On the Configuration and Planning of Dynamic Manufacturing Networks

Nikolaos Papakostas, Konstantinos Efthymiou, Konstantinos Georgoulias and George Chryssolouris

Abstract Manufacturing organizations have been attempting to improve the operation of supply networks through efficient supply chain management. Dynamic Manufacturing Networks (DMNs) constitute chains of diverse partners, whose operation and interaction may change in a rapid and often not predictable way. While the existing supply chain models are quite static, and examine transportation modes, product changeover and production facility options with fixed suppliers and over a long period of time, the DMNs address operations and risks on a daily basis. In this paper, a novel decision-making approach is proposed for supporting the process of configuring a DMN from a holistic perspective, taking into account production, transportation and time constraints as well as multiple criteria, such as time and cost.

1 Introduction

In a volatile market environment, today's manufacturing organizations strive to improve their performance, whilst providing customers with more customization options [1]. The main classes of attributes to be considered when making manufacturing decisions, i.e. cost, time, quality and flexibility, are closely interrelated and have been investigated towards optimization, in an attempt to improve product quality, to confront market competition, to shorten lead times, as well as to reduce

This contribution was previously published in Logistics Research (2012) pp. 105–111.
DOI:10.1007/s12159-012-0086-9.

N. Papakostas · K. Efthymiou · K. Georgoulias · G. Chryssolouris (✉)
Laboratory for Manufacturing Systems and Automation, Department of Mechanical Engineering and Aeronautics, University of Patras, Patras, Greece
e-mail: xrisol@lms.mech.upatras.gr

K. Windt (ed.), *Robust Manufacturing Control*, Lecture Notes in Production Engineering,
DOI: 10.1007/978-3-642-30749-2_18,

costs. These aspects constitute the main reason for the increasing complexity met in modern manufacturing systems. Controlling this complexity with conventional methods, such as the approaches based on Manufacturing Resource Planning (MRP II) principles and concepts, require more and more data and is becoming extremely difficult to manage. One of the top business pressures, dealt by enterprises, is the need to react to demand changes in a timelier manner. Further to having to address the increase in year-over-year fulfillment and transportation costs per unit, companies have been attempting to improve the cross-channel supply chain flexibility in order to achieve a faster reaction to demand changes and to improve supply chain responsiveness [2]. Manufacturing companies should be able to quickly restructure or transform the supply chain execution (source–deliver processes) in response to an evolving global, multi-channel supply chain scenario. However, a lot of companies still do not have the ability to respond to dynamic demand cycles, while, at the same time, the increased globalization pushes the demand uncertainty at even higher levels [2]. In the retail domain, for instance, the demand has been so uncertain in the time span between mid 2010 and end of 2011 that the volume of inventory has either been too high or too low [2]. The recent events, concerning the volcano's eruption in Iceland and the nuclear disaster in Fukushima, have reaffirmed the need for greater flexibility in order for manufacturing organizations to cope with the dynamic nature of the market and its fluctuations.

At the same time, the existing, off-the-shelf Supply Chain Management software platforms and tools are too expensive to be implemented and deployed at a broader networked enterprise scale, including smaller companies with limited Information and lower Communication capacity, and are unable to:

- Cover all actual phases of a manufacturing network lifecycle and
- Cope with the highly dynamic and uncertain nature of demand.

It is not enough for today's manufacturing enterprises to be networked: they have to be able to change and adapt to a continuously evolving environment and to form dynamic alliances with other companies and organizations in a fast and cost-efficient manner.

2 Current Approaches for Manufacturing Network Management

The variations at trade barriers level and the worldwide evolution of the transportation and communication means have led to the globalization of manufacturing activities [3]. New global strategies have pushed forward the internationalization of manufacturing systems [4]. The manufacturing landscape has become more competitive, dynamic and complex.

A large number of studies have addressed various aspects of the supply chain management problem. The initial configuration of supply chains and the selection of partners constitute one of the most critical phases in the lifecycle of a supply network.

