Agent-based Modeling to Support Operations Management in a Multi-plant Enterprise

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ABSTRACT

A global industrial enterprise is a complex network of different distributed production plants producing, handling, and distributing specific products. Agent-based modeling is a proven approach for modeling complex networks of intelligent and distributed actors. In this paper, we will demonstrate how an agent-based model can be used to evaluate the dynamic behavior of a global enterprise, considering both the system-level performance as well as the components' behavior. This quantitative model can be very useful for predicting the effects of local and operational activities on plant performance and improving the tactical and strategic decision-making at the enterprise level.

KEYWORDS:

Agent based models, multi-plant enterprise, operation management, abnormal situation management

1. **Introduction.** To remain competitive in today's ever-changing markets, companies have to examine alternative solutions for their logistics network. One of these solutions may be shifting from one-plant manufacturing facilities to multi-plant enterprise. Such shifting can bring many advantages, i.e. being close to low cost raw materials, proximity to market, flexibility in producing many products and specialization in activities [1]. On the other hand, the physical network of a multi-plant enterprise and the social network of actors involved in its operation collectively form an interconnected complex system where the actors determine the development and operation of the physical network and the physical network affects the behavior of the actors.

An industrial enterprise system can be viewed as a multi-level system, whether hierarchically interconnected or decentralized, with a number of operational regimes at the various system levels. Usually, at each level of the decomposed system local performance objectives are defined which should, preferably, not be restricted to the optimization of local goals, but rather aim at optimally contributing to the overall goal. However, the relation between local and overall system performance objectives may be rather fuzzy, especially since the overall objective is often not defined in detail and concerned with a longer time horizon. The local objectives are generally more detailed, concerned with a shorter time horizon and often with the specific interests of an individual actor (e.g. a business unit). To facilitate an overall optimization of the performance of the system as a whole, a kind of coordinator may be required to supervise local decision making in its relation to the overall goal. Therefore, a complex network of production plants needs a special form of operations management to coordinate plant-dependent activities and to ensure that the enterprise as a whole can realize its optimum performance [2]. This operations management involves among others decision making on global enterprise resources planning systems: how to best operate a multi-plant enterprise and at the same time how to operate the separate plants in an optimal way. These decisions can be categorized into long, medium, and short-term decisions. The long-term decisions basically deal with operations strategy, product planning, and the design of facilities and processes. The medium- and short-term decisions are concerned with planning and control of production activities; more precisely, procurement and inventory management, sequencing and scheduling, quality management and maintenance management [3]. Although some of those decisions can be made by an individual company, in a multi-plant enterprise each plant is a part of a corporate network and its relation with other plants is as important as its internal operation. With an appropriate operations management, the enterprise can respond more quickly to dynamic market events, reduce its operating costs and increase customer satisfaction. Moreover, during an abnormal situation (e.g. unexpected shutdown of one production plant) it can be more resilient and recover from disruption more rapidly.

A multi-plant enterprise model can be helpful in finding a deeper view of network components' behavior and their effects on the enterprise overall performance. Such a model can help decision makers to study alternative scenarios and also to improve the operation with respect to some important performance indicators.

In the last two decades many analytical methods for modeling and optimizing different scenarios in a multi-plant enterprise are discussed. Bhatnagar *et al*. study some issues concerning the coordination of production planning among multiple vertically integrated plants in a firm [2]. They considered two levels of coordination in such multi-plant enterprises. The first and general level is the coordination between different functions in a plant, e.g. inventory planning, marketing, production planning, etc. At another level, the coordination problem is addressed between decisions of the same functions in different plants in the same enterprise.

Moon *et al*. propose an integrated process planning and scheduling (IPPS) model for the multi-plant supply chain [4]. The model is formulated as an integer programming method and its objective is to determine the schedules for minimizing tardiness through analysis of the alternative machine selection and the operation sequences in the multi-plant supply. Timpe and Kallrath describe a general mixed-integer linear programming model covering the relevant features for managing a multi-plant production network with emphasis on chemical industries [5]. Their model considers production plants located in different countries and different customers and combines aspects related to production, distribution as well as marketing. Besides standard features of lot sizing problems (raw materials, production, inventories, demands), further aspects such as different time scales attached to production and distribution, the use of periods with different lengths, the modeling of batch and campaign production are also considered.

