Multi-agent Systems for Production Management in Collaborative Manufacturing

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Abstract. The paper aims to analyze multi-agent management structures in Small-Mid Enterprises (SME), such to investigate how collaborations among agents could be improved. A SME manager has generally to face with three issues: data management, organization of the production phases, interactions with mid-level management (denoted by "agents"). Data management is necessary in order to have a clear representation of the many types of data about products, orders and resources of the company. The organization of production phases consists on the management of the production process phases from design up to recycling. Based on a clear representation of the product life cycle, the manager will be able to organize the interactions between these agents (each one dedicated to handle a process phase) so as to facilitate the collaboration, and to make effective each mid-level management as far as it is concerned with controlling the operations to be carried out in each process phase. A model of the mid-layer multi-agent management negotiation, according to the "game theory" viewpoint, is proposed, and its main characters are analyzed, in view of its application.

Keywords: Collaborative manufacturing · Multi-agent systems · Game theory

1 Introduction

In today global markets, factory managers are under pressure to optimize technological processes and to reduce production costs. Adequate tools and sufficiently robust procedures do not support Small and Medium Enterprises (SME) in the organization of work and in the management of the product life-cycle phases. On the other hand, a number of formal approaches have been developed for solving individual processing/managing problems in manufacturing, but their utilization in SMEs find obstacles in the insufficient knowledge of managers and enterprise owners [1, 2].

A SME manager generally face with three issues: how to have a clear representation of data concerning products, orders and resources; how to organize the various phases of the production process, from design up to recycling; how to interact with employees to whom management and control duties have been assigned.

These problems have a common point: use a clear representation of the product life cycle, highlighting the sequence of process steps [3]. Using this representation, the manager will be able to reform/re-engineer the management structure of his/her company based on the following logic:

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(a) To organize the stages of the product's life cycle, divide them into management duties, and assign each stage, as management duty, to a mid-level manager of the company with precise responsibilities and authority;
(b) To organize the interactions between these mid-level managers (one dedicated to handle a phase) so as to facilitate the collaboration between the mid-level managers themselves and therefore make them more profitable for the company; this organization aims to optimize the "enterprise integration", i.e. cooperation within the enterprise;
(c) To make effective the management of each mid-level manager as far as it is concerned with controlling the operations to be carried out at each stage; this corresponds - with reference to the "production" phase, for example - at shop-floor management, that is, the collaboration between manufacturing resources within a shop-floor.

The two points (b) and (c) generally represent the greatest difficulty for a top manager/owner. Instead, the organization of the product life cycle phases and the operations to implement them is a simpler task for top management of SMEs since, often, the top manager is also the founder of the enterprise and the "initial designer" of the first product that the company manufactures.

This work is therefore devoted to the analysis of an organizational structure designed to support the manager in solving the problems mentioned in (b) and (c).

2 Some Hints on the Multi-agent Structure of a Manufacturing SME

The multi-agent modeling approach of a manufacturing mid enterprise is here discussed with reference to the main results of the EU project ame-PLM - Advanced Platform for Manufacturing Engineering and Product Lifecycle Management [3].

As above mentioned, product and production engineering in mid industrial companies are typically fragmented across different functional units, dedicated to the complementary phases of a product life cycle. A typical scheme of these phases is in Fig. 1, with reference to a generic product and to its main life cycle phases.

With reference to Fig. 1, conceptual design and preliminary design activities are typical of the SME manager/owner, while other activities involve several mid-level managers, as illustrated in the following figures referred to the "detailed design" phase (Fig. 2), the "production" phase (Fig. 3), and the "utilization" phase (Fig. 4).

The group of mid-level managers that can be recognized in Figs. 2, 3 and 4 are embedded into a network of interactions, each one corresponding to a negotiation. In fact, every mid-level manager has the duty of achieving two goals: (i) to optimize the efficiency of the plant/service/shop-floor managed by himself; (ii) to give the maximum possible contribution to the enterprise profit.

The first goal could be individually obtained by any mid-level manager (for brevity denoted in the following "**agent**"), irrespective of any interaction with the others, but the second goal is of prevailing importance. That generates a two-layer approach in order to manage the enterprise activities: (1) a higher-layer interactions among agents, i.e.