A few research efforts have proposed the use of mixed-integer mathematical models with the objective to maximize profits or minimize the overall supply chain operation costs [5]. Others have focused on the identification of the optimum transportation modes for minimizing the total transportation and inventory costs, including those addressing multi-product cases for identifying optimal shipping times and loading policies [6]. Production planning and transportation problems have also been addressed jointly [7]. Another stream of research work has dealt with the problem of having the supply chain flexibility increased, whilst retaining the capability to produce towards satisfying demand, by leveraging the alternative supply chain options and the routing flexibility within a pre-defined planning horizon [8]. The problem of locating or relocating production facilities for satisfying the varying local demand has also been modeled by a few researchers. In some cases, transportation mode and product switching decisions have been addressed jointly [9, 10].

Collaborative planning of fixed supply networks is another issue that has attracted the interest of many research teams. The objective is to align the plans of the individual supply chain partners and coordinate the production of the supply chain towards achieving a series of common, or in some cases partner-specific, objectives [11]. Hierarchical approaches, initiated by the Original Equipment Manufacturer (OEM) have also been proposed, where each partner's tier performs all production planning activities and then provides these plans to the next tier for carrying out its own process of production planning, until all tiers have completed their production planning activities [12]. Merging the planning activities of several partners into one planning domain may improve the results of the upstream collaboration [13]. Negotiation-based collaborative planning approaches have been reported, focusing on the use of upstream planning at the beginning and then on the employment of a negotiation process in order for the overall performance to be improved [14].

The vast majority of the research work reported, dealing with the supply chain management and optimization, dealt with very specific parts of the phases of a supply chain lifecycle. A few recent studies have dealt with the challenges related to each phase of the supply chain lifecycle in a more integrated manner. The combined problem involving multiple transportation modes, diverse supply chain flexibility options and dynamic facility locations has been tackled in [8], experimenting with different adaptability schemes of a supply chain.

In [4], the integrated planning and transportation problem is addressed, proposing a mathematical model with production and transportation capacity constraints.

In general, so far, the approaches towards managing supply chains have dealt with static instances of their operation: parts or the entirety of the supply chain model are fixed and only a few alternative options are available. A few attempts deal with different transportation modes, some others take into account alternative facility locations and product changeover options and very few, in principle the recent ones, propose a more sophisticated methodology in order for more facets of the problem to be addressed simultaneously.

Our modeling approach allows for the formation of alternative dynamic production network configurations as well as for their validation via simulation in a series of network and demand settings, ensuring that the network be adaptive and capable of addressing the demand requirements. It may take into consideration partners who have not been part of the network in the past, requiring minimal information from their part regarding the initial configuration and planning of the manufacturing network. This way, a significant number of suppliers may be considered initially and therefore the chances towards achieving an adaptive network configuration are significantly increased. At the same time, the uncertainty related to the demand, the production process and the transportation of products, subassemblies and parts may also be considered, so that the risks regarding the operation of the network be taken into account.

The development of highly adaptive manufacturing networks is a very important objective in today's volatile environment. The proposed approach employs an integrated holistic view of the network and attempts to evaluate the performance of the network against multiple criteria, such as time and cost. At the same time, it offers a mechanism for generating, evaluating and ranking a set of alternatives, so that the stakeholders involved be provided with more options, when having to decide about the configuration of a manufacturing network.

3 Dynamic Manufacturing Networks Modeling

The manufacturing networks have to be more adaptive to the fluctuating demand in order for a more responsive and efficient operation to be achieved. Towards this direction, a new modeling approach, employing a holistic view of the overall network performance, is proposed. The major steps are depicted in Fig. 1.

The principle objective is to use minimal information, so that potential partners with minimal Information and Communication capacity may take part in a Dynamic Manufacturing Network (DMN).

3.1 Information Requirements

This approach requires that some minimal information regarding the production orders and the partners' capacity and network be available, in order for different alternative DMN configurations to be generated and evaluated.