Similarly, Fengqi & Grossmann [6], Dondo *et al*. [7] and Grossmann [8] discuss mathematical formulations for operation management in multi-plant industrial networks. These works propose the term Enterprise Wide Optimization (EWO) for solving the combined production/distribution scheduling problem in multi-plant environments by using mathematical programming approaches.

All these analytical approaches do not easily take into account social aspects of the intra- and inter-organizational complexity of the multi-plant enterprise problem. An alternative can be offered by agent-based models which have actor-centric perspective instead of the activity-centric one [9]. To safeguard adequate functioning of the total system the actions of the individual agents must be steered towards an acceptable overall performance of the whole enterprise in terms of e.g. reliability, affordability, availability, and quality of products and services.

The next part of this paper is structured as follows. In Section 2, agent-based modeling and its applicability for multi-plant enterprise modeling is discussed, followed by an agent-based model for a multi-plant enterprise in Section 3. Section 4 discusses the application of this model with an illustrative example. In Section 5, some areas for future possible research are presented. Finally, Section 6 gives some concluding remarks.

2. **Agent-based Modeling.** Agent-based modeling (ABM) is a promising approach to modeling systems comprised of interacting autonomous agents [10]. In this approach a system is described by defining its actors (agents) and possible interactions between them. The system behavior then emerges from the behavior of the model components and their interactions. In fact, instead of taking a top-down view in modeling, it is possible to model the system from a bottom-up perspective. Because of this, agent-based modeling can be a natural approach to model distributed and decentralized problems. Generally speaking, agents have the following main characteristics. Agents have a certain level of autonomy, which means that they can take decisions without a central controller or commander. To achieve this, they are driven by a set of rules that determines their behavior. Agents are capable of acting in their environment, which means that they are able to perceive the changes in the environment in which they are immersed and then respond to those changes with their own actions whenever necessary. Agents have proactive ability, which means

having their own goals; they do not just act in response to changes that have occurred in their environments. Finally, agents have social ability to communicate with each other [11].

A multi-plant enterprise is a modular, decentralized, changeable and complex system. It has many different heterogeneous components and its overall behavior emerges from interaction of its components. Each production plant has some level of autonomy to control its own actions and internal states. Decision making in each plant is distributed across various departments, such as procurement department, operation department, etc. Obviously, each of these departments has a specific role and performs certain tasks. In addition, all departments have their own goals and they have some level of autonomy to achieve these goals. In fact, in many cases there is also a central actor that has authority to coordinate the behavior of different production plants at different geographically locations. The departments interact with each other through material and information flows. Accordingly, the overall dynamic behavior of a multi-plant enterprise emerges from the interaction of production plants and their individual departments. Obviously, in modeling multi-plant enterprise the network components have the basic characteristics that an agent in agent-based modeling can have: autonomy, social ability, reactivity and pro-activeness; and agent-based modeling can be an appropriate approach for this modular, decentralized and complex system.

In addition an agent-based model of a multi-plant enterprise due to its flexibility can easily be used to formulate many experiments related to the structure and the local behavior of agents to study their effects on the desired performance of the system.

3. **An Agent-based Model for a Multi-plant Enterprise.** To develop an agent-based

model for a multi-plant enterprise, we consider a multi-plant enterprise as a complex socio-technical system in which a network of different geographically distributed actors (customers, a multi-plant enterprise and suppliers) determine the development and operation of the physical network. The behavior of such a system cannot be understood by merely looking at the structure and dynamic behavior of either the physical or the social network [12]. Both are interconnected and interwoven in many ways. Accordingly, the decision making and social interactions in social network determine the development and operation of the physical network and the physical network affects the behavior of the agents and their possible policies (Fig. 1).

To represent a multi-plant enterprise as a socio-technical system an ontology developed in Energy & Industry group of the Delft University of Technology is used [13]. This ontology is a formal representation of relevant concepts, their properties and relationships and it is a basis for implementation of an agent-based model. In other words, to start building an agent-based model, we conceptualize the problem in the form of an ontology that is a medium for sharing the information and communication between agents. It is important to be sure that when agents communicate, they have a similar interpretation of the main concepts. Moreover, this ontology is a useful tool for sharing knowledge between modelers, domain experts and users.

