15th Triennial World Congress, Barcelona, Spain

INTELLIGENCE AND COOPERATION IN VIRTUAL MANUFACTURING

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Abstract: A "virtual enterprise" results from a temporary agreement among some enterprises, which decide to cooperate together into a given value chain for a limited time horizon. The crucial point in the development of said network is "to search for partners" and organize interactions among firms. In practice, a first problem has to be approached each time a re-organization of the network can be applied, by either including a new component firm or leaving a component to be independent. A second crucial problem refers to an individual enterprise, which has to decide about its own convenience to be a partner in a newtrok. The paper aims to define some criteria for supporting these two design problems. The scope is to have simple conditions able to evaluate if cooperation among potential partner firms could be successfully stipulated,.

Keywords: Negotiation; Cooperation; Production planning; Virtual enterprise.

1. INTRODUCTION

A "virtual enterprise" is a temporary network of firms which decide to cooperate together in a given value chain for a limited time horizon.
More precisely all enterprises which agree to be included into a virtual enterprise and then be active inside the same supply chain, must sign an agreement to cooperating together in defining common production plans for specific products. Obviously, they could also maintain their independence and autonomy for any other production.
Among the different types of agreements, which can generate effective synergy of partners, a potential <u>organization of enterprises</u> can be originated on the basis of their complementarities. In this case, different enterprises, able to produce parts which can be utilized in similar final products, can give rise to a network, often denoted "supply chain" (Tayur et al, 1999; Villa, 2001/a).
This type of agreement presents some particular features of direct interest for several Small & Mid-scale Enterprises (SMEs). On one hand, the agreement can be temporary, because it only involves a part of the core business of any member. On the other, it does not completely reduce the autonomy of each member, since each one can still process proper items and then operate on proper markets. Finally, the agreement can also be used such as a transient situation during which all involved SMEs can verify their effective interest to become a partner in a consortium, for instance, or something else more structured.
Owing to its potential impact on the supply chain management problem, a virtual enterprise organization needs to be deeply analysed and accurately modelled in order to develop methodological tools, which could support its design and management.
Two main problems concerning a virtual enterprise viewed as a time-varying dynamic organization, have to be analysed:

a) when and how an existing virtual enterprise, according to its own *intelligence* of the market evolution, should start a re-organization of its own network of component firms, either with the aim of including a new component firm or reducing the number of network components;
b) when and how an individual firm should start a proper analysis of its own convenience either of being included into a virtual enterprise (thus defing a *cooperation agreement*), or leaving the virtual enterprise of which it has been a component for some time.

The main concept on which all considerations must be based is that the network of component firms can be modelled by a "graph of production services and markets, alternatively connected": each production service

is connected to other services through an intermediate market (Villa, 2000).
Then, a formal model of a virtual enterprise can be defined in terms of a large-scale distributed-control optimisation problem, because each production service (i.e., each component firm) is an autonomous "*agent*" in a multi-decision-makers frame (Cantamessa & Villa, 2001).
Based on said model, the contribution will devote a special attention to analysing the management actions to be applied to a virtual enterprise organized in the form of a Multi-Stage Multi-Firm (MSMF) production system where each production stage, aiming to process specific component parts of the final product, is composed by a number of firms, which can either compete or cooperate together. Between two consecutive production stages, a "negotiation space" exists, here denoted "inter-stage market", in which interactions among suppliers (firms in the upstream stage) and buyers (downstream stage) will occur.
The paper contents are as follows.
Section 2 addresses the problem of designing a virtual enterprise by focusing two steps: the definition of coherent production plans at the different component firms, and the organization of non-conflicting interactions among the firms themselves. Section 3 introduces a model of the production management problem, by presenting a proper mathematical formulation in terms of large-scale production planning task. Section 4 will discuss the above mentioned production planning problem, in order to deriving conditions which can motivate decentralization of sufficient autonomy to local agents. Finally, the concluding Section 5 will propose some conditions for an effective cooperation of the component enterprises together.

