subsystem unexpected events that may cause partial or complete distribution schedule re-planning are managed.
- The inter-plant communication subsystem, where unexpected events occurred at a plant that may affect other plants are handled. In the same manner, at the multi-agent inter-depot communication subsystem unexpected events happened at a depot that can affect other depots are managed.
- The production–distribution communication subsystem, in which unexpected events occurred in plants that may affect depots, or unexpected events arisen in depots that may affect plants are handled.
- The supply chain communication subsystem, where unexpected events arisen at a plant or warehouse that may affect suppliers or customers are handled.

Figure 1 General communication framework of a multi-plant enterprise with multiple local depots (see online version for colours)



4 Multi-agent approach

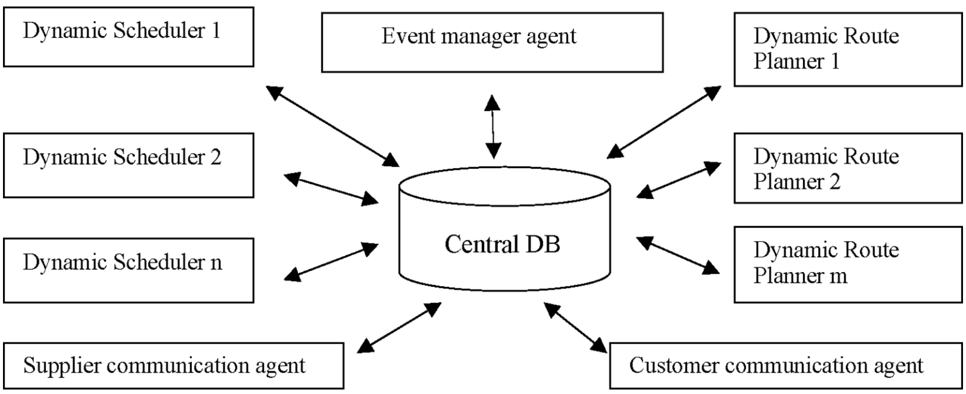
An agent is a software element that connects with others to solve a problem that cannot be addressed in an autonomous way. A supply chain can be represented as a group of agents that share information to solve such problems. In this research, different types of agents have been identified (see Figure 2).

- The dynamic schedulers are in charge of handling exceptions that arise at their respective plants and adjust the active schedules for those plants. The job-shop manufacturing context allows for flexibility in the possible routes of the products.

- The dynamic route planners decide the changes to be made to the active routes for each vehicle when unforeseen events occur on the way to the customers.
- The supplier communication agent allows vendors to be contacted when disturbances take place regarding the quality or delivery time of their orders.
- The customer communication agent enables customers to participate in the decision-making process related to changes in either the production schedules or the routes.
- The central database agent stores all the information that is shared by different agents of this architecture so as to allow coordination among them.
- The event-manager agent is in charge of continuously monitoring the information that is written in the central database to coordinate the events that affect other plants, warehouses, suppliers or customers. In addition to that, it updates information in this database that can be read by other agents to trigger the necessary corrective strategies.

The approach that has been selected for the aforementioned agents is based on the continuous supervision of the active schedules and routes, to detect possible exceptions and apply corrective actions in a real-time manner, i.e., a reactive strategy is used before sudden changes. To meet that goal, a decentralised architecture has been applied, where the independence of the different levels is respected, since companies would not give up their own decisions to other organisations. Therefore, this architecture comprises several agents that perform tasks in an autonomous way but whose behaviour can be influenced by the event-manager agent in response to the upcoming events that happen in the supply chain. The exchange of information among agents is performed through the central database.

Figure 2 Multi-agent architecture



5 Exceptions

Exceptions are related to those situations where things happen in a different way as they were expected. Exceptions are often unpredictable and occur during the production or distribution process, leading to delays or inconsistencies in the schedules and routes previously generated. One of the main contributions of the proposed framework is that it provides exception handling in real time, giving an almost immediate response to unexpected events. Exceptions have been divided into two groups, namely internal and external. Internal exceptions are company-related and may have their origin in production or distribution. Otherwise, external exceptions are caused by disruptions related to either suppliers or customers.

