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Capacity sharing in a network of independent factories: A cooperative game theory approach

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ABSTRACT

Market changes, uncertainties and unpredictability characterize the market environment nowadays. The possibility to cooperate in a network allows companies to stay competitive. This paper proposes a game theory coordination mechanism for a network of independent plants; the approach is based on the OWEN's theorem properly simulated in order to investigate different performances in various environmental conditions. To support the network and face the capacity sharing issue, a Multi-Agent Architecture has been specifically developed. The simulation results show that the proposed mechanism could be considered a valid alternative to the more usual negotiation approaches in several market conditions. The plants gain considerable benefits by participating in a network supported by the cooperative mechanism proposed.

1. Introduction

The investment in production capacity is often a critical factor for several manufacturing sectors such as the semiconductor, consumer electronics, telecommunication and pharmaceutical industries. For example, a new semiconductor fab costs one to four billion dollars to build, and the price for a single machine may be as high as four to five million dollars with high obsolescence rate and high demand volatility [1]. In recent years, manufacturing companies compete in a market characterized by high demand volatility, short product life cycle, rapid technology obsolescence, new product introduction, etc. These unpredictable market changes force the manufacturing enterprises to choose between two options. They can adopt a conservative capacity expansion policy that can lead to reduced customer satisfaction. Alternatively, they can increase investment in production capacity with higher risk. Moreover, factories constantly face unexpected events such as demand fluctuation, machine breakdowns, rush orders, and delays by suppliers. Due to the stochastic behavior of these events, factories can have excess or insufficient capacity in a short-term period. In this context, production networks made of different and geographically dispersed plants can be a valid cooperation paradigm to improve responsiveness and proactiveness in regard to unpredictable market changes [2]. The networks allow factories to react to the capacity disequilibrium caused by unexpected events in the different regional areas in which they operate. The network seems to be a most promising approach, but it needs a coordination mechanism to reach a global objective. In general, two main approaches support coordination in distributed organizations: centralized or decentralized systems. Concerning the centralized approaches, many authors have highlighted several drawbacks [3,4]. For example, they are not practical in real applications when the number of actors is large. They tend to have problems reacting to disturbances and may fail to respond effectively to the presence of real-time events. Independent enterprises often avoid using centralized information systems. To overcome these disadvantages the decentralized approach is often utilized. In this case, each actor makes its own decision, while common goals are reached through a coordination mechanism. Negotiation is undoubtedly the more used mechanism; it is characterized by several parameters that affect the performances of the coordination process. The main parameters are: strategies of the involved actors, the number of negotiation rounds, the amount and quality of information to exchange among the opponents and the ending criteria of the process. In our mind, approaches based on game theory can be a valid alternative to this standard approach. In comparison the negotiation, the main advantages are: the reduction of time to reach an agreement; the reduction of the exchanged information; the reduction of the alternatives that the opponents can select at each round of the process. The aim of this research is to investigate an innovative cooperative approach based on game theory for a network of independent factories facing capacity sharing issues. The proposed approach can reduce, in the short-term period, the productive disequilibrium for all the factories involved in the network. Specific Multi-Agent Architecture has been realized to support the network activities together with

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a discrete simulation environment in order to highlight the benefits of the proposed approach. The analysis of the performances has been conducted in several dynamic market conditions and compared both with negotiation and a low intelligence based approach with any kind of cooperation. The paper is organized as follows: Section 2 gives a literature review on capacity sharing in a network. The Multi-Agent Architecture is described in Section 3. Sections 4 and 5 present, respectively, the proposed coordination strategy based on the negotiation approach and the game theoretic one. The simulation environment is shown in Section 6. In Section 7 the simulation results are presented and, finally, conclusions and future developments are discussed in Section 8.