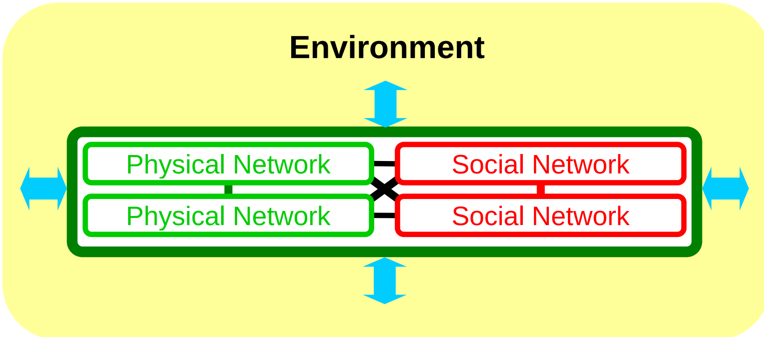

FIGURE 1. Multi-plant enterprise as a socio-technical system.

Some key concepts of the ontology used are:

Social Node (Agent) represents the actors in the system who are the owner of one or more physical nodes, control them and make decision on their operation. It has some properties, such as location, and also some rules of behavior that is defined by its policies and activities.

Physical Node (Technology) is a physical element such as production facilities specified by its design and operational properties (e.g., the production capacity).

Social Edge is an interaction between two agents or the link between social network and physical network. Two important social edges in the model are Order (between two agents) and Ownership (between an agent and a technology). Each of these social edges has some specific properties, e.g. starting time and ending time .

Physical Edge is a link between two physical nodes (e.g., a mass or energy flow). It is also defined with some specific properties.

Good is representing one type of material (e.g., raw materials, final products) in the system that flows through physical edges.

Activity represents the unit of behavior of one agent that can be for example receiving, processing or shipping an order. These activities are carried out by agents.

Policy is the logic under which agents behave. Therefore, it is a rationale for one or a series of activities. As an example, for a procurement agent, the “reorder point” is a policy for managing the raw material level and according to it, this agent places a raw material order at appropriate time (as an activity).

Clearly, some of these concepts are describing the social aspects of a multi-plant enterprise (e.g., Agent, Social Edge, Order, Activity, Policy) and others describe the technical components in the system (e.g., Technology, Physical Edge, Good). Consequently, it can provide a realistic representation of the socio-technical nature of a multi-plant enterprise.

The mentioned concepts are implemented in open- source Repast simulation platform [14] and Java programming environment. The ontology is defined in Protégé. Through the shared ontology (which can be seen an interface between model components, models and modelers), a library of building blocks and a set of procedures, models for industrial networks can be built re-using (parts of) existing models. Models built with this framework have already successfully been designed and implemented for various infrastructures, including transport, energy and industrial networks [15].Using these source-codes, it is possible to construct an agent-based model for a multi-plant enterprise, formulate many experiments and study its performance under different scenarios.

Next section illustrates the application of agent-based modeling for analysis of a multi-plant enterprise operation management.

4. **A Case study.** In this section, an illustrative case study analyzing the operation of a chemical multi-plant enterprise is presented. This enterprise comprises a global sales department which directly interacts with customers and three production plants at different geographical locations [16, 17]. Each production plant itself has several functional departments, each with a specific role and performing certain tasks; performance of each production plant is a result of its departments' behavior and their interactions. All these production plants operate make-to-order and can produce three types of products after receiving an order from the customer. Each product is produced from eight different raw materials. The goal is to fulfill a set of customer orders in the first possible time through assigning them to different production plants and coordinating the behavior of different departments in each plant. (Fig. 2):

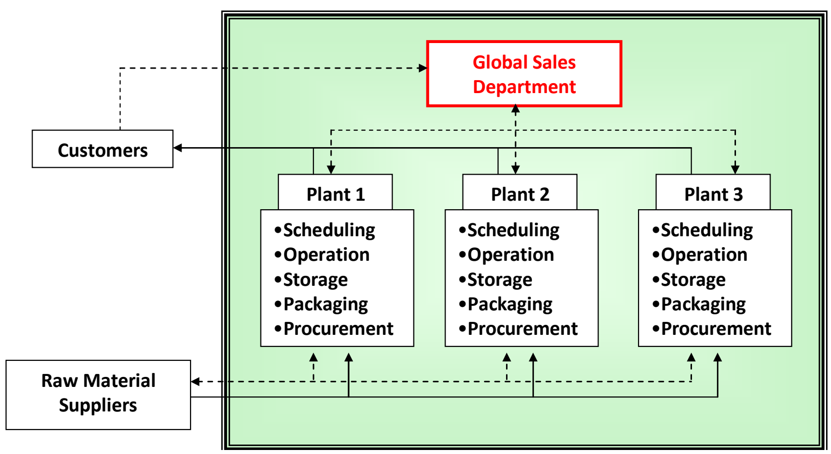

FIGURE 2. Main actors (agents) in a multi-plant enterprise (solid lines show material flow and dashed lines show order flow).