Table 1 Types of exceptions

Internal exceptions		*External exceptions*	
Production-related	*Distribution-related*	*Supplier-related*	*Customer-related*
Machine breakdown	Damaged vehicle	Returned material	Increase of order quantity
Suspended order	Missing driver	Partial delivery	New rush order
Missing operator	Unavailable auxiliary transport element	Delayed delivery	Decrease of order quantity
Unavailable auxiliary resource	Unfulfillment of distribution period	Faulty delivery	Changed due date
Operation moved to a different plant	Order not delivered	Cancelled delivery	

5.1 Exception handling

In the context of the dynamic production scheduling and distribution problems, the most common exceptions have been considered. At this point, a brief explanation about how an unexpected event is handled by the system is provided.

5.1.1 Damaged vehicle

This exception takes place when a vehicle is not able to distribute any goods due to a breakdown. It may happen when the vehicle has not yet begun its route or during the course of its route. It can affect any vehicle of any depot. Figure 3 shows the UML diagram of this event.

To process the exception, two possibilities must be considered: the first one appears when the exception happens before the vehicle starts its route, and the second one takes place when the exception arises while the vehicle is already on the way.

- *Vehicle damaged before starting route*. Here, two different cases have been considered:
    - *Replacement vehicles available*. This case happens when there are some vehicles available, either in the current depot, or in another nearby depot of the company, to transport the pending orders of the damaged vehicle. For those vehicles, it is necessary to verify that they have enough capacity to distribute all the transport pending orders of the damaged vehicle. In this case, the distribution will proceed else a subset of priority transport pending orders will be selected for distribution, according to the limited capacity of the available vehicles.
      In case the distribution of all the involved transport pending orders can be taken on by just one vehicle, the original route of the damaged vehicle can be applied, whereas if the distribution is partial or more than one replacement vehicle is

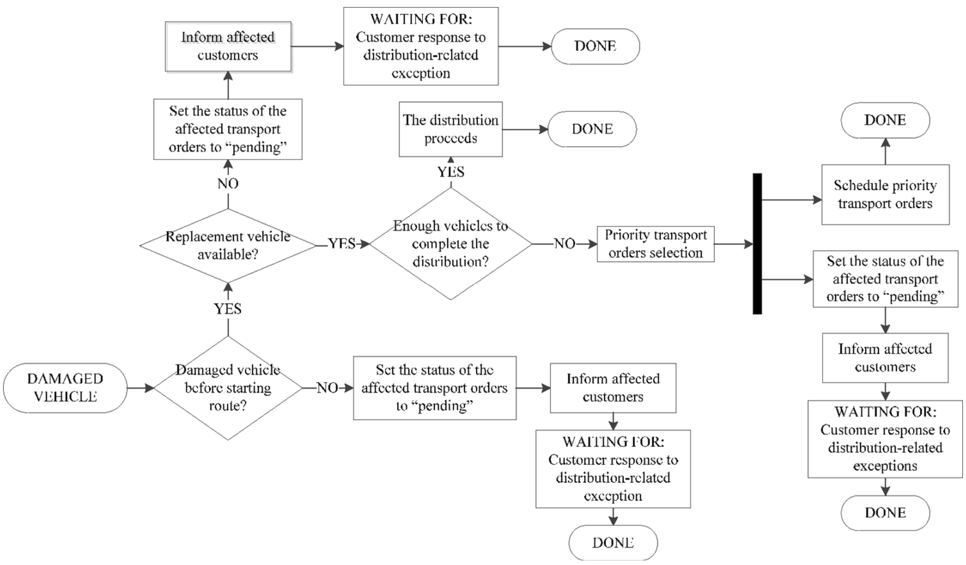
necessary, new distribution routes must be designed for the replacement vehicles. The status of the transport orders that cannot be distributed owing to lack of capacity will be set to pending, and every affected customer will be warned. At this point, the process remains waiting until the customer gives an answer to this exception (*Customer response to distribution-related exception*). The possible options that are offered to the customer are the following:

- delivery at a later distribution period
- delivery by the customer himself or herself
- urgent delivery by subcontracting an external vehicle, with additional charges.

- *Replacement vehicles are not available*. The status of the transport orders of the broken-down vehicle will become pending, and every affected customer will be warned. At this point, the process remains waiting until the customer gives an answer to this exception (*Customer response to distribution-related exception*). The same three possible options mentioned in the previous case are offered to the customer.