2. DESIGNING A VIRTUAL ENTERPRISE

As mentioned above, a virtual enterprise is a network of firms, which agree to partially cooperate together in order to make available all qualifications required to completely processing a given final product.
With reference to a "product tree" (Brandimarte and Villa, 1995) describing all components of the final product and their respective component-to-component relations, each firm to be potentially included into a virtual enterprise must be able to apply some processing capabilities such as to cover a part of the product tree itself. Then each candidate firm will be a potential element of the whole supply chain, thus being assigned to a production stage in the MSMF system.
Owing to its own original autonomy, each candidate firm is characterized by a proper planning objective and by a proper aim to negotiate with its own candidate suppliers (upstream) and buyers (downstream). Then the design of a new virtual enterprise organisation (i.e. of the enterprise network as well as of its management architecture) must solve the following two complementary problems.

<u>Problem A: Cooperative Production Planning</u>. Assign a sufficient local autonomy to each candidate firm (i.e., decentralize) while assuring a sufficient global efficiency to the complete supply chain, but once a real cooperation of all agents together is assured.

<u>Problem B: Inter-stage Negotiation Design</u>. Define efficient-effective negotiation procedures at each inter-stage market space, once each involved agent can autonomously decide about its local production plans.

Problem A can be defined such as to approach the global production planning problem through decentralization, once interactions among suppliers and buyers at each inter-stage market are assumed known. For each pair of consecutive production stages, the Problem B consists of designing the client-server interactions and then describing the inter-stage market operations. The latter problem refers to the design of the virtual enterprise structure whilst the former to the design of its management architecture. Intuitively the complete design of a new virtual enterprise will result from the joint solution of the two mentioned problems, each one dependent on the other.
In order to approach both problems through a common formulation, the design of a virtual enterprise can be stated as the task of optimising a global production management system, composed by a network of several decision-making stages (the local agents). This formulation implies to use a large-scale mathematical optimization model, showing the necessity of minimizing the production costs at each stage for given interactions among the stages themselves.
By analysing the solution conditions of said optimization model, clear suggestions and prescriptions for the virtual enterprise design will follow.

3. MODELING A MULTI-AGENTS MANUFACTURING ORGANIZATION

The goal of the following model formulation is to have at disposal a simplified but adequate description of a set of agents, each one associated to a proper firm into a given network of production stages. As a consequence the model to be developed will be oriented:

(a) to describe the throughput flow from each work shop such as a function of the production rate of the shop itself; the local production rate will specify the control variable at disposal of the local firm manager, and it will also denote the interaction variable of the firm with the other ones in the plant;
(b) to represent the demands for parts flows incoming to each firm from the downstream ones;
(c) to define a significant performance index by which each manager can estimate the local firm efficiency.

The model statement is based on the following notations:
$i\ (=1,\ldots,NA)$, denotes a local agent (firm);
$k\ (=1,\ldots,NP)$, denotes the processed product;

t (=1,…NT), denotes the time step;

x_{ikt} local production rate, the agent assigns to its own firm i for processing products k at time t;

d_{jikt} local inter-firm demand, arriving to the firm i from firm j for processing products k at time t;

d_{ikt} exogenous product demand, arriving to a boundary firm i from external market, for processing products k at time t;

I_{ikt} local inventory;

R_i local production capacity of the firm i;

S_{ijk} transfer rate of product k outgoing from firm j and addressed to firm i;

$A_{jk,down}$ set of downstream firms asking for products k to the firm i;

$U_i(.)$; U performance index of the individual firm i and of the whole manufacturing system, respectively;

c_{ik}, b_{ik} unitary cost to measure the local efficiency at shop i, depending on the inventory and the production rate, respectively.

L, μ_i, λ_i respectively denote the Lagrangian cost and variables to be used for the mathematical statement of the decision-making problem in terms of mathematical optimization problem, as in the following.

Based on above notations, the problem of optimizing the production plans at all component firms of a virtual enterprise can be can be approached in terms of large-scale stochastic Aggregate Production Planning – APP problem (Brandimarte and Villa, 1995).

