An Agent-based System for Sales and Operations Planning in Manufacturing Supply Chains

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Abstract: - A major problem faced by manufacturing organizations is providing efficient and cost-effective responses to the unpredictable changes taking place in global markets and in supply chains. Sales and Operations Planning helps giving better customer service, lower inventory, shorten customer lead times, stabilized production rates. Sales and Operations Planning provides top management with a handle on the business, supporting a company to get and keep demand and supply in balance over time. This paper proposes an approach that would enable small and medium manufacturing organizations to dynamically achieve cost-effective aggregate sales and operations plans exploiting two emerging concepts: agent-based agile manufacturing systems and e-manufacturing. A complex manufacturing system and its supply network is modeled as a multi-agent system and scenarios with respect to the balance between supply and demand are dynamically simulated through the coordinated interactions amongst agents. This paper presents the main features of the proposed system and it finally discusses the benefits highlighted by its application in real industrial contexts.

Key-Words: - Supply Chain Operations Planning; Multi-Agent System; Intelligent Manufacturing; Agile manufacturing

1 Introduction

Sales and Operations Planning (SOP) is a process to help giving better customer service, lower inventory, shorten customer lead times, stabilized production rates, and to give top management a handle on the business. According to several authors [1], the process is designed to support a company get demand and supply in balance and to keep them in balance over time putting the operational plan in line with the business plan. This balance must occur both at an aggregate level, i.e., at the level of major groups of products, and at the detailed individual product level. In addition, the available total capacity must never be exceeded over time. Since the demand is dynamic, it is important monitoring the expected needs from 3 to 18 months or further in the future; in fact a typical corporate plan contains a section on manufacturing that specifies how many item units must be produced in each major product line over the next 12 months to meet the sales forecast. Provided that the organization has enough aggregate capacity, the individual product planners determine the daily and weekly launching of individual product orders to meet short-term demand taking into account aggregate capacity constraints. The main purpose is to identify aggregate plans, i.e. the so-called Master Production Schedule (MPS), specifying the optimal combination of production rate, resource capacity, inventory on hand, and backordering costs [2]. The MPS is used to feed the master-planning phase, i.e., both Material Requirement Planning / Capacity Resource Planning (MRP/CRP) and Available To Promise / Capable To Promise (ATP/CTP) modules. Even though the aforementioned phases could be accomplished manually, the time required to elaborate several alternative scenarios is considerable. Furthermore, changes in delivery plans or urgent orders require a rapid partial or total regeneration of mid-term plans in order to react timely to market. Therefore, SOP is considered a heavy duty for single manufacturing organization. What about SOP in manufacturing Supply Chains (SC)? Supply and demand balance seeks solutions through the integration, optimization and alignment of operations across the entire SC at the enterprise level [3]. Unfortunately, the complexity level increases as the number of nodes in the SC increases, becoming soon uncontrollable, at least for human decision makers. Supply Chain Management

(SCM) systems address these issues integrating Enterprise Resource Planning (ERP) systems and Manufacturing Execution Systems (MES). In recent years, ERP systems have been implemented in many manufacturing firms [4]. Several companies selling ERP packages now include optimization facilities based on powerful operational research approaches to help improving the quality of operations planning and scheduling [5]. However, these optimizers are usually expensive and need sophisticated ERP platforms to work on. These requirements are not suitable for a large set of small and medium enterprises (SME), aiming at facing Supply Chain Management (SCM) issues. SME usually would operate according to the agile manufacturing paradigm. Agile manufacturing aims at providing manufacturers with the methodologies and systems to rapidly and cost-effectively respond to changes that take place in the manufacturing environment [6]. They would like to be supported by simple to use but effective information management systems, avoiding complex mathematical formulation requiring formal resolution methods. Agent technology provides a natural way to address such problems, and to design and implement efficient distributed intelligent manufacturing systems; hence, multi-agent systems (MAS) have been recognized as one of the technologies that would facilitate agile and intelligent manufacturing by providing manufacturing enterprises with the capabilities to meet the ever-increasing needs for flexibility, robustness and adaptability to the rapid changes occurring in the manufacturing environment [7]. The Supply Chain Operations Planning (SCOP) system presented in this paper has been designed and developed through the collaboration with an Italian software vendor of Advanced Planning Systems (APS) to harness the strengths of two manufacturing paradigms such as agile manufacturing and multi-agent systems. The proposed SCOP system deals with multi-site production, dynamic allocation, and multiple constraints allowing decision makers to execute a performance driven scenario-based analysis. The decision makers act on different parameters and negotiation rules, used by the involved agents, so deriving different scenarios that are then evaluated in terms of performance indexes. The rest of the paper is organized as follow. Section 2 introduces a formal description of the considered SCOP problem. Section 3 describes the proposed approach, and Section 4 provides a general discussion of its application in real life manufacturing contexts. Finally, Section 5 draws some conclusions.