Based on the ontology described in previous section, an agent-based model with 9 agent types has been developed:

Customer. The customer sends its orders to the global sales department. Each order is described by the required product type, its quantity and the order expected due date.

Global Sales Department. After receiving an order from the customers, the global sales department will assign it to one of the available production plants. For this purpose, the global sales department passes the order details to the scheduling department of production plants and each scheduling department then replies with the earliest date when the plant can make the product and deliver it to the customer. Based on the replies, the global sales department will assign the customer order to the plant with first possible fulfillment date. If none of the plants are able to produce and deliver the product on time, the sales department will suggest the first possible date as a new due date to the customer. Once the date is fixed, the sales department would assign this order to the plant with the first possible time.

Production Plant. Each production plant consists of the following departments:

Scheduling department. The scheduling department performs two main functions: first, after receiving a new order from the global sale department, it should determine the first possible time for fulfilling this new order. For this purpose, the scheduling department adds the new order to its current non-assigned orders and determines a new schedule according to the actual scheduling policy. According to this schedule, this department will determine the first possible time for fulfilling the new order. This time should be sent to the global sales department to decide on assigning the order. Second function of scheduling department is activating the current order for operation department based on the schedule.

Operation department. The operation department processes raw materials into products following a unique recipe. According to this recipe, it sends the required raw material information to the storage department and receives the desired material accordingly. Following, the produced products are sent to the packaging department.

Storage department. The storage department provides raw materials for the operation department and also manages the raw material inventory level. Raw material procurement is performed on the basis of a pre-defined reorder point policy, e.g. with 15% safety level. Reaching the reorder level, the storage department reports to procurement department to place an order for the desired raw material.

Packaging department. The packaging department packs the finished product. The assumption is that there is no final product transportation and customer picks up the fulfilled order after packaging. For this purpose, the packaging department informs global sales department about finishing an order.

Procurement department. The procurement department calculates the required raw material and places an order with a supplier. Each raw material order has an amount and a delivering time. After receiving an order, the procurement department will inform the storage department about the order delivering and consequently, the inventory of that raw material will increase.

Supplier. Supplier provides raw materials according to the order sent by the procurement department.

This agent-based model can be used to do many experiments and to study important factors that influence the behavior of each plant separately as well as the performance of the enterprise as a whole. These experiments can be defined by implementing different behaviors for different departments (i.e., changing their properties and/or their working methods). Some of those experiments are presented hereunder.

Experiment 1: Evaluating the performance of enterprise during normal operation

The developed agent-based model is an appropriate quantitative tool to evaluate the effect of local behavior and policies on the enterprise-level performance. For this purpose, it is necessary to define some performance indicators for the system and study the dynamic behavior of enterprise. Examples of these performance indicators are "number of late orders" and "total tardiness (in days)". Due to flexibility of modeling, it is possible to define many other performance indicators and study the effect of local behavior on those performance indicators.

As an example, considering the EDD (Earliest Due Date) policy for the scheduling department and reorder point policy set to 15% for the procurement department, Fig. 3 shows the inventory level for raw materials for production plant1. The inventory levels for raw materials trend down due to raw material consumption during production activity and goes up after delivering raw materials from supplier. Similar profiles can be presented for the other two plants, helping to track inventory variations. As presented in Table 1, with mentioned policies, there are 5 late orders with 7 tardy days in total in 100 days time horizon for enterprise.

TABLE 1. Enterprise performance with EDD policy and fixed reorder point (15%)

Number of Orders assigned to ProductionPlant1	*33*
Number of Orders assigned to ProductionPlant2	*33*
Number of Orders assigned to ProductionPlant3	*34*
Number of Orders assigned to All Production Plants	***100***
Number of Late Orders by ProductionPlant1	*2*
Number of Late Orders by ProductionPlant2	*2*
Number of Late Orders by ProductionPlant3	*1*
Number of Late Orders by all Production Plants	***5***
Total tardiness for ProductionPlant1 (Days)	*2*
Total tardiness for ProductionPlant2 (Days)	*3*
Total tardiness for ProductionPlant3 (Days)	*2*
Total tardiness for all Production Plants (Days)	***7***