- *Vehicle damaged on the way*. The transport orders that cannot be distributed will be left pending, and every affected customer will be warned. At this point, the process remains waiting until the customer gives an answer to this exception (*Customer response to distribution-related exception*). The same three possible options mentioned in the previous cases are offered to the customer. This option is only possible for returns, since, as the vehicle broke down on the way, it is necessary to wait for the vehicle to arrive to the depot to recover the deliveries that have not yet been distributed.

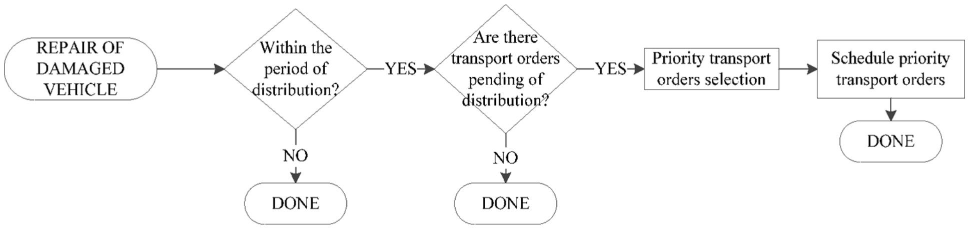
Figure 3 UML diagram of a damaged vehicle exception



5.1.2 Repair of damaged vehicle

This exception takes place when the repair process of a damaged vehicle is finished. It is processed as follows (see Figure 4). If this event happens within the period of distribution, i.e., if there is enough time before the end of the distribution period to deliver some orders, and there are some transport pending orders in the depot, the priority transport orders will be selected, taking into account constraints related to the truck capacity and the available time, and the corresponding distribution route will be planned.

Figure 4 UML diagram of the repair of a damaged vehicle exception



5.1.3 Customer response to distribution-related exception

This is a communication exception that arises when the customer selects one of the options offered by the company after an internal distribution-related exception (*damaged vehicle*).

In accordance with the option selected by the customer, the following cases come up:

- If the option is “delivery at a later distribution period”, the transport order will be planned in the following distribution period.
- If the option is “delivery by the customer himself or herself”, the response is registered without any additional processing.
- If the option is “urgent delivery by subcontracting an external vehicle, with additional charges”, the transport order will be processed by a *subcontracted transport order* internal exception.

5.1.4 Subcontracted transport order

This exception turns up when the company decides to subcontract the delivery/pick-up of a customer order by means of an external vehicle upon customer’s request. This event happens when a customer asks for the urgent delivery/pick-up of an order owing to any distribution-related exceptions, as the company cannot deliver/pick up it directly due to time or capacity limitations of the vehicle fleet of the depot.

The processing of this exception implies that the order is registered as subcontracted, without any additional consideration.

5.1.5 End of subcontracted transport order

This is the complementary exception to that of *subcontracted transport order*. It happens when the subcontracted transport order really finishes. The processing of this exception implies that the order is registered as finished, without any additional consideration.

5.2 Supplier-related exceptions: Delayed delivery and complementary events

5.2.1 Delayed delivery of material

It is a communication exception from supplier to company that arises when the supplier cannot provide the requested material on time due to any internal problem. It can affect any purchase order of material.

To process the event, the following steps must be followed:

a First, it is necessary to check whether the estimated delay of the pending material causes considerable delays in the work orders that are going to use this material. In case no work order is delayed, the original plan is kept, and the exception is finished.

b Second, it is compulsory to make sure that there is available material (not compromised for scheduled orders) in the factory warehouse or in any other close depot of the company in enough quantity to cover the material that is not going to be delivered in time by the supplier. In this case, simply the quantity in stock is reduced, the original plan is kept, and the exception is finished.

c Otherwise, it is imperative to examine other vendors who could deliver the pending material on time. For that reason, the list of alternative suppliers sequenced by priority must be followed to look for a suitable one. At this point, the process remains waiting until the customer gives an answer to this exception (*Supplier response to urgent request of material*).

d In case the previous alternatives fail, i.e., if the delayed delivery involves some work orders, no material is available in stock and there are no alternative suppliers, the status of the involved operations will become pending up until the material arrives (*Arrival of pending material due to delayed delivery* exception). In addition, if the estimated delay entails that some customer orders will not be delivered on time, every affected customer will be warned about it. At this point, the process remains waiting until the customer gives an answer to this exception (*Customer response to supplier-related exception*). The possible options for the customer are:

  - to deliver the order after the due date (backlog)
  - to cancel the order.