2 The Supply Chain Planning Problem

The main characteristics of the considered Detailed SCOP (DSCOP) problem, consisting in a dynamic multi-site production planning over a rolling horizon, are illustrated in this section. A SC system corresponding to a multi-site production context is assumed. In particular, the multi-site structure can be associated with the various levels characterizing the production of the different items needed for manufacturing the finished products (end items) of the whole supply chain. Each production site is responsible for the production of a subset of items that, generally, are in turn composed by other component items and must be used for the production of other child items. The independent (exogenous) customer demand of end items then generates a dependent (endogenous) demand for the component items needed at the various level of the SC. Each production site is composed by a set W of work centers owning the resources used to manufacture some kinds of item. Therefore, the whole production system can be viewed as a three level resource hierarchy rooted by the whole multi-site system and including plants at the second level and the work centers at the lower one.

2.1 Modeling assumptions

A planning period of length T is assumed and planning decisions must be taken in correspondence of time periods (also so-called *time buckets*) $[t, t+1]$, $t=0, 1,\ldots,T$. Note that the adopted time scale is arbitrary and may be adapted to different production scenario (e.g., the unitary time bucket length may correspond to any fixed Δt). Note also that usually the DSCOP should be dynamically solved on a rolling planning horizon H, i.e., revising the plan every H periods to take into account of changes, as for example new customer order arrivals. Let I the set of items that can be produced in the supply chain system, including both component and end items. The orders for end items received from the system customers are assumed known at the beginning of the planning period; note that the demand may correspond to actual orders or forecasts. A set of orders identifies for any end item $i \in I$ and any time $t \in [0, T]$ a demand D_{it} denoting the quantity of i requested at due date t. In general, the demand for an item $i \in I$ can be assigned to a subset of sites composed in turn by one or more work centers owning the resources needed for the production of i. Then, the sets S_i and W_{si}, with $s \in S_i$, represent respectively the set of sites and work centers within a site compatible with the production of item i.

Each order demand D_{it} can be in general split in a set of n_i lots of size L_i such that $L_i \geq L_{i,min}$, being $L_{i,min}$ a specified minimum lot size for i, and $D_{it} = \sum_{h=1}^{n_i} L_i$. Then the decision about the production order i correspond to the decision about the associated lots. However, note that, for the sake of simplicity, in the formal problem definition we will continue to refer to the production of the whole item orders. A fundamental difference between the considered DSCOP and the SCOP described in the literature (e.g., in [8]) is the necessity of determining the assignment of item orders first to the compatible sites and then to the work centers within the sites. A planned lead time p_i is assumed for each item $i \in I$, corresponding to the estimation of the production time needed to complete the item, having assigned to the production of i the required resource capacity q_i (note that the planned lead times can be periodically revised according to the actually measured lead times). As planned lead times are in general longer than a single time period, the production of the items is executed on a sequence of consecutive buckets (*multi-period production*). A further relevant difference among the classic SCOP and the DSCOP here considered is that the assignment of orders to sites and work centers can be changed over the planning period: in particular, it has been assumed that the production of an order started in a work centre can be completed in a different work centre included in the same site with a negligible transfer cost, whereas a fixed transfer cost tc_{rs} is paid for each order moved from site r to site s. Taking into account the production structure of the considered items, a *Bill Of Material* (BOM) $M=[m_{ij}: i,j \in I, i \neq j]$ matrix, whose elements denote the number of unit of item i needed for the production of item j, is specified. Then, given the set of end item orders characterized by their due dates, the endogenous gross demand for component items is generated by a backward BOM explosion. Note that raw material requirements are dealt with as demand for special items requested to external sites, i.e., not included in the controlled supply chain system. Each work centre $j \in W$ includes a set of production resources in general corresponding to machines, tools, personnel and so on; an available maximum capacity c_{jt} is defined for work centre j which may depends on the time period t considered.