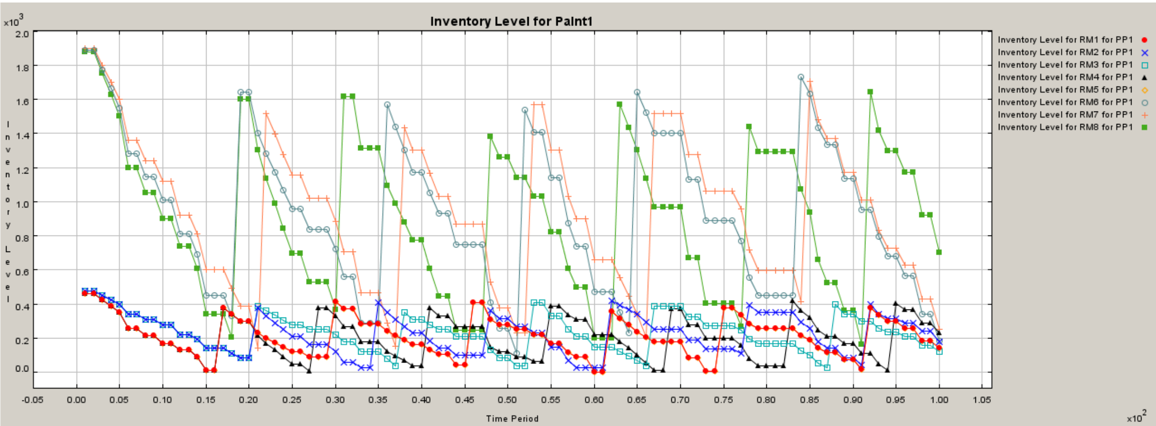

FIGURE 3. Inventory level for eight raw materials for the production plant1.

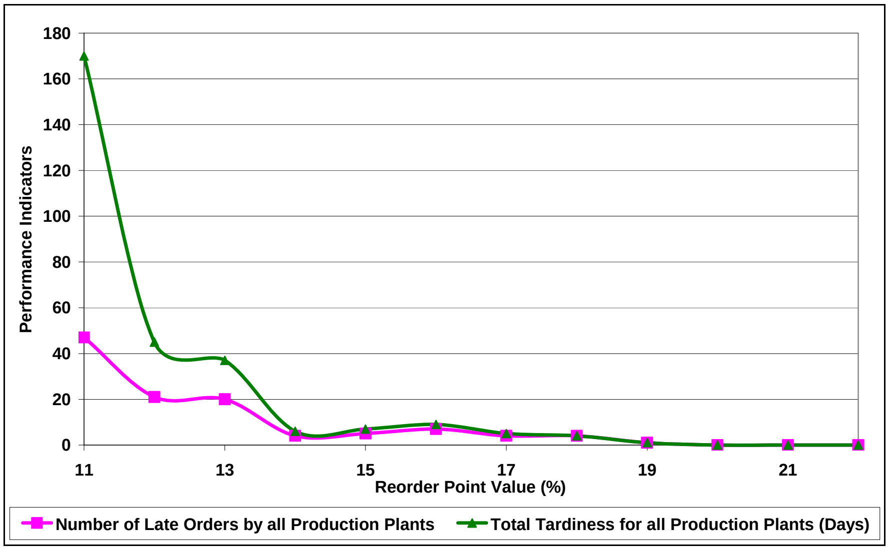

FIGURE 4. The effect of procurement policy (reorder point) on overall system performance (total tardiness and number of late orders).