Assuming that:

- S: The overall number of partners (including manufacturers, suppliers and customers),
- P: The number of products, subassemblies and parts,
- O: The overall number of orders,
- M: The number of different modes of transportation (e.g. ground, air, etc.),
- t: The time unit (e.g. day, shift, hour, etc.), $t = 1 \ldots T$,

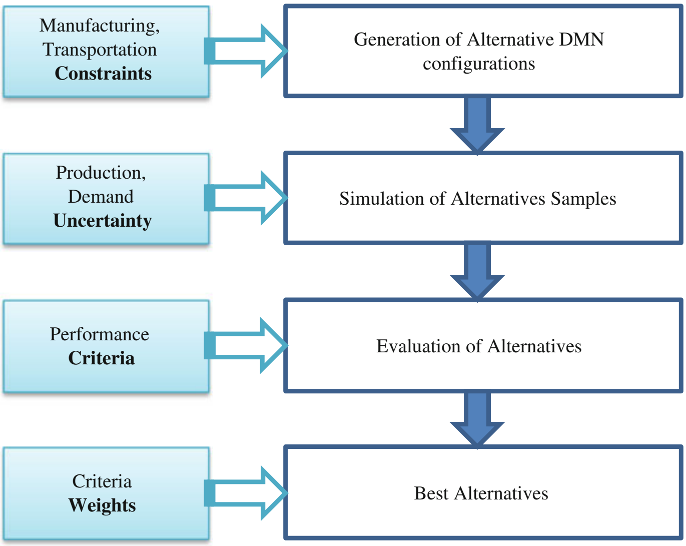

Fig. 1 Overview of the proposed approach

- T: The scheduling horizon,
- A: The number of alternative DMN configurations to be generated,
- N: The number of samples (simulation runs) for each alternative,

the following information is required:

- PP_{ij}: This variable represents the bill of materials (BOM) of all products, subassemblies and parts that may be produced or are available; when $PP_{ij} = 1$, with $i = j$, product i does not require other parts for being produced.
- SPC_{sp}: The cost of manufacturing one unit of product p in partner s.
- SPI_{sp}: The inventory cost per unit of product p in the facilities of partner s.
- $SSR_{ss'pm}$: The cost of transferring one unit of product p from partner s to partner s' using transportation mode m.
- $SST_{ss'pm}$: The time required for transferring one unit of product p from partner s to partner s', using transportation mode m.
- $SSTV_{ss'pm}$: The stochastic variation of the time required for transferring one unit of product p from partner s to partner s', using transportation mode m, following a uniform distribution $[-SSTV_{ss'pm}, SSTV_{ss'pm}]$.
- SP_{sp}: The capacity per time unit required for producing product p in the facilities of partner s, with $0 \le SP_{sp} \le 1$, $s = 1 \ldots S$, $p = 1 \ldots P$.
- SPV_{sp}: The stochastic variation of capacity per time unit required for producing product p in the facilities of partner s, following a uniform distribution $[-SPV_{sp}, SPV_{sp}]$.
- S_{max}: the maximum number of partners that may produce the same part within the DMN.

Table 1 An alternative DMN configuration example

Partner	Product P_1	Product P_2	Product P_3	Product P_4
S_1	0.0	0.4	0.0	0.0
S_2	1.0	0.6	0.0	0.0
S_3	0.0	0.0	0.8	0.0
S_4	0.0	0.0	0.0	0.7
S_5	0.0	0.0	0.2	0.3
S_6	0.0	0.0	0.0	0.0
S_7	0.0	0.0	0.0	0.0

- ST_{st}: The capacity already allocated in time unit t for partner s.
- STV_{st}: The stochastic variation, regarding the capacity already allocated in time unit t for partner s, following a uniform distribution $[-STV_{st}, STV_{st}]$.
- SY_{sp}: The quantity of product p in the inventory of partner s.
- PO_{ops}: The quantity of product p of order o, issued by partner s.
- DD_o, ED_o: The due date and the simulation end date of order o.
- AD_o: The arrival date of order o.