In general the production of an order for an item may be on-time (i.e., completed at the required due date), early or tardy: in case of early production the order is not delivered before its due date and a unitary inventory cost α_{it}, which may depends both on the item and the time period, is charged; on the other hand, tardy delivery are allowed incurring in a unitary backorder cost β_{it} for item i at period t.

2.2 DSCOP formal statement

The objective of the DSCOP problem is determining a plan for the multi-site production system corresponding to a MPS, that is, an assignment over time to the work centers of the item orders needed to satisfy the customer demand, taking into account the capacity of the available resources and minimizing a (weighted) sum of all the cost incurred. The formal statement of the DSCOP problem then is the following. Given the demand D_{it} for each item i and period t in the planning horizon that extends over T periods, determine the production level Q_{it}, inventory level Y_{it}, and capacity level C_{jt} for each work center $j \in W$, and for each period $t = 1, 2, \ldots, T$ that minimize the relevant costs over the planning horizon. In particular, the solution must determine for any $i \in I$ and any time $t \in [0, T]$:

- the item order time planning Q_{it}, i.e., the specification of the quantity of item order i that must be completed at a given time t (note that this corresponds to specifying the dimension L_i and the number n_i of lots for each item order i);
- the level of inventory Y_{it}, i.e., within period $[t, t+1]$;
- the gross requirement G_{it};
- the backorders B_{it};
- the capacity level C_{jt};
- the site and work centre assignment, respectively X_{its}, $s \in S_i$, and X'_{itw}, $w \in W_{si}$
- the work centre capacity allocation V_{itw}, $w \in W_{si}$, $s \in S_i$

The cost to be minimized corresponds to the sum of inventory, backorder, production and transfer costs, in particular:

$$Z = \sum_{t=0}^{T} \sum_{i \in I} (\alpha_{it} Y_{it} + \pi_{it} Q_{it} + \beta_{it} B_{it} + \sum_{s \in S_i} f_{is} X_{its} + \sum_{w \in W_{si}} f'_{iw} X'_{itw}) + \sum_{i \in I} \sum_{s} \sum_{r:r \neq s} tc_{sr} \cdot Tr_{isr} \qquad (1)$$

where π_{it} is the unitary production cost of item i in period $[t, t+1]$, f_{is} and f'_{iw} the assignment costs of item i respectively to site s and work centre w, whereas X_{its} and X'_{itw} the corresponding binary assignment variable, and finally Tr_{isr} a binary variable used to indicate if the production of an item order i is moved from site s to site r.

3 The Proposed Approach

In designing the approach presented here we would agree with the Proud's standpoint [2], which considers the planning process a tool through which the four cornerstones constituting each manufacturing supply chain system, i.e., customers, resources, products and suppliers, can be connected. On the basis both of agility requirements and the above standpoints, we design an approach allowing planning a multi-site manufacturing supply-chain by adopting a multi-agent architecture [9].

3.1 The Agent Architecture

A spurious control structure using a semi-hierarchical architecture with two different levels is adopted [9]. Since the proposed system is devoted to real industrial applications, a trade-off to balance the quality and speed of the system's responses has been investigated. This led to the simple but quite effective architecture showed in figure 1. Given a set of demands, the requests are sequentially processed, according to a priority list. The adopted priority rules are usually defined by the planner and are generally based on some common practice. In this way, the system favors demands processed first and gradually penalizes the following ones since the availability of the resources for processing these latter is progressively reduced by the assignments to previous ones.