Experiment 2: Finding the optimal procurement policy

Generally, any change in the policy of agents can influence the enterprise performance as a whole. As an illustration, the effect of changing the reorder point (procurement policy) on system performance is studied. The results are shown in Fig. 4: as the reorder value increases, generally, the overall performance of enterprise improves (total tardiness and number of late orders decrease); since without raw material, the operation department should pause performing an order and wait for receiving raw materials from the supplier. This causes delay in fulfilling customer orders that are assigned to that production plant. Generally speaking, with a higher reorder point the raw material availability can be a less important bottleneck for production plant. Fig. 4 suggests considering 20% as an optimum reorder point for this set of customer orders. This is because 20% is the first reorder value that both total tardiness and number of late orders equal to zero; all customer orders are fulfilled here. Undoubtedly, this value is an optimum value for one special set of customer orders. Therefore, having the exact pattern of customer orders for an enterprise, the optimum reorder point regarding mentioned performance indicators can be determined. But in the real world, customer orders are not fixed and are not certain. Their amount, the due date and the product type can be different from what considered in this example. To take into account such uncertainties, different customer order patterns with random amounts, due dates and product types are investigated with the model. The optimum reorder point for theses experiments changes from 18% to 24% and the average for all experiment is 21%. In addition, the results show that for 82% of customer order sets, the optimum reorder point is between 20% and 22%. Therefore, it seems that the optimum reorder point for a random set of customer orders should not be far from the pre-defined reorder point. This means that the optimal reorder point for the current situation can be determined on the basis of the historical data. It should be stressed that for this reorder point, the inventory level is not a bottleneck for production and order fulfillment.

Experiment 3: Evaluating the performance of enterprise in abnormal situations

Next to determining the normal behavior of an enterprise, many experiments can be formulated to study the enterprise performance during different abnormal situations and to find effective strategies to cope with them. As an example, an unexpected shut down in production plant 1 at the 70th day of the time horizon is considered. Consequently, starting with the 71st day, all orders should be fulfilled by production plants 2 and 3. The simulation results are summarized in Table 2. The assumption was that all production plants were working according to their optimum reorder point (20%). As it is expected, the overall performance is affected by this disruption, resulting in a number of late orders and the nominal optimum reorder point is not optimal anymore for the disturbed situation.

TABLE 2. Performance data for enterprise during an abnormal situation (Plant1 shut down)

Number of Orders assigned to ProductionPlant1	*22*
Number of Orders assigned to ProductionPlant2	*39*
Number of Orders assigned to ProductionPlant3	*39*
Number of Orders assigned to All Production Plants	***100***
Number of Late Orders by ProductionPlant1	*0*
Number of Late Orders by ProductionPlant2	*7*
Number of Late Orders by ProductionPlant3	*7*
Number of Late Orders by all Production Plants	***14***
Total tardiness for ProductionPlant1 (Days)	*0*
Total tardiness for ProductionPlant2 (Days)	*16*
Total tardiness for ProductionPlant3 (Days)	*18*
Total tardiness for all Production Plants (Days)	***34***

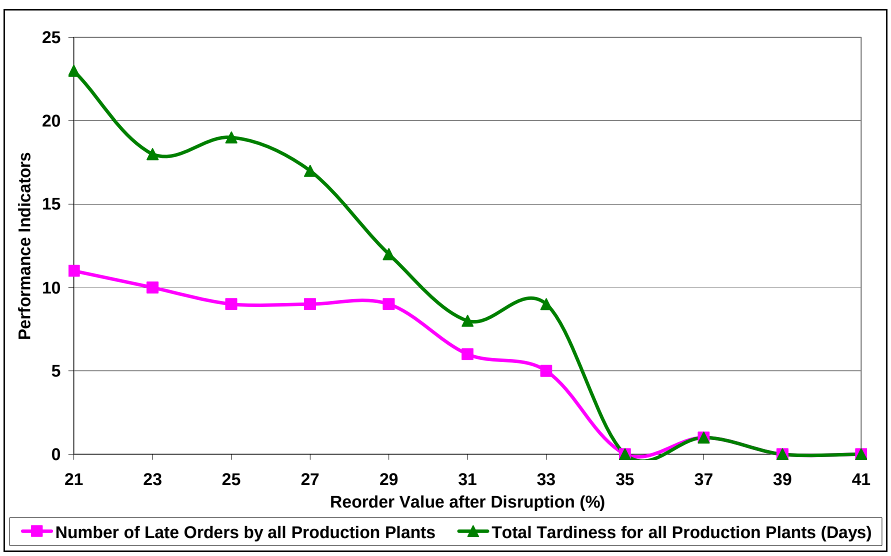

FIGURE 5. The effect of procurement policy (reorder point) on overall system performance (total tardiness and number of late orders) during an abnormal situation (plant1 shut down).