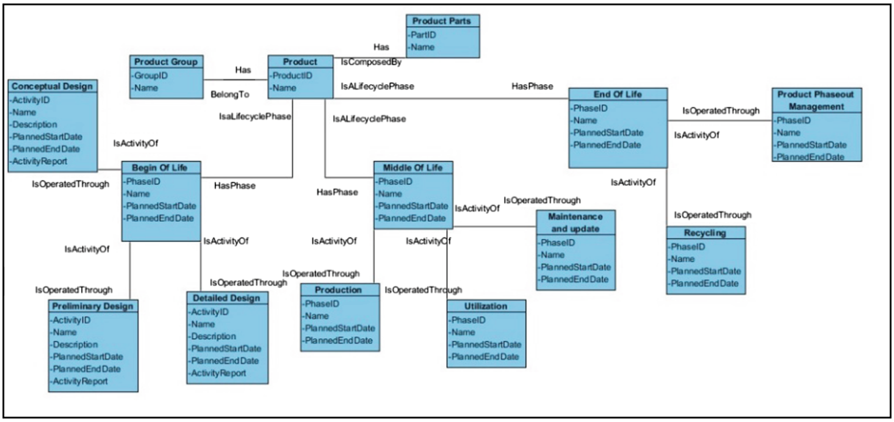

Fig. 1. Main phases of the product life cycle and their macro-activities.

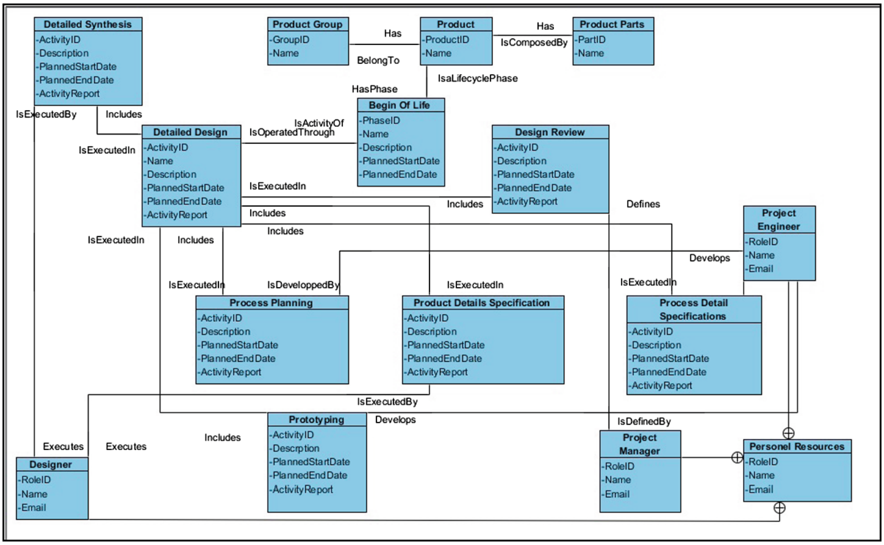

Fig. 2. The detailed design phase.

negotiations with the aim of obtaining the strongest possible coordination of tasks and efforts; (2) a lower-layer individual optimization of the operations required at each phase.

With reference to the higher-layer negotiation, this has to be based on the network of interactions linking agents, as well as on the presence of a "moderator/broker", who will be the owner/top manager. The presence of the "moderator" ensures that negotiation is a converging process towards a common goal [4]. The kind of agents' network can favor the negotiation process, busting conflicts between agents wanting to maximize their own goals, as in case of the managers in a SME network [5–7].