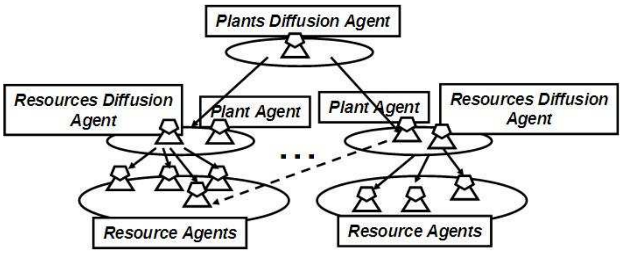

Fig.1 - The multi-agent system architecture.

Given the demand D_{it} for each item i period t, a Demand Agent (DA) deals with the Plant Diffusion Agents (PDA). According to plant capabilities, the PDA requests several Plants Agents (PA) to explore their own Resource Agents (RA) in order to build a bid for the item to be manufactured. Then the PDA evaluates the collected bids and selects the best proposal that communicates to the Demand Agent (DA). The PDA acts as a supervisor and a switch within the control system, selecting messages to be exchanged among different kinds of agents and evaluating bids according to some performance index (in our case the equation (1)). The negotiation protocol is represented in figure 2 of Appendix A.

3.2 The System Decision Variables

Whenever multi-agent architectures including supervisor agents are considered, their performances are usually influenced by the opportunities offered to the agents in generating different alternative bids. These opportunities, corresponding to decision variables, can be summarized in four different categories:

1. Plant manufacturing capabilities;
2. Lot size for item orders splitting;
3. Alternative routings on site resources;
4. Anticipation or delay of capacity allocation.

The first category can be evaluated by a *what-if analysis* varying the technological capabilities associated with each plant. Lot sizing, which determines the number of lots composing an order item (D_{it}), affects the planning flexibility in allocating working capacity. Alternative routings clearly increases the possibility to find work centers with the required capacity. Finally, anticipation or delay provides a further degree of freedom in finding a feasible capacity allocation. The rest of this section describes the way the opportunities (2, 3, 4), are used in the proposed system.

3.2.1 Lot sizing for item orders splitting

A demand D_{it} expresses the total quantity of item i requested at time t, which corresponds to a requested working capacity q_i on the compatible work centres in S_i. In general, the allocation of q_i could exceed the available capacity at given time t for a work center. Then a suitable strategy is to split q_i into a set of smaller dimension lots. In fact, the greater is the item quantity of a D_{it} the smaller are the chances to find a feasible allocation on a work center pool, satisfying the imposed constraints. On the other hand, too small lot sizes generate not acceptable set-ups and reordering costs. For this reason a trade-off has to be determined in order to balance planning flexibility provided by small lot dimension with costs due to splitting. The proposed approach allows splitting a demand D_{it} in a set of n_i lots of size L_i. The size of these lots can be determined through the scenario based-analysis capability of the proposed approach. Such an analysis is performed starting from a minimum lot size for each item i that is progressively increased it of a fixed step evaluating the consequent performance variation according to (1). The concept used by the proposed system can be described with an example showed in figure 3. Let us assume a constant demand for each bucket (the black thick line, Demand Flow, it is a theoretical representation of a one single piece flow production). Satisfying such demand would require a pure agile SC system, able to manufacture continuously variable lots in order to constantly chase the demand considering negligible set-up costs; in this case the SC system would be able to fulfill such demand producing at the same demand rate, with minimal (null) inventory and backlog costs. Nevertheless, in real life industrial contexts economic and production order lots have to be considered. Figure 3 shows (the step-wise blue line), the profile of the cumulative economic production lot for the constant demand flow, which would characterize the optimal production of a system with unlimited capacity. However, if the available capacity is limited, alternative routings and/or production anticipation/delay become necessary. In the figure 3 the step-wise dark black line is a possible production profile generated by the agent negotiation. In particular this profile is associated with a demand split corresponding to the economic production lot: production anticipations are highlighted by dashed arrows, whereas delays by round-dotted arrows. Note that the maximum anticipation and maximum delay are constrained respectively by the maximum inventory level (gray line) and by the maximum backorder time (red line).