To account for the modular structure of the virtual enterprise, the basic idea is to apply an APP model for each individual agent within the supply chain, under the assumption of uncertain demands from downstream stages.

The single-agent stochastic APP problem can be formulated as follows (Cantamessa & Villa, 2001):

$$\min U_i ; U_i = \sum_{k=1}^{NP} \sum_{t=1}^{NT} E\{c_{ik} I_{ikt} + b_{ik} x_{ikt}\} \qquad (1)$$

subject to:

$$I_{ikt} = I_{ik,t-1} + x_{ikt} - \sum_{j \in A_{i,down}} d_{ijkt} \qquad (2)$$

$$\sum_{k=1}^{NP} r_{ik} x_{ikt} \le R_i \qquad (3)$$

$$d_{ijkt} = \begin{cases} S_{ijk} x_{jkt}, \\ d_{kt}, \end{cases} \qquad (4)$$

$$I_{it} ; x_{it} \ge 0, \forall i, t$$

where notations have been previously defined.

The formulation of the complete APP problem for the whole supply chain (the MSMF network) will be obtained by composing the set of locxal firm constraints (2)-(4) and adding all cost terms U_i . It can be approached through Lagrangian, being the Lagrangian variables incharged to assuring coordination among individual production policies x_{ikt}.

In mathematical terms, solution of this optimization problem can be derived by solving well known optimization conditions.

But the problem to be approached now is referred to the conceptual utilization of said model to analyze how global and local efficiencies can be affected by the agents' autonomy. Then, the first step must be to recognize how and where the local agent autonomy is considered and described in the model above. If so, the sensitivity of the expected solution with respect to the local agent autonomy can be evaluated.

Once the effect of local autonomy on the global system efficiency has been recognized, the concept of cooperation of several autonomous agents together has to be stated. The motivation is clear: only if a cooperation is assured, a real autonomy can be allowed to local agents without introducing management conflicts.

Finally, if cooperation is assured, a practical solution approach of the complete stochastic APP problem can be searched for. Said approach must be based on the idea that, in any multi-agent system, the global solution will be as closer to the optimal one as better coordination among agents is assured. In fact, if one refers to the significance of Lagrangian variables, an effective coordination can occur if agents can conform their decisions to a more and more accurate estimation of the interaction variables.

Then, instead of directly approaching an extremely complex optimisation problem, it seems convenient in practice to first analyse to which alternative between the two following ones the considered APP problem belongs: either to allow local independent production planning, with autonomous estimation of inputs, or to provide agents with more accurate estimations of local demands (to be computed by a coordinator and then sent to individual agents), depending on the cooperation strenght.

4. REALISTIC COOPERATION OF LOCAL AUTONOMOUS AGENTS

The above mathematical formulation, despite its denomination, states a "*centralized optimization problem*", that means the problem of optimizing a LSS through a decomposition based on the mathematical structure of the constraints;

But the aim here is different from solving this very complex stochastic APP problem, since several solution procedures can be found in the literature.

Now the goal is to show how the global plant efficiency is affected by local autonomy (Villa, 2001/b).

To this aim, let us refer to the global stochastic APP problem. Intuitively, the global production plan (in case local autonomy is allowed to individual agents) will depend on the local inter-firm demands: then, it will be an uncertain strategy. As a consequence, one can affirm that:

"*the approximation of the a priori knowledge of top manager with reference to local agents' de-*

cision is a measure of the local agent autonomy".

In practice, the model of uncertainty associated to local decision-making activity is also a model of the local autonomous decision-making process, as it is understood by the central co-ordination manager.

At the same time, equation (2) can represent a second model of local autonomy, now stated according to the point of view of the individual agent at shop *i* :

The number of alternative local strategies which an agent can apply, depending on it's a-priori knowledge of alternative input scenarios which could occur, is a measure of the local agent autonomy.