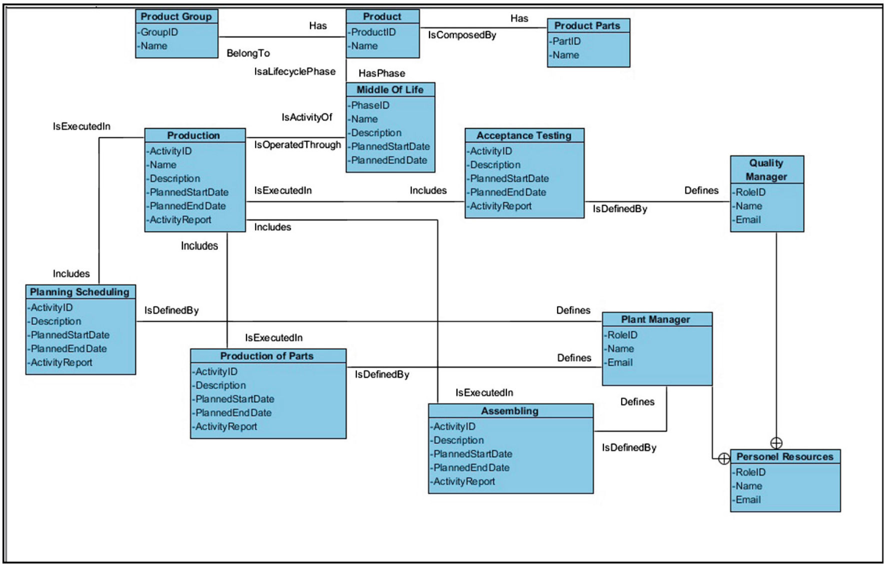

Fig. 3. The "production" phase.

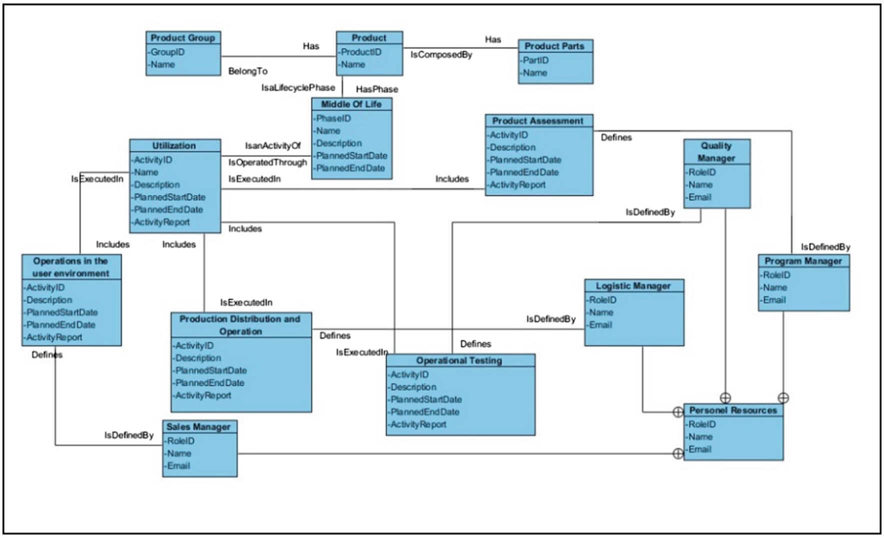

Fig. 4. The product "utilization" phase.

An example of agents' network, that can be derived from Figs. 2, 3 and 4, is illustrated in the following Fig. 5:

- two partial negotiations, one between the "plant manager" in Fig. 3 and the "project manager" in Fig. 2, and the other between the "plant manager" and the "program manager" in Fig. 4;
- one loop transferring requests for improvements from the "program manager" towards the "project manager".

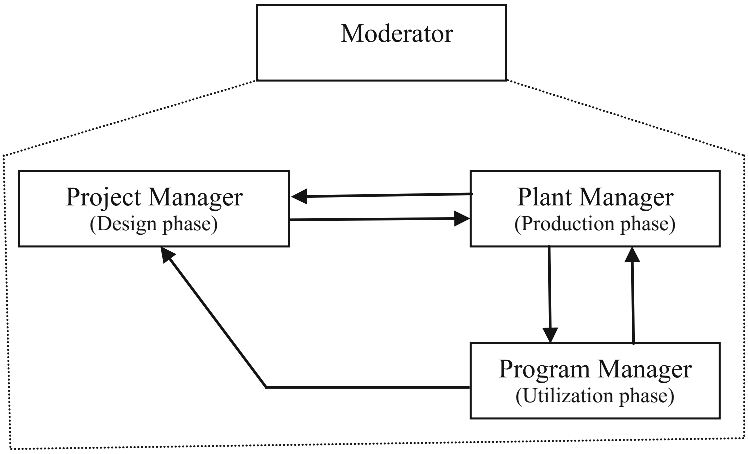

Fig. 5. Simple negotiation scheme among the three agents, with the "Moderator" busting conflicts between agents

Therefore, it is now necessary to discuss a formal model of the multi-agents negotiations, oriented towards the evaluation about when an active collaboration among agents could be activated.