The above is the minimal information required for generating alternative DMN configurations, without having to take into account the process plans and the specific details of each partner's production equipment.

3.2 Generation of Alternative DMN Configurations

We define as an alternative DMN configuration the SxP matrix A_{sp}, where each element of this matrix a_{sp} represents the probability that partner s produces product p.

This probability actually defines which partner will be producing which product, part or subassembly, when an order (either for an end product or for a subassembly or a part required for manufacturing the end product) arrives or is issued within the DMN.

An example of an alternative DMN configuration (matrix A_{sp}) is shown in Table 1: with reference to the case scenario described in Sect. 4 (alternative #4 of Table 4), where 5 suppliers (S_1 to S_5) and 2 customers (S_6 and S_7) have to collaborate for the dispatch of a number of orders, product P_1 will entirely be produced by S_2, whilst partner S_1 will produce 40 % of the quantity ordered of P_2 and S_2 will produce the remaining 60 % of the quantity ordered of P_2. We consider as a DMN the set of all potential partners that could take part in the dispatching of an order. Contrary to the existing hierarchical approaches, the cooperation among the DMN members is considered being loose, without having to identify which partners have a leading role or not. Orders may actually be received by all partners. In this paper, however, it is assumed that the partners who can manufacture and deliver a specific product are the ones who usually receive an order for this product and therefore initiate the DMN configuration process.

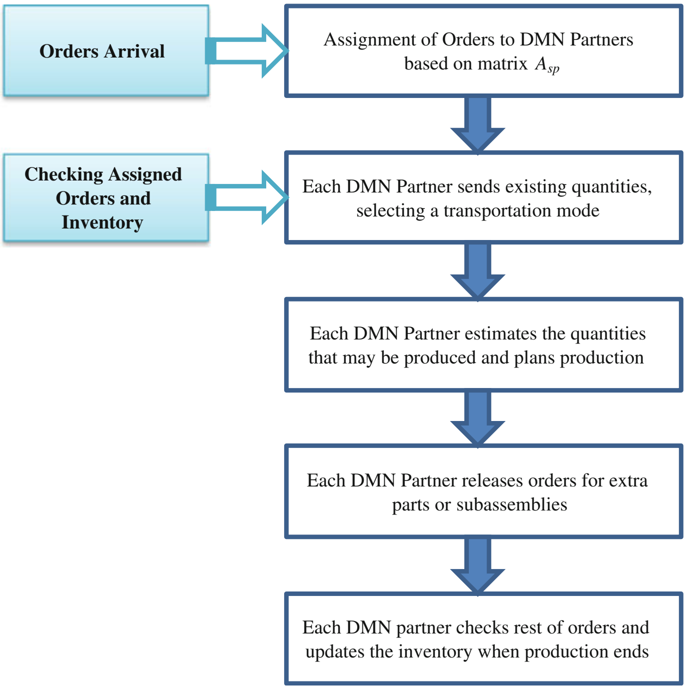

Fig. 2 Overview of the simulation process

3.3 Simulation of Alternatives Samples

For each alternative DMN configuration a number of samples is simulated (Fig. 2). For each sample, in each time unit, the orders received are randomly assigned to the partners available, the ones who can produce the products ordered, as per the matrix A_{sp}. Each partner checks the assigned orders and in case a part of an order may be fulfilled, a transfer order is released towards the partner who has released the original order. In order to take into account different transportation options in all samples, thus considering how adaptive the DMN configurations, in terms of transportation efficiency, are, a random transportation mode m from the ones available is selected for each sample. The associated transportation cost and time $SSR_{ss'pm}$, $SST_{ss'pm}$, $SSTV_{ss'pm}$ are used in the process of calculating the corresponding transportation cost and time of order o for sample n (TC_{on}). The remaining product quantities of the assigned orders are then checked against their requirements of subassemblies and parts. If the production for a part of the order may be initiated, a production order is released and planned, having taken into account the production capacity already allocated (ST_{st}, STV_{st}) as well as the capacity requirements of the products to be produced (SP_{sp}, SPV_{sp}). In case extra subassemblies or parts are required for the fulfillment of an order, new ones are