3.2.2 **Alternative routings and capacity allocation**

As stated above, the adopted multi agent system is based on Supervisor Agent, which corresponds to the PDA. This agent manages the negotiation process, driven by a rule-based approach, amongst Resource Agents (work centers) of each manufacturing site belonging to the SC. The human planner must define a list of rules, choosing for each rule the values of several parameters as well as selecting alternative agents' behaviors. The MAS planning engine proceeds considering the rule according to their priority order, and elaborates for each rule an alternative-planning scenario providing the resulting performance index to the decision maker. The rules priority can be, for example specified, to incrementally relax the constraints in order to increase agents' opportunities of providing valuable bids. A rule can include evaluation methods (i.e. balancing workload over resources) to guide Supervisor Agent in bid selection activity. The rules also define how to explore resource availability over space (alternative routings) and time (anticipation and delay). The degree of freedom allowed for space exploration refers to the possibility of using a resource different from the one a priori specified as preferred (checking the capability compliancy), included in the same plant or in a different site (in this last case a transport mission is evaluated according to a planned lead time and the cost computed). The space exploration allows the planning engine to resolve capacity unfeasibility at a given time. The alternatives relevant to time exploration correspond to the possibility of anticipating or delaying a work load on a resource (typically anticipation is the default choice), within a range defined respectively by a maximum anticipation time and the corresponding inventory level and by a maximum admissible backordering time. The time exploration allows the planning engine to resolve capacity unfeasibility on a fixed resource. The planners, according to best practice common criteria, can combine exploration over space and time; he/she must also define the maximum admissible inventory level, and the maximum backordering time for each item *i*. Note that the proposed system includes a rule builder user interface trough which is possible to define even complex multi-level conditional rules reflecting decisional processes typically performed from SC planners.

4 Discussion

It is apparent that the approach to the DSCOP here presented corresponds to an heuristic method based on a decomposition of the decision process in a number of cooperating actors (the agents) playing different and complementary roles. We should note that exact optimization approaches to the DSCOP are also possible (e.g., based on mixed integer programming models). Nevertheless, the dimension of the problem instances considered in real industrial context, that is, the number of items manufactured, of different sites belonging to a supply-chain and of the alternative routings to be explored is generally so high to make most of the time impractical the use of exact algorithms. In contexts with a flexible production mix, with flexible routings and assignments to be made in a multi-site supply chain, the use of a multi-agent architecture including supervisor and switch agents can successfully generate feasible plans incorporating decision maker's experience in the form of rules. This type of architecture provides solutions that can be explicitly understood and thus adopted by the planners since system agents "incorporating" the decision-maker's experience can drive negotiations towards an "expected-acceptable" solution hopefully near optimal. This is the type of approach generally preferred small and medium size organizations. The research here presented focused on the integration of agent-based planning with existing systems used in manufacturing enterprises (in particular with ERP and MRP systems), and has been validated in industrial settings. The above claims are based on the following features emerged from the experience gathered during the implementation of the system in several industrial contexts:

- A agent architecture able to model medium multi-site and multi-distribution organizations;
- A meaningful representation of products structure through the use of family bills and bill of materials;
- Flexibility in managing shifts, working periods, overtime costs, exceptions, and bucket dependent resource capacity;
- Easy management of physical and logical constraints (productive and logistics);
- An extensive use of multiple in-memory simulation scenarios to facilitate the comparison of different strategies and the impact of manual modifications.

5 Conclusion

The proposed system is devoted to manage a Dynamic Supply Chain (DSC), with respect to internal and external resources, over a multi-site manufacturing network. The designed allocation engine is based on a backward allocation procedure and it dispatches demand to production sites taking into account the limited resources capacity and trying to minimize the total aggregate cost. The proposed system can support companies in dealing with SCOP problems through the evaluation of costs incurred in anticipating or delaying production activities, as well as in showing evidences of conflicts between commercial needs (demand fulfillment) and multi-site/multi-supplier constrained supply-chain network. The industrial adoption of this system appears to be still limited to the simplest functionalities. Anyway authors are improving the system by developing a new bidding process to fix drawbacks caused by fixing a sequential order for rule invocation, which strongly influence the order assignment to resources.