Based on this model, the main characteristic of a multi-agent management system can be stated according to the following property:

Property: *A distributed management system, composed by a number of autonomous agents, must be cooperative: each local agent must be allowed to evaluate its own convenience to contribute in improving the global system objective.*

This intuitive concept of cooperation needs to be deeply specified.

Cooperation of several autonomous agents together: *Considering a set of agents, each one characterized by a proper, two types of cooperation among agents can be stated.*

(a) *A weak cooperation among agents can be established if:*
  (i) agents have proper objectives non-conflicting each other and with the overall system objective, and
  (ii) each agent can measure its own convenience to contribute in improving the overall system objective.

(b) *A strong cooperation among agents can be established if:*
  (i) a weak cooperation among agents exists, and
  (ii) between each pair of agents directly related together, the information exchange can generate a precedence relation in the joint decision-making process.

The above stated cooperation concept has already received a number of different application in real industrial situations: for instance, a client-server connection in a production environment is justified by the idea of "strong cooperation", whilst distributed control of traffic lights in an urban area is usually based on the "weak cooperation" concept (Villa, 1991).

Based on these concepts, one can derive the main peculiarity of the global problem solution from noting relations between system complexity (i.e. the number of component centers), uncertainty of the overall system response (then, uncertainty of top manager in dealing with the local agents co-ordination), and cooperation strenght.

Result 1: *The overall system efficiency proportionally depends on the effectiveness of the co-ordination.*

This first result is just a rewriting of an intrinsic peculiarity of the Lagrangian decomposition approach to the LSS decentralized optimization, as stated in the above mentioned books.

Result 2: *As better the coordination operates over the set of agents, as better the estimation of agents' interactions will be.*

Proof comes from a typical character of standard Lagrangean formulation: as greater the co-ordination action is in order to assure optimized interactions, as accurate the interaction variables will result.

In the present application frame, Result 2 suggests clear actions to be adopted by the top management, directed to local agents. Co-ordination indeed can be affected by local uncertainty but it always plays a benefic role: its strength is more and more useful also in uncertain situations.

Result 3: *As better the interactions' estimations are, as better the local efficiencies will be.*

This result directly derives from the above statement of local APP problem.

In practice it means that an efficient management of individual work shops requires a better and better co-ordination performed by the top manager: this appears to be the effectively crucial condition for a continuously improved management of a multi-agents plant.

A final peculiarity can be obtained as direct derivation of the above two results, because they allow to link together global and local efficiencies.

Result 4: *In case Result 3 is assured, then the overall system efficiency positively depends on the local efficiency.*

A more interesting version of Result 4 comes from noting that the "local efficiency" of every agent is directly related to the agent's autonomy, as we have discussed in previous Sections. As it has been observed several times, autonomy pushes agent to be motivated in his own decision-making activity, then it forces agent to be efficient.

Then Result 4 can be rewritten as:

Result 4-b: *"The overall production system efficiency as much increases as much autonomy of local agents is guaranteed".*

5. SOME COOPERATION CONDITIONS

The two concepts of "local autonomy" and "cooperation" suggest to analyze how a centralized management strategy for a large-scale network of firms can be substituted by a distributed management architecture, i.e. a set of local and cooperative strategies.
Some measures of the a-priori either weakness or strength of the potential cooperation between two *complementary agents* (i.e. agents candidate to be connected in a buyer-supplier link within the supply chain of a virtual enterprise) can be introduced (Villa, 2001/c)

Definition 1: Given two complementary agents with proper performance measures defined by an integral form including several elemental costs of different types (as in (1)), the *likeness* of the two respective performance measures is given by the relative number of common elemental costs.