A flow chart of this event is shown in Figure 5.

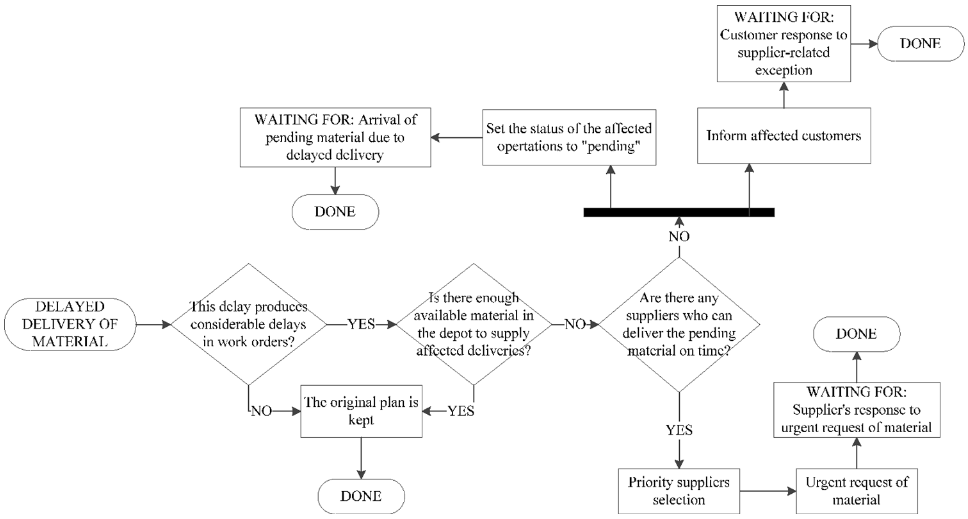
5.2.2 Arrival of pending material due to delayed delivery

This exception takes place when the original supplier delivers in the agreed terms the pending material of a previous delivery that suffered a delay.

To process the event, the following possibilities may come up:

- If the delayed delivery did not affect any work orders, the exception is finished.
- If the pending material was replaced with material available in stock, the stock is replenished, and the exception is accomplished.
- If there are some pending operations due to the delayed delivery, they will be rescheduled.

Figure 5 UML diagram of a delayed delivery of material exception



5.2.3 Supplier response to urgent request of material

This is a communication exception that takes place when the supplier accepts a request to supply material generated by some another event (*Delayed delivery of material*).

The processing of this exception is as follows. If the supplier response is positive, the original production schedule is kept. In addition to that, if the material had a previous purchase order associated to another supplier, the order is cancelled, and the exception is finished. In the opposite case, the list of alternative suppliers of the material must be checked again, existing two possibilities:

- If there are some more alternative suppliers, the next supplier in the list will be asked. At this point, the process remains waiting until the customer gives an answer to this exception (*Customer response to supplier-related exception*).
- If there are no more alternative suppliers, the status of the operations of the involved work orders will be set to pending. If the requested material had a previous purchase order associated, no changes will be made to this order and the material will be provided by the original supplier with the compromised delay. The operations of the involved orders will be rescheduled when the above-mentioned material is received (*Arrival of pending material due to delayed delivery* exception). Otherwise, the estimated delay will correspond to the normal delivery time of the usual supplier, and the operations of the involved orders will be rescheduled in the following period of static scheduling. In any case, if the estimated delay of the supply implies that some customer orders are delayed, every affected customer will be warned. At this point, the process remains waiting until the customer gives an answer to this exception (*Customer response to supplier-related exception*). The possible options for the customer are:
  - to delay the delivery date of the order
  - to cancel the order.

5.2.4 Customer response to supplier-related exception

It is a communication exception that arises when the customer selects one of the options offered by the company after an external supplier-related exception that delays the manufacturing process of the order (*Delayed delivery of material*).

According to the option selected by the customer as response, two cases come up:

- If the option is "to deliver the order after the due date (backlog)", the operations of the work order associated with the customer order remain pending (they are not rescheduled until the necessary material is received), and the exception is finished.
- If the option is "to cancel the order", the operations of the work order associated with the customer order will be eliminated from the production schedule, and the work order will be cancelled.