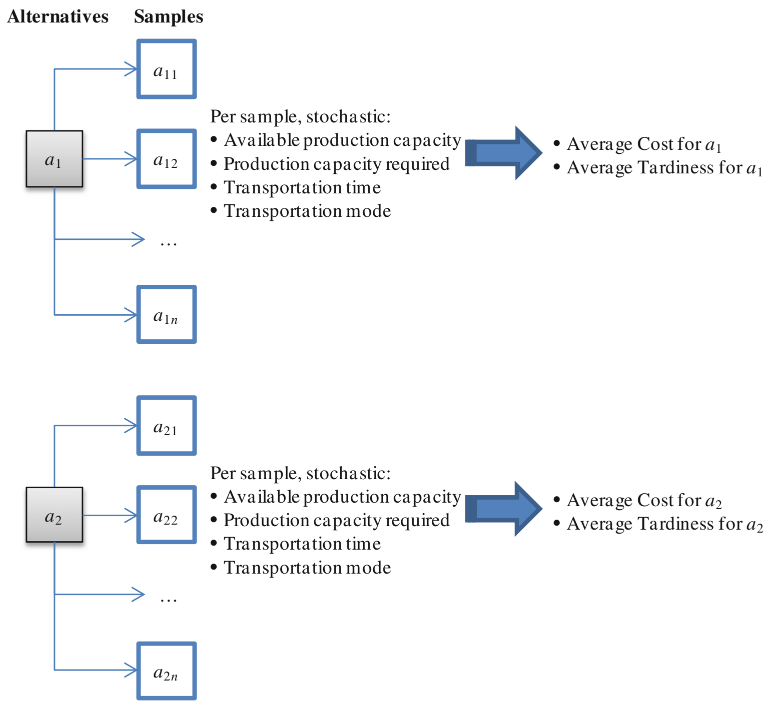

Fig. 3 An example with alternatives and samples

released towards the DMN partners. When all orders have been dispatched, the simulation of the samples is completed and other ones are then simulated until all *N* samples of all *A* alternatives are evaluated (Fig. 3).

3.4 Evaluation of Alternatives

All the samples of alternatives are evaluated against the criteria of average tardiness and cost. In particular:

$$Tard_a = \frac{\sum_{n=1}^{N} \sum_{o=1}^{O} \{max(ED_{on} - DD_{on}), 0\}}{n} \quad (1)$$

$$Cost_a = \frac{\sum_{n=1}^{N} \sum_{o=1}^{O} TC_{on}}{n} \quad (2)$$

Using the simple additive weight method and having already identified the criteria weights for defining their relative importance, the overall utility of each alternative may be calculated with the aid of a software application. This way, all alternatives may then be ranked and presented to the user. The average cost and

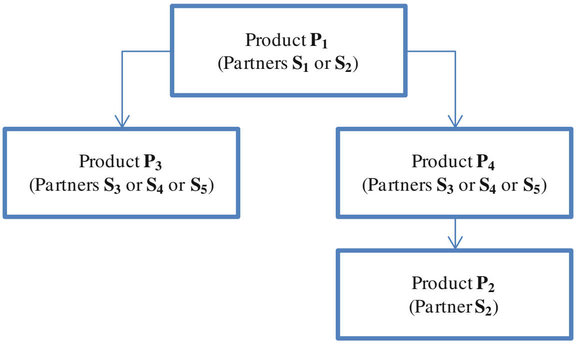

Fig. 4 Case scenario: bill of materials and suitable partners

Table 2 Description of the case scenario

DMN properties	Value
Number of partners	7
Number of products	4
Number of tiers	3
Transportation modes	2
Evaluation criteria and weights	Cost: 50 %, tardiness: 50 %

tardiness values of the alternative DMN configurations are considered as a measure of the DMN's adaptability towards demand requirements. Apparently, future demand scenarios may also be taken into consideration for each alternative.