References:

[1] G. E. Palmatier with Coleen Crum, *Enterprise Sales and Operations Planning*, J. Ross Publishing, 2002

[2] J. Proud, *Master Scheduling: A Practical Guide to Competitive Manufacturing*, Wiley, 1994

[3] J. J. Kanet, W. Faisst and P. Mertens, Application of information technology to a virtual enterprise broker: The case of Bill Epstein, *International Journal of Production Economics*, Volume 62, Issues 1-2, 20 May 1999, Pages 23-32

[4] M. Kennerley and A. Neely, Enterprise resource planning: analysing the impact, *Integrated Manufacturing Systems*, Volume 12, Issue 2, 2001, Pages 102 -113

[5] A. G. Robinson and D. M. Dilts, OR & ERP: A Match for the New Millennium?, *OR/MS Today,* 1999, Volume 26, Issue 3, Pages 30-35

[6] M. Paolucci, R. Sacile, *Agent-Based Manufacturing and Control Systems: New Agile Manufacturing Solutions for Achieving Peak Performance*, CRC Press, 2004

[7] W. Sheng, Q. Hao, H.J. Yoon, D.H. Norie, Applications of agent-based systems in intelligent manufacturing: An updated review, *Advanced Engineering Informatics,* Vol. 20, 2006, Pages 415-431

[8] J.M. Spitter, C.A.J. Hurkens, A.G. de Kok, J.K. Lenstra, E.G. Negenman, Linear programming models with planned lead times for supply chain operations planning, *European Journal of Operational Research,* Vol. 163, 2005, Pages 706–720

[9] R.J. Rabelo, L.M. Camarinha-Matos, H. Afsarmanesh, *Multi-agent-based agile Scheduling*, *Robotics and Autonomous Systems,* Vol. 27, 1999, Pages 15-28