This model is being implemented in Visual C++.

6 Distribution

As was previously explained, in this project there are two stages, the first one is referred to production, and the second one deals with distribution. The former has already been explained in previous publications by the authors of this paper (Álvarez and Díaz, 2011). The latter is in charge of delivering products to customers and is the one that has been selected to be explained more in-depth in this paper.

6.1 The distribution problem

In this problem, a distribution network composed of multiple warehouses or depots has been defined. These depots serve previously assigned clients, based on several factors such as proximity. This means that a customer will only be served by vehicles belonging to a single depot.

6.2 Specification of the problem

The problem to be tackled is the so-called Dynamic Vehicle Routing Problem with Soft Time Windows and Backhauls (D-VRP-STWB), which is a hybrid of three different problems of routing vehicles. Although these issues have been studied separately many times, they have never been addressed at the same time. These features of the problem, i.e., backhauls, time windows and dynamism, have been described in the literature review section.

6.2.1 Soft time windows

In this problem, soft time windows are used, considering the lower limit as a restriction, the upper limit as an optimisation objective, and applying a penalty if this objective is not fulfilled. In addition, in this particular case, customers requesting delivery of materials have tougher time windows than customers who want a pick-up, because, logically, they need to receive the goods more urgently.

6.2.2 Backhauls

Customers are allowed to order either pick-up or delivery, but not both things simultaneously. In addition, deliveries are done first, and then pick-up. This is so because, otherwise, a rearrangement of materials within the truck could be necessary. This may happen, for example, if we put materials at the front of the truck when there are some other goods that still have to be delivered at the back. In our problem, reverse logistics could be necessary when a customer is not satisfied with the order received, either because it is defective or because a delivery error has occurred.

6.2.3 Dynamism

In this case, dynamism is due to unexpected events, several of which have already been explained in the previous section. Once such an event occurs, distribution must decide whether to reschedule some of the routes, or accept some delays in customer deliveries. To take this decision, the potential cost of each option is calculated, so that the least expensive option is chosen. To implement this fact with the aim to be realistic, we must take into account factors such as overtime or backlogs, all of this added, of course, to factors of distance travelled and number of vehicles used.

6.3 Mathematical formulation of the problem

According to the previous concepts, we have defined a problem where customers can request either delivery or pick-up of materials, within certain time windows. Apart from this, it covers the dynamism coming from untoward events, which may affect the feasibility of the distribution plan.

The problem is mathematically defined in the following way:

- A depot of the company deals with the distribution of goods to p customers.
  Each customer i has a geographical location and a distribution time window, denoted $[a_i, b_i]$.
- To distribute the goods, the depot has a fleet of q heterogeneous vehicles.
  Each vehicle i has a few particular characteristics of maximum load w_i (weight in kg), fixed cost c_i, average consumption of fuel f_i (litres per km) and average cost of distribution in a route rc_i (datum estimated or calculated from log information).
- The goods are distributed in groups of $m + n$ transport orders, classified in two different types: m delivery orders and n pick-up orders. Each transport order i is associated with one customer and has a weight u_i (in kg) and a net value v_i.
  In addition, when assigning an order to a vehicle, the distribution time t_i of the order is calculated, according to its position in the distribution route of the vehicle.
- A route of a vehicle i is represented by a list of $r + s$ variables $(x_{i1}, \ldots, x_{ir}, x_{i,r+1}, \ldots, x_{i,r+s})$, where x_{ij}, for $j = 1, \ldots, r$, represents the delivery order that occupies the position j in the distribution sequence of deliveries, and $x_{i,r+j}$, for $j = 1, \ldots, s$, represents the pick-up order that occupies the position j in the distribution sequence of pick-ups.

The problem constraints are related to the capacity of the vehicles (the total weight of the transported orders is limited by the maximum load of the vehicle), to the distribution sequence of the transport orders (e.g., delivery orders must be dispatched before pick-up orders), and to the customer time windows (the distribution time of a transport order cannot be previous to the beginning of the customer time window).