4 Implementation and Experiments

For the purpose of testing and validating this proposed approach, a software application with a simulation engine has been implemented and a series of experiments has been carried out. A 3-tier case scenario is demonstrated with 7 partners (including 2 customers) and 4 products. Part P_1 may be produced by partner S_1 and S_2, whereas, P_2 is produced by S_2 only and P_3 and P_4 may be produced by partners S_3, S_4, S_5 (Fig. 4).

The properties of the DMN are shown in Table 2.

The information regarding the orders is depicted in Table 3.

Four experiments have been carried out with a different number of alternatives (A) and a maximum number of partner (S_{max}) who could take part in the manufacturing of the same product or part. For the first two experiments only one partner may produce each part, while in experiments 3 and 4, up to 2 partners may produce each part. The results of the best alternative generated in each experiment are shown in Table 4.

Twenty samples were generated per alterative for all four experiments. The performance of the best alternatives suggested in these experiments is compared

Table 3 Orders information

Order#	Product	Customer	Quantity	Due date (days)
1	P_1	S_6	1	2
2	P_1	S_7	2	4
3	P_1	S_6	2	7
4	P_2	S_7	1	2
5	P_3	S_7	2	3

Table 4 Experiments and performance of best alternatives

#	A	S_{max}	$Cost_a$ (€)	$Tard_a$ (days)	Util	P_1 partners	P_2 partners	P_3 partners	P_4 partners
1	5	1	55400	5.24	0.00	S_2 (100 %)	S_1 (100 %)	S_3 (100 %	S_4 (100 %)
2	50	1	36765	4.20	0.88	S_1 (100 %)	S_2 (100 %)	S_3 (100 %)	S_4 (100 %)
3	5	2	41747	4.53	0.63	S_1 (40 %)	S_1 (70 %)	S_3 (40 %)	S_3 (50 %)
						S_2 (60 %)	S_2 (30 %)	S_5 (60 %)	S_4 (50 %)
4	50	2	38275	3.87	0.96	S_2 (100 %)	S_1 (40 %)	S_3 (80 %)	S_4 (70 %)
							S_2 (60 %)	S_5 (20 %)	S_5 (30 %)

and their utility is estimated, taking into account the criteria weights. It is obvious that the more alternatives are generated, simulated and evaluated the more promising the best alternative DMN configuration looks. It is also interesting to note that the performance of the DMN is better when more options are available, in terms of the maximum number of partners that can produce the same part.

5 Conclusions

A novel approach for modeling Dynamic Manufacturing Networks as well as for generating and evaluating alternative configurations has been proposed. This method requires minimal information regarding the status of the manufacturing systems belonging to the network partners. This information is in principle limited to the capacity available per partner over the scheduling horizon, their production capabilities, the status of their inventory and the existing modes of transportation.

The dynamic nature of the manufacturing network is addressed in the following ways:

- The uncertainty associated with the production and transportation times, as well as with the demand profile is also considered via the sampling mechanism of the proposed approach: many different scenarios are therefore simulated beforehand, in order to ensure that the manufacturing network may operate efficiently under different conditions.
- This method enables collaboration schemes of specific products, subassemblies and parts, i.e. their production may be distributed to many partners. The uncertainty related to the partners' production capacity is taken into consideration and

therefore collaborative schemes with more partners are proposed in case it is likely that a partner cannot deliver.

- The different transportation modes provided are also taken into account, along with the corresponding costs and times for each alternative via the sampling mechanism. This way, the adaptability of the proposed DMN configurations in terms of how well they behave in terms of transportation efficiency is considered; in case any transportation problems emerge, the proposed DMN configurations are expected to cope well with these problems.
- Whenever a disruption in the operation of a DMN occurs, the proposed approach may be executed again, towards modifying the initial DMN configuration.