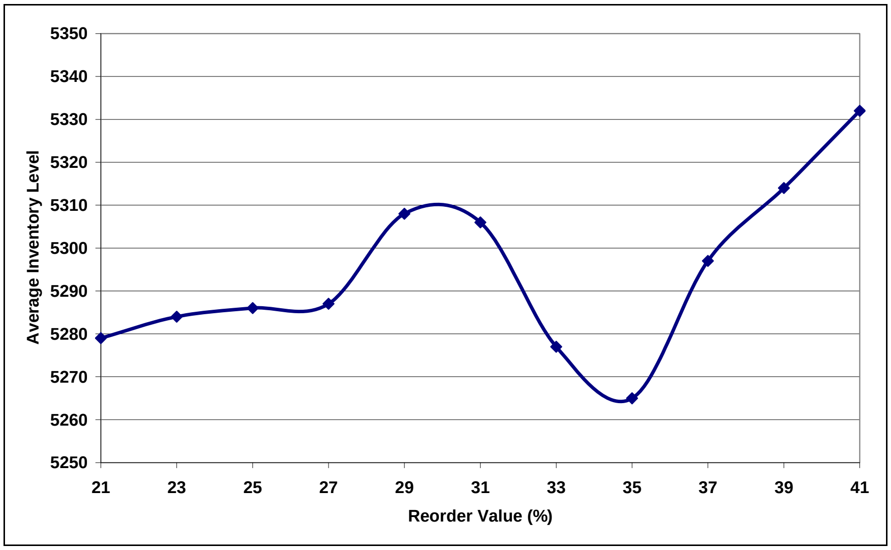

FIGURE 6. The effect of procurement policy (reorder point) on overall system performance (average inventory level) during an abnormal situation (plant1 shut down).

To handle this disruption, the enterprise can adapt its scheduling and/or procurement policies, e.g. changing its nominal reorder point. Accordingly, after disruption in Plant 1, Plants 2 and 3 change their reorder point to a new value. Fig. 5 shows the relation between changing the reorder point for production plants 2 and 3 after disruption and the total tardiness as well as the number of late orders. In general, increasing the reorder point improves these two performance indicators; but on the other hand, a higher reorder point will increase raw material holding cost, too. Fig. 6 shows the effect of reorder point on average inventory level for all production plants. Totally, with increasing reorder point, the average inventory level should be increased; but the inventory level is also dependent on the number of finished orders. Having more finished orders means more raw material consumption and lower average inventory level. Based on this analysis, setting the reorder point for the two open production plants to a value around 35% will result in desirable levels for both customer satisfaction and raw material holding cost. Of course, for a real case, according to the storage-related costs, a more precise value can be determined. Meanwhile, an enterprise may react to an abnormal situation with many different strategies and changing reorder point can be a part of a comprehensive crisis management package.

5. **Extension and Future Works.** Proposed model shows the application of agent-based modeling approach for a multi-plant enterprise problem. The relevance of simulation models allowing experimentation as decision-supporting tools is very high for many players in the world of multi-plant firms. In all systems that exhibit interactions and interdependencies between subsystems, where multiple functionality plays a role, where capacity allocation in a complex and dynamic environment is an issue, feasible concepts for a decentralized operation contributing significantly to an overall performance are called for. A particular challenge is posed by the application of multi-agent models for the decentralized decision making in a multi-plant operation, where communication and cooperation schemes should enable agents to come to decisions that are both acceptable locally and ensure an as good as possible overall system performance. The design of appropriate incentives to steer individual agents' decision making towards overall goals and to enforce adequate communication and collaboration schemes is certainly a challenging question. For example, similar to the scheduling and procurement departments, it is possible to consider different policies for other departments, too and to study the effects of their performance and behavior on the overall system performance indicators. In addition, many other abnormal situations can be defined and the methods to cope with them can be studied. Having more suppliers and different customers with different geographical

locations, considering more sophisticated architecture for some agents and developing more complex decision making process for current agents will be the next steps in the future work.

Besides, applying model to real cases and evaluating the simulation results with real data will be another important direction for the future research.

6. **Concluding Remarks.** The potential of using agent-based modeling paradigm for operation management of multi-plant enterprise has been demonstrated. Decision making for such problems is distributed among a set of autonomous and heterogeneous actors and the overall system behavior emerges from interactions of these actors. To demonstrate the applicability of agent-based modeling for multi-plant enterprise problem, an illustrative case study is presented and some experiments are carried out. In addition, the developed model is used to analyze an abnormal situation and the effects of possible policies to managing it. Initial results of the model underline the application of agent-based models for decision making in multi-plant enterprise problems. The proposed model can be easily extended with more complex decision making approaches and more realistic behavior for agents to have an appropriate decision support framework to support tactical and operational decisions at the enterprise as well as at the plant level.

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