The objective function is to minimise the total incurred cost. This cost has several components that are evaluated as follows:

$\sum_{i=1}^{q} CD_i = \sum_{i=1}^{q}\left(c_i + cf \cdot f_i \cdot \sum_{j=1}^{r_i+s_i-1} d(x_{ij}, x_{i,j+1})\right)$	*Cost of distribution*. CD_i is the distribution cost of the transport orders of vehicle i (total cost of the fuel consumed in the route), which equals the product of the cost of fuel cf, the average consumption of fuel of the vehicle f_i, and the total distance of the route $\sum_{j=1}^{r_i+s_i-1} d(x_{ij}, x_{i,j+1})$, where $d(x_{ij}, x_{i,j+1})$ is the distance between costumers associated to transport orders j and $j + 1$
$\sum_{i=1}^{q} \mathrm{CUV}_i = \sum_{i=1}^{q}\left(\mu_1 \cdot rc_i \cdot \frac{w_i - \sum_{j=1}^{r_i} u_j}{w_i}\right)$	*Penalty cost for underuse of vehicles*. CUV_i is the penalty cost for underuse of vehicle i, which equals the product of the average cost of distribution of the vehicle rc_i the quotient between the capacity not used of the vehicle in the deliveries $w_i - \sum_{j=1}^{r_i} u_j$ and its maximum load w_i, and a percentage of penalty μ_1
$\sum_{i=1}^{m+n} CD_i = \begin{cases} \sum_{i=1}^{m+n}\left(\mu_2 \cdot v_i \cdot H(t_i - b_i)\right) & \text{if } t_i > b_i \\ 0 & \text{if } t_i \leq b_i \end{cases}$	*Penalty cost for distribution delay*. CDD_i is the penalty cost for distribution delay of transport order i with regard to the customer time window, which equals the product of the net value of order v_i, a percentage of penalty for hour of delay μ_2, and the number of hours of delay $H(t_i - b_i)$, where t_i is the distribution time of transport order i, and b_i is the end of the time window of the customer associated with order i
$\sum_{i=1}^{q} \mathrm{CCR}_i = \sum_{i=1}^{q}\left(\frac{k \cdot \mu}{m+n} CD_i \right)$	*Penalty cost for changes in route replanning*. $\mathrm{CCR_i}$ is the penalty cost for changes in route replanning of vehicle i, which equals the product of the distribution cost CD_i, the percentage of transport orders that have changed after route replanning $\frac{k}{m+n}$, and a factor of influence of the change in the global goal μ

The objective function that has been proposed for this D-VRP-STWB is the sum of all the aforementioned costs and is given by:

$$\sum_{i=1}^{q} CD_i + \sum_{i=1}^{q} \mathrm{CUV}_i + \sum_{i=1}^{m+n} \mathrm{CDD}_i + \left[\sum_{i=1}^{q} \mathrm{CCR}_i\right].$$

This objective function is subject to the following constraints:

- Constraint of capacity of the vehicles in the deliveries. The total weight of the delivery orders assigned to a vehicle is limited by the maximum load of the vehicle:

$$\forall i \in \{1,...,q\} : \sum_{j=1}^{r_i} u_j \leq w_i.$$

- Constraint of capacity of the vehicles in the pick-ups. The total weight of the pick-up orders assigned to a vehicle is limited by the maximum load of the vehicle:

$$\forall i \in \{1,...,q\} : \sum_{j=1}^{s_i} u_j \leq w_i.$$

- Constraint of complete distribution of deliveries. All the delivery orders must be assigned to the vehicles of the fleet:

$$\sum_{i=1}^{q} r_i = m.$$

- Constraint of complete distribution of pick-ups. All the pick-up orders must be assigned to the vehicles of the fleet:

$$\sum_{i=1}^{q} s_i = n.$$

- Constraint of no delivery order repetition. A delivery order cannot be assigned to more than one vehicle:

$$\forall i, j \in \{1,...,q\}, \forall k \in \{1,...,r_i\}, \forall h \in \{1,...,r_j\} : i \neq j \Rightarrow x_{ik} \neq x_{jh}.$$

- Constraint of no pick-up order repetition. A pick-up order cannot be assigned to more than one vehicle:

$$\forall i, j \in \{1,...,q\}, \forall k \in \{1,...,s_i\}, \forall h \in \{1,...,s_j\} : i \neq j \Rightarrow x_{i,r_i+k} \neq x_{j,r_j+h}.$$

- Constraint of customer time window. A transport order cannot be distributed before the beginning of the customer time window:

$$\forall i \in \{1,...,m+n\} : t_i \geq a_i.$$

Note: The constraint of precedence of the delivery orders with regard to pick-up orders in the route of every vehicle is guaranteed by the structure of the routes.