Nevertheless, a series of assumptions were made for testing, validating and presenting the proposed approach:

- Production capacities have been assumed to be evenly distributed,
- A randomly generated demand profile was used including the orders' due dates.

However, without loss of generality, the proposed methodology may easily be used with other statistical distributions and demand profiles.

Through the simple case scenario given and the experiments carried out, it has been shown that the proposed approach could be used for determining adaptive DMNs in a volatile and highly uncertain global market environment. The problem of integrating complex products/parts and suppliers' interrelationships, the finite production capacity of the potential partners, different transportation modes and the uncertainty pertaining to available and required production capacities and process times cannot be handled by conventional Mathematical Programming and Operations Research approaches.

Going beyond the configuration and planning phases, further features would include options for lot sizing within the DMN as well as options for expanding the use of the proposed approach in the domain of the manufacturing scheduling, where detailed process plans and configurations have to be considered at each partner's level. Integrating data from the shop floor and the logistics network for monitoring the operation of a DMN is also another idea that is worth experimenting with. More sophisticated scenarios may also be tested, involving the transportation activities and organizations as part of the DMN.

DMNs are expected to be in charge of an increasing part of the global manufacturing activity and therefore, providing new methods and tools for improving their operation and overall efficiency is of paramount importance.

Acknowledgments The work in this paper has been partially supported by the FP7 Integrated Project "IMAGINE—Innovative End-to-end Management of Dynamic Manufacturing Networks", funded by the CEU.

References

1. Chryssolouris, G.: Manufacturing Systems—Theory and Practice. Springer, Berlin (2006)
2. Permenter, K., Anand, S.: State of Cross Channel Retail Supply Chain Execution. Aberdeen Group, Boston (2011)
3. Chryssolouris, G., Papakostas, N., Mavrikios, D.: A perspective on manufacturing strategy: Produce more with less. CIRP J. Manuf. Sci. Technol. **1**, 45–52 (2008)
4. Scholz-Reiter, B., Morosini Frazzon, E., Makuschewitz, T.: Integrating manufacturing and logistic systems along global supply chains. CIRP J. Manuf. Sci. Technol. **2**, 216–223 (2010)
5. Viswanadham, N., Gaonkar, R.S.: Partners selection and synchronized planning in dynamic manufacturing networks. IEEE Trans. Robotics Autom. **19**, 117–130 (2003)
6. Speranza, M.G., Ukovich, W.: Minimizing transportation and inventory costs for several products on a single link. Oper. Res. **42**, 879–894 (1994)
7. Theattre, K., Graves, S.: Tactical shipping and scheduling at Polaroid with dual lead-times. In: Innovation in Manufacturing Systems and Technology (IMST) Report, http://web.mit.edu/sgraves/www/SMA%20paper%20Oct%2001.pdf
8. Seifert, R.W., Langenberg, K.U.: Managing business dynamics with adaptive supply chain portfolios. Eur. J. Oper. Res. **215**, 551–562 (2011)
9. Vidal, C.J., Goetschalckx, M.: A global supply chain model with transfer pricing and transportation cost allocation. Eur. J. Oper. Res. **129**, 134–158 (2001)
10. Klincewicz, J.G., Luss, H., Yu, C.-S.: A large-scale multilocation capacity planning model. Eur. J. Oper. Res. **34**, 178–190 (1988)
11. Stadtler, H.: A framework for collaborative planning and state-of-the-art. OR Spectr. **31**, 5–30 (2009)
12. Bhatnagar, R., Chandra, P., Goyal, S.K.: Models for multi-plant coordination. Eur. J. Oper. Res. **67**, 141–160 (2004)
13. Pibernik, R., Sucky, R.: An approach to inter domain master planning in supply chains. Int. J. Prod. Econ. **108**, 200–221 (2007)
14. Dudek, G., Stadtler, H.: Negotiation-based collaborative planning between supply chain partners. Eur. J. Oper. Res. **163**, 668–687 (2005)