A Appendix

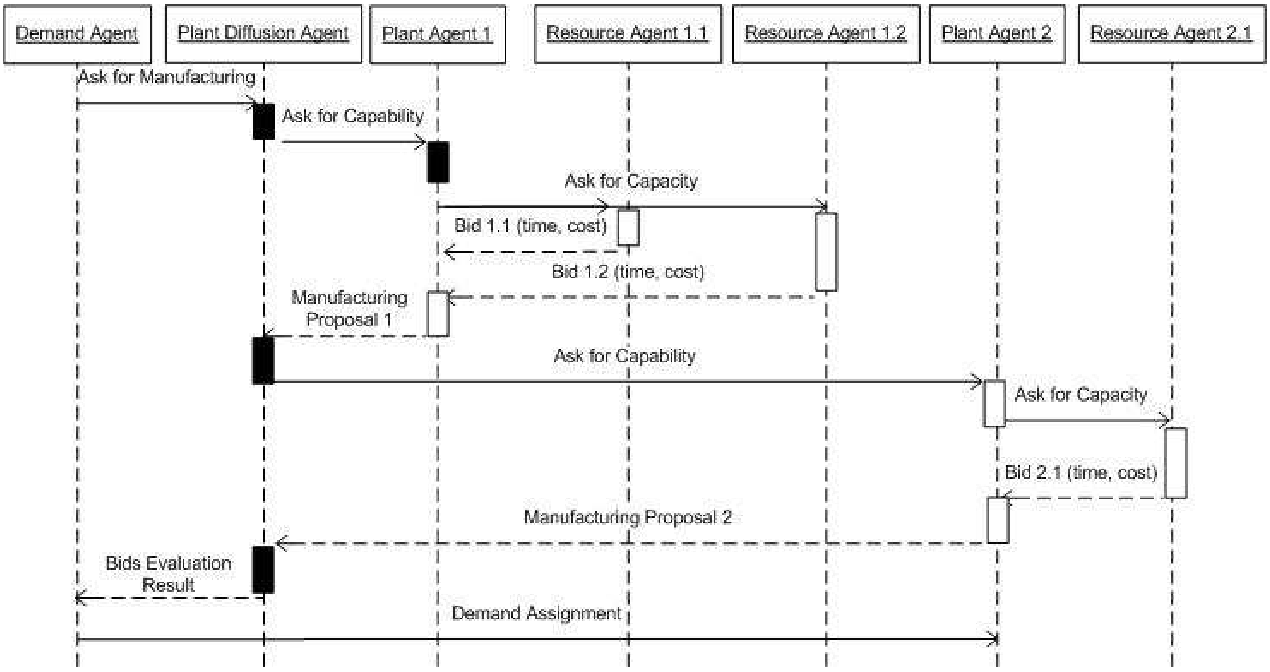

Fig.2 – Agent Negotiation Protocol

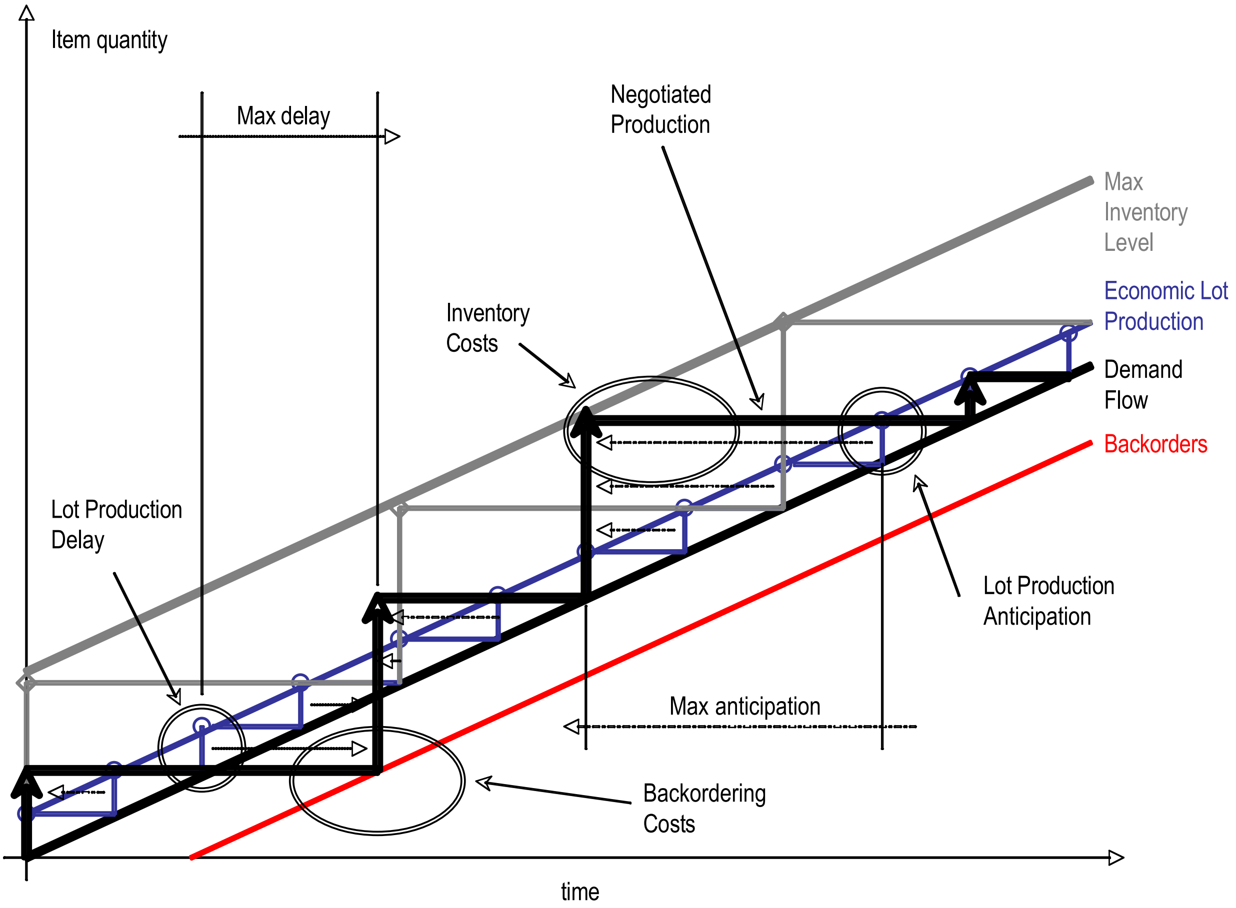

Fig.3 – An example of capacity allocation corresponding to a constant demand