2. Literature review

Many authors have addressed the problem of capacity allocation or capacity sharing for geographically distributed factories which belongs to the same company, but few studies were proposed in a network of independent plants due to strong difficulties of information sharing. Tonshoff et al. [5] described a conceptual framework in a decentralized production environment concerning several sales unit and production sites geographically distributed. The capacity allocation plan is made by a mediator in a centralized approach. Jiang [6] developed the architecture and a bidding approach to solve the capacity shortage of bottleneck tools among the production units in a wafer foundries environment. In the individual factory domain, several mathematical models are formulated for practical purpose by considering several different characteristics of make-to-order manufacturing, make-to-stock and stochastic demand. The approach proposed by a framework is based on the negotiation mechanism with different preferred attitudes and asymmetric local information. The approach concerns only tools to share among units. Ip et al. [7] proposed an approach concerning planning and scheduling problems in a multi-products manufacturing environment by using genetic algorithm; the approach is centralized and not applicable in an environment with independent factories. Christie and Wu [8] proposed an approach to manage the capacity planning in a multi-fabs environment. Each fab is modeled as a single resource with variable production level. Several discrete scenarios are considered in a multi-period, multi-stage and stochastic programming model. The goal is to minimize the expected mismatch between planned and actual capacity allocation as defined in the scenarios. Wang and Lin [9] developed two models to determine the profitable decision in resource planning. The focus of the research was: what type of and how many testers should be invested under budget constraint and how to allocate tester capacity for the orders in order to maximize the company profit. This research develops a genetic algorithm simultaneously to resolve the two issues. A mathematical model is constructed and its answer serves as a benchmark. Moreover, a modified ant algorithm is also proposed for solving mixed-integer linear programming problems. In this case only the tester resources were considered to allocate in multi-unit fab. Ahmed and Garcia [10] proposed a two-stage stochastic integer programming model for the dynamic capacity acquisition and assignment problem where the assignment costs and the processing requirements for the tasks are uncertain, with the objective to minimize the cost of resource expansion and the assignment of the resources to tasks. A decomposition-based branch-and-bound strategy is developed for this problem. Wu et al. [1] presented a methodology for solving the tool planning problem in an environment, which involves multiple and probabilistic demand volumes for a given product mix ratio with a target mean cycle time. The methodology proposed is based on genetic algorithm; the methodology is centralized because operates in a single factory and concerning a probabilistic demand as dynamic aspect. Wu et al. [1] and Hsiung et al. [11] modeled the demand uncertainty with several demand scenarios with associated probabilities. The former developed a genetic algorithm embedded with a queueing analysis to solve this problem. This model considers several aggregating demand scenarios with a fixed product mix. From a similar perspective, the latter proposed a similar model that also uses a genetic algorithm embedded with queuing analysis to solve this problem in the context of a multiple product mix. Demand is forecast aggregately, and the product mix may change during one period. Both of these papers are based on the queuing model developed by Connors et al. [12]. However, both methods take a long time and do not give the global optimal solution. Argoneto et al. [13] proposed a game theoretic approach to coordinate a production networks made of different and geographically dispersed plants that, in case of unpredictable market changes, can be reconfigured in order to gather a specific production objective. The proposed approach has been benchmarked with a distributed mechanism based on negotiation, and a centralized model. Chou et al. [14] modeled the uncertainty of demand as a geometric Brownian motion process, focusing on the problem of adapting capacity strategy according to the characteristics of demand and business plan. They compared the conservative and reactive capacity strategies. Empirical data analysis finds that the capacity strategy should be chosen by considering the combined effect of demand growth and volatility. Wang et al. [15] formulated the resource expansion and capacity allocation decision as a nonlinear mixed-integer mathematical programming model with the goal of maximizing its overall profit. A constraint programming-based genetic algorithm was developed. To meet the needs of a shorter product cycle time and higher output by reducing the risk of processes or tools causing bottlenecks.

Wu and Chang [16] presented a capacity trading method for two semiconductor fabs that have established a capacity-sharing partnership. The proposed method involves three modules: a discrete-event simulation to identify the trading population; secondly, some randomly sampled trading portfolios with their performance measured by simulation are used to develop a neural network, which can efficiently evaluate the performance of a trading portfolio; thirdly, a genetic algorithm embedded with the developed neural network is used to find a near-optimal trading portfolio from the huge trading population. Chen et al. [17] proposed a model that enables a collaborative integration of resources and demand. A negotiation algorithm is utilized to sharing capacity from factory that selling to factory that requires extra capacity. Each factory applies an economic resource planning model based on genetic algorithm to improve its local objectives. The models proposed in Wu and Chang [16,17] were tested only between two factories: one seller and one buyer. Moreover, the developed approaches are based on a centralized model based on Genetic Algorithm. Renna and Argoneto [18] proposed a distributed approach, for a network of independent enterprises, to facilitate the resources sharing process. The distributed architecture is based on Multi-Agent Architecture paradigm and the coordination mechanism was performed by a negotiation protocol. The proposed approach was tested by a discrete-event simulation environment in order to evaluate the performance indexes.

Huang and Ahmed [19] proposed a generic multi-period capacity planning problem under uncertainty involving multiple resources, tasks and products. They compared two-stage and multi-stage stochastic integer programming approaches for this problem. The concept of value of multi-stage stochastic programming is discussed and informative analytical bounds are developed. The model proposed is a centralized approach. Renna and Argoneto [20] proposed a game theory approach based on NASH bargaining solution for capacity sharing. The simulation results show that the proposed approach is suitable for capacity sharing problem. This research is limited to a fixed dimension of the network and the game