For solving the aforementioned problem, the use of three different meta-heuristics has been proposed. The first two techniques are the genetic algorithm (GA) and the tabu search (TS). The third one is a new population-based meta-heuristic for solving combinatorial optimisation problems. This technique works with a population of individuals, which are feasible solutions of the problem, which are divided into different groups forming subpopulations. As in genetic algorithms, each individual has associated a value called 'fitness', which is assigned by an objective function. Subpopulations improve the fitness of their individuals independently and cooperatively. Apart from this, subpopulations compete against each other, which is crucial to decide the migration of individuals between populations and to decide the successor function of each of them. The main difference with the typical evolutionary algorithms is that our technique prioritises individual improvement of each individual, making crossovers between them only when it is necessary and when it is known that it is going to benefit the results.

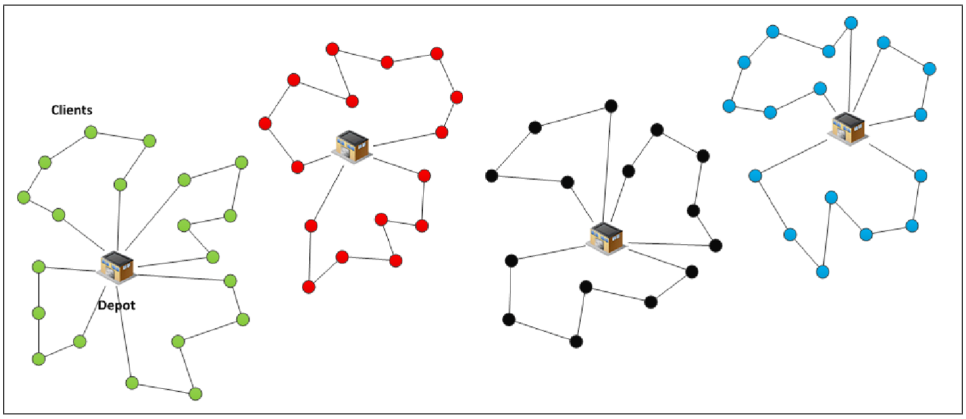
6.4 Case study

The distribution case that has been defined includes four different depots, or warehouses, which are randomly scattered across a particular geographic area. These warehouses have previously assigned clients, based on several factors, one of which is the proximity. This means that a customer can only be visited by vehicles belonging to a single depot. The number of customers varies between 15 and 20.

Each customer can decide his or her soft time windows, taking into account that the lower limit is going to be compulsorily met, but the upper limit is going to be flexible. In addition, an order can be delivered to each customer or picked-up from him/her. Each warehouse has its own fleet of vehicles, to distribute goods to customers. The first one has four vehicles, the second one has two, and the last two have three vehicles. Additionally, each depot has its own driver equipment, and there is one driver for each vehicle.

A simplified representation of the case study is displayed in Figure 6.

Figure 6 A simplified representation of the distribution problem (see online version for colours)



7 Conclusions

This paper describes a multi-agent approach for dynamic production and distribution scheduling. This approach entails continuous monitoring of the active schedules and programmed routes, to detect possible exceptions and apply corrective actions in a real-time and coordinated manner. Moreover, it combines existing scheduling systems of decentralised companies with a central database. The possible exceptions have also been categorised into four groups depending on whether they come from production or distribution, customers or suppliers. Then, two types of exceptions have been described using UML diagrams that include several possible courses of action. Finally, regarding distribution, the problem has been mathematically formulated as a DVRP-TWB, and three combinatorial optimisation meta-heuristics have been proposed as solving techniques.

The main advantages of the proposed approach can be summarised as follows:

- accurate information exchange at the different levels
- better responsiveness
- use of a decentralised approach that respects the independence of the different levels combined with a central database that contains the relevant information to coordinate the different levels.

Next steps include further tests of the three meta-heuristics proposed and software development of a prototype of the system.

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