3 Multi-agent Collaboration Model Based on Game Theory

Based on the above considerations, now the agents network of negotiations is modeled by the game theory [4], according to the idea that any agent (in practice, a mid-layer manager) wants to be competitive but must assure his/her best contribution to the enterprise profit.

Then, the requirement from any agent of the network is to understand the payoff of the part of production system managed by himself. In order to evaluate this payoff, it is necessary to adopt a network model based on "cooperative game theory" that shows the different way of "players" (here, the agents) to interact together and cooperate.

A cooperative game (N, v) is constituted by two elements:

- the finite set of players $N = \{1, 2, \ldots, n\}$, i.e. the enterprises that compose the network;
- the characteristic function v, that associates to each subset $S \subset N$ a number $v(S)$ that represents the value created by each subset of players.

$v(N)$ is the total value created, i.e. the value created when all the players in N cooperate together.

Given the set N and a specific player $i \in N$, the **marginal contribution** $\boldsymbol{MC_i}$ of player i is:

$$v(N) - v(N \backslash \{i\}) = MC_i \tag{1}$$

The marginal contribution of player *i* is the amount that the total value would lost if the payer do not belong to the network.

Given a cooperative game (N, v), an **allocation** $\boldsymbol{x}$ is a sequence of numbers $(x_1, \ldots, x_n)$ where x_i is the value received from the *i-th* player.

An allocation is **individually rational** if $x_i \geq v\{i\}\ \forall i = 1, \ldots, n$.

An allocation is **efficient** if

$$\sum_{i=1}^{n} x_i = v(N) \tag{2}$$

An allocation $(x_1, \ldots, x_n)$ satisfies the principle of the **marginal contribution** if

$$x_i \leq MC_i \forall i \tag{3}$$

An allocation is in the Kernel of the game if it is efficient and so that

$$\forall S \in N : x(S) \geq v(S) \tag{4}$$

An efficient allocation is in the Kernel if and only if

$$x(S) \leq MC_S \tag{5}$$

From these definitions and considerations, we can demonstrate the following theorem.

Theorem. The global value generated from the cooperation of all players in set *N* is greater or equal than the sum of the values generated from subsets of *N*:

$$v(N) \geq v(S) + v(N \backslash S) \tag{6}$$

Dim. Let us consider $x(S)$ an allocation of subset S that is in the Kernel and it is individually rational:

$$v(S) \leq x(S) \leq MC_S \Rightarrow v(S) \leq MC_S \tag{7}$$

This means that the marginal contribution that a player or a subset of players in N gives to the network is greater than the value that all the players would generate playing by alone without cooperation.

The definition of marginal contribution is $MC_S = v(N) - v(N \backslash S)$, so by replacing this expression in the previous equation we obtain:

$$\begin{aligned} v(s) \leq MC_s = & v(N) - v(N \backslash S) \Rightarrow v(s) \leq v(N) - v(N \backslash S) \Rightarrow v(N) \\ & \geq v(s) + v(N \backslash S) \end{aligned} \tag{8}$$

Thus, the value generated by the cooperation of all the players is greater than the sum of the values generated by any subdivision of players into groups.

This condition will assure the convenience for the system of players (i.e., the multi-agent system) to collaborate.

4 Some Concluding Remarks

From the point of view of practical application in a multi-agent structure, the above approach to organizing the network of agents by maximizing the gain (7) could reflect in supporting agents with higher efficiency.

This theoretical solution, indeed, implies some practical defect, among which that of generating an unbalanced network, with some agents, well organized and with greater impact on the system performance, mainly supported, against some others, not so equipped and assessed.

This consideration suggests that the above “game-theory-based” formal model should be used for clarifying the concept of multi-agent network design, but it must be followed by a validation of the resulting negotiations and of the effectiveness of the collaborations of agents together, as discussed in some EU-funded projects [8, 9].

This further step, even if it could be done by applying a simulation tool, needs a deeper analysis of the completely multi-agent system, as well as of the interactions between the two layers, with a more accurate definition of the lower-layer individual optimizations.

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