In formal terms, considering two agents *a* and *b*, with individual performance measures defined by:

$$J_a = \sum_{k=1}^{NP} \left[PI_a(k) * I_a(k) \right]$$

$$J_b = \sum_{k=1}^{NP} \left[PI_b(k) * I_b(k) \right]$$

where:
PI_a (PI_b) are the potential elemental costs, which can be included in a general formulation of the agent performance measure;
I_a (I_b) are the zero-one "selection constants", i.e. if $I_a(k)=1$, then the *k*-th elemental cost is included in the performance measure of agent *a*,

then the likeness of the two agents is computed by:

$$SI_{a,b} = \frac{1}{NP} \sum_{k=1}^{NP} \left[I_a(k) * I_b(k) \right] \qquad (5)$$

Definition 2: Considering two consecutive stages *i* and (*i+1*) in a MSMF network, said stages only include either pairs of two complementary agents or terminal agents (i.e. agents with none inter-stage connection). Then, the *likeness* of the consecutive stages is measured by the average likeness of the pairs of complementary agents there included.

Rule 1: Given two consecutive stages in a MSMF network, their relative likeness is as greater as the average likeness of the pairs of included complementary agents approaches 1.

Definition 3: Given two consecutive stages *i* and (*i+1*) in a MSMF network with its proper set of interconnecting links (the common information pattern), the *wideness of the information exchange* is given by the rate of the number of active connections among the complementary agents there included, with respect to the number of connections which could be potentially activated among agents.

In formal terms, it holds:

$$AI_i = (N° \text{ active links}) / (N° \text{ potential links}) \qquad (6)$$

Rule 2: Given two consecutive stages *i* and (*i+1*) in a MSMF network, their relative wideness of the connecting information exchange is as greater as AI_i approaches 1.

Definition 4: Given two complementary agents *a* and *b* with proper production capacity at disposal, which bounds admissible production rates (as in (3)), the *dominance* of an agents over the other is measured by the rate of its own capacity value with respect to the capacity value of the other agent.

In formal terms:

$$DI_{a,b} = R_a / R_b \qquad (7)$$

where:
R_a (R_b) denote the respective maximum production capacities of the two complementary agents, defined as in (3)

Definition 5: Considering two consecutive stages *i* and (*i+1*) in a MSMF network as defined by Definition 2, then the *dominance* of one stage (e.g. stage *i*) over the other (e.g. stage *i*+1) is measured by the average values of dominance between the pairs of complementary agents included in the two consecutive stages.

Rule 3: Given two consecutive stages *i* and (*i+1*) in a MSMF network, the *dominance equilibrium* of a stage (e.g., stage *i*) over the other is as greater as DI_i approaches 1.

Consequence 2: Considering two consecutive stages in a MSMF network, their potential cooperation is as stronger as better all the measures of likeness, wideness of the information exchange and dominance equilibrium will approach 1.

6. CONCLUSION

The proposed measures of relative likeness, wideness of the common information pattern and dominance equilibrium can offer evident suggestions to the agents, which aims to generate together a virtual enterprise in the form of a MSMF network operating such as a wide supply chain. The resulting design suggestions can drive agents in selecting either independent but naturally coordinated policies (in case relative measures will approach 1) or exogenously coordinated strategies, otherwise.
Obviously a wide range of different situations can occur in real multi-stage chains.

As an example, when considering two consecutive stages of a MSMF business line, the structure of the connecting information pattern must be better detailed. For istance, in case of two consecutive stages, situations of the following types can occur:

- if $AI_i = 1$, then we can still have competition between buyers in case the value of the "internal *AI*" at stage *(i+1)* is approaching zero;
- if the value of the "internal *AI*" at the stage *i* is approaching 1, then a case of "industrial cartel" can occur.

This simple example shows that the above introduced concepts and proposed measures of strong (weak) cooperation surely represent useful concepts for offering suggestions in the design of a virtual enterprise, but further research efforts are needed.

First of all, a classification of the potential information patterns must be completed, such as to denominate different situations of cooperation, conflict, dominance, competition. Then relations among the different information patterns and values of the measures of likeness and dominance have to be stated. Once such classifications will be at disposal, designers and managers will be able to select the best-suited connections before to approach the planning problems, thus avoiding the present hard complexity of the complete supply chain design and management task.

Acknowledgements: This research has been partially supported by the Italian Ministry of University and Technological Research, within a national research programme 40%.

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